CO2 Network

Case Study: ...

Tobia Wyss*[2], Luise Middelhauve†[1], Luc Girardin‡[1], and François Maréchal§[1]

[1]*Industrial Process and Energy Systems Engineering (IPESE), EPFL*
[2]*Master Student, Energy Management and Sustainability , EPFL*

January 7, 2019

*tobia.wyss@epfl.ch
†luise.middelhauve@epfl.ch
‡luc.girardin@epfl.ch
§francois.marechal@epfl.ch

Todo list

Abstract

District energy systems present a high potential to reduce CO_2 emissions caused by cities, thanks to the implementation of large polygeneration energy conversion technologies connected to buildings over a network. A specific technology, developed by EPFL, using a CO_2 network... A comparative analysis shows that...

Contents

1 Introduction

1.1 Context

Today climate change a fact, emissions explosed. We have to reduce... With the Kyoto protocol, the first international treaty about the fight against climate change, many countries have agreed to drastically reduce CO2 emissions in the coming decades.
One crucial sector is the production of heat, which represents a large share of the total greenhouse emissions. This is especially true countries at higher latitudes, i.e. with cold climates. For example in Switzerland the energy demand for space heating and hot water demand of buildings, accounts for around 41% (96.5 TWh) of the total energy demand of the country, and is still strongly dependent from fossil fuels. If we also include process heat, this figure rises to 54% (123.9 TWh)[?].
On the other side, the energy demand related to cooling is experiencing an exponential growth. This is, on the one hand, because it is becoming affordable for more people, as income levels rise. On the other hand, this increase is due to global warming. There are today 1.6 billion air conditioners (AC) in use, and about 50% of them are distributed in only two countries: China and USA. In some countries, especially in the Middle East, as well as in parts of the USA, during extremely hot days cooling can represent more than 70% of peak residential electricity demand. A huge problem with respect to this, is the quality of ACs. The majority of ACs that are sold in large markets, have an efficiency, which is only 50% or lower than the one of the best products available. This engenders, obviously, an important augmentation of the energy demand. Figure 1 shows how the energy demand has tripled since 1990, while the share of cooling energy in total energy use in buildings has risen from 2% to more almost 7% [?].

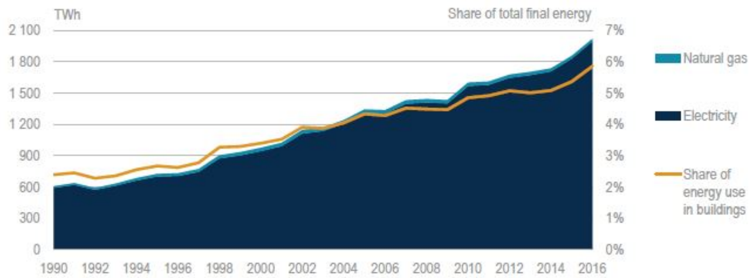


Figure 1: World energy consumption for space cooling in buildings. Source:[?]

A study shows that also in Switzerland cooling demand will strongly increase in the next decades, due to climate change. Figure 2 shows how this is particularly true for modern houses, which are very well isolated and efficient for the winter use. In this case the cooling demand will represent more or less a third of the heating demand[?].

According to the Population Division of the United Nations, the share of the world population living in cities has steadily increased from 34% in 1960 to 55% in 2017. Moreover, they prospect that, by 2050, this number will rise to 66%. In Switzerland, as well as in its neighbouring countries, the percentage of urban population is considerably higher, with 74% (2017) [?]. The fact that people live more and more in concentrated areas, also mean that the density of energy consumption is rising. This becomes particularly interesting for urban heating and cooling demand, since the high density of heat consumers sets the conditions for efficient systems, based on district energy networks.
The UNEP (United Nations Environment Programme) has identified a big potential in modern district energy systems, as the most effective approach to improve energy efficiency for heating and cooling, and enable the integration of renewable energies.
However, these technologies require a high level of technology coordination and planning, since they create more efficient systems that are also more complex to deploy and operate. This is why, further research and technology development are needed in order to foster the spreading of these technologies.

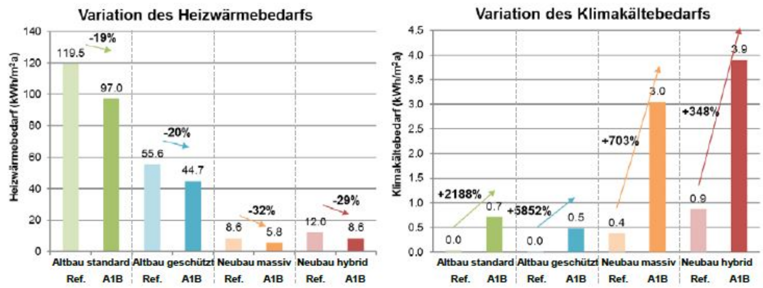


Figure 2: The evolution of median values of heating (left) and cooling (right) demand of the fours case studies ("Old building", "Old builing protected", "Solid construction", "Hybrid construction") between the reference period "1995" (1980-2009) and the period "2060" (2045-2074) in Basel. The percentage variations can be attributed to climate change. A1B corresponds to a median scenario developed by the IPCC. Source: [**?**]

1.2 Scope

The scope of this project is to pursue the study of the application of the CO2 based district energy network technology, proposed by Weber and Favrat[**?**]. In collaboration with Romande Energie, the utility company of canton Vaud, a feasibility study has to be performed on a specific case study: the residential district Eglantine in Morges. The work will try to answer the main research questions:
How does the CO2 district energy network perform - ecologically as well as financially - in the Eglantine district, and under which conditions does it perform better than concurrent solutions?

What are the characteristics of a typical district that favour the choice of the CO2 district energy network technology?

2 Literature review/State of the art

2.1 District heating

The evolution of the technology of district heating (DH) is shown in Figure 3. The first District Heatings (DH) have been installed in the 1880s in the USA, using concrete ducts to distribute steam at high temperature, which was then condensated by the consumers. This system was obviously not very efficient, due to the elevated heat losses during transportation, as well as the exergy losses due to the high temperature level. In the early 1930 a second generation was developed, which based on the use of pressurized water, distributed above 100°C. These networks were installed with the purpose of reducing fuel consumption, as well as to integrate the energy generation through CHPs (Combined Heat and Power). The third generation was introduced in the 1980s and it's main difference was the use of a lower distribution temperature (below 100 °C). In those years the main reasons for the installation of DH was security of supply, since they allowed to replace oil with more local and cheaper fuels such as coal, biomass and waste. Moreover, it allowed to use industrial waste heat, as an energy source. Nevertheless, a distribution temperature between 70-100 °C still origins very high heat losses, and it does not allow to integrate a larger number of heat sources. Moreover, also in space heating systems in buildings, there has been an evolution towards lower operating temperatures, reducing the average demand temperature.
These were the drivers for the development of the 4th generation, for which networks operate at a temperature between 30-70 °C. This enables a much better integration of the heating system into the global energy system, as it makes it possible to include low temperature sources (geothermal, solar thermal, refrigeration systems or waste heat from data centers).

District cooling (DC) networks had a similar development as DH networks, although to a smaller extent.

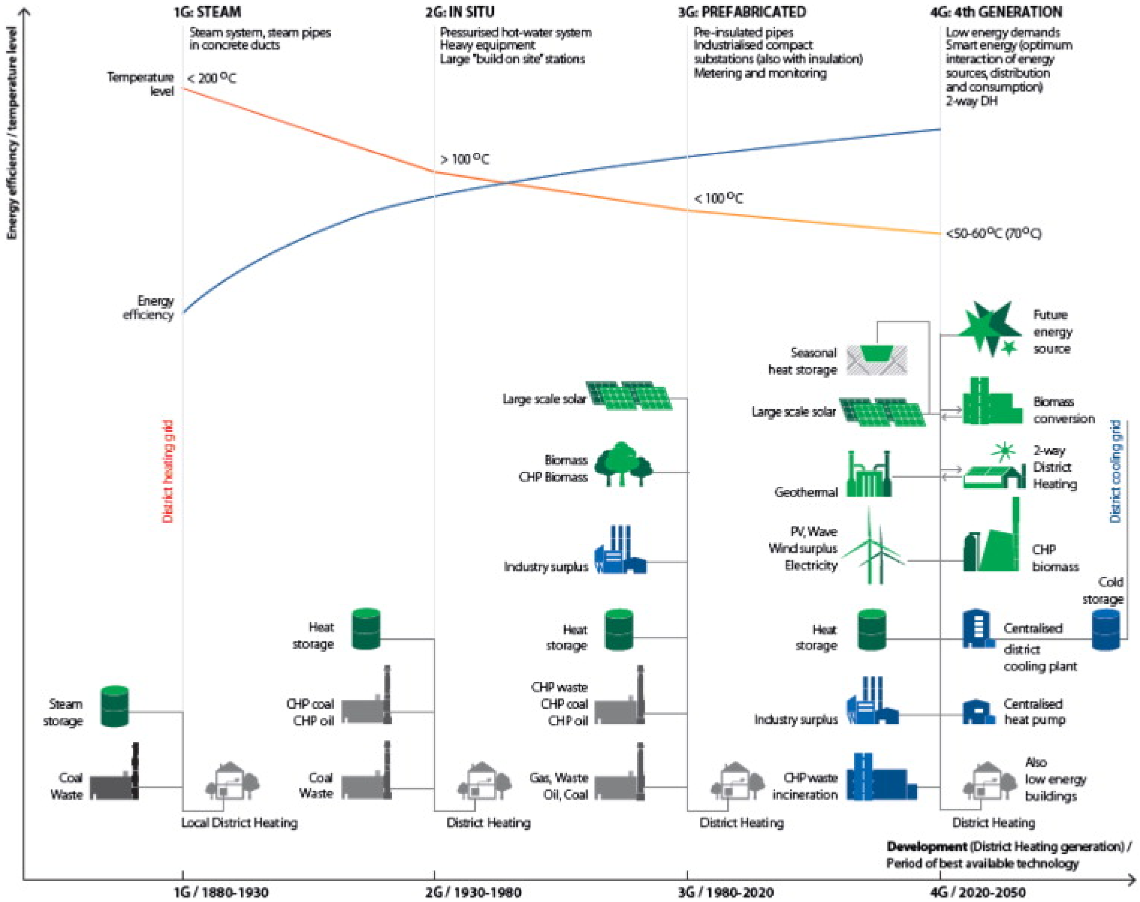


Figure 3: The evolution of the district heating technology, from the 1st to the 4th generation. Source: [?]

2.2 Fifth generation district energy networks

The 4th generation of DH technology, has already achieved remarkable success and has been widely applied, especially in Europe. However, the exergy losses of the system are still very high, due to the diversity of heat levels present in the system, limiting its efficiency. Moreover, the integration of DC, which, as it was mentioned beforehand is already important in cities and will become more and more important throughout the next years, needs the installation of a second and separate networks, which leads to high upfront costs.
This has lead to the birth of a new technology that uses an even lower distribution temperature (10-25 °C) to provide heating and cooling. In fact, the transfer fluid acts as cold network for cooling purposes and supplies, at the same time, evaporator heat to decentralized heat pumps. This is what is known as the 5th generation DH networks, also known as District Energy Networks (DEN) or District Heating and Cooling (DHC).

This technology has appeared in Switzerland in 2007, and it's mostly known as *anergy network*, or in german *Anergienetz*. To the authors knowledge, there are seven such systems operating by the end of the year 2018[?]. A summary of a selection of four of them is shown in Table 1, while more detailed information can be found in the Appendix 9.

All the anergy networks presented in Table 1 still base on water as a working fluid. Therefore, they work on sensible heat, which means that a heat exchange is bound to a variation in the fluids temperature. The challenge of these systems is given by the flow rate that is necessary to limit the temperature difference between the inlet and the return temperature of the network.
Thus, it could be very interesting to use refrigerants, instead of water, that enable to work with latent heat instead, which means collecting and distributing heat through the condensation, or the

Table 1: District energy systems in Switzerland

	Anergienetz ETH Hönggerberg	**Suurstoffi-Areal**	**Anergienetz Friesenberg (FGZ)**	**Genève-Lac-Nations (GLN)**
Location	Zürich	Rotkreuz	Zürich	Genève
Year of construction	2012 - 2026	2010 - 2020	2011-2050	2008 - 2016
ERA [m2]	475'000	172'421	185'000	840'000
Inst. Heating capacity [kW]	8'000	6'732	3'930	4'300
Heating demand '[MWh/a]'	28'450	10'619	35'000	5'000
Inst. Cooling capacity [kW]	6'000	2'327	3'500	16'200
Cooling demand '[MWh/a]'	26'200	2'364	80'000	20'000
Distribution fluid	water	water	water	water
Heat source	Laboratories waste heat +HP	Waste heat buildings + PVT (solar th.) +HP	Waste heat data center+HP	Lake water +HP
Heat storage	Geothermal well field (431 at 200m)	Geothermal well field (215 at 150 m, 180 at 280m)	Geothermal well field (332 at 250m)	None
T of heating pipe	24 °C - 8 °C	25 °C - 8 °C	28 °C - 8 °C	17 °C - 5 °C
T of cooling pipe	4 °C - 20 °C	4 °C - 17 °C	4 °C -24 °C	5 °C - 12 °C
Tot. investments '[Mio.CHF]'	37	n/a	42.5	33
Tot. COP of heating (incl. Pumps...)	5.8	2.7	4.1	6.5

evaporation, of the refrigerant. This poses some additional technological challenges, but has also very clear advantages, as it will be shown in the next chapters.

The choice of the refrigerant strongly depends on the application. In function of the operating conditions, three main criteria are evaluated: affordability, safety and environmental impact. A summary of the history of refrigerants is shown in Figure 4. The Montreal protocol, signed in 1987, designed the phase out of HCFC and CFCs, in order to prevent ozone layer depletion. This boosted the use of HFCs, as a replacement. However, not far later, people realized that despite being less damaging to the ozone layer, they were powerful greenhouse gases. Since 2013, a federal ordinance also strongly restricts the use of these last ones in Switzerland[?]. Also Europe has planned the phase-out of HFC in 2014[?]. This means that today the choice of refrigerants is essentially limited to natural refrigerants - as for example CO2 (R744), ammonia (R717) or propane (R290) - and the new environmentally friendly HFOs - as for example the fluorinated propane isomer R1234yf. According to Danfoss[?], CO2 will dominate industrial refrigeration, together with ammonia. Already today, this technology is widely used. For instance Migros, Switzerland's largest retail company, opened its first supermarket to use CO2, in a low-temperature subcritical system, in 2002. By today, 411 of the 700 supermarkets in Migros's portfolio are equipped with transcritical CO2 systems[?]. The choice of CO2 as a refrigerant relies, besides its thermodynamic properties, on the following arguments[?]:

- it is very abundant in the environment and is also waste of a multitude of industrial processes, resulting in very low cost

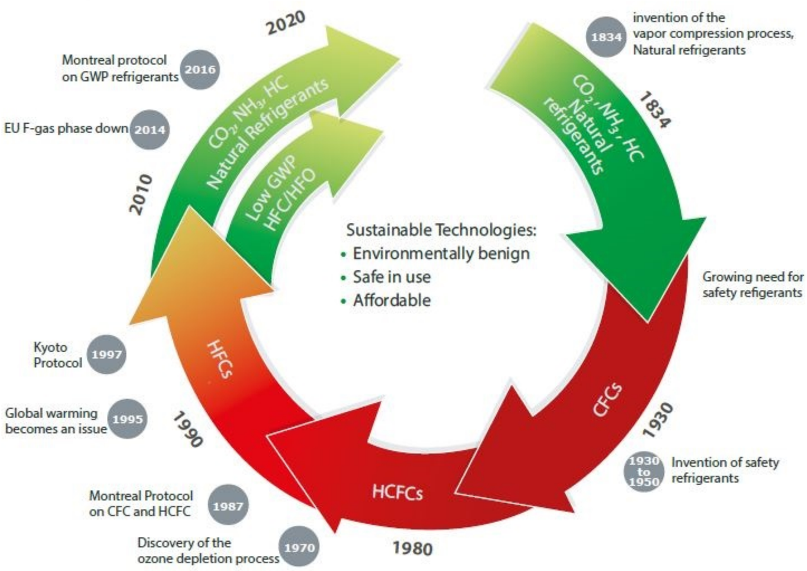


Figure 4: The historical cycle of refrigerants Source: [?]

- it is harmless to the biosphere
- it is non-flammable and non-toxic
- it is an inert gas

2.3 CO2 DEN

Weber and Favrat [?] proposed a new DEN based on the use of subcritical CO2. Also compared with water and HFO R1234yf and proved it best[?].

add anything here?..what?

2.3.1 The technology

As explained above, a refrigerant based DEN technology allows to store and transfer heat through the latent heat of vaporization of the refrigerant. The operating pressure is chosen in order to obtain the desired temperature in the system. That temperature is selected to be as high as possible to represent a good heat source for the decentralized heating heat pumps - resulting in good COP values -, while still allowing free cooling - avoiding the installation of compression chillers, and thus drastically reduce electricity consumption for space cooling.
The network consists of one saturated liquid pipe and of one saturated vapor pipe, both in a saturated temperature range from 12 to 18 °C[?]. The working principle is shown in Figure 5. Heating users can extract heat from the network through condensation of the refrigerant, taken from the vapour pipe. Respectively, cooling users take refrigerant from the liquid pipe and evacuate heat by evaporating it. The heat exchanges between the network and the users occur through condenser-evaporators heat exchangers, which keep the different refrigerant loops isolated[?]. The synergy between simultaneous heating and cooling users allows the recovery of waste heat. Most of the time, the required heating and cooling capacity will not be equal, which means that there is the need for a centralized balancing power. Indeed, a central plant is responsible to balance the overall network, by exchanging heat with the environment. For instance, a sole/water or a water/water heat pump can be used for this purpose.

2.3.2 Why? /Advantages

- Better energetic performance

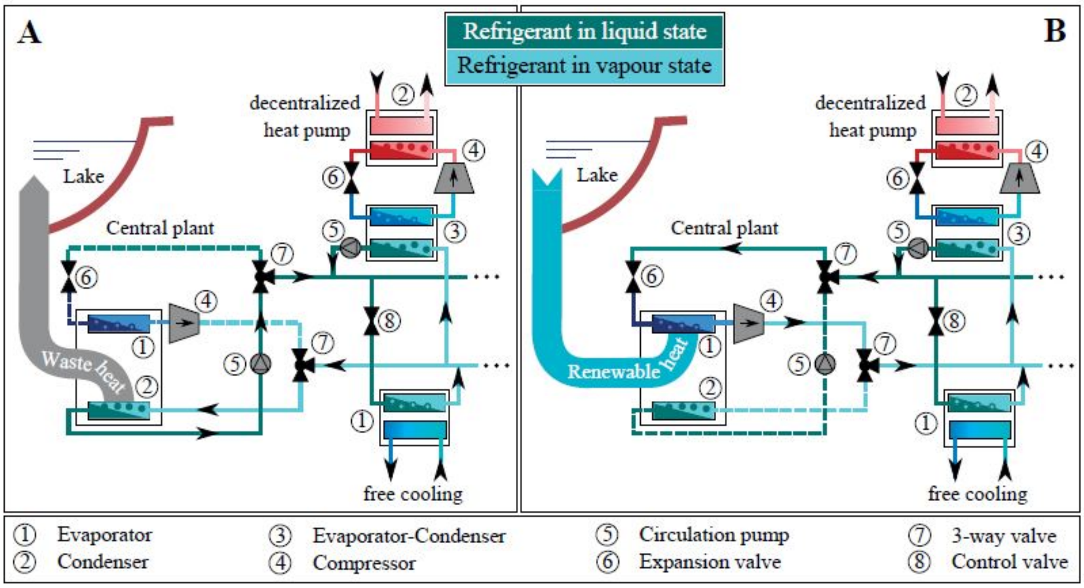


Figure 5: Schematics of a refrigerant based district energy network. Part A represents its net cooling operation, and part B its net heating operation. Source: [?]

- Better economic performance
- Given that no fluids move, only pressure maintenance, no return pipe, length of pipes is half.
- Smaller pipes (latent, not specific heat)
- low cost available CO2
- Facilitate storage (low temp)
- CO2 pipes allow decentralized CO2 collection from capture in CHP generation (ex. SOFC)
- CO2 ideal for PtG integration (storage and availability)
- integration of daily storage (heat buffer? or through latent heat, kinda buffer in the sist?)
- Second level of flexibility, combined with smart grid
- no risk of freezing
- flexibility to scale up
- zero carbon emission and pollution on site
- no chimneys or cooling towers in the city
- ability to recycle waste heat
- economics
- lower capital cost of construction
- lower running costs
- lower maintenance costs

The benefits of Fifth Generation District Heating and Cooling include:

- flexibility to scale up

- zero carbon emission and pollution on site
- ability to recycle waste heat
- economics
- lower capital cost of construction
- lower running costs
- lower maintenance costs

Disadvantages:

- High operating pressure
- Availability of components/technology

2.3.3 Efficiency gain - Study case Geneva

Henchoz et al.[?] performed an analysis of the potential application of a CO2 based DEN in a district in the city of Geneva. A map of the district, called "Rues basses", is shown in Figure 6.

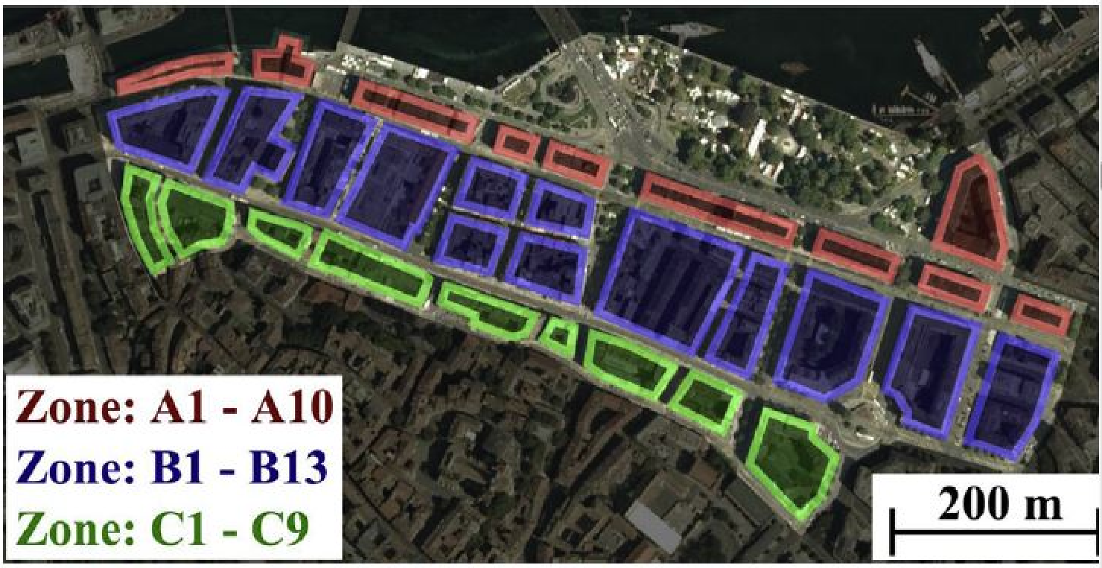


Figure 6: Representation of the the studied area and of its subdivision into 32 zones. Source: [?]

Table 2 shows the distribution of building affectations - which is important to determine the energy consumption - in the studied area. The total ERA is $687'800m^2$.

Table 2: Distribution of the energy reference area for the different zones and building affectations

Zones	Commercial [m^2 ERA]	Offices [m^2 ERA]	Residential [m^2 ERA]
A1 - A10	20'700	89'200	17'700
B1 - B13	97'000	260'700	61'600
C1 - C9	40'400	62'600	48'100
Relative share	23%	60%	17%

The energy demand of heating and cooling in the studied area is shown in Figure 7. The district presents nearly the same heating demand, as for cooling, but that they happen in different seasons.

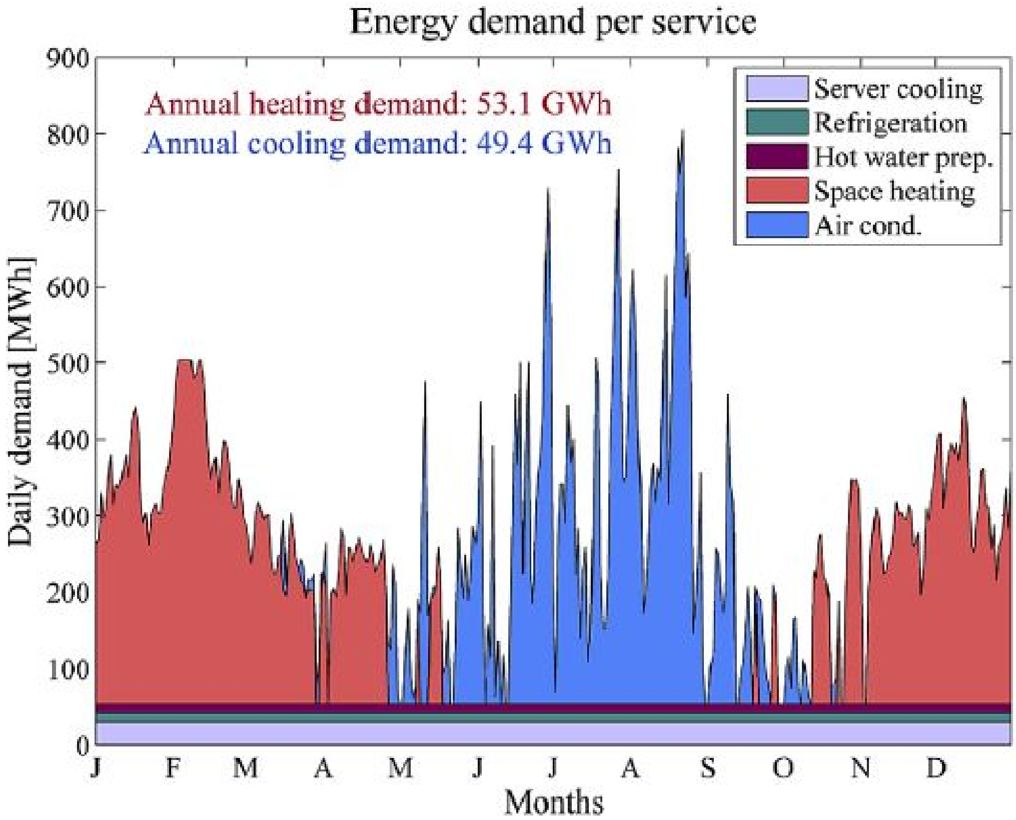


Figure 7: Energy demand for the area studied over the year 2012. Source: [?]

The proposed CO2 based DEN is balanced by a central plant - a heat pump - that exchanges heat with the nearby lake. In order to benchmark the results, this technology has been compared to a traditional heating and cooling system, based on oil boilers and cooled compression chillers. The results are remarkable. In fact, the CO2 based DEN shows a final energy consumption of 10,968 MWh of electricity, which corresponds to a reduction of 84.4 %, with respect to the reference scenario.

- Such networks can reduce consumption by over 80%
- Exergy efficiences are typically around 40-45%
- CO2 is the most profitable fluid for district network
- A cold water network is the second best option, although more expensive initially and thus less profitable, it has several advantages in terms of safety and availability of components.
- The CO2 variants exhibit a much better compactness than the cold water network.

[?]

2.3.4 Study case PtG

One big challenge in the future, especially in higher latitudes, where seasonal variation are consistent, is to ensure energy supply during winter season, when, due to shorter and weaker solar irradiation, PV panels produce less. It is thus important to find a way to store energy the excess renewable energy during the summer, to the winter.
One solution to do that is power to gas (PtG), which defines the process of transforming electrical

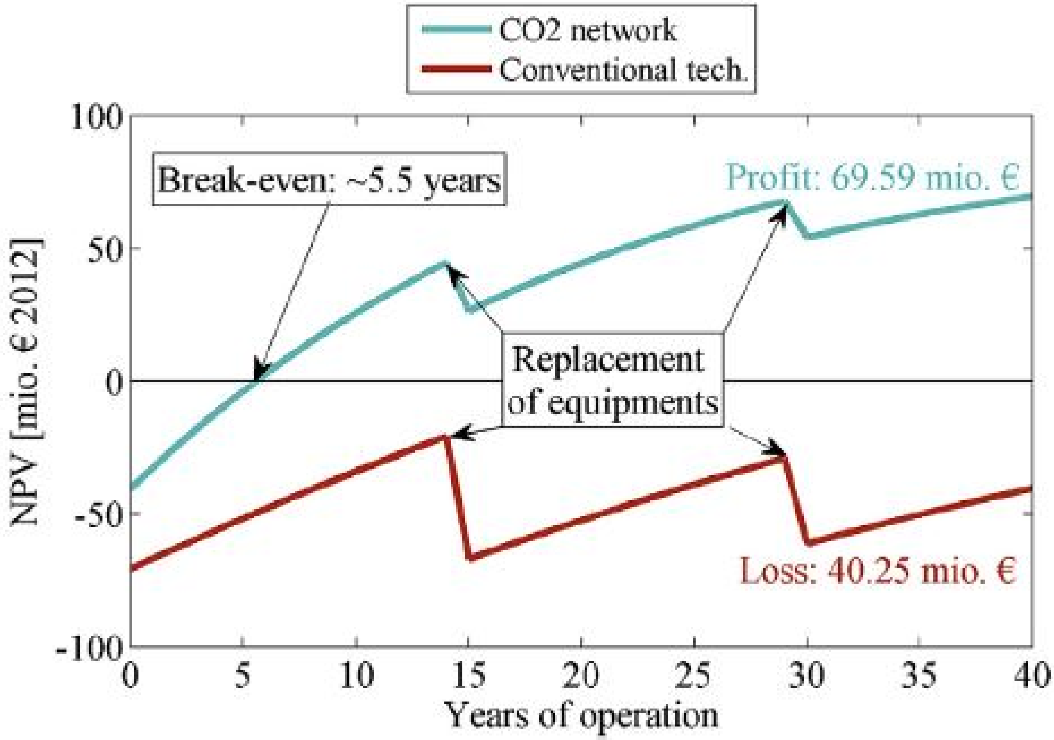


Figure 8: Evolution of the net present value over the lifetime of the two energy conversion technologies. Source: [?]

power to a gas, like methane, which is easy to store. Methane can be used during the winter to produce electricity and heat, in a combined heat and power plant (CHP), as for example a SOFC, a gas turbine, or a combination of them. For this reason, PtG is widely studied across Europe and many such plants have already been built.
A study [?] has been performed on the integration of a CO2 based DEN with decentralized PV and such a PtG system.

The present work evaluates the integration of CO2 district energy network including power to gas systems on a compact urban block considering heating, cooling, electricity, e-mobility and waste management for different European climatic zones. In order to reach fully autonomous blocks using solar PV and municipal and industrial waste heat, a PV area of 10e35m2/cap would be needed. The rooftop area available appears to be sufficient in areas like Southern Europe, while more area or alternative renewable sources such as wind or hydro are needed for other climatic zones. Regarding the economic feasibility of the system, the results show that an investment of 900e1300 V/cap would be needed, with a payback time between 11 and 14 years, depending on the different climate zones in Europe.[?]

2.3.5 Direct-expansion ground source heat pump

For heat pumps based systems, sourcing heat from the sole, instead of from the ambient air, is a very interesting solution at our latitudes, especially, as it has been seen, for integration of a 5th generation DEN, since it improves heating and cooling COPs, and, to a certain extent, it allows heat storage. In traditional Ground-Source Heat Pumps (GSHP), the heat pump and the ground are connected by means of a closed loop, using water, or a water solution. This system, called the secondary loop GSHP (SL-GSHP), is shown on the right side of Figure 9. However, it has been proved [?][?] that the system efficiency can be improved, by allowing to directly expand the refrigerant into the ground and thus let the ground act as a condenser/evaporator. Shown on the left side of Figure 9, this system is called Direct Expansion GSHP (DX-GSHP).

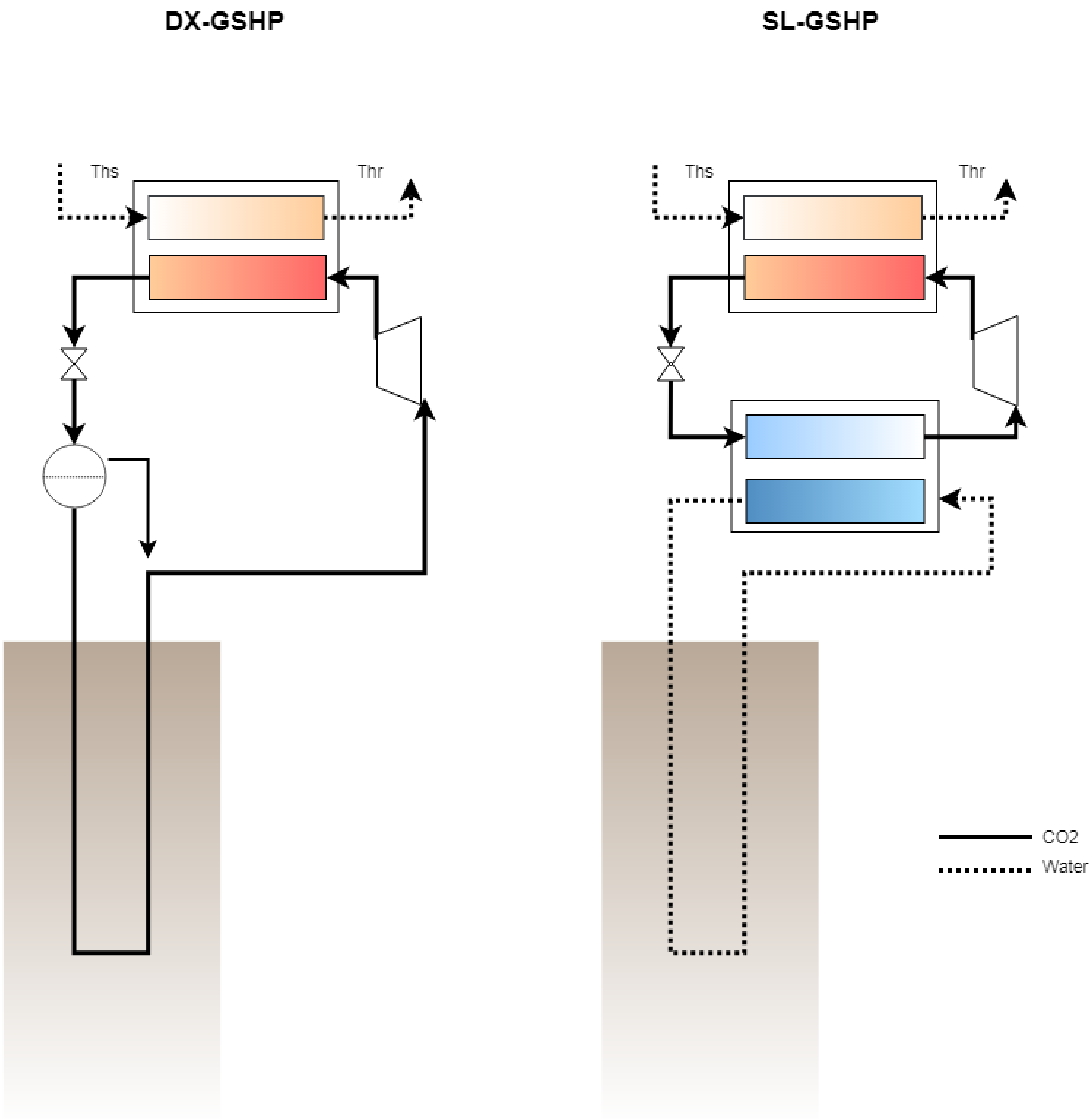


Figure 9: A simplified schematics of the two GSHP technologies

So far not so widely spread because more system design and, if not nat refs are used, environmental impact. Literature about DX-GSHP is still scarce, especially for CO2 as a refrigerant. The are only few numerical CO2-DX-GSHP studies, which are not yet sufficient to obtain a scientific appreciation of the technology. Prototype[?] Experimental set-up [?] Comparison between SL and DX for cooling in China [?] *The average cooling performance coefficients (PFsys) of the DX-GSHP system was obtained to be 6.03 and that of the SL-GCHP system was determined to be 5.64. The average input power values for the DX-GSHP system and the SL-GCHP system are found to be 1.39 and 1.715 kWh, respectively, which means that DX-GSHP has a 23.8% higher efficiency than SL-GCHP in cooling mode. The paper studied the initial investment, the annual cost (AC) and the present worth (PW) of the two systems. It is concluded that the DX-GSHP is more economic than the SL-GCHP*

Show that there is an optimum temperature difference between the soil and the refrigerant inside the evaporator. This temperature depends on thermal permeability of soil and is correlated to the length and total surface of the geothermal probes, as well as the refrigerant flow rate.

Models for DX-GSHP [?] [?] [?] [?]

(9) 4/7 for 13 groundT in https://www.sciencedirect.com/science/article/pii/S019689041630975X

14°C[?] and [?]

So the CO2 DEN with DX-GSHP technology is shown in Figure 10

Assumed temperatures like in ...

2.4 optimization

2.4.1 MILP

Mixed integer linear programming (MILP) is... AMPL a programm, solver using Gurobi, GLPK... Opitmization function

2.4.2 Genetic algorithms

Optimization can be done through empirical algorithms that respect a set of rules. However, it is also possible to explore a space of solutions by reproducing the idea of evolution.

1. Create the population
2. Determine fitness
3. Select the mating pool
4. Breed
5. Mutate
6. Repeat

https://blog.sicara.com/getting-started-genetic-algorithms-python-tutorial-81ffa1dd72f9 https://towardsdatascienc of-a-salesman-a-complete-genetic-algorithm-tutorial-for-python-6fe5d2b3ca35

2.5 Osmose

IPESE developed in-house software for this Lua language Layers, ETs... Equations (mass balances, resource balances, heat cascade...) Creates mod files for ampl optimization Postcompute to export

3 Methodology

3.1 Investment cost function

Take explanation from "MOES EPFL Buildings" report line 127

$$C_{pex} = \frac{I_t}{I_{t,ref}} \cdot 10^{(k_{1,ex}+k_{2,ex} \cdot \log(A_{ex}))} \tag{1}$$

$$CBM_{ex} = C_{pex} \cdot FBM_{ex} \cdot e \tag{2}$$

The annuities are given by the following formula assuming a 20 years investment.

$$IC_{yearly,ex} = CBM_{ex} \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{3}$$

3.2 Minimum approach temperature

Bigger area allows a smaller dTmin, which increases the investment costs but lowers the operating costs, due to the higher COP, and the other way around. So an optimum can be found for each specific application.

Then optimization of dTmin in function of total costs minimization, with help of the following equations. Assumed counter-flow heat exchanger

$$A_{ex} = \frac{Q_{ex}}{U \cdot LMTD} \tag{4}$$

$$LMTD = \frac{(T_{Hot,in} - T_{cold,out}) - (T_{Hot,out} - T_{cold,in})}{\log\left(\frac{T_{Hot,in} - T_{cold,out}}{T_{Hot,out} - T_{cold,in}}\right)} \tag{5}$$

$$U = \frac{1}{\frac{1}{\alpha_{(1)}} + \frac{1}{\alpha_{(2)}}} \tag{6}$$

where $\alpha_{(1)}$ and $\alpha_{(2)}$ are the heat transfer coefficient of the hot and cold fluid. Heat resistivity of heat exchanger plates are neglected.

The optimization is done on water refrigerant hp, with values (ic, Q, COP) from space heating. CO2 dTmin is calculated maintaining same Area as for ref hp.

for CO2 from this paper[**?**]. Validated also by This paper shows R134a and R134yf have same heat transfer coefficient[**?**], comparison with CO2 done in [**?**]. Values are for a diameter and heat flux that could correspond (d = 4.5mm and 20kW/m2) Also a list of previous studies

Table 3: Heat transfer coefficients found in literature

Fluid	Water	R134yf	R744
$\alpha[W/(mK)]$	600	7000	3000

Thus following ΔT_{min} are have been calculated and used for heat exchanges in the model.

fill in table with correct values

Table 4: Minimum approach temperatures used for heat exchanges in the model

Fluids	Ground-Water	Ground-R744	Water-Water	R134yf-Water	R744-Water	R744-R134yf
ΔT_{min} [K]	14?	11	?	3.3	2.7	?

3.3 Exergy

The exergy of a heat transfer is defined as the maximum amount of work that can be extracted from it, through reversible transformations that exchange with the environment. Thus the calculation of exergy losses is a very interesting indicator to analyze a given process or system, since it expresses the quality and the efficiency with which the system operates, with respect to the maximum possible. Therefore, these values are always lower than 100 %.

The maximum work that can be extracted is derived from the first two thermodynamic principles, and is given by the following formula:

$$\dot{E}^{-}_{max} = \sum_i \dot{Q_i}^{+}(1 - \frac{T_a}{T_i}) + \sum_r \dot{M}^{+}_r(h_r - T_a s_r) \tag{7}$$

In order to compute the exergy losses the general approach that can be used is the following:

$$\dot{L} = \dot{E}^{-}_{max} - \sum_j \dot{E}^{-}_j \geq 0 \tag{8}$$

In our case

$$\eta_{exergy} = \frac{\dot{Q}_{cold,a} + \dot{Q}_{hot,r} + \dot{E}^{-}_{grid}}{\dot{Q}_{cold,r} + \dot{Q}_{hot,a} + \dot{E}^{+}_{grid}} \tag{9}$$

$$\dot{L} = (1 - \eta_{exergy})(\dot{Q}_{cold,r} + \dot{Q}_{hot,a} + \dot{E}^{+}_{grid}) \tag{10}$$

3.4 Energy technology models

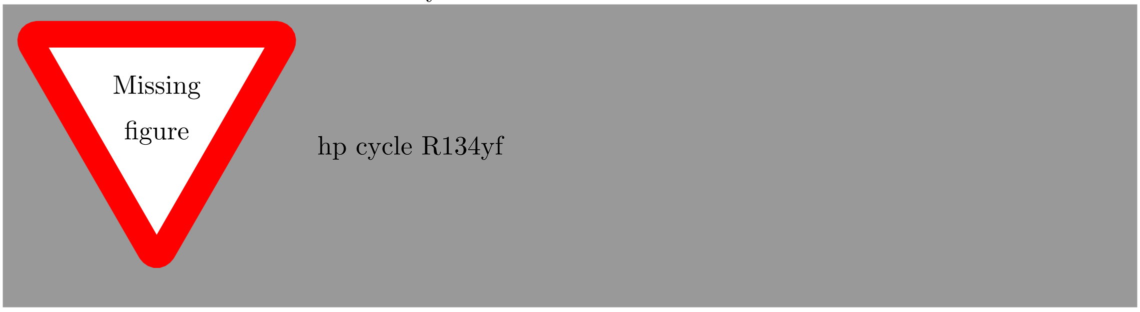
3.4.1 Heat pumps

A simple model can be implemented with the following equations: Basic Carnot cycle model with efficiency.

$$\dot{E}_{compressor} = \frac{\dot{Q}_{evap}}{COP_{real} - 1} = \frac{\dot{Q}_{evap}}{COP_{theoretical} \cdot \eta_{COP} - 1} = \frac{\dot{Q}_{evap}}{\eta_{COP} \cdot \frac{T_c - T_h}{T_c} - 1} \tag{11}$$

where η_{COP} is the Carnot efficiency.

However, given the comparison between new and performant technologies, the differences of performance are relatively small and it might be necessary to provide a more accurate model of the heat pumps, that are able to correctly represent and calculate the operating cycles and conditions. This can be done like this... Given cycle:



explain procedure and equations for hy cycle model

Thermodyn model follows following procedure:

1. fix temp
2. calc pressure
3. at point same temperature
4. overheat
5. ...

In Osmose, these values are calculated with help of *Coolprop*, which is an open-source database of fluid and humid air properties that allows to calculate operating conditions for a large number of fluids and refrigerants. Thanks to a *lua wrapper*, which is a *lua* module that provides an API to the external software, *Coolprop* is called inside Osmose.

3.4.2 Heat pump CO2

In traditional heat pumps, the heat delivery occurs through condensation of the refrigerant, which happens at a fixed temperature. This originates high exergy losses, especially in processes were a high temperature lift is needed in the gas cooler.
Some refrigerants have the particular property of having a very low critical point. At first sight, this normally results in lower energy efficiency. However, it also allows heat to be exchanged on a varying temperature, and the heat pump can be designed to fit the heat demand stream, optimizing exergy efficiency. This can be seen in Figure 11, where the cycle is represented on the temperature-entropy diagram, between point 2 and 3. The different steps of the process are explained hereafter:

- 1 - 2 Compression to transcritical pressure
- 2 - 3 Gas cooling in transcritical area, to heat water
- 3 - 4 Expansion to low pressure
- 4 - 5 Evaporation by cooling down the heat source

- 5 - 1 Superheating in evaporator

Note that, as there is no phase change, the heat exchanger is called gas cooler, instead of condenser.

The operating conditions having a cold stream with a low inlet temperature, as in the case of domestic hot water heaters, are well suited for the use of CO2 as a refrigerant, which has a critical point at 74 bars and 31 °C[**?**].

4 Eglantine

In the framework of the collaboration between Romande Energie and IPESE, a case study shall bring a concrete numerical case study into the discussion. For this, Romande Energie has chosen a real life example of a district in the city of Morges. This district is in the planning phase, and Romande Energie had worked on it, in order to participate in the call for tender. This case study shall be fertile ground to discuss the CO2 DEN technology and it's role in the future energy systems in Switzerland and, more particularly, in the future plans of Romande Energie.

4.1 Case-study

4.1.1 Context

The "Eglantine" is a terrain in the western part of the city of Morges, as shown in Figure 12. It is located in proximity of the key urban facilities, as well as it is close to the countryside. This terrain, which was partly used for agriculture, and partly covered by rich vegetation, belongs to the municipality, who is planning to use it for the urban expansion. At the municipality, they had the vision of building a new district, which would be planned to be exemplary in the sustainable development. After many years of revising and fine-tuning the land-use plan and its vision for the future, in the beginning of 2016, the commune launched a call for tender for the planning of the different aspects of the district. The call for tender regarding the energy system was opened by Losinger Marazzi the 1st December 2017, with a due date the 31 January 2018. The contract with the winner, unknown to the author, has been signed in the end of March 2018.

The call for tender requires the development of a complete energy system, including thermal and electrical energy. Estimated data about the buildings is provided, as seen in Table 5. Those are based on the following assumptions:

- All buildings are certificated Minergie 2017
- Space heating and hot water energy demand follow the SIA 380/1 and SIA 2031 norms
- Air ventilation is defined according to Minergie 2017 principles.
- Installed power values are calculated according to SIA 2024 norm

4.1.2 Buildings

The district, which will host around 1'500 people, is composed of thirteen buildings, as shown in Figure 13, which account for a total energy reference area (ERA) of around $47'000m^2$. The details are shown in Table 5.
The buildings include, beside the residential use, also a small share of commercial and catering use, which are associated with different energy needs. There is also a small swimming pool, located in building one. The use of the buildings is shown in Table 6.

The energy profile of the buildings is calculated according to Minergie standard, as well as the SIA norms. Given the annual energy demand for space heating and hot water, as shown in Table 5, the monthly profile is shown in Figure 14.

where does the percentages come from? did not find them in call for tender

cooling demand?

Typical days: in methodology or here?

Table 5: Estimated energy demand in call for tender

Building	**Energy Reference Area (ERA)**	**Inhabitants**	**Space Heating (SH)**	**Hot Water (DHW)**	**TOTAL**
			MIINERGIE simple flux	SIA 380/1	
	[m2]		[kWh/an]	[kWh/an]	[kWh/an]
1	8'200	273	245'180	170'833	416'013
2	2'615	76	82'308	50'104	132'412
3	2'415	70	76'328	45'938	122'266
4	2'780	92	83'122	57'917	141'039
5	3'700	116	113'246	74'306	187'552
6	1'500	50	44'850	31'250	76'100
7	2'870	83	90'652	54'653	145'305
8	2'500	83	74'750	52'083	126'833
9	4'225	140	126'328	88'021	214'349
10	4'455	148	133'205	92'813	226'018
11	4'190	139	125'281	87'292	212'573
12	2'300	76	68'770	47'917	116'687
13	2'300	76	68'770	47'917	116'687
14	2'300	76	68'770	47'917	116'687
TOT	**46'350**	**1'498**	**1'401'559**	**948'958**	**2'350'521**

Table 6: Estimated use of buildings in call for tender

Building	**Habitat collectif** [%]	**Commerce** [%]	**Restauration** [%]	**Piscine couverte** [%]
1	89.58%	3.10%	4.42%	2.89%
2	97.54%	2.46%	0.00%	0.00%
3	100.00%	0.00%	0.00%	0.00%
4	100.00%	0.00%	0.00%	0.00%
5	93.19%	6.81%	0.00%	0.00%
6	95.79%	4.21%	0.00%	0.00%
7	95.79%	4.21%	0.00%	0.00%
8	100.00%	0.00%	0.00%	0.00%
9	100.00%	0.00%	0.00%	0.00%
10	100.00%	0.00%	0.00%	0.00%
11	100.00%	0.00%	0.00%	0.00%
12	100.00%	0.00%	0.00%	0.00%
13	100.00%	0.00%	0.00%	0.00%
14	100.00%	0.00%	0.00%	0.00%

4.1.3 Pre-study

Some pre-studies have been realized, in order to give, on an indicative basis, the sizing of the energy system. The heat pumps, the geothermal wells, as well as PV have been considered, as shown in Table 7.

4.1.4 Task

Call for tender asks to design a complete energy system...

Table 7: Estimated sizing of energy system in call for tender

Building	**PV**	**HP**	**Geothermal**	
			Nb. wells	**Depth**
	[kWp]	**[kW]**		**[m]**
1	46	223	13	284
2	45	70	4	291
3	35	64	4	269
4	33	76	5	250
5	49	100	6	276
6	55	41	3	225
7	55	77	5	256
8	37	68	4	281
9	66	115	7	271
10	0	121	7	286
11	59	114	7	269
12	33	63	4	259
13	32	63	4	259
14	27	63	4	267
TOT	**570**	**1'258**	**77**	

4.2 Reference scenario

In order to evaluate the potential of alternative energy systems, a reference scenario is defined. Data about the energy system that will be built in the Eglantine district is not available to the author, and therefore a standard state of the art system is used. It is assumed that the heat demand for space heating and domestic hot water is provided by decentralized geothermal sourced heat pumps. The cooling demand is provided by air cooled vapor compression chillers, also commonly known as air conditioners.

4.2.1 Decentralized heat pumps

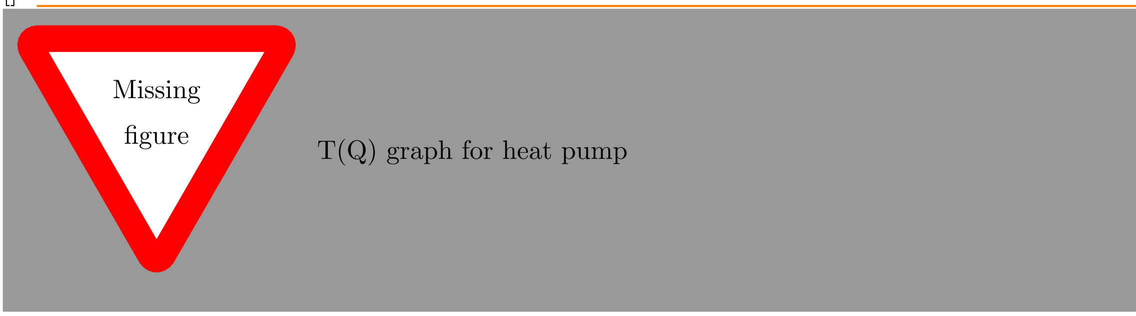
The heating demand is supplied by a set of decentralized geothermal heat pumps, one for domestic hot water and one for space heating in every building. These heat pumps source the ambient heat from a secondary loop, that exchanges heat with the ground through a system of geothermal wells, which is described in the according chapter.
The heat pumps have been modeled with its thermodynamic model, as described in Section 3.4.1. The temperatures at the evaporator and condenser are given by the following equations:

$$T_{evap} = T_{ground} - \Delta T_{min}^{ref/ground} - \Delta T_{water} - \Delta T_{min}^{ref/water} \tag{12}$$

$$T_{cond} = T_{demand} + \Delta T_{min}^{ref/water} \tag{13}$$

with respectively 1 °C and 2 superheating 1 °C and subcooling at the outlet of the heat exchanger [].

missing reference for superheat and subcool temp



4.2.2 Compression chillers

Air cooled, vapor compression chillers. Not as relevant in case study, thus basic Carnot cycle model with efficiency, as explained in Section 3.4.1.
The operating temperatures are defined in the following way:

$$T_{cond} = T_{ext} + \Delta T_{air} + \Delta T_{min}^{ref/air} \tag{14}$$

Where ΔT_{air} is the temperature difference of the cooling air between the input and the output of the condenser, while $\Delta T_{min}^{ref/air}$ is the minimum approach temperature difference needed for heat transfer between a refrigerant and air.

η_{COP} is assumed at , from experimental data[?]. The fans, needed for the cooling of the condenser, originate parasitic power consumption. This is calculated with help of the following equation[?]: missing value

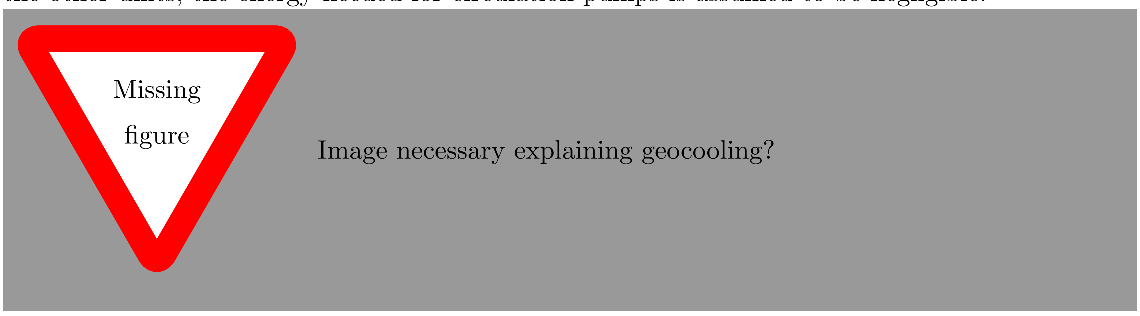
$$\dot{E}_{fans} = \frac{0.605 \cdot \dot{Q}_{cond}}{(\Delta T_{air} + \Delta T_{min}^{ref/air})^{0.9937}} \tag{15}$$

Where $\dot{Q}_{cond}$ is the heat to be delivered to the surroundings by the condenser. Thus, the total energy consumption is a sum of the energy demand of the compressor and the one of the cooling fans.

$$\dot{E} = \dot{E}_{ref} + \dot{E}_{fans} \tag{16}$$

4.2.3 Geo-cooling

Geo-cooling is the use of fresh temperatures of the ground for space cooling. This happens by simply circulating a fluid between the buildings, where the heat is extracted, and the geothermal wells, where heat is released into the ground. In practice, this happens by bypassing the heat pumps and making the water of the secondary loop (geothermal loop) directly exchange with the heating water loop. Investment costs are, thus, limited to an additional heat exchanger. As for the other units, the energy needed for circulation pumps is assumed to be negligible.



4.3 CO2 DEN

4.3.1 Distributed heat pumps

For space heating and domestic hot water. Same model as for heat pumps in reference scenario. Difference is evaporation temperature, since exchange with CO2 network, and thus:

$$T_{evap} = T_{CO2,g} - \Delta T_{min}^{ref/ref} \tag{17}$$

4.3.2 Refrigeration

Cooling heat pump, same as in ref scenario. Difference is at the condenser, which is not cooled by air flow and fans, but by direct exchange with the CO2 network:

$$T_{cond} = T_{CO2,l} + \Delta T_{min}^{ref/ref} \tag{18}$$

4.3.3 Free cooling

Free cooling has been modeled by a simple heat exchanger that evaporates saturated liquid CO2, which is injected back into the network in a superheated vapor state with $\Delta T_{superheating} = 1K$. The mass flow of the CO2 is adapted to satisfy the cooling demand. It is assumed that pressure and temperature losses are negligible.

4.3.4 Central plant

As mentioned before, for obvious reasons, heating and cooling loads in the system are not always balanced. Thus, there is the need for a central plant to balance out the system, able to heat and cool. A centralized heat pump is very suitable for this purpose.

Equations and modelling are the same as for the above described heat pumps. Difference consists in heat source, and thus evaporation temperature. Different options have been studied:

- Lake: sourced from a certain depth, lake water shows an almost constant temperature of around 7.5 °C throughout the year. This solution can be very interesting alternative to geothermal wells, since, if close enough, it might reduce the upfront costs, despite probably slightly increasing the operating costs. In this particular case, the distance to the lake is of 1500 m.
- River: as for the lake, river water can be an interesting source of heat, with the difference of seasonal fluctuations. During the winter, river water can have a temperature close to 0, while in the summer it can rise to more than 20 °C. In the case of the Eglantine district, there is a small stream, called Morges, that passes at the eastern border of the land.
- Geothermal wells: after a certain depth, the ground presents a constant and very interesting temperature throughout the year. This heat can be exchanged with help of a secondary loop or through direct expansion of the refrigerant into the ground coils.

Direct expansion system is assumed (see Section 2.3.5). The operating temperatures are calculating the following way.

$$T_{evap} = T_{source} - \Delta T_{min}^{ref/source} \tag{19}$$

The operating pressure is calculated with help of *Coolprop*. The results are shown in Table 8.

Table 8: Operating conditions for direct expansion of CO2 in heat source

Source	$\Delta T_{min}^{ref/source}$ [°C]	T_{source} [°C]	T_{evap} [°C]	P_{CO2} [bar]
Lake	4	7.5	3.5	38.2
Geothermal	10	11	1	35.8

4.3.5 Network

The length is calculated, according to a simplified method[**?**], with the following equations:

$$L = 2(n_b - 1)K\sqrt{\frac{S}{n_b}} \tag{20}$$

with S being the land area, n_b the number of buildings. The constant K is chosen at 0.5. And diameter of the pipes:

$$d = \sqrt{\frac{4 \cdot \dot{m}}{\pi v_s \rho}} \tag{21}$$

assuming a sizing velocity v_s of 3 m/s. The investment costs are calculated accordingly:

$$C = \sum_{k=1}^{n_b} \frac{L}{n_b}(c_1 d\sqrt{n_b + 1 - k} + c_2) \tag{22}$$

Operating temperature is assumed to be 13/15 °C. Henchoz[?] has 10-12.5 for summer and 22.5 for winter!!!

how has this temperature been chosen? is there a paper? see henchoz with other T

4.4 Heat sources

The heat pumps in a system can source heat from various sources. Depending on the case, it is more convenient to use one or the other, given the varying temperatures and investment costs.

4.4.1 Stream

A small stream flows along the eastern boundary of the area, on which the Eglantine district is being built. The official numbers of the canton Vaud [?] are shown in Figure 15, in which the Temperature and the water flow are plotted. These values represent the average over a period of several years (7 for the temperature, and 12 for the flow rates).

According to this graph, it could be thought of using this river as a heat source for the heat pumps. However, what is not displayed is the minimum values. In fact, during droughts, the flow rate would not be sufficient to cover the heating/cooling demand. In fact, the lowest value has been reached in August 2004 with $0.017m^3/s$, and even in December 2005 the lowest daily flow was of $0.057m^3/s$.
For this reason, the stream has been excluded from further analysis and has not been considered as a viable solution.

4.4.2 Lake

4.4.3 Geothermal wells

Geothermal Ground temperature shown in Figure 16. Extracting power

100 CHF/m http://bawos.ch/erdsondenbohrungen-kosten-und-planung-zur-gewinnung-von-umgebungswaerme/ https://www.energieheld.ch/heizung/waermepumpe/sole-wasser-erdwaerme Average 30 W/m Heating 100/30 = 3600 CHF/kW Th conductivity = 2.5 W/mk papers

- between 2-5 [?]
- other papers, check models for DX

$dT_{min}^{ref/ground} = 11°C$

4.5 External heat sources

The main advantage of a 5th generation district heating network is the ability to recover heat, and exchange it among the diversity of user. In the case of the Eglantine project, inside the district there are only very small heat sources and it is thus necessary to identify potential heat sources, located in the surroundings. Two potential heat sources have been identified:

- The ice rink
- The shopping mall

4.5.1 Ice rink

An ice rink is a place where people can ice skate and play winter sports. The ice surface is normally inside an arena, which ensures comfortable temperatures for the people on the ice, as well as for the public, throughout the season. This also allows to extend the season, avoiding ice melt, when temperatures are warmer outside. A refrigeration system is responsible for the cooling of the ice surface. However, the ice rink often also includes changing rooms with showers, and a cafeteria or a restaurant. Thus, there is also need for heating. Furthermore, the ice surface has to be constantly illuminated, which requires a powerful lightning system. The global system is shown in Figure 17.

The refrigeration of the ice surface leads to a high amount of waste heat, which is normally, or at least in older systems, exchanged with the environment. Connecting it to a 5th generation district heating network, would enable to recover this heat and use it to cover heat demand of other users.

The energy consumption of the ice rink has been estimated through a comparison of existing ice rinks in Sweden, which seems to be the only country for which the data is available and has been studied thoroughly.

Ice rinks normally cooled with indirect system, which is shown in the right part of Figure 18

this allows to use any refrigerant, since it won't come close to human activity. The most common refrigerant, at least in installed systems, is NH3, ammonia. Natural refrigerants, as for example CO2, are also becoming more common in new installations. The connection to the CO2 network is shown in the left part of Figure 18.

A study, conducted on more than one hundred ice rinks in Sweden, shows that the refrigeration system has the largest share in total energy consumption, 43% (in average) as indicated in Figure 8. (Rogstam (a), 2010) Heating with 26% share is the second biggest energy consumer. [?]

The energy demand depends on the temperature of the ice. A typical temperature profile is shown in Table 4.5.1 [?].

Table 9: Ice rink refrigeration profile

Period	**Rink function**	T_{ice} [°C]
0.00-6:00	Night setback	-1
6:00-8:00	Ice maintenance	-1
8:00-16:00	Low load	-3
16:00-18:00	Figure skating	-4
18:00-24:00	Hockey	-6

From sources we have estimated a refrigeration profile shown in Figure ... With the following assumptions:

- Constant load profile throughout the ice season
- Ice season: 1st of August - 1st of April
- $COP_{ref} = 4$ [?]
- Total waste heat $= 1000 MWh/year$ [?]
- $dT_{min}(refrigerant - ice) = 1$°C
- $dT_{min}(refrigerant - refrigerant) = 3$°C

Missing figure

add figure with load profile... superpose temperature on second axis?

An new and efficient cooling system, together with an intelligent (weather, use, conditions...) management system, can drastically reduce energy consumption. This should be considered in the inclusion of the ice rink as heat source, since the renovation of the existing ice rink, or the construction of a new ice rink, would considerably reduce the amount of available waste heat.

4.5.2 Shopping mall

4.6 Analysis/Extrapolation scenario

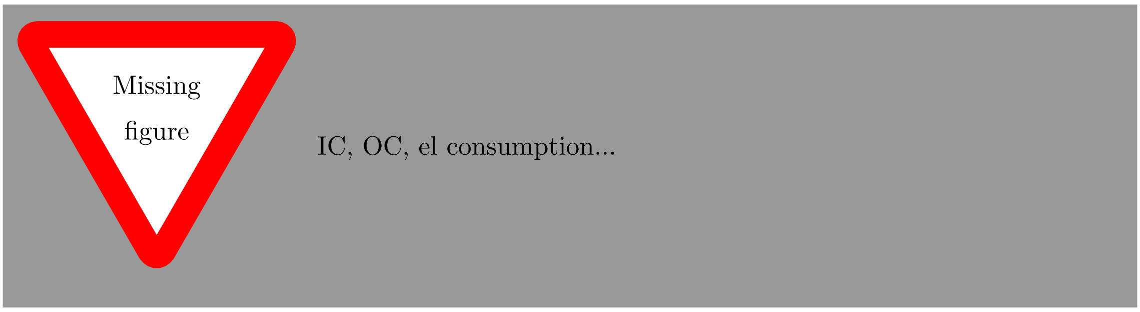
A scenario to study parameters independently from Eglantine. Parameters to study/extrapolate for quick application on other districts:

- influence on IC,OC,TC
- influence on network temperature T_net

Varying % of cooling load, wrt heating load, using typical profiles, as for sh, dhw and ref

5 Results

5.1 Scenario comparison



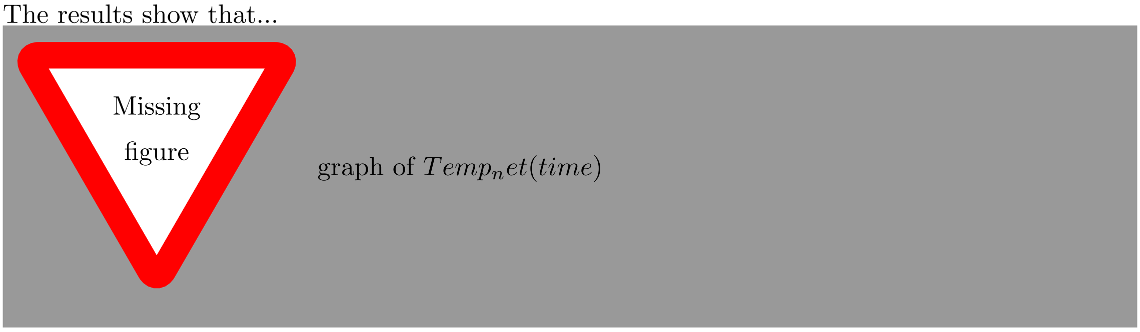
Comparison with existing anergy networks, shown in Table 10.

Table 10: Investment cost comparison for different anergy systems

	Network / pipes		Geothermal		Heating/Cooling		Tot
	[mio CHF]	[%]	[mio CHF]	[%]	[mio CHF]	[%]	[mio CHF]
Anergienetz ETH Hönggerberg	5.8	0.16	12.1	0.33	18.2	0.49	37
Anergienetz Friesenberg	11	0.26	10.0	0.24	21.5	0.51	42.5

5.2 CO2 network temperature control

An optimum for the temperature of the CO2 network has been defined . The question arises if this temperature might vary in function of the operating condition of the network, i.e. the balance of heating and cooling load, the heat source temperature... missing ref
A model has been implemented to study this, by leaving the optimizer choose the optimal operating temperature of the network for every given timestep.
The results show that...



Then a simple representative scenario has been modeled, with a typical building, and a typical refrigeration, and varying % of cooling load, wrt heating load.

Missing figure

graph of $Temp_n et$(% of cooling/heating)

5.3 Sensitivity analysis

Perform sensitivity analysis on:

- PV area
- distance of lake
- size of Heat source (IceRink)
- distance of IceRink
- other ideas?

6 Discussion

7 Outlook

This and this has been analyzed and results have shown.
However, it would be very interesting to make detailed analysis of...
This model should be improved...
This new thing could be integrated...

8 Conclusion

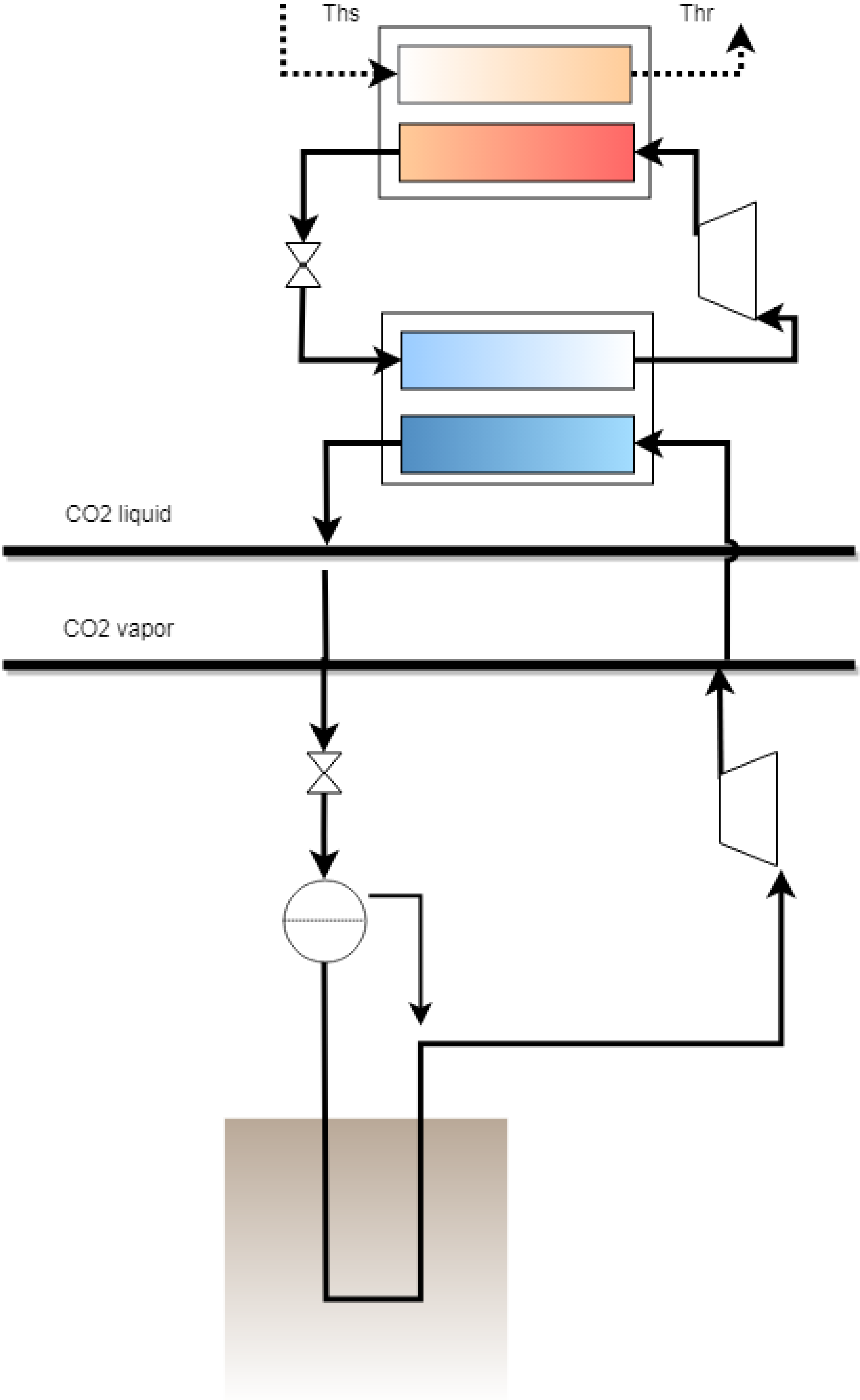


Figure 10: A simplified schematics of the CO2 DEN with DX-GSHP technology

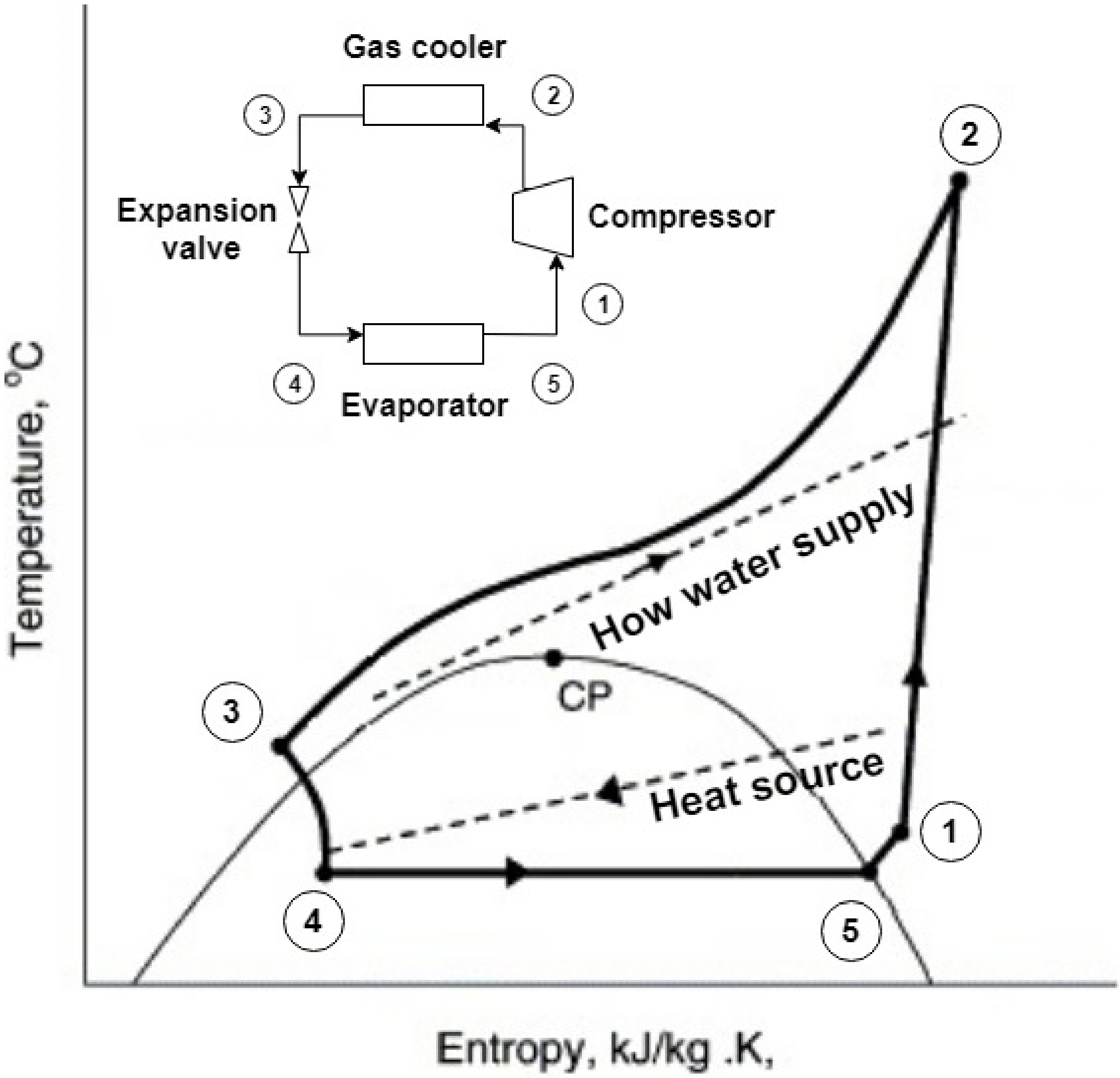


Figure 11: Temperature–entropy diagram of a trans-critical CO2 heat pump system for a domestic hot water production. Source: [?]

Figure 12: Localization of the terrain, at the town scale. Source: www.geo.vd.ch

Figure 13: Map of the planned Eglantine district

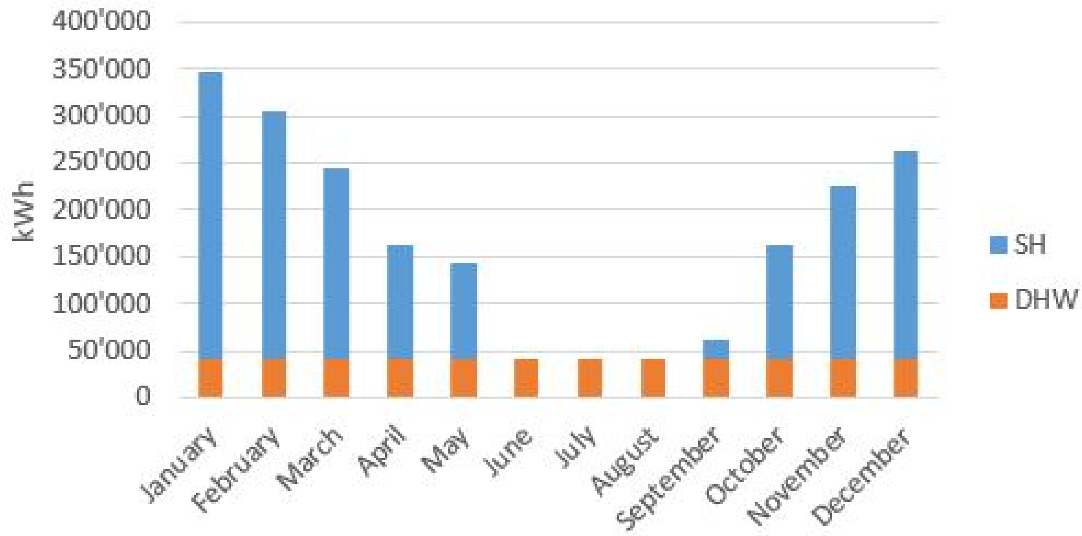


Figure 14: Annual energy distribution for space heating and hot water

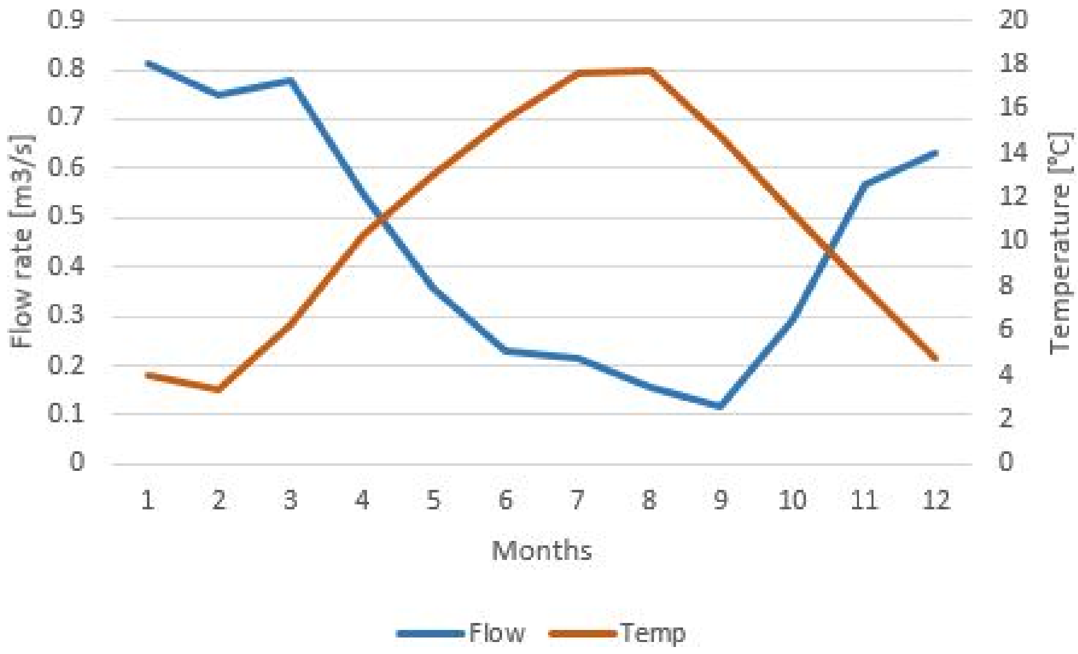


Figure 15: Temperature and flow of the Morges river

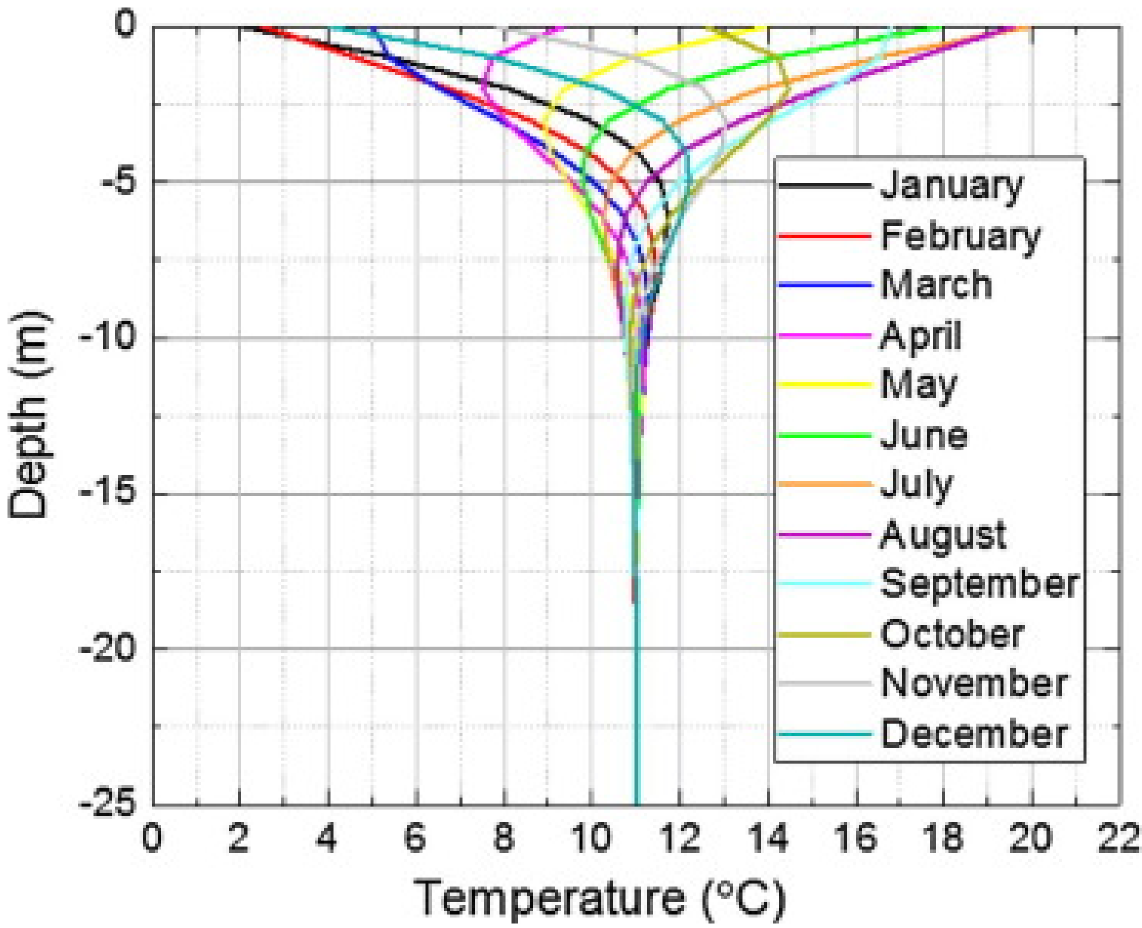


Figure 16: Graphical representation of ground temperature, for different months of the year. Source: [?]

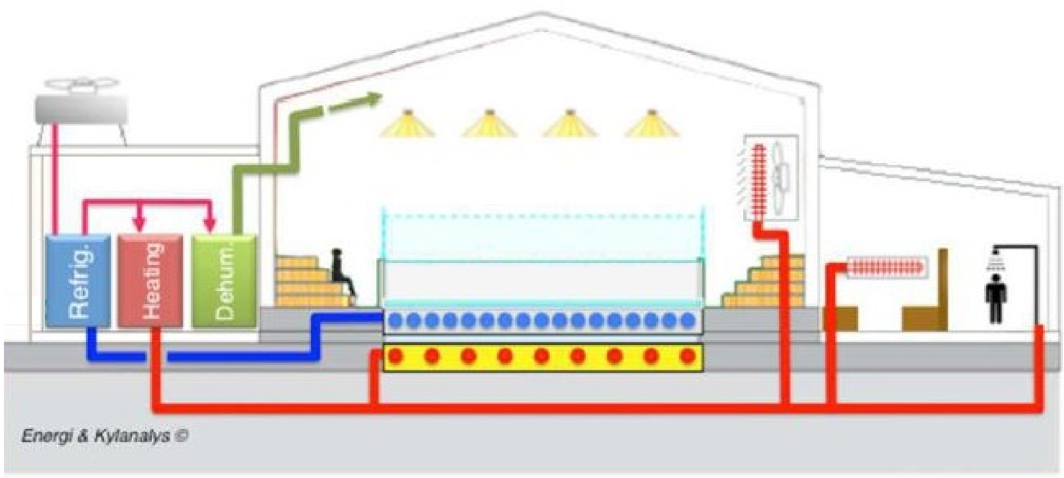


Figure 17: Energy system of a typical ice rink [?]

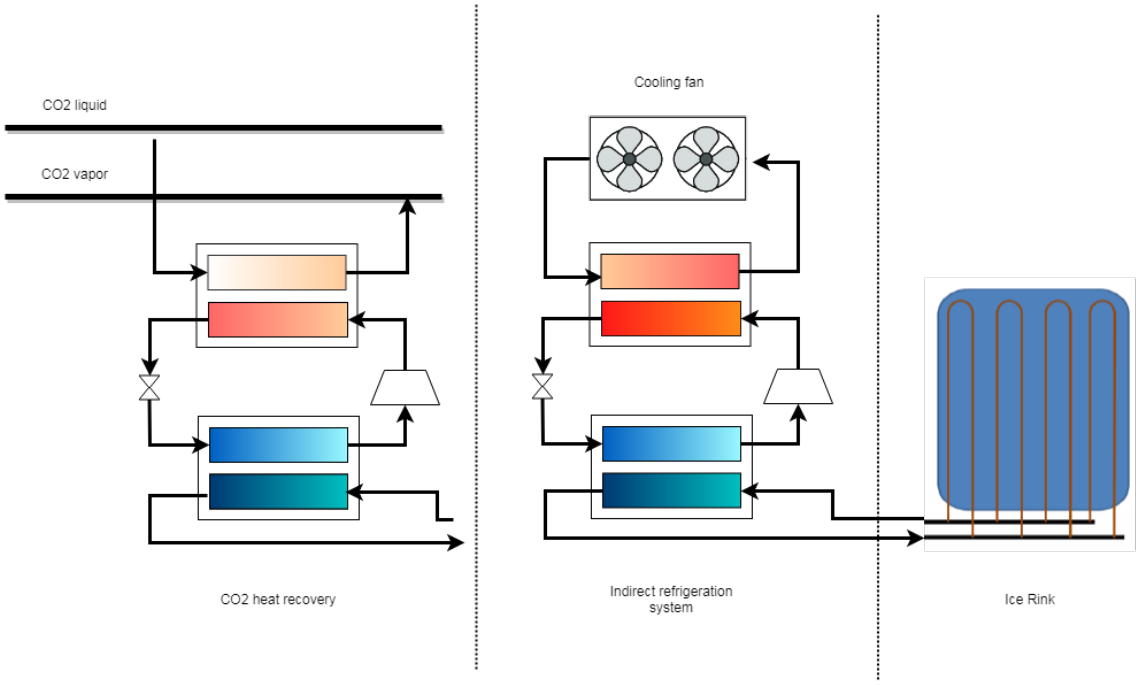


Figure 18: Refrigeration systems for ice rinks

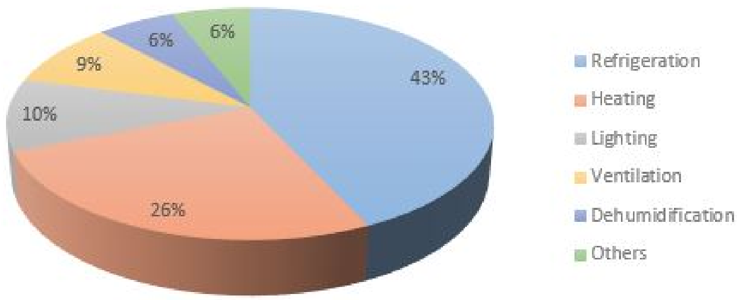


Figure 19: Energy demand of a typical ice rink [?]

References

9 Anergy nets Switzerland

Table 11: District energy systems in Switzerland

	Anergienetz ETH Hönggerberg	**Jardins de la Pâla**	**Suurstoffi-Areal**	**Anergienetz Friesenberg (FGZ)**	**CAD La-Tour-De-Peilz**	**Anergienetz-Visp**	**Genève-Lac-Nations (GLN)**
Location	Zürich	Bulle	Rotkreuz	Zürich	La-Tour-de-Peilz	Visp	Genève
Year of construction	2012 - 2026	2012 - 2020	2010 - 2020	2011-2050	2013 - 2015	2007 - heute	2008 - 2016
Type	¡ 20 °C	¡ 20 °C	¡ 20 °C	¡ 20 °C	¡ 20°C	¡ 20 °C	¡ 20 °C
ERA [m2]	475'000	65'000	172'421	185'000	24 Buildings	160'000	840'000
Use	School Residential	Residential Commercial Industry	Residential Administration Commercial Catering School	Residential Computation	Residential Administration	Residential Industry	Residential Administration School
Status	Partly built	Partly built	Partly built	Partly built	Built	Built	Built
				Data Energy Consumption			
Inst. Heating capacity [kW]	8'000	2'000	6'732	3'930	10'000	3'467	4'300
Heating demand '[MWh/a]'	28'450	3'100	10'619	35'000	812	8'737	5'000
Inst. Cooling capacity [kW]	6'000	1'000	2'327	3'500	None	2'600	16'200
Cooling demand '[MWh/a]'	26'200	650	2'364	80'000	None	3'380	20'000
Heat source	Laboratories waste heat +HP	Groundwater+HP	Waste heat buildings + PVT (solar th.) +HP	Waste heat data center+HP	Lake water +HP	Inudstrial waste heat + HP	Lake water +HP
Heat storage	Geothermal well field (431 at 200m)	Groundwater 12°C	Geothermal well field (215 at 150 m, 180 at 280m)	Geothermal well field (332 at 250m)	None	None	None
				Network data			
Network length [km]	1.5	0.85	2.5	1.5	4.1	4.2	6
Heating pipeT	24 °C - 8 °C	12 °C - 9 °C	25 °C - 8 °C	28 °C - 8 °C	20 °C - 6 °C	18 °C - 8 °C	17 °C - 5 °C
Cooling pipeT	4 °C - 20 °C	4 °C - 17 °C	4 °C - 17 °C	4 °C -24 °C	2 °C - 16 °C	4 °C - 16 °C	5 °C - 12 °C
Pipe diameter [mm]	DN 560	75 - 250	60 - 400	400 - 500	400 -700	DN 400	100 -700
Number of pipes	3	2	2	2	2	2	2

Table 12: District energy systems in Switzerland

	Anergienetz ETH Hönggerberg	**Jardins de la Pâla**	**Suurstoffi-Areal**	**Anergienetz Friesenberg (FGZ)**	**CAD La-Tour-De-Peilz**	**Anergienetz-Visp**	**Genève-Lac-Nations (GLN)**
				Financial data			
Tot. investments '[Mio.CHF]'	37	6	n/a	42.5	32	1.26	33
Interest rate[%]	3.9 - 6.7		n/a	n/a	6.4	5.8 - 8	n/a
Lifespan [a]							
Pipes	50	30	40	50	50	40	n/a
Storage	50	None	80	50	None	None	n/a
Heating unit	20	15	20	20	25	20	n/a
Cooling unit	20	15	20	20	25	20	n/a
Cost of energy '[Rp./kWh]'	7.7 (Heating +cooling)	5.85 – 8 (at the moment only heating)	n/a	18 (Heating)	19.8 (at the moment only heating)	22.9 (Heating + cooling)	n/a
Tot. COP of heating	7.2	4.4	n/a	5.2	n/a	n/a	n/a
Tot. COP of heating (incl. Pumps...)	5.8	2.7	2.7	4.1	3.5-4	4	6.5
Tot. EER of cooling	30.1	n/a	n/a	n/a	n/a	n/a	n/a
Tot. EER of cooling (incl. Pumps...)	6.9	12.1	n/a	n/a	n/a	n/a	n/a