D6.5 – Report on Early Adopters case studies

Fifth generation, low temperature, high exergy district heating and cooling networks
FLEXYNETS

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1 Introduction

In the FLEXYNETS project, many analyses on sources, substations, network, and storages have been carried out. The purpose of this report is to apply the approach developed in these previous analyses to some potential early adopters of the FLEXYNETS concept.

The analyses in this report contain a preliminary planning and pre-design of the FLEXYNETS concept for three case studies in different climatic conditions (Northern, Central and Southern Europe), namely:

1. Wüstenrot in Germany
2. Høje Taastrup in Denmark
3. Trento in Italy

In two of these cases (Wüstenrot and Høje Taastrup), a district heating (DH) network already exists and in Wüstenrot it is a cold-temperature network, very close to the FLEXYNETS concept, although being based on a geothermal source instead of on waste heat recovery. The case in Trento does not have DH yet, but the development of a small network is already planned.
For all these cases, the related stakeholders expressed strong interest and commitment in developing a low-temperature network, with the clear aim of reducing CO_2 emissions (either by improving the network performance or expanding it towards new buildings, and hence dismissing fossil fuel spupply). Most of these activities are already related to other research projects, but all of them still lack final decisions and definitive plans. Here, the preliminary planning for these three case studies will be elaborated for the possible deployment of the FLEXYNETS concept, in order to verify the feasibility of this approach for the different cases.

The report contains a description of each case study. To analyse and compare the three case studies, an Excel tool — which had been developed based on results from previous analyses in the FLEXYNETS project — was used. This tool is the main outcome of Deliverable D6.11 of FLEXYNETS and will be publicly available on the project website www.flexynets.eu/en/Results for at least 2 years after the project end.

2 Early Adopter 1: Wüstenrot (Heilbronn, Germany)

2.1 Introduction to the case study

The German demonstration site is the existing cold-water DH system in the district of "Vordere Viehweide" located in Wüstenrot. If not otherwise referenced, the information presented for this case study was provided by Zafh.net, partner within the FLEXYNETS project.

This district comprises 23 newly built highly energy-efficient residential detached or standalone buildings. The scheme of the system is shown in Figure 1.

The net zero energy supply concept combines a low-depth geothermal system, a cold-water DH grid, heat-pumps and photovoltaic (PV) systems. Each building is equipped with a controllable heat pump and thermal storage. The heat pumps draw heat from the cold-water DH loop and boost its temperature to meet the consumers' requirements. Some buildings have also PV systems and battery storage. A smart management system helps to increase the PV self-consumption and to reduce peak power feed-in on a building level. The PV panels and batteries supply electricity to run the heat pumps.

2.1.1 Original plan and current status

According to the original plan, the cold-water DH system should have supplied 25 buildings, with a total heat demand on the network side of about 250 MWh/year. The network could have been extended to other 5 existing buildings and 10 new buildings, adding a heat demand on the network side of about 270 MWh/year. The amount of heat which could be extracted from the ground was estimated to be between 40 and 70 kWh/m^2/year, so resulting in a total land area for the low-depth geothermal field between 7,500 and 13,000 m^2. These numbers were also in agreement with the expected peak thermal power demand and the heat transfer rate in the geothermal field (Brennenstuhl, 2017).

The preliminary estimated cost for the geothermal field was 240,000 € for an area of 15,000 m^2, and additional 34,000 € for the mono-ethylene glycol to fill the system. The cost of the network was estimated to be 350 €/m. The project received a subsidy of 246,600 € (Brennenstuhl, 2017).

However, the real costs proved to be much higher, due to machine transporting, additional cost for larger installation chambers for monitoring and other problems related to the fact that the installation was a first prototype of its kind. Hence, almost 240,000 € were spent for the implementation of the first part of the geothermal field only (4,400 m^2), resulting in a specific cost of 54.5 €/m^2. Based on the learnt lessons from this first prototype, it is expected that the installation of a new geothermal field in similar conditions would easily cost between 50 % -75 % of the above-mentioned cost. The costs of 350 €/m for the DH network could be considered valid for new districts, when the roads are built at the same time as the DH network. As in the case of Wüstenrot the decision to install the DH network was taken later, the costs were higher, approximately 214,000 € (resulting in 428 €/m). Additionally, the connection of the network to the buildings (including valves and meters) entailed a cost of 2,300 € per building.

The installed low-depth geothermal field showed that the actual heat transfer rate with the ground was higher[1] than originally expected in the planning phase. Consequently, the installed geothermal field of 4,400 m^2 proved to be sufficient to meet the demand of the first 23 connected buildings.

[1] The extracted heat is 256 MWh/year (see later), which, on a surface of 4400 m^2, yields about 58 kWh/m^2.

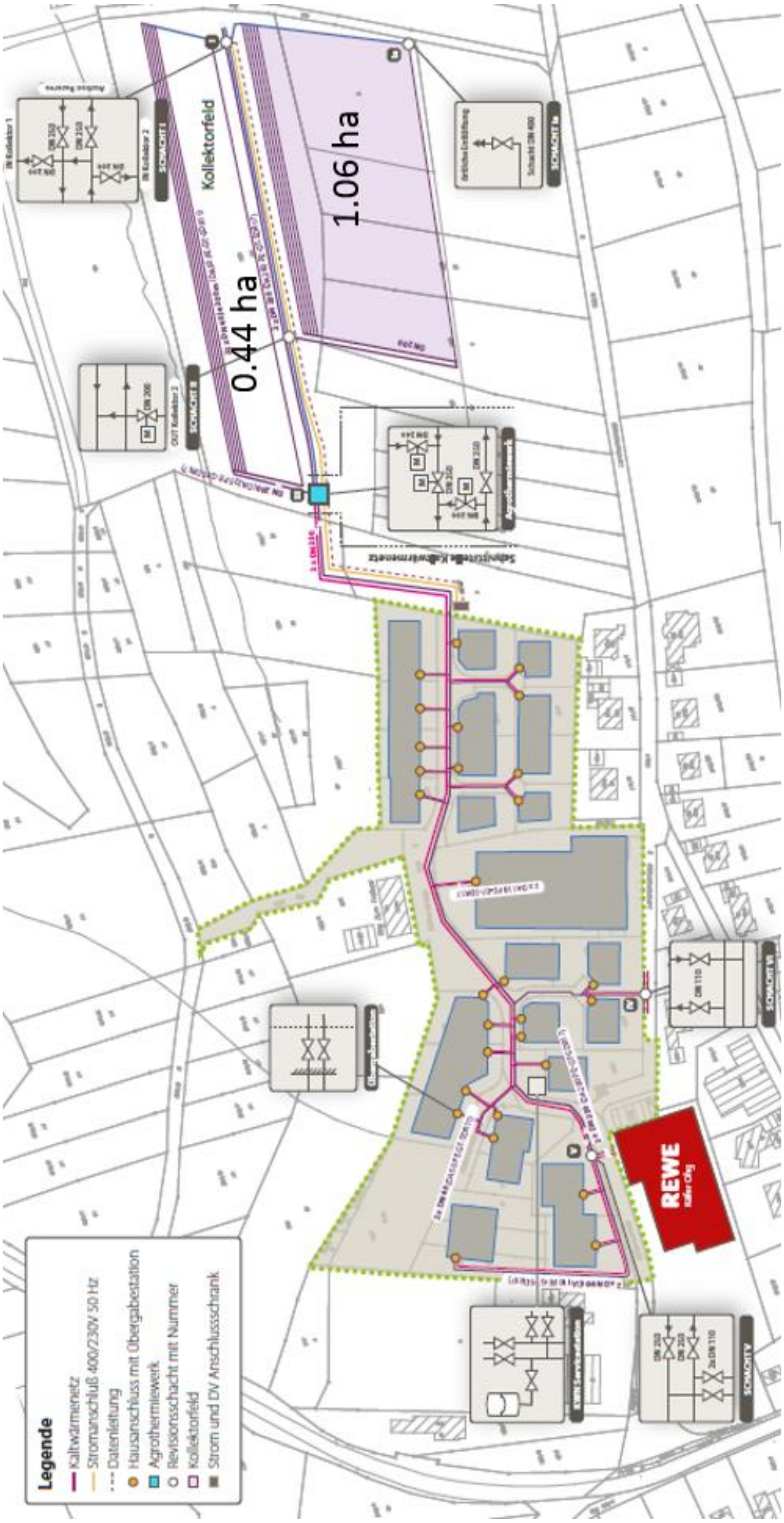

Figure 1. Network map of the Wüstenrot case.

The existing network, as the other few cases of geothermal-based networks across Europe (Buffa, 2018), can be considered an example of a FLEXYNETS network, though some differences can be highlighted: absence of low-temperature waste heat (at least at the moment), lower supply temperature than typically assumed in FLEXYNETS and absence of cooling demand.

In this case study, the possible heat recovery measures considered in the Waste2Heat project are analysed from the FLEXYNETS perspective (with the exception of cooling), in order to provide feedback to the district developers. It is also worth mentioning that the option of heat recovery from waste water for Wüstenrot is included in another recently started project, namely the LIFE4HeatRecovery project of the LIFE program. The proposal for this project, coordinated by EURAC, was prepared during the FLEXYNETS project and can be considered one of its impacts.

2.2 Heat demand

According to the collected information, the district of "Vordere Viehweide" (25,000 m^2 of land area, excluding the low-depth geothermal field) has 23 buildings which are supplied by a cold-water DH loop. The buildings are single family houses, whose floor area can be estimated in 150 m^2/house[2]. However, this information was not used in the tool to estimate the sizing of the network, as more accurate information on the actual network could be retrieved (see Section "Heat supply").

The houses comply to the KfW-55 standard, meaning that their annual requirement of primary energy is 55 % of a comparable new building meeting the German Energy Saving Ordinance. The ordinance defines the maximum values of primary energy consumption that a new building must comply with.

The yearly heat demand for space heating and domestic hot water preparation is estimated to be about 340 MWh, which —assuming a yearly-averaged COP of 4— corresponds to about 255 MWh of heat demand on the network side. Approximately 60 % of the heat demand is used for space heating, while the remaining 40 % for domestic hot water preparation. The heating system of the connected houses work with a supply temperature of 30 °C-40 °C, while the return temperature can be estimated to be 10 °C lower than the supply. Domestic hot water is prepared at 52 °C.

2.3 Heat supply

Currently the only heat supplied to the DH loop comes from the low-depth geothermal field, which has a size of 4,400 m^2. The pipes in the low-depth geothermal field lie parallel to each other at a distance of 0.5-1 m. The pipes were laid down at a depth of about 2 m with a special plough. In this way, the soil stratification was maintained, and the pipes are located far below the roots of the plants. Therefore, no negative effect on the agricultural yield is expected.

The average supply temperature of the DH system in the period August-February was available from monitored data. The supply temperature profile for the entire year was obtained assuming a symmetric profile and is shown in Figure 2. It is seen that the supply temperature of the DH network changes over the year, following a seasonal profile. The reason is that the geothermal field is laid just 2 m below the ground surface, so the atmospheric conditions (ambient temperature, sun, rain, snow) have a direct influence on the ground temperature and hence on the temperature of the heat transfer fluid in the DH system.

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[2] For a land area of 25,000 m^2, this corresponds to a very low plot ratio, namely 0.15, as it could be expected for a rural area.

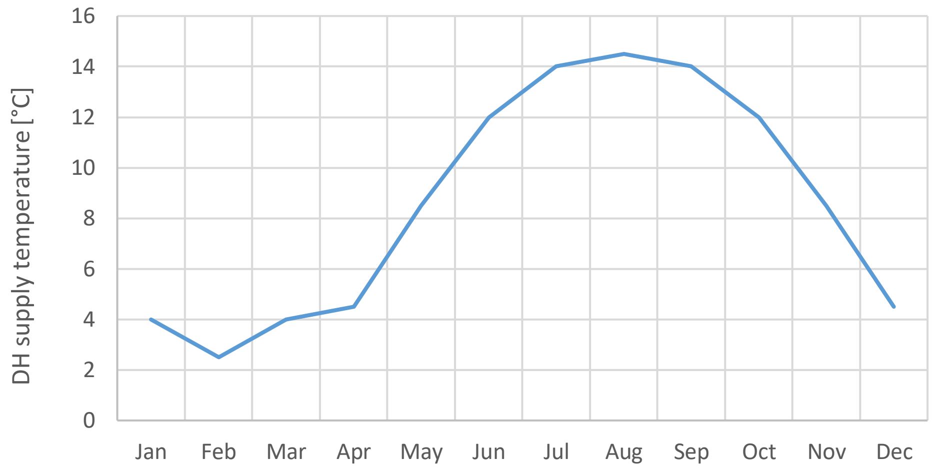

Figure 2: Supply temperature of the DH system.

The DH network consists of a two-pipe system with a large diameter (DN250, see Figure 3) and has a trench length of about 500 m (see Figure 1). The DH pipes were installed considering the future extension of the DH network to other buildings and hence they are currently oversized, if considering only the 23 houses presently connected. Even considering the extension of the network to other 5-10 buildings, the DN250 diameter of the DH pipes may seem oversized for so few buildings. There are several reasons for so large pipes. First, the temperature difference along the evaporator of the heat pumps is rather small, just 4 K. Secondly, the piping of the DH system is meant to be used as a buffer. Thirdly, as there is no central circulation pump —but only local pumps located in each building on the cold side of the heat pumps— the pressure drop in the DH loop must be very low.

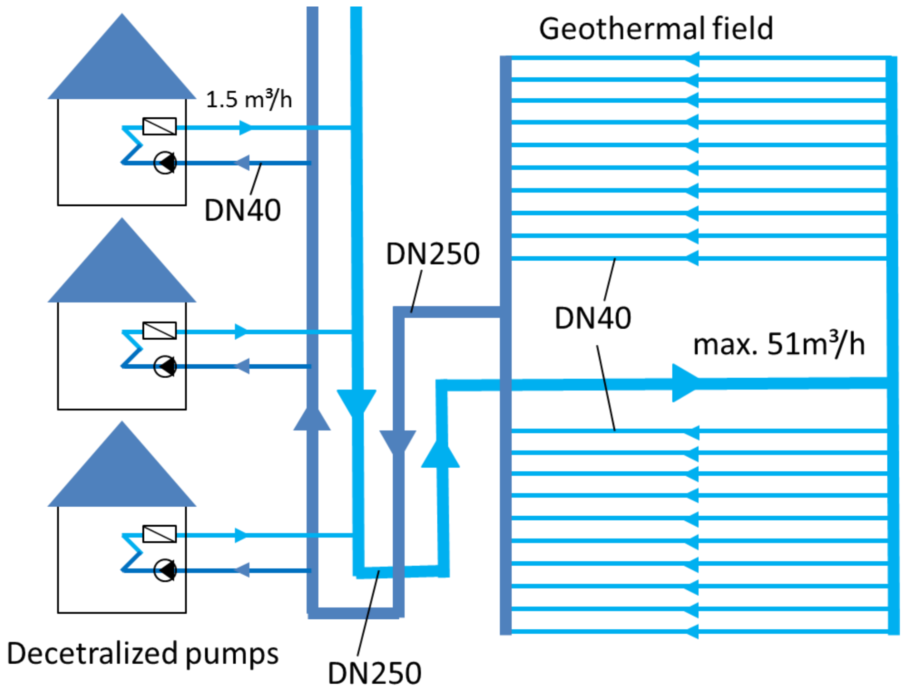

Figure 3: Hydraulic scheme of Wüstenrot case (Brennenstuhl, 2017).

The current peak heat demand of the buildings is about 186 kW, which —assuming a COP of 4 for the heat pumps— corresponds to a peak power drawn from the DH network of about 140 kW and a flow rate of about 32 m^3/h.
The heat transfer fluid circulating in the DH system is a 20 % mono-ethylene glycol/water mixture (see Table 1). The glycol-water mixture does not have to be permanently circulated, because the ground temperature remains available even when it is at a standstill, as no losses occur. So, the DH loop is turned on and off as needed by the individual heat pumps.

Each building is equipped with a controllable heat pump and thermal storage. The capacity of the installed heat pumps ranges from 6 kW to 17.5 kW, depending on the size of the buildings.
The heat pump draws fluid from the supply pipe of the DH network, lowering its temperature by 4 K before injecting it back in the return pipe, which brings it back toward the geothermal field. Heat at the required temperature is generated by heat pumps directly in the homes of the users, where buffer tanks allow a more stable operation of the heat pumps —with reduced on/off operation— and cover short-term peak demand.

Table 1: Assumed physical properties of the mono-ethylene glycol - water mixture circulating in the DH loop in Wüstenrot (from www.meglobal.biz/media/product_guides/MEGlobal_MEG.pdf).

Property	Value	Unit
Mono ethylene glycol concentration	20	%
Freezing point	-8	°C
Reference temperature, T_{ref}	10	°C
Density at T_{ref}	1028	kg/m^3
Specific heat at T_{ref}	3.97	kJ/(kg K)
Dynamic viscosity at T_{ref}	2	10^{-3} Pa s

2.4 Current scenario and numerical investigations

2.4.1 Assumptions

The boundary conditions and information presented in the previous sections were used as input to the pre-design Excel tool, developed within the FLEXYNETS project. This information refers to the extension of the DH area, number of loads, profile of the supply temperature of the DH system, temperature requirement at the consumer side.

Because no information on the heat demand profile was available, the demand for domestic hot water was assumed to be uniformly distributed during the year, while that for space heating followed the profile for retrofitted single-family houses in Stuttgart (obtained in Task 2.1, see Deliverable D2.1). The resulting profile of heat demand is shown in Figure 4.

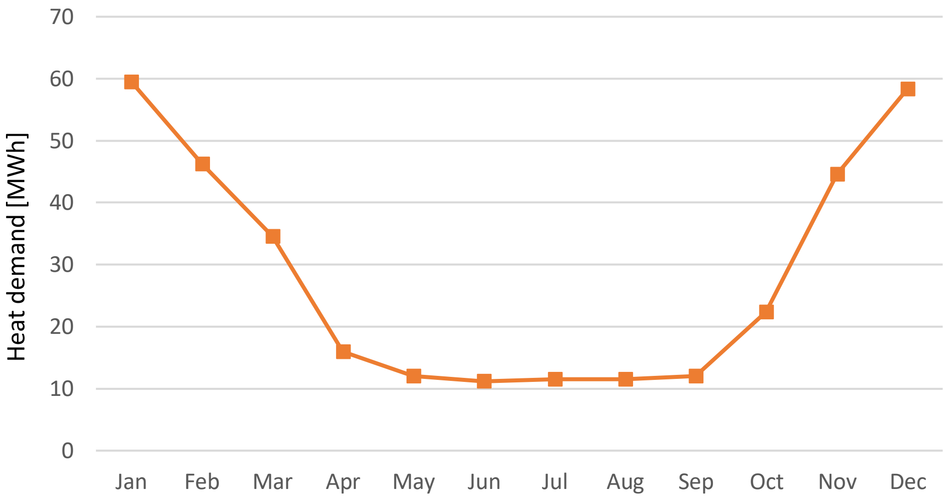

Figure 4: Heat demand profile assumed for Wüstenrot case study.

Lacking more precise information, the heat demand was assumed constant during the day, because the installed buffer tanks were said to allow a stable operation of the heat pumps.

Because the capacity of the installed heat pumps ranged from 6 kW_{th} to 17.5 kW_{th}, depending on the size of the buildings, an average size of 10 kW_{th} was assumed. As the heat pumps were ordered by building owners directly, the real machine + installation costs were not available and an average cost of 1,200 €/kW_{th} (including installation) was assumed. As O&M costs, the default values present in the Excel tool were used.

The investment cost for the low-depth geothermal field was based on the information collected from the case study (Section 2.1.1) and a lifetime of the system of 25 years was assumed.

Because the PV systems were ordered by building owners directly, the real cost figures were not available. However, for Germany the cost for the electricity from roof-mounted PV can be estimated to be 12 c€/kWh, to which a fee of 4 c€/kWh (EEG surcharge for self-consumption of PV electricity in Germany) must be added. Overall, the total cost assumed for PV self-consumed electricity was 16 c€/kWh, which is coherent with the results shown in (Weida, 2016). On the other hand, the price of the electricity bought from the grid was 30 c€/kWh (Eurostat, 2017). Regarding the PV electricity production, the few data available suggested that this covers about 25 % of the electricity consumption of the heat pumps[3].

Regarding the environmental impact of the system, the CO_2 emission factor for grid-supplied electricity for Germany was assumed to be 430 kg_{CO2}/MWh (AGEB, 2018), while a factor of 0 was used for PV-produced electricity[4].

2.4.2 Results

The results shown in this section were obtained by applying the above-mentioned assumptions and boundary conditions in the FLEXYNETES pre-design Excel tool.

[3] Two explicit price values are used in the model. Anyway, one can estimate that the (weighted) average price is 26.5 c€/kWh.
[4] Two explicit emission factor values are used in the model. Anyway, one can estimate that the (weighted) average factor is 322.5 kg_{CO2}/MWh.

Table 2 lists the main indicators of the energy performance of the geothermal DH system as currently implemented in Wüstenrot. Note that

Table 2: Main indicators of the energy performance of the geothermal DH system in Wüstenrot.

Parameter	Value	Unit
Yearly heat demand	340.0	MWh/year
Heat drawn from geothermal field	256.0	MWh/year
Monthly peak energy drawn from geothermal field	43.8	MWh/month
Reversible heat pumps installed capacity	57.5	kW_{el}
HP electricity consumption (from PV)	21.0	MWh/year
HP electricity consumption (from grid)	63.0	MWh/year
Yearly-averaged COP	4.0	-

Figure 5 shows the equivalent annual cost of the low-depth geothermal DH system, including all costs related to covering the heat demand of the 23 connected buildings. The different columns in the diagram represent respectively different cost estimates:

- Case 1: the actual costs of the system were used, and the available subsidy was considered.
- Case 2: the cost which can be expected to be achieved —based on the experience gained from the first prototype installation— were used. The available subsidy was still considered. As the subsidy was higher than the new installation cost of the geothermal field, it was assumed that it would still be granted in its whole and used to cover part of the investment of other components of the system (e.g. DH network, connections to buildings, etc.).
- Case 3: the same cost assumptions as in Case 2 were made, but no subsidy was considered.

The above-mentioned cost assumptions are summarized in Table 3.

Table 3: Cost assumptions used in the Excel tool for Wüstenrot case study.

	Case 1	Case 2	Case 3
Installation of geothermal field [€/m^2]	54.5	30	30
Installation of DH network [€/m]	428	350	350
Heat pumps and installation [€/kW_{th}]	1200		
Building connection [€/building]	2300		
Subsidy [€]	246,600	246,600	-

The economic feasibility of the different scenarios is expressed in terms of equivalent annual cost, which represents the annual cost of owning, operating and maintaining all the components of the system (central plant units, distribution network, heat pumps, etc.). The equivalent annual cost (EAC) is given by:

$$EAC = \sum_i P_i + \sum_i O\&M_i + \sum_i (c_{f,i}\, Q_{f,i})$$

where EAC [€] is the total equivalent annual cost to cover the demand;

P_i [€] is the annualized capital cost of investment of the system component i calculated by the annuity loan down-payment formula, given by

$$P_i = \frac{PV_i\, r}{1-(1+r)^{-n_i}}$$

where PV_i [€] is the present value of the investment for component i;
r [%] is the yearly interest rate (2 % was always assumed);
n_i [year] is the investment lifetime of component i.

$O\&M_i$ [€] is the sum of the yearly fixed and variable O&M costs of the component i;
$Q_{f,i}$ [MWh] is the amount of energy used by the component i (for the presented system the only energy considered is electricity);
$c_{f,i}$ [€ MWh^{-1}] is the price of the energy source/carrier used by the component i.

The composition of the equivalent annual cost of the low-depth geothermal DH system for above-mentioned cases is shown in Figure 5. The resulting costs of heat for the consumers, which are inclusive of all expenses, are listed in Table 4, together with the total and specific CO_2 emissions.

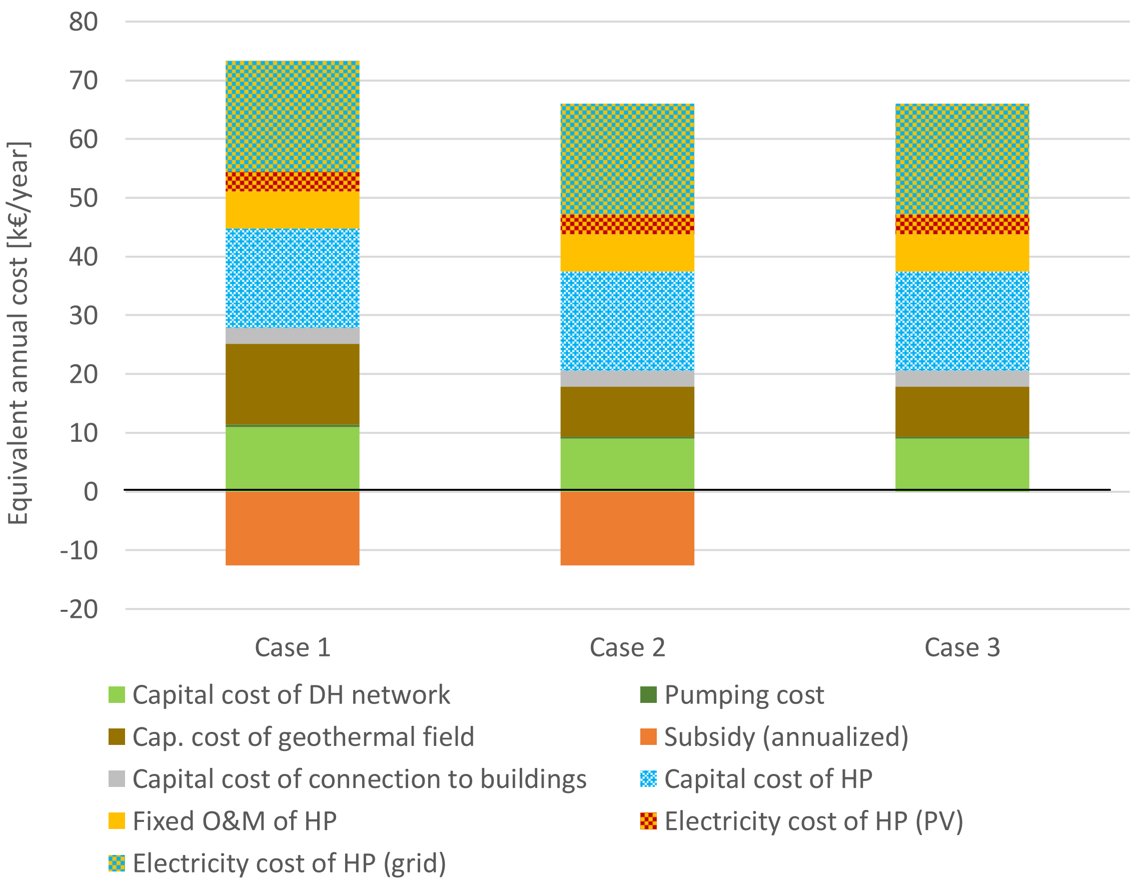

Figure 5: Composition of the equivalent annual cost of the low-depth geothermal DH system in the Cases 1, 2 and 3.

Figure 5 shows that the main component of the equivalent annual cost of the system was represented by the investment cost of the heat pumps. The cost of the electricity drawn from the distribution grid was another major component, due to high electricity prices applied to private consumers in Germany. The actual cost of the DH network and of the geothermal field (Case 1) represented together about 34 % of the overall equivalent annual cost. However, these high costs were also caused by problems and delays relative to this specific and prototype installation. If the cost listed in Table 3 for Case 2 and 3 were assumed, the DH network and the geothermal field would represent about 27 % of the overall cost.

Table 4: Cost of heat for the consumer and CO_2 emissions in the Cases 1, 2 and 3.

	Case 1	**Case 2**	**Case 3**
Cost of heat for the consumer [€/kWh_{demand}]	0.179	0.157	0.194
CO_2 emission [ton/year]	36.7		
Specific CO_2 emission [g/kWh_{demand}]	108		

The cost of heat for the consumers shown in Table 4 may be compared to the reference cost of heat for other heating technologies, shown in Figure 6.

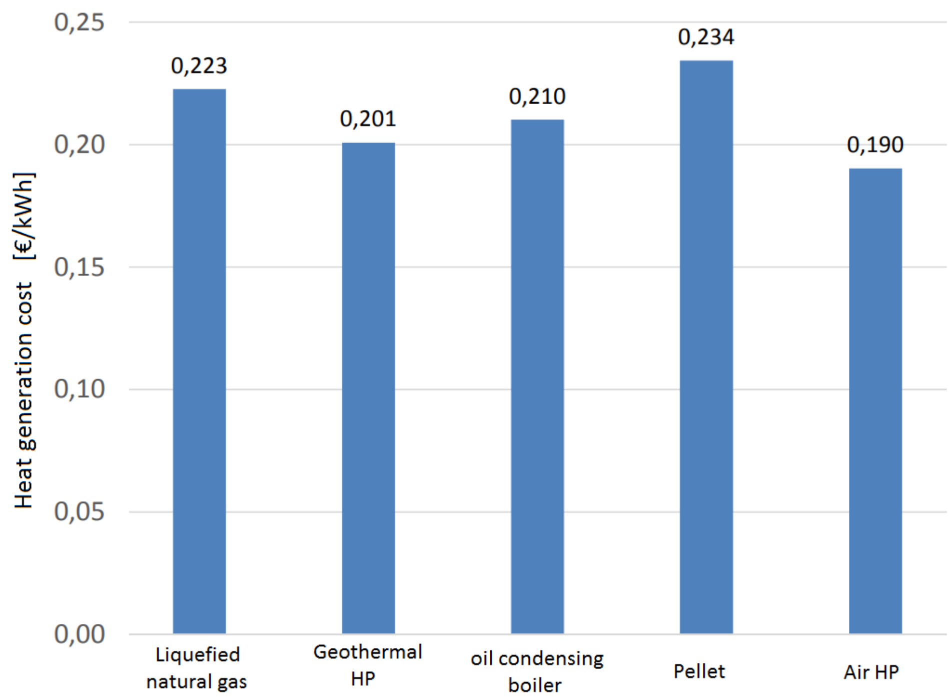

Figure 6: Heat generation cost for different heating technologies in Germany, 2014 (Brennenstuhl, 2017).

2.5 Future developments

2.5.1 Possible extensions and waste heat sources

The cold-water DH network could be extended to the additional 5 existing buildings and 10 new buildings in the next years. The existing old buildings are still heated mostly by oil boilers, with significant CO_2 emissions. The largest challenge in connecting them is their old radiator-based heating system and poor insulation. Before being connected to the cold-water DH system, these buildings have to be refurbished and their heating system made compatible with a low-temperature heat supply.

The extension of the DH system would require the expansion of the low-depth geothermal field, but this is not the only option. In fact, in connection to the extension of the DH network in Wüstenrot and to the Waste2Heat project, two measures are considered, in order to reuse waste heat as energy input to the DH network:

1. In the south-west corner of the DH area, there is a supermarket (see red block in Figure 1), whose chillers currently reject condensing heat to the environment through dry coolers (Figure 7). To use this currently wasted heat, it is considered to integrate heat exchangers in the heat rejection circuit of the chillers and to connect them to the DH system (Figure 7). Especially in summer, this would increase the temperature in the DH grid, improving the COP of the heat pumps. The electrical COP of the waste heat recovery system (defined as the ratio between recovered thermal energy and consumed electricity) has not been calculated yet. However, as the electricity consumption would be that of the pump (related to the pressure drop in the heat exchangers), the COP of the waste heat recovery system is expected to be in the range of 15-25.

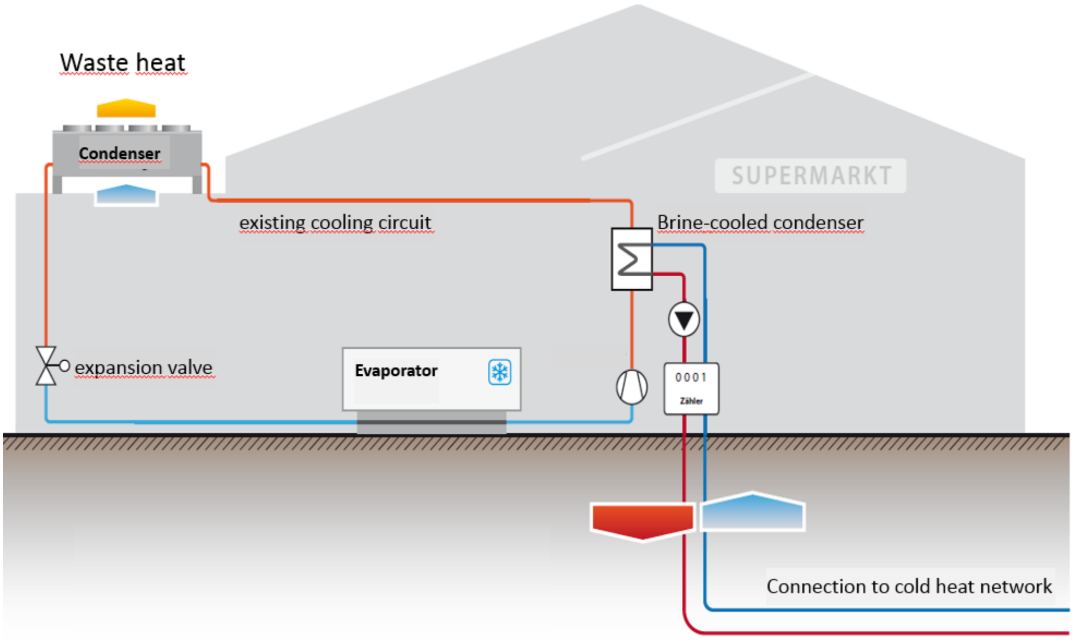

Figure 7. Waste water heat recovery from heat rejection system of the supermarket chillers (Brennenstuhl, 2017).

The installation cost of the heat recovery system is estimated to be 22,000 €, which include hydraulic connection, heat exchanger, pump and control. The cooling demand of the supermarket is about 130 MWh/year, which corresponds to about 180 MWh/year of condensing heat. Preliminary investigations show that 80 % of this waste heat (i.e. 144 MWh/year) could be recovered and injected in the DH network.

2. South of the DH area, the main waste water pipe of Wüstenrot conducts the waste water to the clarification plant, located 3 km east of the district. Within the Waste2Heat project, it is planned to integrate heat exchangers in the waste water pipe with a maximum thermal power of approximately 100-150 kW (Figure 8). To connect the waste water heat exchanger with the cold-water DH grid, a 240 m long pipe needs to be built together with a pumping station. The electrical COP of the waste water heat recovery system (same definition as above) has not been calculated yet, but it is expected to be high (in the range of 15-25).

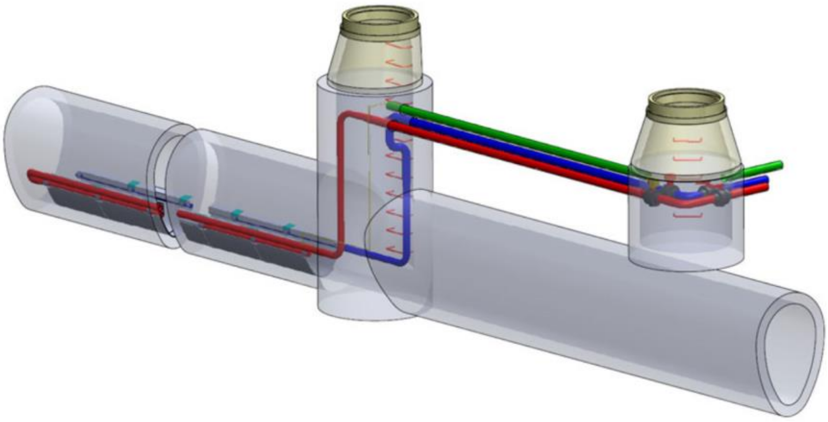

Figure 8. Principle of thermal activation of waste water tubs. A special heat exchanger is installed within the waste water duct (large grey pipe in the figure). Supply and return pipes (red and blue pipes in the figure) of the recovery circuit connected it to the district heating network.

The installation cost of the heat recovery system is estimated to be 140,000 €. This should be almost equally distributed between the actual heat recovery system —which included hydraulics, heat exchanger, pump and control— and the 240 m of connecting pipes. Preliminary investigations showed that the amount of heat which could be recovered would be around 180-230 MWh/year.

If implemented, the two above-mentioned waste recovery systems would reduce the required area of the second geothermal field.

2.5.2 Numerical investigations

The pre-design Excel tool was used to investigate different solutions to implement the extension of the DH network, in order to identify their economic feasibility. The results presented in the following section were obtained based on the following common assumptions:

- 15 buildings are connected to the DH network.
- The newly-connected buildings (after renovation) have a heat demand of 370 MWh/year on the consumer side, resulting in a heat demand of 270 MWh/year on the network side, when considering a yearly-average COP of 4.

- the heat demand on the consumer side is distributed during the year according to the profile shown in Figure 4.
- the DH network must be extended to reach the new buildings. The additional DH pipe length is such that the ratio between the total network length and the total number of connected buildings is the same as in the current DH system, i.e. $\frac{500\ \mathrm{m}}{23\ \mathrm{buildings}} = 21.7\ \mathrm{m/building}$.
- The newly-connected building are equipped with 15 kW_{th} heat pumps (larger than those used in the existing scenario, given the larger energy demand of the new buildings).
- the supply temperature of the DH network is the same as in Figure 2.
- the specific cost of the geothermal field, DH network and building connection are the same as in Case 3, and no subsidy is available (see Table 3).
- the amount of glycol (and hence its cost) is proportional to the DH network length.
- The newly-connected buildings are equipped with PV systems, whose electricity covers 25 % of the electricity consumption of their heat pumps.

2.5.2.1 New geothermal field alone

In this section it was assumed that the additional heat demand on the DH network is entirely covered by an additional low-depth geothermal field.
The potential extension of the cold-water DH network to other 15 buildings is expected to increase the heat demand by about 370 MWh/year on the consumer side and by 270 MWh/year on the network side (see Section 2.1.1). Assuming a distribution of the consumer-side heat demand as shown in Figure 4, the extended DH network (existing + extension) would have a monthly peak energy on the network side of about 90 MWh/month (in January).
The successful operation of the current DH network allows to assume that a low-depth geothermal field of 4,400 m^2 can cover a peak demand of 43.8 MWh/month in winter (Table 2), resulting in a specific land area of about 100 m^2/(MWh/month), which was used a rule-of-thumb for sizing the new geothermal field.

Table 5: Main indicators of the energy performance of the extended DH system (geothermal field only).

Parameter	Existing DH	Extension	Total	Unit
Area of geothermal field	4,400	4,607	9,007	m^2
Number of buildings	23	15	38	-
Trench length of DH network	500	326	826	m
Yearly heat demand	340	367	707	MWh/year
Heat drawn from geothermal field	256	277	533	MWh/year
Monthly peak energy drawn from geothermal field	43.8	46.3	90.1	MWh/month
Heat pumps installed capacity	54.8	53.5	108	kW_{el}
HP electricity consumption (from PV)	21.0	22.7	43.7	MWh/year
HP electricity consumption (from grid)	63.0	68.0	131.0	MWh/year
Yearly-averaged COP	4.0	4.0	4.0	-

The equivalent annual cost of the extended DH system was about 123,000 € and its composition is shown in Figure 9.

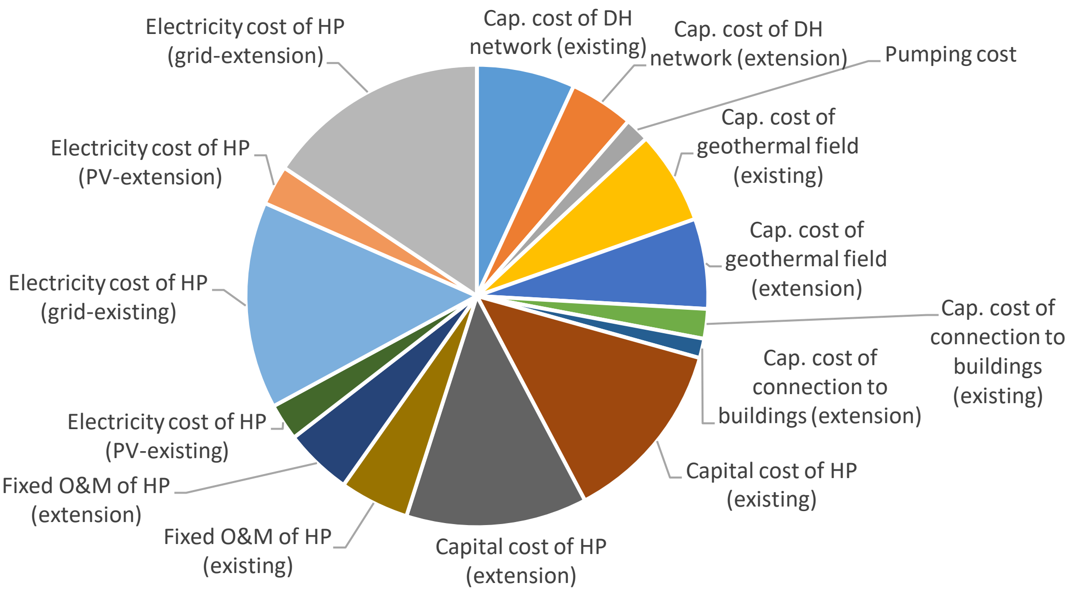

Figure 9: Composition of the equivalent annual cost of the low-depth geothermal DH system in the extended DH system (geothermal field only).

The resulting cost of heat for the consumers was 0.184 €/kWh, in line with that obtained for the existing system in Case 3 (Table 4).
The total CO_2 emissions, related to the electricity consumption from heat pumps and circulation pumps, were 78 ton/year, while the specific emissions were 111 g_{CO2}/kWh_{demand}.

2.5.2.2 Waste heat recovery

The results in this section were obtained assuming that the heat recovered from the waste heat sources (Section 2.5) had the priority in covering the heat demand of the DH network compared to the geothermal field. An additional field was installed, only to cover the possibly unmet heat demand.
Table 6 lists the values which were assumed while carrying out the analysis. Because of the higher electrical COP of the heat recovery system of the supermarket (which is closer to the buildings), this system is given priority of feed-in compared to the waste heat from the waste water pipe.
Figure 10 shows the heat demand on the network side and the availability of waste heat from the supermarket and from the waste water pipe.

Table 6: Assumptions for the waste heat sources.

	Supermarket	Waste water
Waste heat recoverable [MWh/year]	144	220
Yearly/daily profile	Constant	Constant
Investment cost [€]	22,000	140,000
Technical lifetime [year]	25	25
COP [$MWh_{recovered\ heat}/MWh_{electricity}$]	25	15

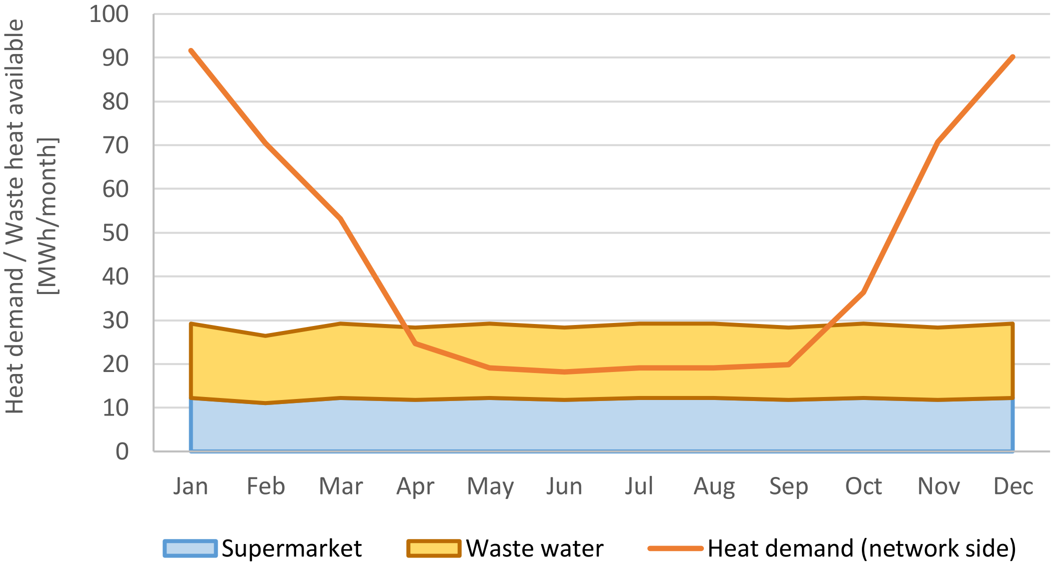

Figure 10: Yearly profile of the heat demand on the network side and of availability of waste heat from the supermarket and from the waste water pipe. The values are expressed in terms of amount of heat per month.

Figure 11 shows the composition of the equivalent annual cost of the extended DH system in three scenarios:

- Case 4: geothermal field only (see previous subsection);
- Case 5: recovery of waste heat from both the supermarket and the waste water pipe;
- Case 6: recovery of waste heat only from the supermarket.

Table 7 lists the cost of heat for the consumer and CO_2 emissions in the above-mentioned cases.

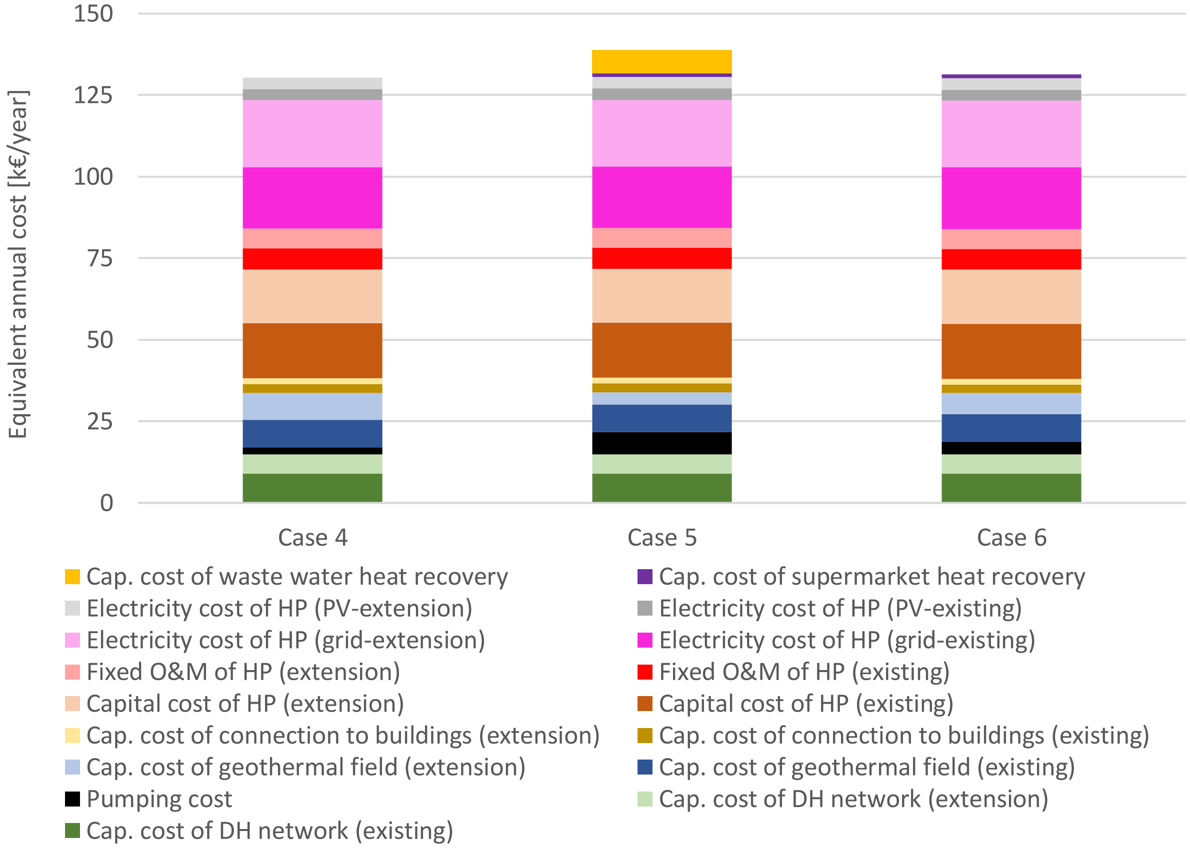

Figure 11: Composition of the equivalent annual cost of the extended DH system in case of 1: geothermal field only (see previous subsection); 2: recovery of waste heat from both the supermarket and the waste water pipe; 3: recovery of waste heat only from the supermarket.

Table 7: Area of the geothermal field, cost of heat for the consumer and CO_2 emissions in the Cases 4, 5 and 6.

	Case 4	Case 5	Case 6
Area of the geothermal field (existing and extension) [m^2]	4,400 + 4,607	4,400 + 1,685	4,400 + 3,384
Cost of heat for the consumer [€/kWh_{demand}]	0.184	0.196	0.184
CO_2 emission [ton/year]	78.3	78.3	78.3
Specific CO_2 emission [g/kWh_{demand}]	111	111	111

Figure 11 shows that case 5 had the highest equivalent annual cost, because of the significant investment cost connected to the heat recovery from the waste water. The economy of this case was further worsened by the fact that not even the entire heat recovery potential from the waste water pipe could be reached, as in summer the total amount of waste heat available was higher than the demand (see Figure 10). Consequently, the resulting specific cost per unit of waste-water recovered heat was higher than the alternative of extending the geothermal field. However, the heat recovery from the waste water may still be a relevant solution, if the extension of the geothermal field proved to be problematic, e.g. due to opposition of the land owner, regulation/legislation on the land use, etc.

Case 4 and case 6 had nearly identical equivalent annual cost, because in case 6 the investment cost for the heat recovery from the supermarket was compensated by the lower cost of the extension of the geothermal field, due to its smaller size compared to case 4.

Because the heat demand was identical in the three cases, the resulting cost of heat paid by the consumers (Table 7) was highest in case 5 and nearly identical in case 4 and 6.

The CO_2 emissions, which were only related to the use of electricity from the distribution grid, were basically identical in the three scenarios. In fact, the electricity absorbed by the HP (identical in all three scenarios) represented the main share of the total electricity consumption, and the electricity consumed by the circulation pumps (both at substation level and in the waste heat recovery systems) were comparable.

3 Early Adopter 2: Østerby (Høje Taastrup, Denmark)

3.1 Introduction to the case study

The case study considered as early adopter for North Europe was the district of Østerby, in Høje Taastrup municipality.

Høje-Taastrup has approximately 50,000 inhabitants and is located about 20 km west of Copenhagen. Most of the city is heated by a DH network, managed by the local DH company Høje Taastrup Fjernvarme. The company, which is owned by the consumers as a cooperative, was built in 1992 and supplies heat to approximately 6,800 buildings through a 233 km long network.

As required by the Danish law, the municipality must decrease its CO_2 emissions by at least 2 % every year. Over the last ten years, the municipality's emissions have decreased by more than 3 % each year. The initiative to reduce its emissions was encouraged by the former EU supported *ECO-Life* project under the CONCERTO initiative (COWI, 2016). Between 2010 and 2015, more than 67 demonstrations were carried out, improving energy efficiency and increasing the use of renewable energy.

More recently the project *Høje-Taastrup Going Green*, supported by the Danish Energy Authority, led Høje-Taastrup to participate in the *Cool DH* project (COWI, 2018), which will help phase out fossil fuels in the near future in a cost-effective way. Already in 2015, 51 % of the district heating supply came from renewable energy sources, such as biomass, municipal waste, solar, geothermal energy, etc.

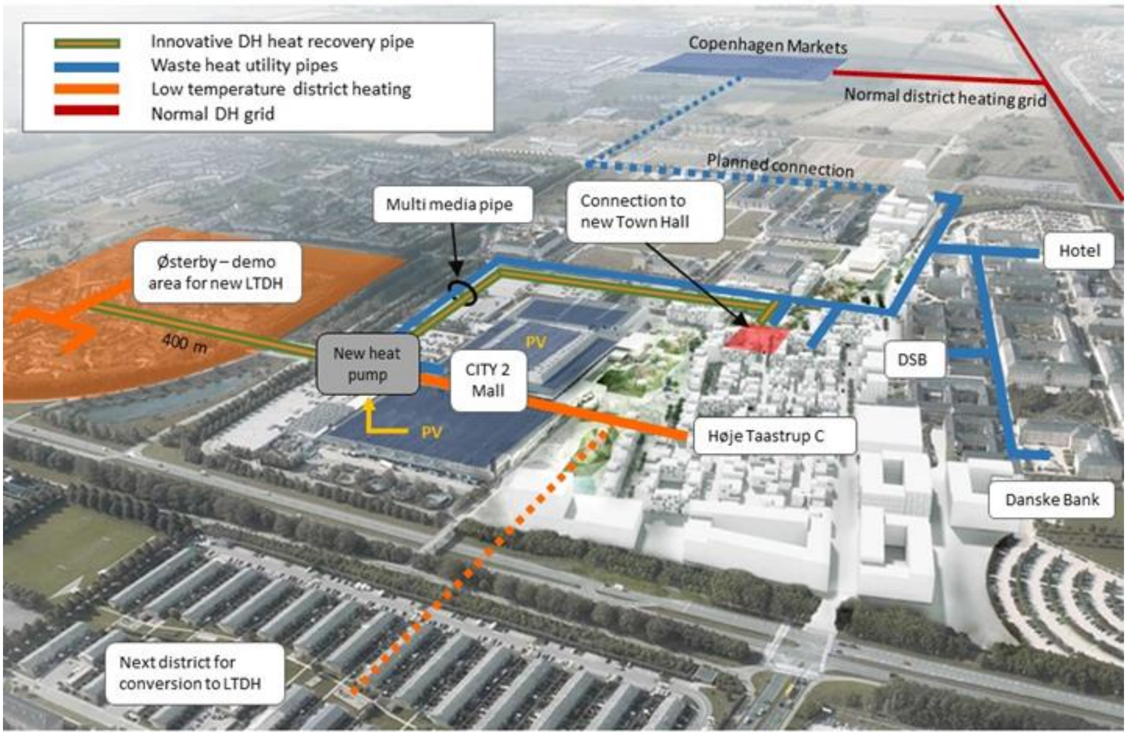

Figure 12: View of Østerby district and surrounding area as foreseen in the Cool DH project (COWI, 2018).

The *Cool DH* project aims at increasing this share even more, by lowering the temperatures of the DH network and exploiting low-grade excess heat from nearby facilities, such as a shopping mall, a hotel, a bank and offices (see Figure 12). The Cool DH project proposes a concept sometimes called Ultra-Low-

Temperature DH (Østergaard, 2017; Yang, 2017): the buildings connected to this innovative distribution network will be supplied heat at low temperature (40 °C/20 °C as supply/return temperature), compatible with low-temperature space heating systems. As domestic hot water must be provided at higher temperature (50-55 °C), the DH supply will be used as pre-heating, while the temperature "topping" (boost) will be covered at the consumers' location by individual heat pumps, which may draw heat from cooling of exhaust air, recovery from wastewater, cooling of PVT, etc. Lowering the temperature of the network would allow to exploit low-temperature heat sources, which are available in the area and which are currently unused.

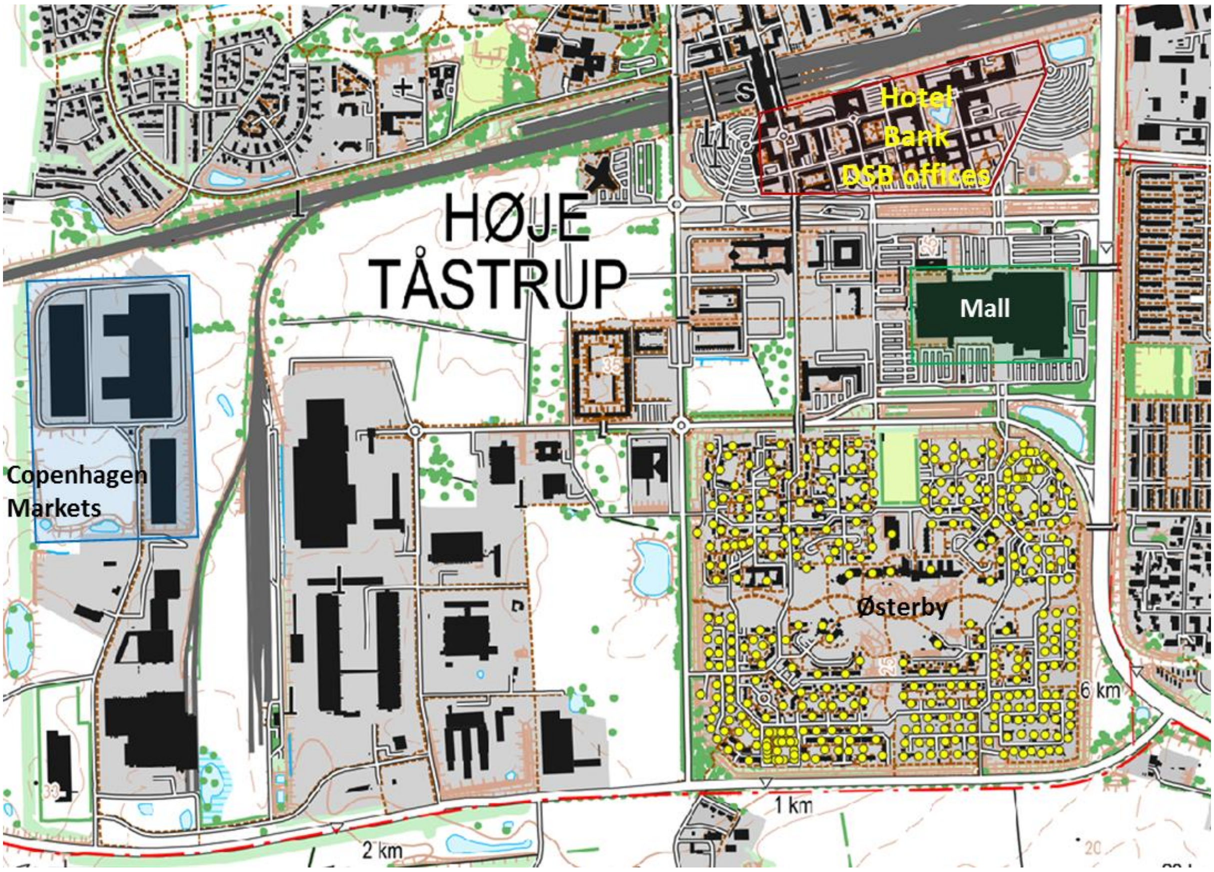

Figure 13: Map of Østerby district and surrounding area. Each yellow dot denotes a DH consumer in the Østerby district. The coloured polygons denote where low-temperature excess heat can be recovered.

Given the similarities between the Cool DH project and the FLEXYNETS concept, the district of Østerby was selected as early adopter case. However, some differences exist between the two approaches. In the Cool DH approach, the network temperature is expected to be higher than in FLEXYNETS, in particular high enough to allow for direct space heating, at least in the context of low-temperature residential heating systems. Heat pumps would only be used to boost the temperature of the supplied water to meet the requirements for domestic hot water preparation. Additionally, these heat pumps draw heat from the external environment rather than from the network. Finally, cooling is not considered of interest in this case.

3.2 Heat demand

According to the data collected from the Danish Heat Atlas (COWI, 2014), the district of Østerby (0.58 km^2 of land area) has 388 buildings heated through DH, for a total floor area of approximately 157,000 m^2. The main settlement categories are residential blocks (61 buildings; 59,000 m^2), row-houses (190 buildings; 58,000 m^2) and single-family houses (103 buildings; 16,000 m^2). These categories correspond to the settlement typologies FL ST 4, FL ST 3 and FL ST 2 according to the categorization presented in the FLEXYNETS deliverable (Jensen, 2016). More than 100,000 m^2 of floor area were built no earlier than 1990 and the oldest buildings are from 1985, which means that the district has relatively new buildings, with relatively high insulation levels. The yearly heat demand is about 14 GWh and the average yearly specific heat demand is 89 kWh/m^2 (square meter of floor area).

3.3 Heat supply

The district of Østerby is currently supplied by the conventional DH network of Høje Taastrup. Lowering the network temperatures, as foreseen by the Cool DH project, would allow to directly exploit low-temperature heat sources which are available in the area. These include:

- Copenhagen markets right west of Østerby district have a constant cooling demand, which results in the availability of low-temperature excess heat.
- Condensing heat from cooling machines at the CITY2 Mall that will operate on power from more than 16,300 m^2 of PV plant with an installed capacity of 2 MW.
- Condensing heat from cooling machines at the Danske Bank data center, DSB and hotels.

In this analysis only the excess heat from the Copenhagen markets is considered. The DH company Høje Taastrup Fjernvarme delivers district cooling to the Copenhagen markets. Since April 2016, two compression chillers supply the cooling, after individual and less efficient cooling systems were replaced. Return flow from the cooling circuit contains heat, which is upgraded through a heat pump to feed into the DH network. The total nominal cooling capacity of the chillers is 2 MW, while the nominal heating capacity of the heat pump is 3.2 MW (Rambøll, 2017). The yearly amount of cooling is about 6,000 MWh, which is raised in temperature by the chillers and heat pump to 75 °C. Figure 14 shows the principle scheme of the interface between the cooling consumers at the Copenhagen markets and the Høje Taastrup DH network.

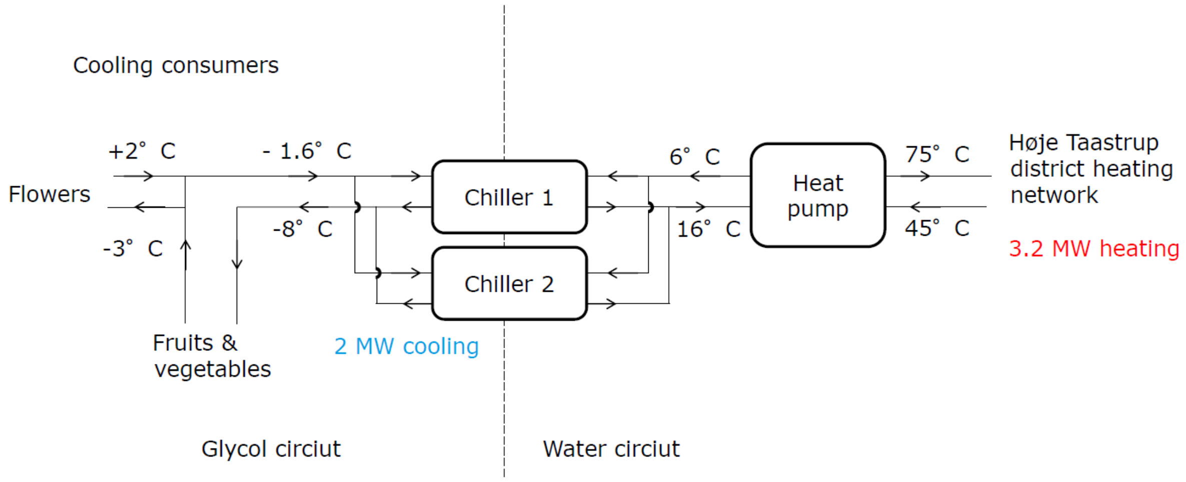

Figure 14: Principle scheme of the interface between the cooling consumers at the Copenhagen markets and the Høje Taastrup DH network: compression chillers and heat pump (Rambøll, 2017).

3.4 Numerical investigations

3.4.1 Assumptions

The boundary conditions presented in the previous sections were used as input to the pre-design Excel tool. These boundary conditions included the extension of the DH area, the number of loads, the temperature requirement at the consumer side.
The tool was used to compare the economic feasibility of a FLEXYNETS system with respect to a conventional DH network, both of them being sized to cover the heat demand of the Østerby district.

The yearly heat demand of the district of Østerby (14 GWh/year) was distributed over the year according to the heat demand profile of the Høje Taastrup DH network (EA Energianalyse, 2017). The resulting profile of heat demand in shown in Figure 15, from which the heat demand for domestic hot water preparation can be assumed to represent 30 % of the total heat demand.

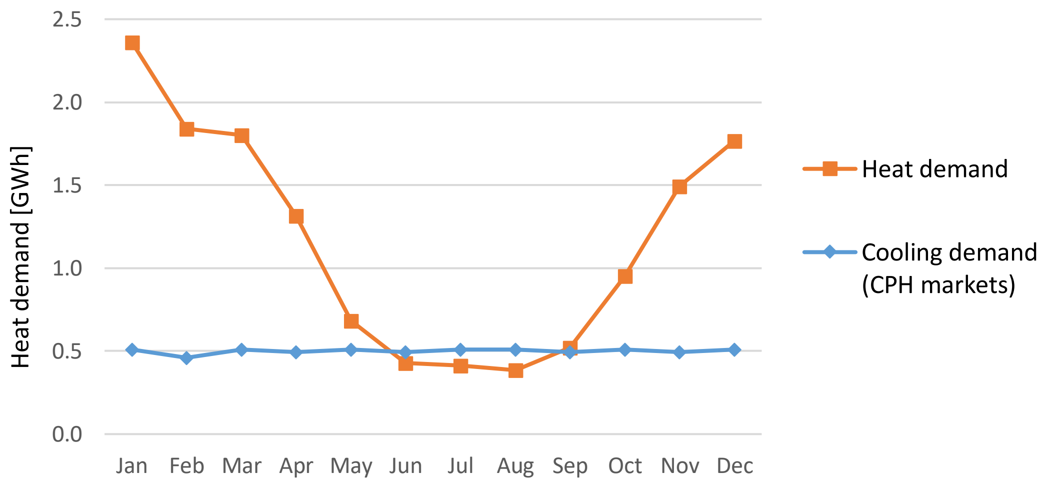

Figure 15: Heat demand profile of Østerby district and cooling demand from Copenhagen markets.

Lacking detailed information, the hourly heat demand profiles (one profile for each season) were set to be the default profiles available in the pre-design Excel tool for Northern Europe, in case of conventional DH. In case of a FLEXYNETS network, constant profiles were assumed during the day, because the buffer tanks connected to the heat pumps are expected to allow for a constant operation.
Both space heating and domestic hot water were assumed to be supplied at a temperature of 50 °C.
The substations and the heat pumps at the consumers' location were sized based on the peak load of the network and assuming a diversity factor of 0.8. The safety margin for the oversizing of the heat pumps was taken to be 1, because a built-in electric heater can cover unexpected peaks.

The yearly cooling demand from the Copenhagen markets was 6,000 MWh. The resulting waste heat made available for DH purposes depended on the efficiency of the chillers and of the heat pump, as well as on the temperature levels of the DH network. The efficiency of heat pump (η_{HP}) was defined as the ratio between the Carnot-performance of the machine (COP_{Carnot}, function of the condensation and evaporation temperatures) and its actual performance (COP), as expressed by the following relation:

$$COP = \frac{\dot{Q}_{cond.}}{W_{HP}} = COP_{Carnot}\left(T_{cond.}, T_{evap.}\right) \cdot \eta_{HP}$$

(The reader should refer to Section 3.5 in the FLEXNYTES deliverable (Bava, 2018) for more information on the topic). The same approach was followed to evaluate the performance of the chillers.
The efficiency of the heat pump and of the chillers was calibrated in specific conditions. For the heat pump (a two-stage heat pump from ICS), an efficiency of 72 % was used, resulting from comparing the performance of a two-stage heat pump from Sabroe (Sabroe, 2018) and the Carnot-performance, when the machine operated between an evaporating temperature of 3 °C and a condensing temperature of 78 °C.
For the two chillers (model BlueAstrum 1800), an efficiency of 58 % was used, resulting from comparing the performance of the machine stated in the technical datasheet of the machine (GEA, 2015) and the Carnot-performance, when the machine operated between the same temperature levels, i.e. 12 °C/6 °C at the evaporator side and 30 °C/35 °C at the condenser side.
The so-determined efficiencies were hence kept constant, making the actual performances of the machines only dependent on the temperature levels between which they operated.
In case of conventional DH (supply/return temperature of 75 °C/45 °C), where the chillers and heat pump were assumed to work at the same temperature as shown in Figure 14, the cooling demand of the Copenhagen markets of 6,000 MWh/year and the above mentioned efficiencies of the machines resulted in an amount of heat available at DH temperature of about 9,950 MWh/year.
In case of a FLEXYNETS system operating at much lower temperature, the ICS heat pump was not necessary, and the chillers could operate at slightly higher condensing temperatures, so to match the supply and return temperature of the FLEXYNETS system. Assuming the above-mentioned efficiency of the chillers of 58 %, the cooling demand of 6,000 MWh/year resulted in an amount of heat available at FLEXYNETS temperatures between 7,000 and 7,300 MWh/year, for supply network temperatures between 15 °C and 25 °C. The lower amount of waste heat with respect to the conventional DH case reflects the reduction of electric consumptions from the centralized heat pump in the Copenhagen markets.

Because no detailed profile of the cooling demand from the Copenhagen markets (and hence of the excess heat availability) could be obtained, a constant profile was assumed throughout the year.
A transmission pipe of 1,500 m connected the Copenhagen markets and the district of Østerby. Its diameter was chosen differently from case to case, so that the pipe could transfer the thermal power made available by the chillers (and possibly by the centralized heat pump) without exceeding a fluid velocity of 2 m/s.
The efficiency of the individual heat pumps in the FLEXYNETS system was 49 % (see the FLEXYNETS deliverable (Bava, 2018)).
The central heater for the network was assumed to be a gas boiler, which could be assisted by an electric boiler (sized as 0.2 times the size of the gas boiler) as backup.
The electricity price paid by private consumers to run a heat pump was assumed to be 27 c€/kWh, hence lower than the electricity price of 30.4 c€/kWh, valid for private consumers in Denmark in 2017 (Eurostat, 2017). In fact, in 2018 the Danish government approved a decrease in the energy tax applied to electricity used for heating purposes. The energy tax will progressively decrease in the period 2018-2021, when it will be 3.4 c€/kWh lower compared to the energy tax valid in 2017. On the other hand, the electricity price for industrial consumers was 8 c€/kWh (Eurostat, 2017).
Regarding other investment costs —such as for DH networks, heat pumps, etc.— the default values of the Excel tool were used. The interest rate used to calculate the equivalent annual cost was 2 %.

Table 8: Summary of the main parameters used as input to the pre-design Excel tool when treating Østerby district.

Total land area	581,300	m^2
Number of consumers (=buildings) in Østerby	388	-
Total floor area	157,541	m^2
Plot ratio	0.27	-
Yearly heating demand of the consumers in Østerby	13,965	MWh
Yearly cooling demand of the consumers in Østerby	0	MWh
Yearly cooling demand (CPH market)	6,000	MWh
Electricity price for industrial consumers	8	c€/kWh
Electricity price for private consumers	27	c€/kWh
Interest rate	2	%
Conventional DH		
Supply temperature	75	°C
Return temperature	45	°C
Insulation class pipes for DH network	SERIES 3[5]	-
FLEXYNETS system		
FLEXYNETS range of supply temperatures	15 – 25	°C
ΔT at the evaporator of the FLEXYNETS' HPs	10	K
Insulation class pipes for DH network	SERIES X[1]	-

[5] For more details on the pipes for DH networks (dimensions, costs, etc.), please refer to the FLEXYNETS deliverable (Bava, 2018).

The price for natural gas was assumed to be 52 €/MWh, based on the gas price and taxation valid in Denmark in 2018 (Eurostat, 2018; PWC, 2015)

Regarding the environmental impact of the system, the CO_2 intensity in electricity generation was assumed to be 163 g_{CO2}/kWh (IEA, 2017).

A summary of the main assumptions used in the analysis is given in Table 8.

3.4.2 Results

3.4.2.1 Conventional DH against FLEXYNETS with household electricity price

Based on the above-mentioned assumptions and boundary conditions, the economic feasibility of a conventional DH system and of a FLEXYNETS system were accessed, together with their environmental impact in terms of CO_2 emissions.

Table 9 lists the main energy-related quantities obtained with the pre-design Excel tool in two different scenarios:

- DH1: Conventional DH system using the same boundary conditions and assumptions as described in the previous sections.
- FL1: FLEXYNETS system using the boundary conditions and assumptions as described in the previous sections. The supply temperature of the system was assumed to be 15 °C (constant during the year).

Figure 16 represents the composition of the equivalent annual cost in the same two scenarios and shows that the FLEXYNETS system was roughly twice as expensive as the conventional DH solution, under the assumed boundary conditions.

As seen in Table 9, the higher electricity consumption from both the chillers and the heat pump in the Copenhagen markets in case of conventional DH increased the availability of excess heat compared to the FLEXYNETS scenario, where only the chillers operated. In both scenarios the amount of heat made available by the Copenhagen markets could not be completely used, because in summer the heat made available was higher than heat demand from the network. This surplus could potentially be delivered to the Høje Taastrup DH network (directly, in case of conventional DH; after been boosted e.g. by a heat pump, in case of FLEXYNETS). However, this possibility and the resulting economic value of this excess heat was not considered in this analysis.

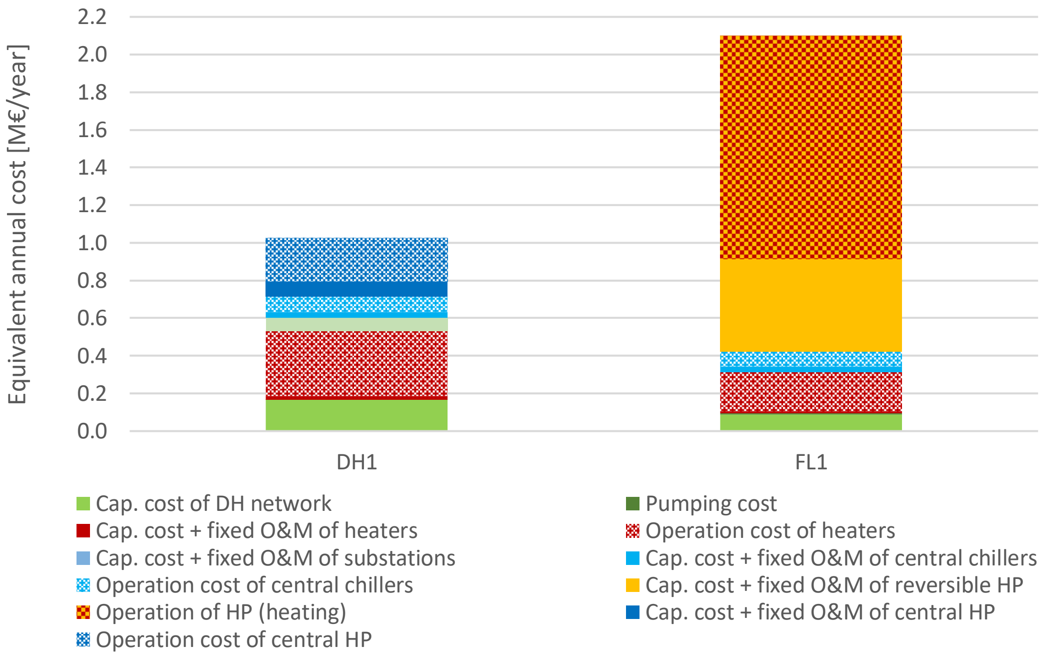

Figure 16: Composition of the equivalent annual cost in case of conventional DH (DH1) and FLEXYNETS (FL1).

Table 9: Main energy-related quantities in case of conventional DH (DH1) and FLEXYNETS (FL1).

Parameter	DH1	FL1	Unit
Yearly heat demand	13.96	13.96	GWh/y
Yearly cooling demand of CPH markets	6.00	6.00	GWh/y
Electricity used by CPH markets' chiller	1.03	1.00	GWh/y
Electricity used by CPH markets' HP	2.91	-	GWh/y
Heat made available at CPH markets	9.94	7.00	GWh/y
Heat from CPH markets used	8.81	5.77	GWh/y
Surplus of available heat from CPH markets	1.13	1.23	GWh/y
Heat production from central heater	6.67	4.02	GWh/y
Network heat losses	1.53	0.23	GWh/y
Electricity for pumping	0.02	0.04	GWh/y
Electricity used by individual HPs	-	4.37	GWh/y

The length of the distribution network, calculated on the plot ratio, was 7.5 km, in agreement with the distribution of the buildings and the disposition of the roads in Østerby district. The lower excavation costs and material cost in case of SERIES X pipes assumed in FLEXYNETS made the annualized investment cost of the FLEXYNETS network about half of that of the conventional DH system (Figure 16).

Figure 16 shows that the conventional DH system was also more expensive in term of investment and fuel cost of the central gas boiler. In fact, as seen in Table 9, the central heater produced more energy output in case of conventional DH. After using the heat made available from the Copenhagen markets, the central heater covered the heat demand of the consumers and the higher thermal losses from the network pipes. In case of FLEXYNETS, the gas boiler covered only a portion of the heat demand which was not covered by the excess heat from the Copenhagen markets, as the rest was covered by the electricity absorbed by the individual HPs at the consumers' substations.

The investment cost, operation hours and operation cost of the chillers at the Copenhagen markets were almost identical in the two scenarios. What made the FLEXYNETS system significantly more expensive than the conventional DH system was the installation cost of the individual HPs and the electricity these HP consumed, which was paid at a very high price (household consumers' price).

Table 10 lists the cost of heat for the consumers and CO_2 emissions in the two above-described scenarios. In the latter respect, it is evident the benefit given by the FLEXYNETS system, which reduces emissions by about 15 %.

Table 10: Cost of heat for the consumers and CO_2 emissions in case of conventional DH and FLEXYNETS system (scenario #1).

	DH1	FL1
Cost of heat for the consumer [€/kWh$_{demand}$]	0.074	0.150
CO_2 emission [ton/year]	1982	1689
Specific CO_2 emission [g/kWh$_{demand}$]	142	121

3.4.2.2 Effect of the supply temperature in the FLEXYNETS system

Section 3.4.2.1 showed that the cost of the electricity used by the individual heat pumps in the FLEXYNETS system represented a major component of the overall annual cost of the system. For FLEXYNETS to be competitive against conventional DH under the boundary conditions of Østerby district, a lower electricity price was key. Therefore, in the current and in the following sections it was assumed that the electricity used by the individual heat pumps was paid at a price equivalent to that of industrial consumers, i.e. 8 c€/kWh instead of 27 c€/kWh (see Table 8). This could correspond to the case of a business model where the substations are owned by the network instead of by single customers.

In this section, the effect of the supply temperature on the economic feasibility of the FLEXYNETS system was investigated. Three new scenarios were considered, having respectively a supply temperature of 15 °C (FL2), 20 °C (FL3) and 25 °C (FL4). The composition of the equivalent annual cost and the CO_2 emissions in these three scenarios are shown in Figure 17. The conventional DH scenario DH1 from Section 3.4.2.1 is also shown as comparison.

As seen in Figure 17, the equivalent annual cost for the FLEXYNETS system was dramatically reduced by the assumption of industrial price for electricity, although it was still more expensive than the conventional DH solution. Regarding the effect of the different supply temperatures in the FLEXYNETS system, it is seen that the higher the temperature, the lower the equivalent annual cost. A higher supply temperature increased the COP of the individual heat pumps, resulting in a lower electricity consumption. On the other hand, it entailed a higher condensing temperature of the chillers installed at the Copenhagen markets, so decreasing their COP and increasing their electricity consumption. Of these two opposite trends, the former was more important —due to the larger amount of electricity consumed by the individual heat pumps compared to the central chillers— and determined the overall reduction of the equivalent annual cost of the system.

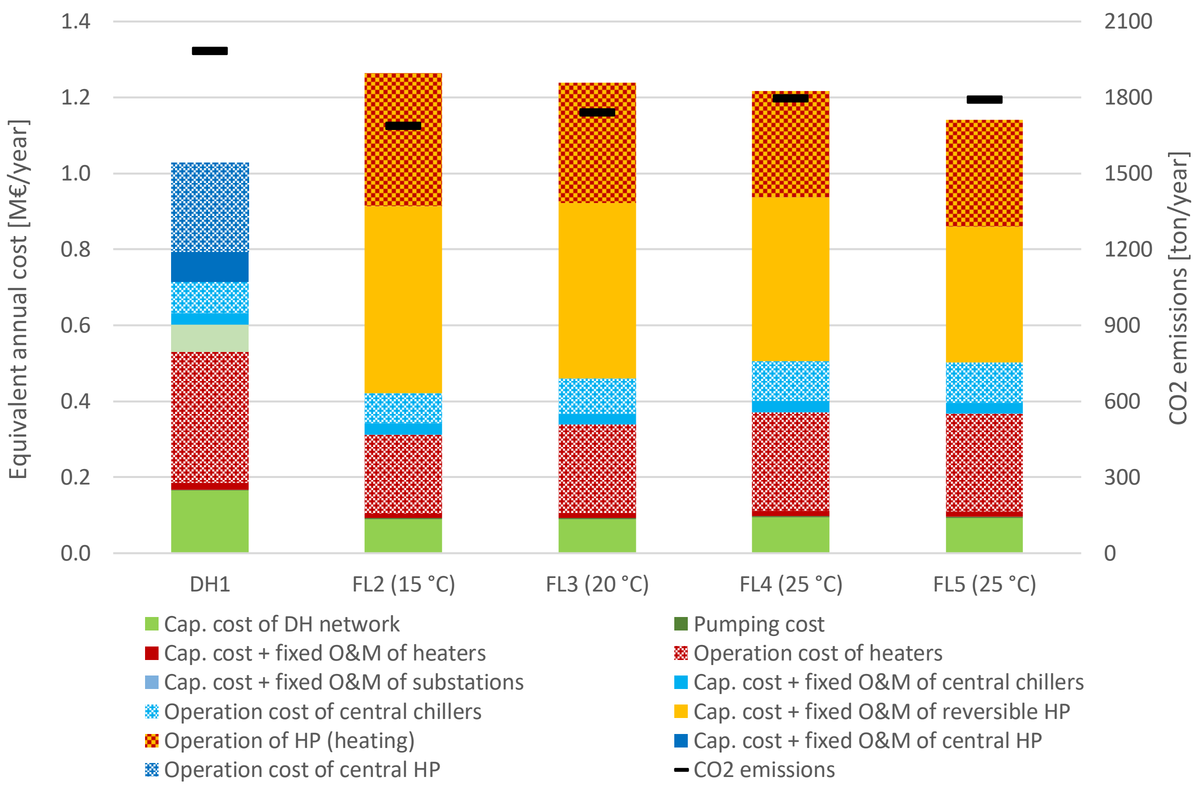

Figure 17: Composition of the equivalent annual cost and CO2 emissions in the scenarios DH1, FL2, FL3, FL4 and FL5.

The operation of the central heater was also affected by the different supply temperatures. The higher COP of the individual HPs at higher network temperatures entailed that more heat was drawn from the network to cover the same heat demand of the consumers. Therefore, the additional heat demand of the network was mostly covered by an increased heat output from the central boiler. This also explains why the CO_2 emissions of the system increased at higher network supply temperatures.

Another relevant component of the equivalent annual cost in case of FLEXYNETS was the investment cost of the individual heat pumps. Therefore, we investigated the possibility of reducing this investment cost by reducing the number of machines and increasing their average size, so to exploit the economies of scale. This new scenario was named FL5, and the composition of its equivalent annual cost is shown in Figure 17. In the FL5 scenario not all the 190 row-houses present in Østerby district were equipped with their own heat pumps —as assumed in the previous scenarios— but a unique and larger heat pump was installed every 4 row-houses. This meant that 48 heat pumps supplied the 190 row-houses, so that the district had in total 246 heat pumps. Because a higher network temperature was shown to improve the economic feasibility of the system (Figure 17), a supply temperature of 25 °C was assumed. As shown in Figure 17, the cost composition in the case FL5 was basically identical to that of the case FL4, with the only difference being a capital cost of the investment for individual heat pumps about 13 % lower.
Table 11 lists the cost of heat for the consumers and CO_2 emissions in the above-described scenarios.

Table 11: Cost of heat for the consumers and CO_2 emissions in case of conventional DH and FLEXYNETS system (scenario #1).

	FL2, 15°C	FL3, 20°C	FL4, 25 °C	FL5, 25°C
Cost of heat for the consumer [€/kWh$_{demand}$]	0.15	0.091	0.089	0.087
CO2 emission [ton/year]	1689	1740	1796	1791
Specific CO2 emission [g/kWh$_{demand}$]	121	125	129	128

3.4.2.3 Centralized heat pump as central heater

The previous section showed how a higher supply temperature in the FLEXYNETS system improved the economic feasibility, but at the same time worsened the environmental impact in terms of CO_2 emissions. The higher COP of the individual heat pumps increased the amount of heat drawn from the network and, because the central heater supplying heat to the network was a fossil fuel-fired boiler, this entailed higher emissions.

In this section it was therefore investigated the possibility of having a centralized heat pump as a main heat source for the network, instead of a gas boiler. Unlike the individual heat pumps of the FLEXYNETS concept and the heat pump installed in the Copenhagen markets, this heat pump was not a fluid-to-fluid heat pump, but an air-to-fluid heat pump, drawing heat at the evaporator side from the environment.

The centralized heat pump was applied to the scenarios DH1 and FL5 (the so-defined scenarios are therefore named DH1_HP and FL5_HP), while all other boundary conditions were the same as in the original cases.

For the centralized air-to-fluid heat pump, an efficiency of 55 % was assumed and its COP was calculated for each month based on the monthly-averaged ambient temperature. The lowest COP for the centralized heat pump —which referred to an ambient temperature of -5 °C and based on which the heat pump was sized— was 2.7 in case of conventional DH and 4.7 in case of FLEXYNETS. The large difference in COP was due to the much higher condensing temperature in case of conventional DH compared to FLEXYNETS.

The composition of the equivalent annual cost and the CO_2 emissions in these two scenarios are shown in Figure 18, where also the original scenarios DH1 and FL5 are also shown as comparison. Table 12 lists the cost of heat for the consumers and CO_2 emissions in the above-described scenarios.

Table 12: Cost of heat for the consumers and CO_2 emissions in case of conventional DH and FLEXYNETS system (scenario #1).

	DH1	DH1_HP	FL5	FL5_HP
Cost of heat for the consumer [€/kWh$_{demand}$]	0.074	0.077	0.082	0.072
CO_2 emission [ton/year]	1982	1101	1791	941
Specific CO_2 emission [g/kWh$_{demand}$]	142	79	128	67

From Figure 18, it is seen that in case of conventional DH the different technology of the central heater had little influence on the overall annual cost of the system. In fact, although the investment cost of the centralized heat pump was much higher than that of the gas boiler, this was almost entirely compensated by the lower operation cost. On the other hand, the scenario using the centralized heat pump performed significantly better in terms of CO_2 emissions, which were almost halved compared to the scenario using the gas boiler.

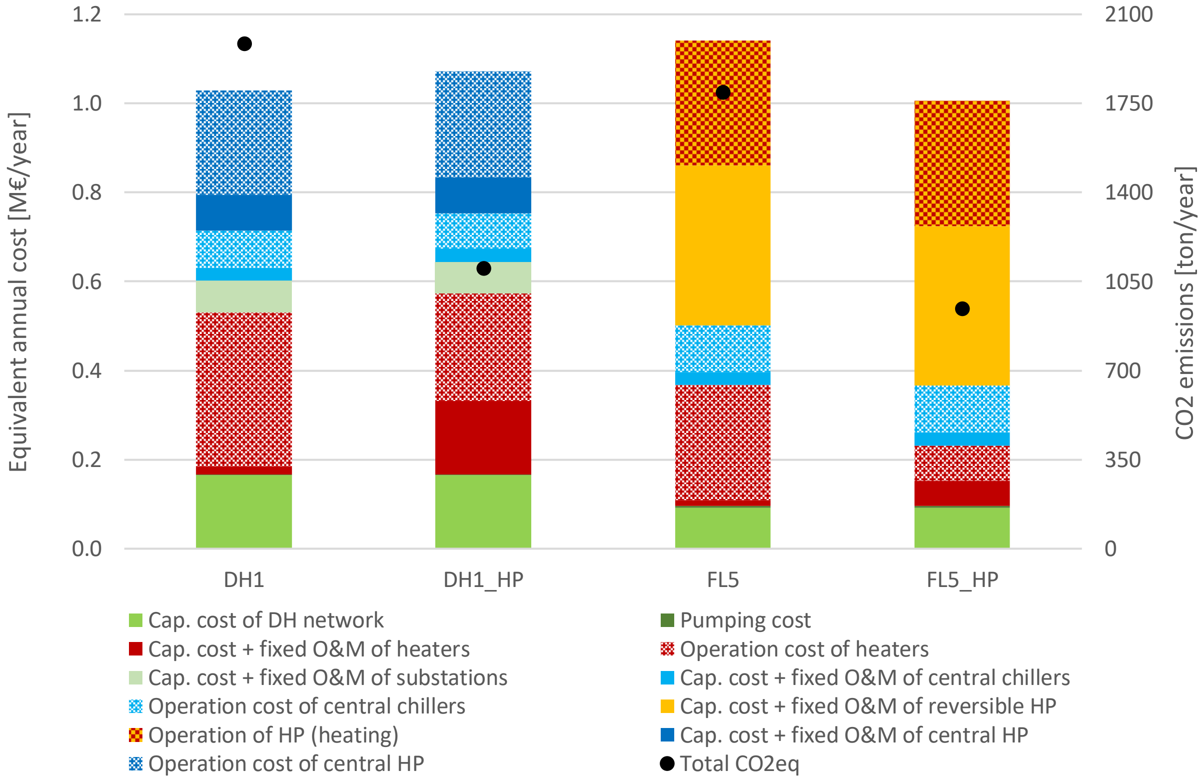

Figure 18: Composition of the equivalent annual cost and CO2 emissions in the scenarios DH1_HP and FL5_HP using a centralized heat pump as central heater. The cases DH1 and FL5 using gas boilers are also shown as comparison.

Considering the FLEXYNETS scenarios, the implementation of the centralized heat pump instead of the gas boiler was preferable both economically and environmentally. In fact, the centralized heat pump benefited from the low supply temperature of the FLEXYNETS network: the electric capacity of the heat pump was significantly lower compared to the DH1_HP case (0.43 MW_{el} against 1.3 MW_{el}) and the monthly COPs were much higher, so entailing a lower electricity consumption. Due to the high price of natural gas for DH purposes in Denmark, the centralized heat pump proved to be very competitive heat source in case of a FLEXYNETS system. Overall, the FLEXYNETS scenario using a centralized heat pump was both economically and environmentally more competitive than the same scenario implementing a conventional DH system.

Similar to the conventional DH case, the use of a centralized heat pump significantly decreased the CO_2 emissions (by about 50 %) compared to the case with the gas boiler.

This significantly positive result heavily relies –especially from an economic point of view– on the assumed electricity prices. From this point of view, it has to be pointed out that the situation of Denmark is rather peculiar with respect to other EU countries. Indeed, here industrial electricity prices are very low, while residential electricity prices are very high (see Deliverable D3.2 for on overview of electricity prices across Europe). Moreover, the CO2 emission factor of the electric grid is much lower than the EU average (see again D3.2). It is therefore not obvious that this solution is positive as well for other EU countries. As a final remark, it is anyway important to note that the considered solution showed how FLEXYNETS strategies can be beneficial even in Northern countries, in spite of the absence of residential cooling demand.

4 Early Adopter 3: Madonna Bianca (Trento, Italy)

4.1 Introduction to the case study

The Italian case study considered as early adopter is the district of Madonna Bianca, in the southern area of the city of Trento (Italy).

Trento is a city located in the northern part of Italy, with a climate typical of the Alpine region. The district of Madonna Bianca (Figure 19) was realized in the '60s and comprises a social housing residential complex with a common swimming pool. Located nearby are a University Campus and a large commercial centre and service area, including a large supermarket and the health services Data Centre. The social housing complex consists of 14 towers lying in a common green area of approximately 300,000 m² with a population of 1800 inhabitants. The complex was built in the '70s and each tower has 13 floors for a total floor area of roughly 4,631 m^2.

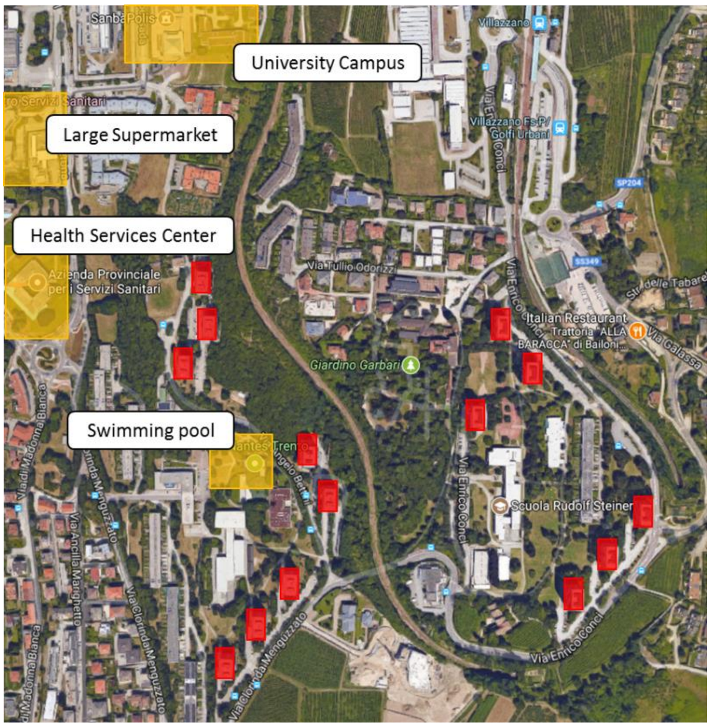

Figure 19: Madonna Bianca district (Trento). The towers of the social housing complex are highlighted in red.

Madonna Bianca is one of the main areas of intervention for the city of Trento within the H2020 European project Stardust, which aims at promoting the transformation of the carbon supplied cities into smart, highly efficient, intelligent and citizen-oriented cities, developing green solutions and innovative business models, integrating the domains of buildings, mobility and efficient energy through ICT, testing and validating these solutions, and enabling their fast roll out in the market.

To this aim, 3 of the 14 towers in Madonna Bianca will be renovated within the Stardust project according to a *net zero energy building* vision. Among the planned actions, it is foreseen to: refurbish the buildings envelope integrating PV modules in the façades, create a low-temperature smart DH system (Figure 20) replacing gas heating with ground source heat pumps. Furthermore, the connection of the local supermarket to the smart grid and the recovery of the supermarket's waste heat will be evaluated.

More in detail, the existing centralized gas boilers will be replaced by an innovative, small-scale prototype of a low-temperature (5-15 °C) DH network, providing thermal energy to the buildings by means of 3 ground-source heat pumps and building thermal storage systems (5,000 l storage capacity per tower). The ground heat exchangers will work both for heat extraction and ground thermal energy storage.

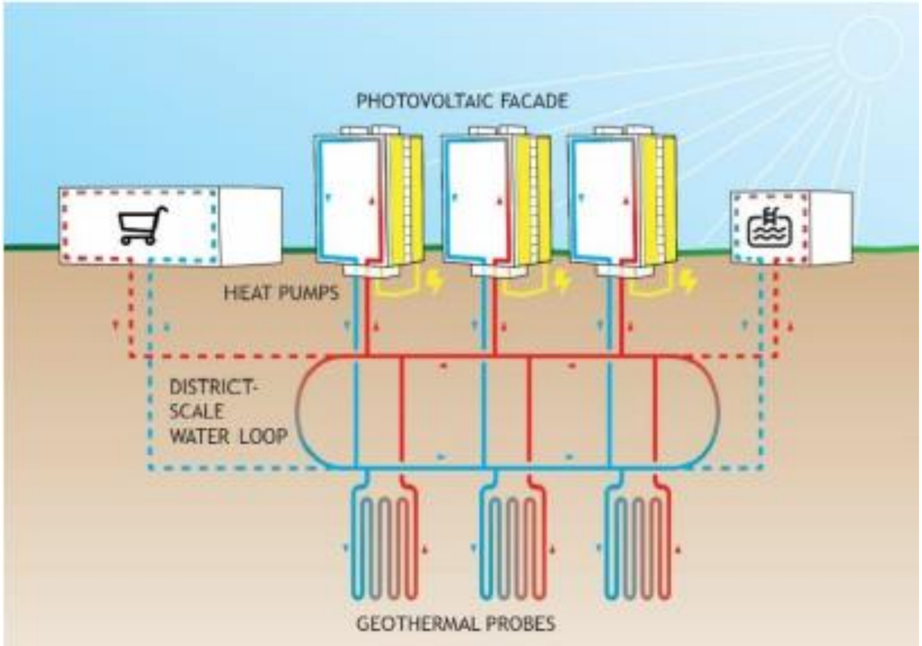

Figure 20: Low temperature smart district heating system to be realized within the Stardust project.

Concerning the future integration of low-temperature waste heat sources from neighbouring activities, in order to estimate the likely available waste heat that can be recovered from the refrigeration systems, the following calculation was used as a preliminary estimate. According to the results of the European project CommONEnergy (see also Deliverable D3.2 of FLEXYNETS), the average specific electric consumption for refrigeration (valid for large shopping malls) is 250 – 500 kWh_e/m^2 per year. Considering a supermarket surface area of 600 m², an average COP of the refrigeration system of 3, and a schedule rather uniform along the year (about $h_{y,w}$ = 8,000 h/y), the corresponding yearly waste heat and the electric power would be respectively 450 – 900 MWh_t/a and 19 – 37 kW_e.

For a number of user operating hours equal to 2,000 h/y, the available energy would correspond to 225 – 450 kW_t. In practice, with 20 – 40 kW of electric power and a seasonal storage (e.g., geothermal), one could possibly cover a thermal consumption equivalent to more than 200 – 400 kW of thermal power.

Hence, the local activities like supermarkets, bar and manufacturing activities are detected and involved in a survey for a deeper feasibility analysis (Figure 21).

The network planned in Madonna Bianca is similar to the one in Wüstenrot (Section 2). In this case, vertical boreholes will be installed instead of a low-depth geothermal field, possibly with some benefit in terms of operating temperatures. The possibility of exploiting waste heat and the best solution for its integration is investigated in the following sections. Similar to the LIFE4HeatRecovery project for Wüstenrot case, also the Stardust project proposal was written taking into account the FLEXYNETS experience and can be seen as one of its impacts.

Figure 21: Supermarkets and manufacturing activities in Madonna Bianca district. A survey including the southern area of the city – and not only the neighbourhood of the three considered towers – was carried out. This will allow to apply the analysis also to potential future extensions of the planned network.

4.2 Heat demand

The towers considered in this analysis are the 3 out of the 14 in Madonna Bianca which are planned to be renovated according to a net zero energy building vision. After the refurbishment of the building envelope, each tower is expected to have a yearly heat demand on the consumer side of approximately 344 MWh, which —assuming a yearly-averaged COP of the ground-source heat pumps of 3.26— correspond to about 220 MWh of heat demand on the network side. The yearly heat demand from the three towers (assumed identical to each other in terms of consumption and load profile) is therefore[6] 1,032 MWh, distributed along the year according to the profile shown in Figure 22. The daily load profiles —expressed as the ratio between the heat load in a 1-hour period and the daily heat load— are shown in Figure 23 for the months of January, March and May, as representative profiles of winter, spring/fall and summer respectively. According to these profiles, the peak heat demand for each of the three towers is 190 kW.

[6] The building refurbishment is expected to give rise to an overall heating demand of 74 kWh/m² (including DHW)

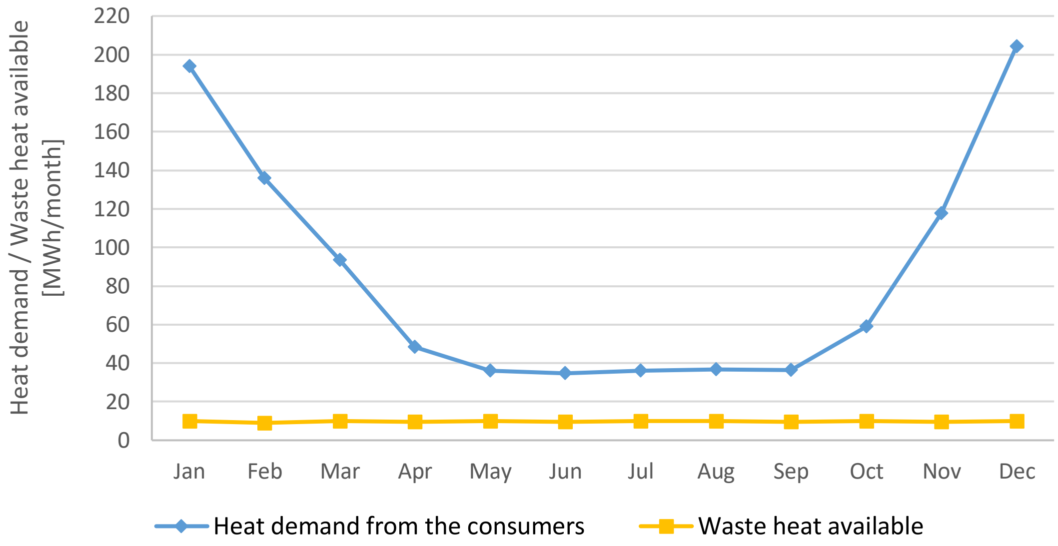

Figure 22: Yearly profile of the heat demand on the consumer side and of availability of waste heat from the supermarket.

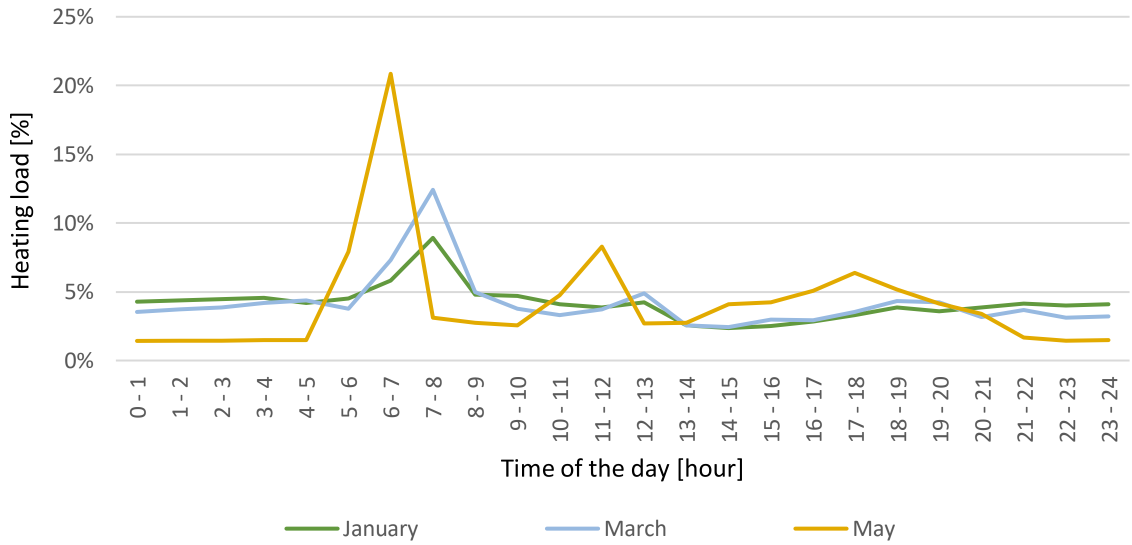

Figure 23: The daily load profiles expressed as the ratio between the heat load in a 1-hour period and the daily heat load.

The three towers will be supplied by a low-temperature distribution network, with an overall trench length of 200 m (100 m from the geothermal field to the closest tower and 50 m for each of the pipe connecting this tower to the other two towers).

Approximately 57 % of the heat demand is used for space heating, while the remaining 43 % for domestic hot water preparation. Both the heating system and the domestic hot water are supplied at a temperature of 50 °C. The return temperature from the heating system is estimated to be 10 °C lower than the supply.

4.3 Heat supply

In this feasibility study, the heat supplied to the low-temperature DH loop comes primarily from a geothermal field, consisting of 55 boreholes, each 150 m deep, for an overall drilled depth of about 8,300 m. The heat transfer capacity per unit length of borehole was estimated in 35 W/m.

Differently from the low-depth geothermal field in the Wüstenrot case (Section 2), the depth of the geothermal field in Trento reduced drastically the influence of the atmospheric environment on the temperature of the geothermal field. The ground temperature was estimated to be about 13 °C, roughly constant during the year. Therefore, the fluid temperature was assumed to be 5 °C at the inlet of the geothermal field and 10 °C at the outlet.

In the district of Madonna Bianca there would be the possibility of connecting a local supermarket to the low-temperature DH system, so to exploit the waste heat which would otherwise be dissipated to the environment. The pipe distance between the supermarket and the network is about 600 m. The average thermal power output from the supermarket is 15 kW thermal (10 kW of cooling demand, COP of 2). Considering the supermarket surface, this value is much lower than the general estimate based on the CommONEnergy project (roughly 1/4, in terms of energy per square meter). This can however be explained by the fact that this is a very small supermarket, without a centralized refrigeration system, while the CommONEnergy project values refer to larger shopping malls. It was estimated that 90 % of this waste heat could be recovered into the low-temperature network, resulting in about 118 MWh/year of recovered heat at a temperature of 30 °C. The profile of the waste heat availability was assumed constant throughout the year (Figure 22).

In the analysis it was assumed that the geothermal field could work as a storage. According to this approach, it was assumed that the availability of waste heat would allow to rescale the geothermal field not on the peak power (i.e., making the geothermal field smaller by about 15 kW), but on the energy. As the overall heat which could be recovered from the supermarket was 118 MWh/year (i.e. 16 % of the yearly heat drawn by the heat pumps on the evaporator side), the geothermal field could be reduced in size (and therefore in cost) by 16 %. The lower peak power which would result from the smaller field was assumed to be compensated by operating the boreholes at a slightly lower temperature in winter. Because the thermal power extracted from the geothermal field is proportional to the temperature difference between soil and the circulated water, the thermal power can be increased by lowering the temperature at the outlet of the heat pumps' evaporators (i.e. the temperature at the inlet to the geothermal field).

The peak heat demand on the consumer side of each tower is estimated to be 190 kW. Each tower is equipped with a 140 kW (thermal output) heat pump. Hot water tank storage is used to meet the peak demand. As back-up and possibly to cover unexpectedly high peak heat demand, an 80 kW gas boiler is also installed in each tower[7].

[7] The 190 kW of peak power were here estimated on the basis of hourly profiles. More detailed studies based on lower time steps show higher peaks. This more detailed calculation goes however beyond the capabilities of the approximated pre-design tool. For consistency, apart from the boiler sizing which does not influence the network side, the estimates of the pre-design tool were used here.

The heat pump draws water at 10 °C from the supply pipe of the DH network, lowering its temperature to 5 °C before injecting it back in the return pipe, which brings it back toward the geothermal field.
Each tower is expected to be equipped with a façade-integrated PV array, with the following characteristics:

- peak power: 276.7 kW.
- annual production: 288 MWh.
- self-consumption: 25 %.
- resulting equivalent price of the self-consumed electricity: 25 c€/kWh.

4.4 Numerical investigations

4.4.1 Assumptions

The boundary conditions and information presented in the previous sections were used as input to the pre-design Excel tool.

The yearly and daily profile of the heat demand were the ones shown in Section 4.2 (Figure 22 and Figure 23).

The assumed capacity of the installed heat pumps was 140 kW_{th}. Based on the network temperature, on the hot water temperature and assuming a heat pump efficiency of 50 %, the COP was 3.26, which corresponds to an electric capacity of 43 kW. Both the investment cost and the O&M costs were calculated based on the default values present in the Excel tool.
Regarding the investment for the low-depth geothermal field, a cost of 50 €/m (length of borehole[8]) and a lifetime of 30 years were assumed.

For the PV systems the equivalent price of the self-consumed electricity was 25 c€/kWh. The cost of the grid electricity can be assumed to have the same cost. Regarding the environmental impact of the system, for Italy the CO_2 emission factor for grid-supplied electricity was 344 kg_{CO2}/MWh (Koffi, 2017), while a factor of 0 was used for PV-produced electricity.

4.4.2 Results

The results shown in this section were obtained by applying the above-mentioned assumptions and boundary conditions in the pre-design Excel tool.
Table 13 lists the main indicators of the energy performance of the geothermal DH system as assumed for Trento, valid both in the scenario without and that with the heat recovery from the supermarket.

[8] This estimate is for budgetary purposes, as actual costs are not yet available. With more detail: the cost of boreholes and pipes only is expected to be slightly lower, order of 40 €/m; however, turnkey costs include other works, e.g., initial geophysical test –like ground response test (GRT) to assess the actual ground conductivity– pipe manifolds, general civil works. Here, all these extra contributions have been estimated to increase the base cost by 25 % (hence the increase from 40 to 50 €/m).

Table 13: Main indicators of the energy performance of the geothermal DH system in Trento.

Parameter	Value	Unit
Yearly heat demand	1,032	MWh/year
Heat drawn from the network	715	MWh/year
Reversible heat pumps installed capacity	129	kW_{el}
HP electricity consumption (from PV)	72	MWh/year
HP electricity consumption (from grid)	245	MWh/year
Heat pump's COP	3.26	-

The composition of the equivalent annual cost of the geothermal DH system in Trento —both in the scenario without and that with the heat recovery from the supermarket— is shown in Figure 24.

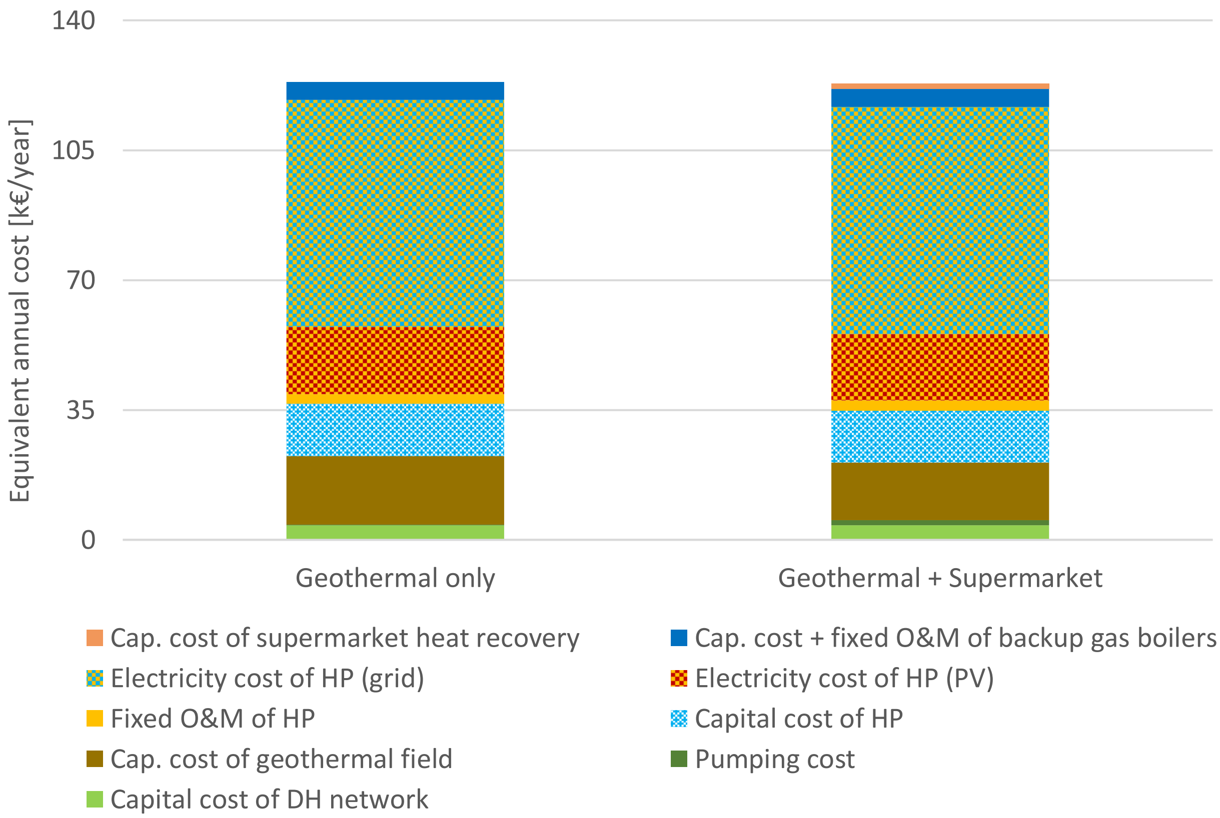

Figure 24: Composition of the equivalent annual cost of the geothermal DH system in Trento.

Figure 24 shows that in both scenarios the main component of the equivalent annual cost of the system was represented by the cost of electricity absorbed by the heat pumps. The electricity cost for the heat pumps represented in fact 64 % of the overall equivalent annual cost. The second most relevant cost was related to the installation of the geothermal field: 15 % of the overall cost in the case where the geothermal field was the only heat source to the network, and 12.5 % in the case that waste heat was recovered from the supermarket. However, the latter case had the additional cost of the heat recovery system, of the connecting pipes between supermarket and the towers (included in the *capital cost of the DH network* in the diagram), and the related pumping cost (included in the *pumping cost* in the

diagram). These components almost perfectly compensated the lower capital cost of investment of the geothermal field, so that the equivalent annual cost of the two systems was basically identical.
Consequently, also the specific cost per unit of heat demand was roughly the same: 0.120 €/kWh in case of geothermal field only and 0.119 €/kWh in case of geothermal field + waster heat recovery. These costs are expected to be 10-20 % larger than the ones for individual gas boilers.
The CO_2 emissions in both scenarios were approximately identical and about 84 ton/year, resulting in a specific emission factor of 82 g/kWh_{demand}. This value was significantly lower than the specific emission factor of the similar geothermal DH system in Wüstenrot, mainly due to the lower CO_2 emission factor of the electricity delivered from the grid in Italy compared to Germany.

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