Key energy and technological aspects of three innovative concepts of district energy networks

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1. Introduction

Urban areas represent an ever increasing challenge in term of energy use and environmental impact associated with it. According to the World Bank [1], the share of the world population living in urban areas rose steadily from 34% to 53% over the period 1961–2013, and projection from the United Nation expect this number to reach 68% by 2050. In Switzerland the current figure is 73% which is on parity with the value in Europe. According to URBACT [2] the building sector in the European Union accounts for 40% of the final energy consumption and 36% of the emissions of greenhouse gases. It also considers that energy efficiency in buildings located in urban areas represent one of the greatest potential to cut down greenhouse gases emissions and reduce the impact of the European society on climate. According to the Swiss Federal Office for Energy [3], the final energy consumption associated to thermal energy services in the sectors of households, services, industries are 87.6%, 71.5% and 68% respectively. Therefore, in order to realize the potential of energy savings in urban areas, it appears crucial to develop efficient energy conversion technologies dedicated to the thermal services. Obviously, other measures have to be taken jointly in order to reach the full potential of savings in the urban building sector. Measures such as improvement on the buildings envelope, management of solar and internal gains, better integration of electrical and thermal energy services, etc ... will also contribute.

The basic concept of using a CO2 network for both district heating and cooling was described in Ref. [21] based on theoretical demands. A second paper [23] illustrated its application to a real district.

The present study compares three concepts of district energy network for the same real district as in Ref. [23] on an energy basis and also from a technical point of view. Two of such networks are based on the use of the latent heat (refrigerants including CO2) while the third one refers to “so-called anergy networks” with water [18–20]. The goal is to provide a valuable insight on the potential of such networks, as well as on the technological similarities/particularities that characterize them. Note that bulky 4 pipe networks (two hot and two cold) have not been considered in the comparison since they would hardly allow the synergy between users that was looked after.

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2. Historical and current trends in district energy networks

District heating network have been used to provide thermal energy services to buildings in densely populated area for over a century. In fact, the first mentioned use of a heat distribution network dates back to 1332 where geothermal water was provided to houses in the village of “Chaudes-Aigues” (France) via a piping network. This system is still partly used today. However, modern district heating networks only date back to the end of the nineteenth century. In 2011, member countries of Euroheat and power [4] had over 482000 km of district heating in operation, 2/3 of which for Russia and China only, they provided 3276 TWh of heat to the final users. The share of the population connected to district heating networks in all these countries is in average 28.6%. Two major technological shifts have occurred over the twentieth century with regard to the technology of district heating. The first shift concerns the supply temperature that gradually decreased as new networks were being built. Networks built in the early 1900’s typically distribute steam at ~300 °C, while those built between 1930 and 1970 rely on superheated water above 120 °C and more recent networks operate with water at ~80 °C. The trend toward lower supply temperatures continues as networks at ~50 °C are considered for the supply of energy efficient building areas [5–7]. For instance, since 1985 space heating is delivered to the campus of EPFL by two networks one with a supply temperature of 65 °C (at Tsa = −10 °C) feeding the oldest buildings and one at 50 °C for the newer constructions. The second shift concerns the conversion technologies used in these networks. Initially, fossil fuelled heat-only producing boilers were the only technology, but over the years, and especially after the oil crises of 1973 and 1979, steam cycle based cogeneration plants became widespread. In 2011 and for the OECD countries the share of district heat provided by cogeneration plants reached 79% [8]. One has also to mention the successful integration in district heating of biomass fired and municipal solid wastes fired boilers and CHP plants, of gas turbines either in single or combined cycles, of electric and absorption heat pumps and of solar thermal collectors [9–13].

Since the 1980’s, district cooling networks have also been in use [14], they consist in distributing cold water to the customers through a network of pipes, either in a closed or open loop. The cold water can be directly pumped from a river, a lake or a sea and sent through the network or it can also be used in a heat exchanger at the central plant to cool down the water from the network. Finally, if the water from the source is not cold enough, centralized water cooled chillers are used.

Where both district heating and cooling networks coexist, heat pumps at the central plant are sometimes used to provide both services simultaneously [14]. Another trend of development is the use of a single network to provide heating and cooling services. It has been proposed to use a district heating network to deliver heat to the hot source of absorption chillers installed at the users end, allowing the delivery of cooling services which reduce the relative thermal loss during the hot season. The use, at the user end, of absorption heat pumps and/or small cogeneration units based on ORCs is also a mean to increase the energy efficiency when an existing high temperature district heating networks is used to provide heat to modern buildings equipped with low temperature hydronic loops [15,16]. In some cold water networks, essentially built for cooling purposes, decentralized electric heat pumps are sometimes used to deliver heating services [14]. The major interest of using decentralized heat pumps is to supply heat at a temperature adapted to each user, thus reducing the electricity consumption when the buildings stock is heterogeneous as compared to a centralized solution with a single supply temperature fixed by the most demanding consumer. There is a maximum limit to the use of decentralized heat pumps in networks where the users are connected in series (no return line) to avoid freezing in the pipes. For a network with the users connected between a supply and a return line, there is no such limit, the maximum amount of decentralized heat pumping being mostly linked to the maximum flowrate and the supply temperature. For instance, at the time of writing, a 28 MW district heating network relying on a cold water loop feeding decentralized heat pumps is under construction in “La Tour-de-Peilz” (Switzerland) with its operation that started in 2016.
Yearly energy requirements per square meter for the different services.

Table 1

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</thead>
<tbody>
<tr>
<td>Space heating</td>
<td>124.6</td>
<td>66</td>
<td>55</td>
<td>55</td>
<td>37.5</td>
<td>70.6</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>70</td>
<td>66</td>
<td>45</td>
<td>45</td>
<td>12.5</td>
<td>21.4</td>
</tr>
<tr>
<td>Hot water prep.</td>
<td>7.4</td>
<td>66</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>30</td>
<td>10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Data centre cooling</td>
<td>–</td>
<td>–</td>
<td>8</td>
<td>45</td>
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</table>

Over the last decade, concepts of enhanced networks have been proposed. They are able to supply heating and cooling at temperatures adapted to each building. They also allow the recovery of waste heat emitted by cooling users for valorisation at the heating users. These concepts operate at similar temperatures, between 5°C and 15°C, allowing the use of direct cooling for most of the cooling services and provide heat via the extensive use of decentralized heat pumps. Furthermore, they all use a small temperature difference between the two pipes they rely on. The main topological difference that can be identified is the use of water vs. refrigerant fluids as heat transfer media. The water-based advanced district energy networks seem to have appeared in Switzerland over the last 5 years, in the German speaking part they are referred to as “Anergienetz”. To the authors’ knowledge, three such networks are in operation [18–20], the largest one, on the campus of ETHZ – Honggerberg, is part of a set of measures that should allow the campus to reach the per capita targets of 2 kW average primary energy consumption (in fact 2 kW·year/year) and 1 ton/year emission of CO2 equivalent [18]. Refrigerant-based district energy networks are promising, since they rely on the latent heat of evaporation/condensation of a refrigerant to collect and transfer heat across the network [21–23]. At the time of writing, the focus is on the use of CO2 as a refrigerant, as it is the only non-toxic, non-flammable of the natural refrigerants available [24]. However, CO2 still presents some challenges and the recent appearance of HFO refrigerants makes the question of the choice of the heat transfer media worth re-investigating.

3. Case study

The following study is based on the implementation of a heating and cooling district network in the area of “Rues Basses” in Geneva described in Ref. [23]. This area is divided in 32 subareas composed of different types of buildings, each of them being characterized by the five following services:

- Space heating
- Air conditioning
- Hot water preparation
- Refrigeration (for commercial use)
- Cooling of data centres.

Yearly energy requirements of these services are based on the Swiss Standards [25] and the literature [26]. Their values are given in Table 1 for the six types of building considered. The computation of the space heating and air conditioning requirements is based on the definition of the building’s loss coefficient and the use of daily heating and cooling degree days as explained in Ref. [23]. Fig. 1 shows the energy demand expressed in daily values of the entire area in 2012. 53.1 GWh have to be provided annually by the network to satisfy space heating and hot water preparation requirements. The heat removed by the network to satisfy cooling services amounts to 49.4 GWh. By connecting heating and cooling users together, the network allows thermal exchanges between them.

4. Energy conversion technologies

4.1. CO2 network

The concept of the CO2 network studied here is the one described by Weber and Favrat in Refs. [21,22]. Heat transfer between the network and users is achieved using the latent heat of carbon dioxide near the saturation state in a vapour and a liquid line. The choice of CO2 as a heat transfer fluid comes from the fact that it is the only non-toxic, non-flammable, natural refrigerant available in the desired range of temperatures for the network. The lowest pressure and its corresponding saturation temperature is chosen such as to enable the use of free-cooling for air conditioning and the cooling of data centres, which constraints the maximal temperature of the network at 12.5°C during the air conditioning season (Ta > 18°C) and 22.5°C the rest of the time. The saturation pressure corresponding to these temperatures is respectively 47 and 61 bar, representing a challenge from the point of view of the acceptability of the technology by the authorities and the public. It also corresponds to high reduced pressures of 0.637 and 0.827 respectively, which translate into relatively high densities for both the vapour and liquid phases. Thanks to the use of the latent heat of evaporation of 190 kJ·kg⁻¹ and 135 kJ·kg⁻¹ respectively, it results in networks requiring pipelines that have a small cross section.

To allow the fluid to flow directly though the evaporators, the pressure of the liquid line is set 1 bar above the saturation pressure of the vapour line. The refrigeration requirements are satisfied by local vapour compression chillers in which the CO2 from the liquid line is expanded through an expansion valve, evaporated and recompressed in the vapour line (Fig. 2 left). The installed power of the decentralized cooling equipments is based on a design atmospheric temperature of 30°C [23]. The installed heat exchanger
area is computed based on the LMTD in the exchanger and assuming a heat transfer coefficient of 2.5 kWm⁻²K⁻¹. The electrical consumption of the refrigeration systems is approximated using ideal Carnot cycles multiplied by constant exergy efficiency as explained in Ref. [23]. Space heating and hot water preparation are based on the heat provided by the condensation of the CO₂ vapour. In each subarea, intermediate heat pumps are used in order to transfer this heat from the network to the users and to adapt its temperature to the desired level. The use of intermediate heat pumps is the consequence of the low critical temperature of CO₂ (31.0 °C) that prevents efficient heat pump open cycles to be used for space heating applications. Considering the trend of restricting the use of HFC refrigerants in Switzerland and in a foreseeable future in the rest of the world [24,27], the HFO refrigerant R1234yf is considered to be the working fluid of these intermediate heat pumps. The design temperature of the heating equipment is based on an atmospheric temperature of -7 °C. The heat pump cycle calculations are described in Section 4 and are used to define the compressor work and the necessary installed power. As explained in Refs. [23], the installed electric power per heat pump is limited to 67 kW. Depending on the subarea requirements, multiple heat pumps have to be installed.

The electrical consumption of the refrigeration chillers and heat pumps depend on the setpoint temperatures of the corresponding services given in Table 2. For space heating, a heating curve defined in Ref. [23] was used. It relates the hydronic loop supply temperature to the daily mean atmospheric temperature.

The cooling, respectively heating requirements not being balanced throughout the year, a central plant is used to supply or remove heat from the network. It was supposed that the necessary heat can be taken or released in a water source at a constant temperature (7.5 °C) [13 and 28]. Considering a pinch temperature of 1.5 K (ΔT_minHR) and a temperature difference of 0.5 °C between the inlet and the outlet of the water source, the minimal network temperature is limited to 9.5 °C. A more detailed description of the central plant operation is given in Ref. [23]. Based on the energy requirements of the 32 subareas and their distribution along the network, the CO₂ massflow in the lines can be computed as presented in Ref. [23]. The massflow needed by a subarea takes into account internal exchanges. For example, in winter, the vapour rejected by the refrigeration systems is directly used by the heat pumps of the subarea, which reduces the massflow of vapour that has to be provided by the network itself. According to [29], the liquid pipe diameters have to be chosen so that the liquid velocity doesn’t exceed a certain limit above which cavitation can occur. This limit is 2.1 ms⁻¹ for 200 mm diameters, 2.5 ms⁻¹ for 300 mm diameters and 3 ms⁻¹ for diameters above 500 mm. For the case studied in this paper, a liquid CO₂ line diameter of 270 mm is sufficient to respect this velocity constraint. Note that the maximum massflow is defined by the air conditioning peak of demand in summer. (See Fig. 1.)

Pressure drops along the vapour and liquid lines have been computed using Churchill’s correlation. High pressure drops can cause temperature variations along the lines and decrease the efficiency of decentralized heat pumps. It can also promote the emergence of two-phase flows that have to be avoided for operational reasons. In order to limit these two effects, pressure drops are limited at 1 bar. Booster compressors and pumps are therefore installed along the lines to fulfill this pressure drop constraint. The liquid pipe diameters given by the velocity constraint allow a single pump to be used on the liquid CO₂ line. A vapour pipe diameter of 330 mm is necessary to require only one single booster compressor along the line. This was found to be the optimum economic trade-off between investment in piping and machinery vs. operating costs [23].

4.2. Water network

Instead of the latent heat, the sensible heat of liquid water can be used to satisfy the heating and cooling requirements. This type of network uses similar equipments (Fig. 2 middle) as the CO₂ network, but unlike the latter it can be operated at a much lower pressure of few bar only. A minimal temperature difference of 2 °C between the hot and the cold water lines was set. As for the CO₂ network, air conditioning and the cooling of data centres are also

Table 2

<table>
<thead>
<tr>
<th>Networks characteristics and annual electrical consumptions.</th>
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<tr>
<td>Units</td>
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<tr>
<td>T₁ winter °C</td>
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<tr>
<td>T₁ summer °C</td>
</tr>
<tr>
<td>Dvap [mm]</td>
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<tr>
<td>Dina [mm]</td>
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<tr>
<td>Heat pumping [GWh/yr]</td>
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<td>Refrigeration [GWh/yr]</td>
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<td>Pumping [GWh/yr]</td>
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<tr>
<td>Central plant [GWh/yr]</td>
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<tr>
<td>Total [GWh/yr]</td>
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<td>COPH</td>
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Fig. 2. Decentralized heating and cooling equipments of the three different networks.

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satisfied using free cooling. The hot and cold water temperatures are therefore limited to respectively 16 °C and 12 °C when air conditioning is needed and to 26 °C and 22 °C the rest of the time. Unlike CO2, water cannot be directly used in refrigeration systems. An additional heat exchanger has been installed to decrease the system’s efficiency. A modification must also be done at the central plant in heat pumping mode (Fig. 3). The renewable heat is used to evaporate an intermediate refrigerant (R1234yf) that is then compressed and condensed to transfer the heat to the water network. The operating principle of the central plant removing heat from the network (“summer” mode) is simply done using a heat exchanger like in the CO2 network. Instead of having only a single CO2-water heat exchanger that can be used as an evaporator (“winter” mode) or as a condenser (“summer” mode), the central plant of the water network needs to be equipped with three different heat exchangers.

The water mass flow calculations are similar to the one presented for the CO2 network in Ref. [23] with the latent heat being replaced by the enthalpy difference between hot and cold water. The pipe diameters are defined according to the limit indicated by Ref. [29]. It is directly linked to the temperature difference between hot and cold water. A temperature difference of 2 °C corresponds to a diameter of 1085 mm. Knowing the pipe diameters and the necessary water mass flows of the 32 subareas the pressure drop evolution along the lines is computed also using Churchill’s correlation. Depending on its heating and cooling load and its location the evolution along the lines is computed also using Churchill’s correlation. The pressure drop of 1 bar along the CO2 network corresponds approximately to a drop in saturation temperature of 0.9 °C. The same drop in temperature is obtained for the R1234yf with a pressure drop of 0.15 bar only. Every time such a pressure drop is reached along the liquid or the vapour line, a booster pump or compressor has to be installed. For a liquid R1234yf line diameter of 270 mm, pumps have to be installed at four different locations along the line. To require only one booster compressor along the vapour line, the diameter of the latter would have to be 710 mm.

4.3. R1234yf network

The use of refrigerant R1234yf instead of CO2 is another way to reduce the operating pressure of the network while keeping the advantage of playing with the latent heat. For saturation temperatures varying between 12.5 °C and 22.5 °C, the corresponding pressures vary between 4.7 and 6.4 bar which is typical of natural gas urban networks. The temperature of R1234yf critical point is 94.7 °C instead of 310 °C for CO2. This allows using open-cycle heat pumps (Fig. 2 right) taking the R1234yf directly out of the saturated vapour line, compressing it, condensing it to provide the refrigeration needed and to control the hot and cold water temperatures varying between 12.5 °C and 22.5 °C. The network temperature is limited by the same constraints as the CO2 network with the addition of latent heat. For saturation temperatures varying between 12.5 °C and 22.5 °C, the corresponding pressures vary between 4.7 and 6.4 bar which is typical of natural gas urban networks. The temperature of R1234yf critical point is 94.7 °C instead of 310 °C for CO2. This allows using open-cycle heat pumps (Fig. 2 right) taking the R1234yf directly out of the saturated vapour line, compressing it, condensing it to provide the refrigeration service.

5. Electrical consumption of the networks

5.1. Sensitivity of the global electrical consumption

The pipe diameters of the different networks are fixed by applying the velocity constraint on liquids, by considering that compressors are installed at only one location along the vapour lines and by limiting the pressure drops to 1 bar for CO2 and 0.15 bar for R1234yf. The values are summarized in Table 2. Hence, the energy consumptions (electricity) of the different networks are only dependant on the network temperatures. The central plant and the decentralized heat pumps represent the most important electrical consumption. During the air conditioning season (Ta > 18 °C), the temperature of the network has only a very limited impact on the overall electricity consumption since it only affect the production of domestic hot water and the refrigeration. Fig. 4 shows the sensitivity of the annual electrical consumption of the three networks to their respective temperature in “winter” (no air conditioning demand). Table 2 summarizes the results for the temperatures of the network that minimize the global electrical consumptions. Note that the temperature difference between hot and cold water is

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**Fig. 3. Central plant operating principle for phase change fluid networks and water network.**
constant throughout the year.

As expected, when the winter temperature of the networks is increased, the electrical demand of the decentralized heat pumps decreases while the one of the central plant increases. However, the winter temperature that minimizes the overall electrical demand differs for each variant of network, according to the relative importance of the exergy losses in either the central plant or the decentralized heat pumps. More specifically, the exergy efficiency of the central plant in the CO2 network is lower than that in the R1234yf counterpart, which explains the lower optimal winter temperature for the CO2 variant. For the water network, the temperature difference between the hot and cold line forces down the evaporation temperature in the decentralized heat pumps causing some exergy losses. This effect shifts slightly the balance between the electricity consumption of the decentralized heat pumps and the central plant towards a higher optimal winter temperature. Of the three proposed network, R1234yf exhibits the best energy performance, mostly because of the open cycle heat pumps (both centralized and decentralized) that eliminate the exergy losses in the evaporators of the decentralized heat pumps as well as in the condenser of the centralized heat pump.

At equal temperature the saturated vapour density of the R1234yf (24 kgm\(^{-3}\) at 9.5 °C) is much lower than the one of CO2 (133 kgm\(^{-3}\)) that leads to larger vapour line diameters. A reduction of the R1234yf vapour line diameter to the CO2 network’s value (330 mm) would require booster compressors to be installed in eight locations along the line instead of one. The electrical consumption due to pumping (booster pumps and compressors) would increase to 2.28 GWh/yr, which is around eight times the consumption obtained for a diameter of 710 mm.

The network efficiency is evaluated by the COP\(_{H,C}\) of the network that is obtained by dividing the sum of the annual heating and cooling requirements (102.5 GWh) by the network annual electrical consumption as defined in Equation (3).

\[
\text{COP}_{H,C} = \frac{\int (Q_H + Q_{H,W} + Q_{A,C} + Q_{\text{data}} + Q_{\text{ref}}) \, dt}{\int \dot{E} \, dt}
\]  

5.2. Impact of the heating and cooling requirements on the electrical consumption

As expected, when the winter temperature of the networks is increased, the electrical demand of the decentralized heat pumps decreases while the one of the central plant increases. However, the winter temperature that minimizes the overall electrical demand differs for each variant of network, according to the relative importance of the exergy losses in either the central plant or the decentralized heat pumps. More specifically, the exergy efficiency of the central plant in the CO2 network is lower than that in the R1234yf counterpart, which explains the lower optimal winter temperature for the CO2 variant. For the water network, the temperature difference between the hot and cold line forces down the evaporation temperature in the decentralized heat pumps causing some exergy losses. This effect shifts slightly the balance between the electricity consumption of the decentralized heat pumps and the central plant towards a higher optimal winter temperature. Of the three proposed network, R1234yf exhibits the best energy performance, mostly because of the open cycle heat pumps (both centralized and decentralized) that eliminate the exergy losses in the evaporators of the decentralized heat pumps as well as in the condenser of the centralized heat pump.

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\]  

Fig. 4 provides the T-s diagrams of the cycles in space heating heat pumps for the winter design conditions (Ta = −7 °C). The assumptions used in computing these cycles are similar to those described in Ref. [23–32].

The values of the COP of the centralized and decentralized heat pumps are provided in Table 3 for each variant of network. Note that the values for decentralized heat pumps are those at the winter design conditions.

Fig. 4. Sensitivity analysis of the network annual electrical consumption to the network temperature in winter (the top left figure shows a decomposition of the various consumption for the CO2 network).

Fig. 5. Sensitivity analysis of the network annual electrical consumption to the network temperature in winter (the top left figure shows a decomposition of the various consumption for the CO2 network).
temperature towards a higher value.

6. Advantages, shortcomings and particular features of the proposed network

Based on the model described previously, the differences between the three variants of network cannot be used as an indicator to determine the most promising one. The economic aspects are not able to distinguish between the three types of networks either, as it will be discussed in details in another article. As a consequence of these relatively equivalent performances, other decision factors are going to play a defining role on the future of each of the three proposed technologies.

This paragraph is focused on identifying and describing the decision factors that are going to impact the proposed networks and the associated issues. Obviously these elements are those that the authors are aware of at the time of writing.

Note that it is not the aim of the present study to give a definitive answer on which of the proposed networks is the best candidate. Firstly, because some of these issues require a very significant amount of work and secondly, the nature of the urban area considered is also likely to have a decisive impact.

However a smaller scale experimental study is underway to further analyse the potential dynamic effects of such networks. Preliminary results in cooling mode only show no particular pressure phenomena to be worried about.

6.1. Safety

The safety of a technology is a very important factor regarding its potential of development. A technology can be considered safe as long as it does not threaten unacceptably the human population and/or the environment during its construction, use and dismantling/disposal. The threat is associated to the concept of risk, generally defined by the multiplication of a probability of occurrence of a given event and of the severity of the damage caused by this particular event. Since the beginning of the industrial era, the introduction of safety measures has been done through various mechanisms, like new laws and regulations, technical standards, and risk insurances [33].

In the context of the proposed networks, one has to make a distinction between the variant using water as a heat transfer fluid, and the two using refrigerants instead. For the water variant, it is fairly obvious that no uncertainty exists with respect to the safety of the network. Indeed, the central plant is similar to "standard" network's central plant equipped with large heat pumps and the heating/refrigeration users' substations are submitted to the technical standards that apply to refrigeration and heat pumping equipments [34–36].

Regarding the refrigerant based networks, the rules and technical standards for refrigeration and heat pumping equipments also apply to the central plant and to all users' substations in spite of their novelty. For all these equipments, the foundation of the safety analysis is given by the European union's pressure equipment directive [37]. It defines safety categories for the pressure equipments according to the fluid they are filled with (toxic and/or flammable vs. others), the product of the maximum operating pressure times the volume for each component that can be assimilated to a tank, and the product of the maximum operating pressure times the nominal diameter for each component that can be assimilated to a pipe. The safety category of the equipment is defined by the category of its "worst" component. The

<table>
<thead>
<tr>
<th>Units</th>
<th>CO₂</th>
<th>Water</th>
<th>R1234yf</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP</td>
<td>3.9</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>COP_{central}</td>
<td>22.6</td>
<td>12.6</td>
<td>17.0</td>
</tr>
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Table 3: Decentralized heat pumps and central plant performances for the three different networks at winter design conditions (T_{a} = -7 °C).

Fig. 5. Decentralized space heating heat pump cycles with R1234yf as a working fluid (used for the different networks).
higher the category, the more stringent the certification procedure becomes. It also affects the choice of the control devices. Indeed, for devices constituting a part of a control chain ensuring safety functionality, the required safety integrity level is a function of the safety category of the equipment [38–40]. The European standard for refrigeration and heat pumping equipments [34–36] that also applies, considers differently equipments with compressors and tanks installed in unoccupied machinery rooms than those that aren’t and if they use secondary loop (indirect system) for the distribution or not (direct system). The latter cases require more safety measures to be taken.

In the case of the CO₂ and R1234yf based networks, the safety requirements at the user-end substations are very likely going to be more demanding than for the water variant. Indeed, the system would likely fall into the “direct system” category as a large amount of refrigerant is contained in pipes located outside the machinery room. Whereas in the case of the water network, the same installation could be made an “indirect system” by keeping the entire refrigerant circuit enclosed in the machinery room. In the case of the direct system it is most likely that, to meet the standard, it would be necessary to install a dedicated ventilation system controlled by a gas detection.

The major uncertainty regarding safety is linked to the presence of pipelines in a densely populated area. On the one hand, for the water network, the pipeline system is in all points similar to already existing district cooling networks, consequently one can argue that no supplementary risk is involved and the same sets of safety regulations, technical standards, and good practice rules apply.

On the other hand, in the case of refrigerant based networks the requirements for the pipelines themselves are not clear as the idea was not put into practice yet. Pipeline specific regulations do not apply on the CO₂ and R1234yf as they only focus on fuel dedicated facilities [41]. The European pressure equipment directive remains applicable [37] while the European standard on refrigeration and heat pumping equipments does not [34–36]. Eventually, in the case of Switzerland, and after a discussion with local authorities from the city and state (canton) of Geneva, it appeared that the art. 10 on disaster prevention of the environment protection act [42] would apply, leading to a procedure described in the Ordinance on Protection against Major Accident [43] (MAO).

The MAO procedure follows two steps. The first one – the summary report – consists in identifying the various possible disaster scenarios and evaluating the damage caused by the worst case scenario identified. The state (cantonal) authorities decide if the second step has to be carried out based on the gravity of the damage identified in step 1. In Step 2 – the risk report – a quantitative evaluation of the damage and probability of occurrence of all the envisaged disaster scenarios is done. A cumulative risk curve is generated on which the authorities decide whether the risk is acceptable or not and in the latter case, will ask for more safety measures and if necessary will limit or forbid the operation. Though the tediousness of the MAO procedure and its seemingly uncertain outcome can appear discouraging, it has to be kept in mind that it is a common procedure that many industrial facilities are required to fulfil, like natural gas and petroleum products transportation pipelines, railways potentially useable for the transportation of hazardous material, sites with a total storage capacity of chemical substances exceeding the MAO threshold quantity (for instance 20 tons of LPG, 2 tons of Ammonia or 500 tons of diesel/heating oil.) Facilities like these continued to exist and operate in Switzerland, after the introduction of the MAO in 1991. The main objective of the approach is for the authorities to know about the potential industrial hazards present on the territory and for the companies operating potentially hazardous facilities to be aware of the risks and to act on reducing both probability of occurrence of disastrous events and the extent of the damages they would cause.

In the case of very common facilities requiring MAO procedures, such as fuel and LPG storages, or natural gas transportation pipelines, examples have been made available by the Swiss Federal Office for the Environment [44–51], thus drastically reducing the amount of work necessary to do the study. However, in the case of the CO₂, respectively R1234yf network the MAO procedure,

![Fig. 6. Sensitivity analysis of the networks annual electrical consumptions and the networks temperatures in winter to heating and cooling requirements (the base case requirements values are in red). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)](image-url)
required prior to the construction of at least the first pilot plant, can be expected to be more cumbersome, as the accident scenarios analysis will likely require some modelling effort. For instance, in order to simulate realistically the propagation of a plume of CO₂/R1234yf in an urban area after an uncontrolled release.

The MAO procedure, to be done during the design stage of the first CO₂ or R1234yf network, will help defining a set of design rules and construction principles that will ensure safe operations of such a network. These rules and principles could then be reused for new networks. Depending on the result of the first MAO procedure and on the experience gained over the construction/operation of the early networks, it might as well be that the MAO procedure will or will not be required for subsequent networks.

The damages that the two proposed refrigerant networks can cause are listed in Table 4. It also specifies whether a particular damage applies to a CO₂, respectively R1234yf network and provides example of events that could cause them as well as some of the technical measures that can prevent the occurrence of such events and/or reduce the magnitude of the ensuing damage. Obviously other kind of prevention and protection measures should be taken. It includes avoiding unauthorized persons to be in direct contact with sensitive and/or potentially hazardous parts of the network, using a properly equipped and trained staff to operate and maintain the system. Regular training should also be organised for the staff to rehearse the procedure in case of a catastrophic event in coordination with the authorities. Finally, adequate personal protection equipments should be made available to the staff.

A last point on the safety concerns the refrigerant R1234yf. This fluid was developed as a replacement of the R134a in automotive air conditioning applications in order to meet the new greenhouse gas emissions standards set by the European Union. Over the last 4 years a controversy raged among the automotive industry regarding the potential hazard that the new refrigerant could cause in a fire. Indeed, on the one hand some manufacturers claim that during such a fire the R1234yf degrades into a dangerous chemical compound and used this argument not to operate the transition to the new fluid waiting for what they perceive as a safer alternative to be available, namely CO₂ based air conditioning equipments. On the other hand, a report from the society of automotive engineers [52] stresses the low risk for an individual to be exposed in a car to an open flame or to an excessive concentration of hydrogen fluoride. In Switzerland, the Federal office for environment considers R1234yf to be of safety group A2, that is non-flammable and non-toxic. However, it also says that it is not a definitive decision [24]. Overall, looking at the evolution of the controversy, it seems that R1234yf will eventually be widely adopted as a refrigerant.

6.2. Compactness

It is a known fact that district heating and cooling should be placed preferentially in areas with high energy density. However, as high energy density is generally correlated with a high population density, many reasons can impede the realization of a district heating/cooling network in a given area, such as:

- A congested underground, due to the presence of other infrastructures such as fresh water pipes, sewers, natural gas pipelines, underground power or telecommunication lines.
- The presence in the area of important public transportation facilities that would be too difficult/costly to re-route or interrupt during the construction of the network.
- A re-routing of the road traffic during the construction that would be too difficult.

All these constraints could be released, if a more compact form of network could be built. Smaller cross sections would give more freedom to lay the network between the other underground infrastructures. It would also reduce the footprint and the time duration of the construction, which translates into smaller perturbations of the road and public transportation traffic as well as reduced costs.

Among the three proposed networks, the water variant is the least favourable from the point of view of the compactness. The primary reason is the low energy density that results from the small enthalpy difference between the two lines. The resulting large mass flowrate of water to be transferred in the network combined with the restriction on the maximum velocity in the pipes leads to large pipe diameters. The second reason is the necessity to bury the pipes deep enough to prevent the water inside them from freezing, should a section of the network be disabled for long enough in winter time. Note that thanks to the low temperature differential between the water and the ground surrounding the network, the amount of insulation required is small in comparison to the one used in more conventional networks operating at higher temperatures. Typically for Geneva, the minimum freeze safe depth is 90 cm above the top of the pipes. For pipes directly buried in the ground, as opposed to those put into utility tunnel, a minimum depth is also required to avoid excessive loading on the pipes for instance due to heavy vehicles. Minimum depth of 1.2 m above the top of the pipes is required to withstand the mechanical load. This is in contrast with the gas variant, that requires only enough electrical field. Table 4

<table>
<thead>
<tr>
<th>Damage</th>
<th>CO₂</th>
<th>R1234yf</th>
<th>Events</th>
<th>Technical measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injuries/Damage to things due to projection of debris</td>
<td>Yes</td>
<td>Yes</td>
<td>Equipment failure after an uncontrolled pressure build-up or an act of a third person.</td>
<td>Place pressure release valves in accordance with the EU-PED. Indicate the presence of the pipeline. Use double wall pipes or place pipes in a suitable utility tunnel.</td>
</tr>
<tr>
<td>Asphyxia due to Suffocation</td>
<td>Yes</td>
<td>Yes</td>
<td>Leak from an equipment due to faulty sealing. Large leak after a pipe/equipment failure or misuse.</td>
<td>Avoid proximity with potential ignition sources. Place network sectioning valves.</td>
</tr>
<tr>
<td>Burns</td>
<td>Yes</td>
<td>(Yes)</td>
<td>CO₂: dry ice projection after a failure/ misuse of a piece of equipment. R1234yf: combustion of the fluid during a fire.</td>
<td>Avoid proximity with potential ignition sources. Place network sectioning valves. Apply the appropriate fire safety standards.</td>
</tr>
<tr>
<td>Intoxication</td>
<td>No</td>
<td>(Yes)</td>
<td>(R1234yf: combustion of the fluid during a fire leading to emission of noxious chemical compounds.)</td>
<td>Avoid proximity with potential ignition sources. Place network sectioning valves. Apply the appropriate fire safety standards.</td>
</tr>
<tr>
<td>Electrocut</td>
<td>Yes</td>
<td>No</td>
<td>Dry ice projection after a failure/ misuse of a piece of equipment and submitted to a strong enough electrical field.</td>
<td>Apply appropriate electrical standards</td>
</tr>
</tbody>
</table>

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imposed by bridge-class SLW60 vehicles for DN600 – DN1000 pre-insulated pipes [53,54]. Hence, in the present case, the depth of the trench is constrained by the necessity to withstand the design load.

There is a possibility to improve the compactness of the proposed cold water network by increasing the temperature spread between the two lines, thus increasing the enthalpy difference, but, as Fig. 4 shows clearly, it comes at the cost of higher electricity consumption. In the current study, the choice of using free cooling for the cooling of data centres and the air conditioning imposes a maximum temperature spread that result from the required temperature for those services. However, if vapour compression chillers were used instead, the temperature spread could be further increased. Obviously, the penalty on electricity consumption would be even costlier.

The two refrigerant networks would be more compact than the water variant as the diameter of vapoour and liquid pipes shown in Table 3 clearly demonstrate. Secondly, the problem of the depth of burial of the refrigerant networks is not constrained by the necessity to avoid freezing but only by the mechanical design load, assumed to be SLW 60 vehicles [53]. If it is assumed that double wall pipes are required for refrigerant networks a minimum depth on top of the pipes of 0.9 m is required [55]. On the left side of Fig. 7 are represented the trench's cross sections for the three proposed network at scale, for pipelines directly buried in a road used by heavy vehicles. The shaded area shows the minimum size of the excavation according to [54,55]. The greater compactness of the refrigerant based variants is obvious. In term of excavation work, the volume of material to be processed is 75.4%, respectively 82.2% lower for the R1234yf and CO2 network. Such reductions have the volume of material to be processed is 75.4%, respectively 82.2% excavation according to [54,55].

6.3. Equipments availability

The various equipments required for a successful implementation of all three networks are in general available on the market. For the equipments that are not readily available, sometimes it is possible to slightly modify the configuration of the system so as to avoid the use of one component and in general the amount of development to obtain the desired component can be considered as reasonably. In terms of equipment availability the CO2 network is the most critical as the number of equipments compatible with this fluid is relatively small, mostly because of the high operating pressure. However, as CO2 becomes a more widely used refrigerant, mostly for commercial refrigeration plant [56], the number of components on the market tends to increase. Mainly two types of equipment pose some problems.

The decentralized heat pumps used for space heating and domestic hot water production should have an evaporator-condenser at their cold source. In this heat exchanger, the CO2 on one side condenses, delivering its heat to the refrigerant that evaporates on the other side at slightly lower temperature. Today's commercially
available heat pumps do not have heat exchangers strong enough to withstand the pressure on the CO2 side. However the modification required is relatively minute and should not prove too difficult. A second possibility would be to use an intermediate water loop connecting an off-the-shelf water-water heat pump to the CO2 condenser on the network. Though very simple, this solution causes a significant penalty in term of energy efficiency, the COP of the heat pump being degraded by the lower temperature of evaporation imposed by the intermediate water loop.

The available pumps on the market that could be used as condensate pumps at the heating users’ substations are not very numerous. These pumps are required to pump the condensed CO2 from the decentralized heat pump’s heat exchanger back into the liquid CO2 line of the network. At the time of writing, one manufacturer proposes a range of suitable refrigerant pumps that could be used for heat pumps with a cooling capacity at their cold source of up to ~200 kWth\[57\]. A higher cooling capacity would require either a custom built pump, or to install several of the existing models in parallel.

In the present study, heat pumps used for domestic hot water production are assumed to use another working fluid than CO2. From an energy performance point of view, the use of a transcritical CO2 heat pump would be beneficial. The evaporator could be removed, the vapour being directly taken by the compressor from the vapour line, and the liquid directly sent to the liquid line after the expansion valve. Over the present network, the gain in performance would be minute as domestic hot water represents only a small fraction of the energy demand in the area studied. However in some particular cases such as hotels, hospitals or elderly homes, the development of such “open cycle” transcritical heat pumps would have to be considered. Domestic hot water heater using transcritical CO2 cycles have been used in Japan for more than a decade, and over 3 mio. units had been delivered in 2011. It would be also possible to change the heat exchanger at the cold source, such that it can accommodate CO2 from the network on one side and CO2 from the heat pump on the other. This solution has the advantage of preventing the migration of the compressor’s lubricating oil into the network. However, in the same time it is likely to cause a slight drop in energy efficiency.

In the case of the R1234yf network, the components are easier to obtain, as in general a direct conversion to R1234yf of an R134a dedicated equipment can be done. The use of R1234yf is still in its infancy, but it is spreading rapidly in spite of the controversy it fuelled regarding its safe use. To this date, the major concern for a R1234yf network is the price of the fluid that still is very expensive, and would represent a very significant part in the total cost of the system. Nevertheless, it can be expected that the price will decrease as more production capacity will be commissioned. Another point worth mentioning is the possibility for the fluid to be banned in the long run, as it has been the case for CFC and HCFC refrigerants and as the countries in the G20 council agreed to phase down HFCs\[27\]. Such a possibility poses a threat to a piece of infrastructure like a district energy network, as it is typically built to last for several decades.

Finally, it has to be mentioned that there is no issue regarding the availability of components for the water network proposed in the present study.

7. Conclusion

Among the three variants of network proposed, the one using R1234yf as a working fluid appears to be the most energy efficient, however not by a very significant margin. Though not discussed in the present study, the evaluation of the investment costs showed that none of the three types is significantly more advantageous than the other two. As a result, one can expect other, more secondary elements, to play the defining role in choosing which of the proposed solutions is the best. Compactness is one of these elements and it is not in favour of the water variant as it requires a significant amount of space due to the low energy density of the heat carrier. On the other hand, one can expect the laying of the pipes to be easier in the case of a CO2 or a R1234yf network, since the required size of the pipes and the necessary excavation work are much smaller than for the water counterpart. As a conclusion, in spite of relatively similar performances to the one of the water network proposed in this study, refrigerant based networks exhibit

Fig. 8. Possible implementation of a refrigerant network in a “surface” utility tunnel and with a typical technical room accommodating network’s sectioning valves and other safety devices.
a significant potential, particularly in urban areas that cannot be reached by the proposed water variant because of a highly congested underground, or because of the difficulties that the construction of a bulkier network might cause to the surrounding urban environment. This potential however will be at reach only once safety and regulatory issues linked to the construction and operation of refrigerants based district energy network will have been addressed.

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