DISTRICT HEATING AND COOLING SYSTEMS WITH HEAT PUMPS

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Abstract: District energy systems have the potential to decrease the CO_2 emissions linked to heating, cooling, electricity and hot water. This is true in particular when considering the prospect of large polygeneration energy conversion technologies, allowing a more rational use of energy and a better sharing of resources between users. Significant improvements towards lower greenhouse gas emissions will however not be possible without rethinking the way heating and air-conditioning shall be met, namely changing from individual solutions to more rational solutions, including the consideration of networks when dealing with high energy density districts. Several alternatives of advanced networks exist. They range from relatively high temperature networks with local organic Rankine cycles or absorption cooling units, to low temperature networks with or without phase change fluids but with heat pumps. The paper presents a new network operated with CO_2 and connected to a central plant with an open cycle CO_2 heat pump. The system is discussed and compared with a double water network that would meet the same heating and cooling demands.

Key Words: ***heat pumps*, *district energy system, CO_2, piping, cogeneration of heat and cold***

1 INTRODUCTION

District energy systems have the potential to decrease the energy consumption and the CO_2 emissions linked to energy services (heating, cooling, electricity and hot water). This is true in particular when considering the prospect of large polygeneration energy conversion technologies allowing a more rational use of energy and a better sharing of resources between users. In Switzerland, like in many industrialized countries, the energy consumption, related to heating, amounts to more than 40% of the distributed (final) energy. Even though major efforts are done to improve the envelope of the buildings, this trend is slow on a global scale. Moreover the increasing frequency and length of heat waves in the summer, with peaks of electricity demand for air-conditioning, are also to be considered.
Significant improvements towards lower greenhouse gas emissions will however not be possible without rethinking the way energy services such as heating and air-conditioning shall be met, namely changing from individual solutions to more rational solutions, including the consideration of networks when dealing with multi-occupation urban districts. The paper reviews several alternatives of networks ranging from relatively high temperature networks with local Organic Rankine Cycles or absorption cooling units, to low temperature level networks with phase change fluids and heat pumps. The paper presents several concepts including other media than water as energy transfer fluid through the network. In particular, a novel two tubes CO_2 network is discussed in details and compared with more conventional approaches.

2 DISTRICT ENERGY SYSTEMS

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 extent, cooling systems, have been proposed or installed in significant number from the eighties in Europe (Almqvist 1988), Asia (Narita 1984) or America (Calm 1988). However, when considering the large variety of building energy and temperature level requirements due to the age or the level of 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 (Lorentzen 1990) or optimized in simple network configurations (Curti et al 2000). Configurations including a three pipes system, circulating a refrigerant to take advantage of the latent heat, have been analysed (Favrat et al.1991). 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.

In this paper, a new CO_2 based district energy system is presented, that takes advantage of the latent heat of CO_2, and that alleviates the major drawbacks of conventional water based district energy systems, by allowing an optimal energy exchange between users and therefore a more rational use of energy.

3 DISTRICT ENERGY SYSTEMS OPERATING WITH WATER

Most urban 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 (Söderman et al. 2006) and in Switzerland (Felix et al.2006). 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 guaranteeing 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) units exploiting the exergy difference between the supply temperature and the temperature required by the building heating network (Kane et al. 2003), 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. Moreover water can freeze causing damages in case of network problems at very low atmospheric conditions. As a consequence water pipes are often installed below the freezing soil line as the use of anti-freeze is not welcomed because of environmental problems in case of leaks. There are basically two solutions to add the cooling services to already existing district heating systems:

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 (Söderman et al. 2006), 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.

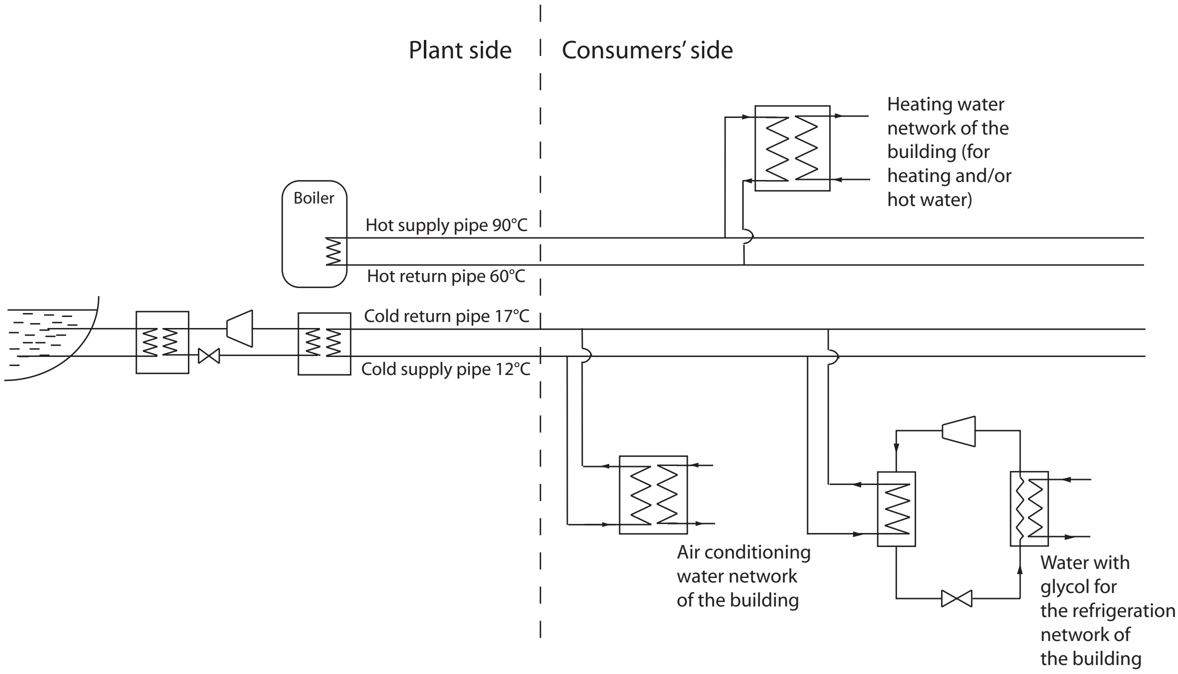


Figure 1: Connections between the network and the users in a district energy system using water as energy transfer medium

Solution 1 requires four pipes altogether, which implies a lot of space and high digging costs. It can also become problematic when space in existing underground channels is limited. An example of the implementation of Solution 1 above is done for instance in Turku, in Finland, where it is considered a logical, symmetric solution to the already existing heating network (Söderman et al. 2006). In the case of Turku, 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 already exists.

Water as a distribution fluid has the drawback of being a fluid that can freeze which often requests to install pipes below the soil freezing part.

To alleviate the main drawbacks of water systems mentioned above (namely exergy losses and space), a new CO_2 system is proposed, which could potentially be installed near ground and therefore request less digging.

4 CO_2 DISTRICT HEATING AND COOLING NETWORK

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

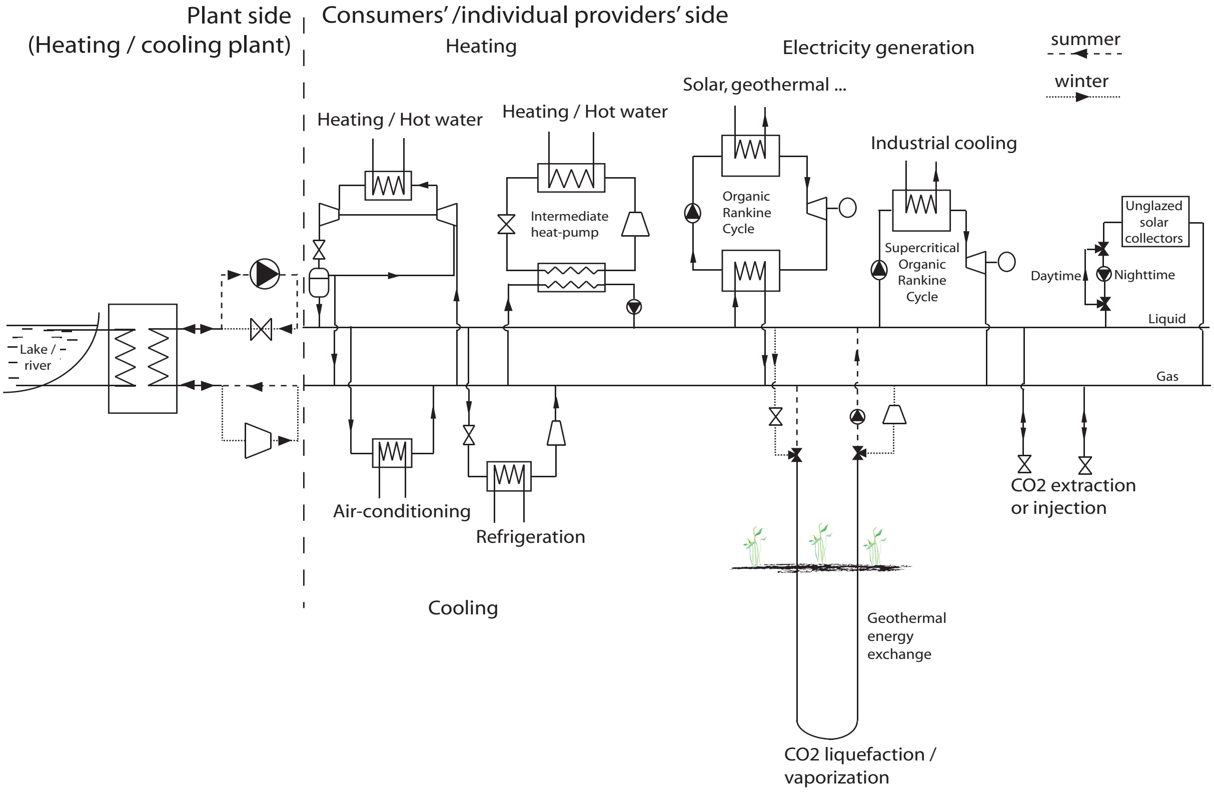


Figure 2: Schematic representation of the CO_2 based network including the users/suppliers

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 NH_3), or a small glide, like HFC407C (or HFC410A). 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 from 12°C to 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 (Söderman et al. 2006).

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.

4.1 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 to be supplied 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.

4.2 Energy conversion technologies at the user's place

At the user's place, the 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. If geothermal collectors are available or possible (under green areas for example), CO_2 vapour could be generated in winter by means of a heat pump, and CO_2 liquefaction 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 panels in winter for instance, if the sun is shining, in order to generate additional CO_2 vapour to meet the heating and hot water requirements. In summer, at night, CO_2 could be liquefied if the atmospheric temperature is below the chosen network temperature (for example 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 "Vapour" 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 vapour 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 vapour phase is directly recirculated to the compressor. If the heating requirements decrease, thus diminishing the needs for CO_2 in the vapour phase, the CO_2 vapour can be circulated directly from the separator back to the vapour 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 vapour pipe. Due to the slight over-pressure in the liquid pipe compared to the vapour 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 vapour 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 (conventional or supercritical) 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 (or without, if the well is deep enough), and therefore help providing the required CO_2 for heating and hot water purposes. On the other hand, in summer, vapour CO_2 can be liquefied (mainly in the night time) 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 vapour CO_2. During the night time, especially in summer, if the atmospheric temperature is below 18° C, the existing heat-exchanger can be used to liquefy vapour CO_2 for the daytime air-conditioning.

8. Fire extinction

The CO_2 contained in the network can be used for fire extinction purposes if needed.

9. CO_2 collection

The network can be used to collect and transport CO_2 from fuel cell or other decentralized cogeneration units.

10. 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 as shown in Figure 3. 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 vapour 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 vapour on the other hand either flows back to the compressor, or, if the heating (and/or hot water) requirements decrease, to the vapour 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 vapour quality, or back to the vapour pipe.

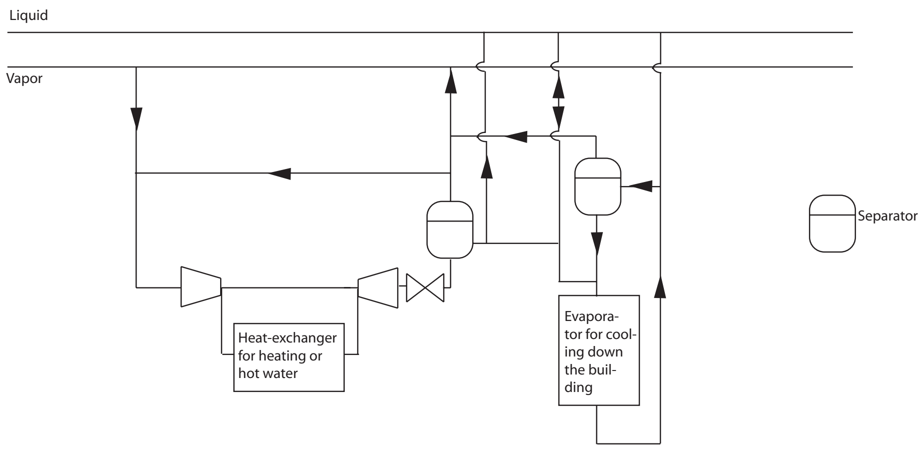


Figure 3: Combined heating and cooling mode

5 CASE STUDY

Figure 4 shows the flowsheet of a district configuration and network proposed in (Weber 2008) with the massflows corresponding to Summer, Mid-season, Winter and an annual average. It includes a central plant feeding through a network a group of three different users with their seasonal demands of heat and cold specified in Table 1.

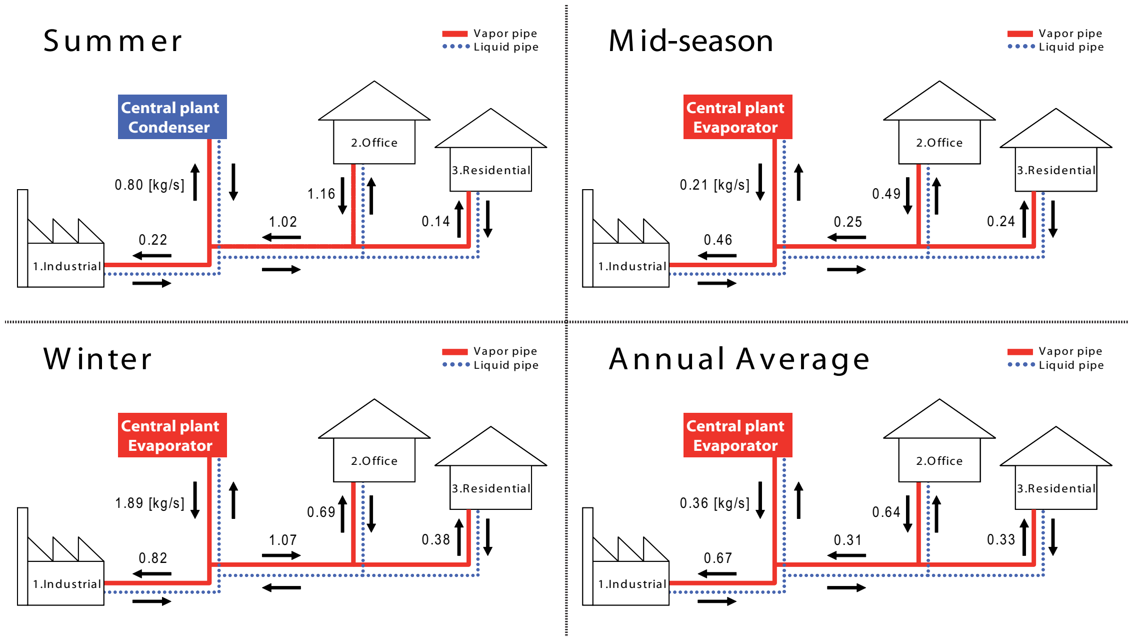


Figure 4: Case study CO_2 network joining 3 users with massflow indications

The modeling is done using gPROMS (Oh and Pantelides 1996) and the thermodynamic properties are calculated with the MULTIFLASH routine of gPROMS after an initial validation using REFPROP (Lemmon 2002).
The heat exchangers are supposed to be counter-current with 100 segments to calculate the supercritical CO_2 cooling.
Compressors are oil-free single-stage and characterized with a constant global isentropic efficiency taken at 75%. Friction losses in the piping are neglected at this stage.

Figure 4 shows the direction of the flow and the massflows in the various pipes at the different seasons. As expected during summer an excess of vapour is formed and the central plant acts as a condenser unit pumping back liquid. In mid-season and winter as well as on the average over the year the central plant works as a first stage heat pump providing vapor at the network vapor pressure. Except for winter the administrative building (user 2) is a net consumer of liquid, while consumers 3 and 1 are net consumers of vapor.

Table 1: Users demand

	Industrial building			**Office building**			**Appartment building**		
Season	Su	Mid	Win	Su	Mid	Win	Su	Mid	Win
Q_h [kW]	24	69	172.2	19.35	56.25	146.7	9.36	27	67.14
Q_{hw} [kW]	24.6	24.6	24.6	18.45	18.45	18.45	21.06	21.06	21.06
Q_c [kW]	0	0	0	218.3	139.1	0	0	0	0
$T_{h\ sup}$ [°C]	29	37	50	29	37	50	29	37	50
$T_{h\ ret}$ [°C]	25	31	40	25	31	40	25	31	40
$T_{hw\ sup}$ [°C]	60	60	60	60	60	60	60	60	60
$T_{hw\ ret}$ [°C]	12	12	12	12	12	12	12	12	12
$T_{c\ sup}$ [°C]	12	12	12	12	12	12	12	12	12
$T_{c\ ret}$ [°C]	22	22	22	22	22	22	22	22	22

Table 2 shows the diameters of pipes in the sections shown in Figure 4. They have been calculated for the maximum flow assuming a maximum velocity of 12 [m/s] for the vapor and a velocity of 2 [m/s] for the liquid.

Table 2: Pipe diameters of the CO_2 network and of water networks for the same duties

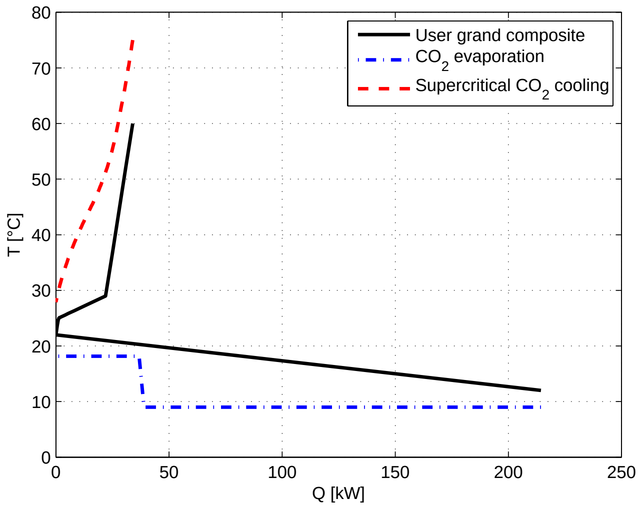
Pipes	**State of CO_2**	**Diameter [mm]**	**Equivalent water networks**	**Duty**	**Diameter [mm]**
From/to central plant	Vapor Liquid	34.4 38.8	Heating Cooling	Supply & Return	42.8 57.7
From/to user1	Vapor Liquid	22.7 25.6	Heating Cooling	Supply & Return	31.6 -
From/to users 2 & 3	Vapor Liquid	25.8 29.2	Heating Cooling	Supply & Return	35.9 57.7
From/to user 3	Vapor Liquid	15.4 17.4	Heating Cooling	Supply & Return	21.2 -

For comparison one heating and one cooling network of water with a temperature difference of 30°C for heating and 10°C for cooling would imply at the central plant pipe diameters of 42.8mm for heating and 57.7mm for cooling (Table 2). Considering that the water pipes will have a significantly larger insulation, this means a significantly larger trench for the dual water network compared to the CO_2 network

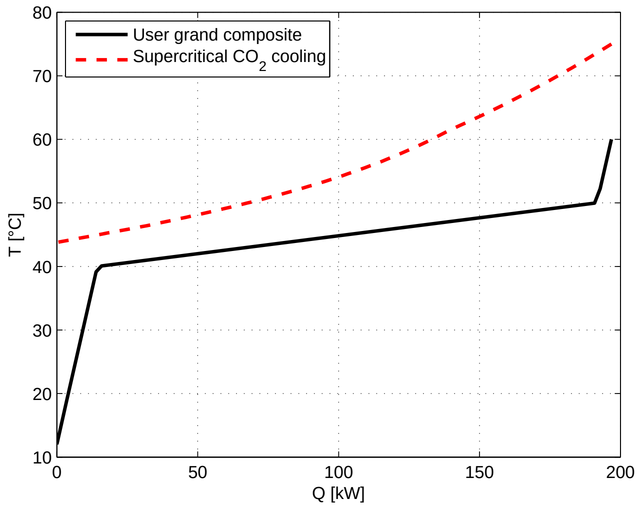
Figure 5 shows selected composites curves of the users and network utilities for the most demanding periods of the year. One can clearly distinguish the lower slope segments of the local heating and cooling networks and the steeper portions referring to the domestic hot water services. Note that the pinch temperature difference of 5°C is very conservative and the decentralized compression ratio could be further optimized for efficiency.

The dotted composites represent the CO_2 contributions. The top one is the heat supplied by the cooling of the CO_2 of a decentralized supercritical heat pump cycle having a pressure ration of 1.9. The lower part shows two evaporation “plateaux”, one being from a simple evaporator at the network saturation temperature and the second being an evaporator downstream of an expansion valve generating vapor to be recompressed with a dedicated compressor.

a) User 2 Summer



b) User 1 Winter



c) User 3 Winter

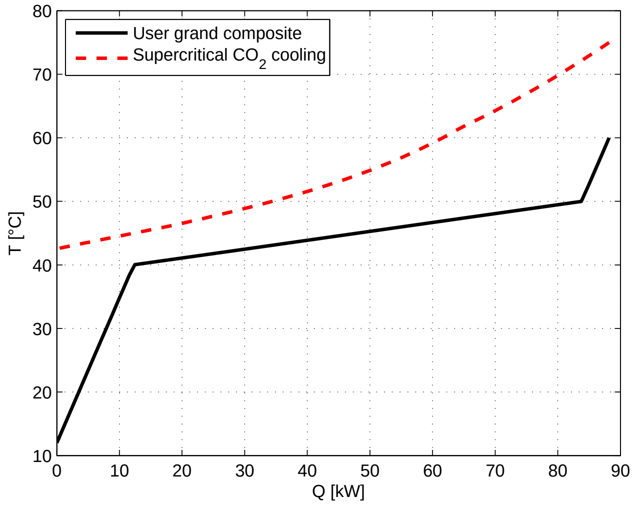


Figure 5: Composite curves of the users with the corresponding utilities provided by the CO_2 network

Compared to a conventional single stage CO_2 heat pump the advantage is that the vapour resulting from the expansion valve needs only to be compressed from the pressure corresponding to the network pressure. The decentralized heat pump acts like the second stage of a two stage heat pump.
For the case considered the seasonal First Law efficiency varies from 2.4 in winter when synergy between duties does not apply to 6.1 in mid-season and 9.8 in Summer. This is based on compressor isentropic efficiencies of 0.7 for the decentralized compressors and 0.75 for the central plant compressor. As already observed further parameters could be optimized for the winter conditions including the pinch temperature difference, the level of pressure in the network and the configuration of the decentralized heat pump.
Further calculations on Second Law efficiencies are still underway.

6 CONCLUSION

A new concept of heat pump based energy distribution system in urban areas is proposed and is shown to require less space and trench work while improving the synergy between the various users for a more rational use of energy in parts of cities. It is one promising path for an increased contribution of heat pumps to more sustainable cities.

7 REFERENCES

Almqvist P. 1988. “Large Heat Pumps in Stockholm”, *Newsletter of the IEA Heat Pump Center*, Vol. 6, Number 3.

Narita K. 1984. “Building the heat pump system in Hikarigaota Park Town: lessons and conclusions”, *IEA Heat Pump Conference*

Calm J.M. 1988. “District heating and cooling with heat pumps outside the United States”, *ASHRAE Transactions*, Vol. 94, Number 1.

Lorentzen G. 1990. “Heat Pumps for District Heating Applications”, *3rd IEA Heat Pump Conference*.

Curti V.,von Spakovsky M.,Favrat D. 2000. “An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace, parts I and II”, Int J. of Thermal Sciences, vol.39, No7.

Favrat D., Grivel T. 1991. “District heating and cooling with heat pumps and refrigerant networks: Utopia or possibility?”, *Proceedings of the Conventional & Nuclear District Heating Conference*, Lausanne, Switzerland.

Söderman J., Öhman G., Aittomäki A., Mäkinen A., Sipilä,K., Rämä M. 2006. “Design and operation of integrated cooling and heating systems in regions and buildings”, *KYLMA* (technical report), Abo Akademi University, Finland.

Felix J.E., Friedli S. 2006, *Personal communication*, Services Industriels de Genève, Geneva, Switzerland.

Kane M. et al. 2003. “Small hybrid solar power system”. Energy 28/14, pp 1427-1443.

Weber C. 2008. “Multi-objective design and optimization of district energy systems including polygeneration energy conversion technologies”, *Thesis 4018*, Ecole Polytechnique Fédérale de Lausanne, Switzerland.

Normes SIA 384/2 1983 – “Puissance thermique à installer dans les bâtiments”, Société Suisse des ingénieurs et architectes

Oh M., Pantelides C. 1996. “A modelling and simulation language for combined lumped and distributed parameter systems”. *Computer and chemical Engineering*, 20-6/7:611-633

Lemmon E., McLinden M., and Huber M. 2002. “NIST Reference Fluid Thermodynamic and Transport Properties - REFPROP, Version 7.0”. *National Institute of Standards and Technology*