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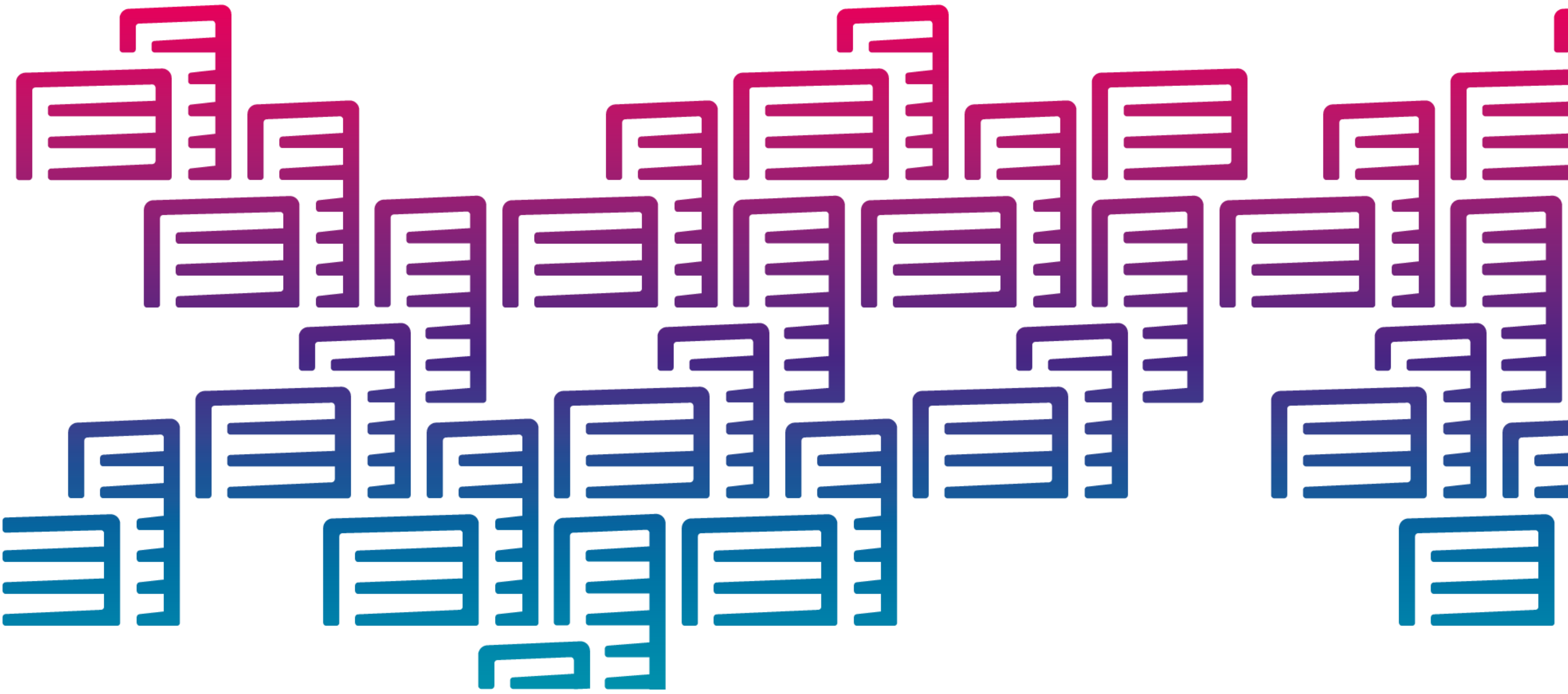
D8.3

WEDISTRICT replicability towards 4th-5th Generation of DHC



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Technical References

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[1] PU = Public
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RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

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V0.10	09.06.2023	Federico Bava (RAMBOLL)	Review
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Executive Summary

The goal of WEDISTRICT project is to demonstrate the integration of multiple sources of renewable energies, storage, waste heat recovery and integration of smart technologies to control and optimise its operation in order to achieve 100% renewable district heating and cooling in three real district heating and cooling systems.

In terms of technology maturity, it is considered that District Heating is now in the 3rd generation. WEDISTRICT looks at the 4th generation horizon by proposing the mentioned combined solutions and in line with this, WEDISTRICT thermal technologies will also have the ability to flexibly adapt to low-temperature demands (<50-60ºC) used for space heating and cooling of low energy buildings.

That is the reason why WEDISTRICT demonstration is established between 3rd and 4th DHC Generation since Córdoba, Bucharest and Lulea operate with a district heating supply temperature between 70ºC and 90ºC, however, technologies and prosumer concept would be part of 4th DHC Generation.

The D8.3 includes in **section 1** a qualitative study describing the evolution of DHC systems from the 1st to the 5th generation, current trend and how WEDISTRICT solutions could fit in 4th and 5th gen.

In **section 2** R2M led a stakeholders' survey to investigate what is the understanding of the technical audience about the concept of 4th and 5th generation of DHC systems and what they would like to have answered on this topic.

Finally, in **section 3** a quantitative analysis was performed by running in TRNSYS two technology solutions in which WEDISTRICT technologies fit into 4th and 5th gen of DHC configurations.

Disclaimer

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

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Abbreviation	Description
CAPEX	Capital expenditures
COP	Coefficient of performance
DHC	District heating and cooling
HP	Heat pump
LCOE	Levelized cost of energy
OM	Operation and Maintenance
OPEX	Operational expenditures
$OPEX_f$	Fixed operational expenditures
$OPEX_v$	Variable operational expenditures
PTC	Parabolic trough collectors
TES	Thermal energy storage
3GDH	3rd generation district heating
4GDHC	4th generation district heating and cooling
RES	Renewable Energy Sources

1. Evolution of DHC systems

1.1. Introduction: Generations of district heating

District heating is a technology which is older than many people think, as the first example of “modern” district heating is regarded to be the one which was established in Lockport (New York) in 1877 by American hydraulic engineer Birdsill Holly.

Since then, district heating technology has changed significantly and under every aspect (generation technologies, distribution system, temperature, etc.). Conventionally the historical development of district heating is divided into four generations, briefly described here below.

1.1.1 First generation

The first generation of district heating was introduced in the US in the 1880s and became popular in some European countries. It was state of the art until the 1930s.
It used steam as heat carrier fluid, flowing in pipes laid in concrete ducts. Due to the high temperatures, the temperature losses were high, and the system was therefore quite inefficient. Other drawbacks of this generation were its reliability and safety, due to the hot pressurized steam tubes.
On the generation side, coal was the most common fuel.
Nowadays, this generation is technologically outdated. However, some of these systems are still in use. Other systems, originally built as first-generation district heating, have been converted to later generations.

1.1.2 Second generation

The second generation spanned from the 1930s until the 1970s. Steam was replaced by pressurized hot water as heat carrier, with supply temperatures above 100 °C.
The distribution system consisted of water pipes laid in concrete ducts, mostly assembled on site.
On the generation side, combined heat and power plants running on coal and oil were the most common generation technology.
While also used in other countries, typical systems of this generation were the soviet-style district heating systems that were built after WW2 in Eastern European countries.

1.1.3 Third generation

The third generation was developed in the 1970s and became quickly the main technology used for the new system throughout the world.
Water with temperatures typically below 100 °C is used as heat carrier fluid, flowing through prefabricated, pre-insulated pipes, which are buried into the ground.
The third generation was developed as a response to the two oil crises of the ‘70s, with the goal of increasing the security of supply and improving the energy efficiency. Developed at the time of the oil crises, these systems usually used coal, biomass and waste as energy sources, but other heat production technologies (like geothermal and solar) were later added, which was made possible by the low operating temperatures.

1.1.4 Fourth generation (4GDH)

Currently, the fourth generation is being developed, with its main objectives being the integration of high shares of renewable energy and providing high flexibility to the electricity system.

According to literature[1], a district heating system can be considered as 4th generation if it meets the following characteristics:

1. Ability to supply low-temperature district heating for space heating and domestic hot water (DHW) to existing buildings, energy-renovated existing buildings, and new low-energy buildings.
2. Ability to distribute heat in networks with low grid losses.
3. Ability to recycle heat from low-temperature sources and integrate renewable heat sources such as solar and geothermal heat.
4. Ability to be an integrated part of smart energy systems (i.e., integrated smart electricity, gas, fluid, and thermal grids) including being an integrated part of 4th Generation District Cooling systems[2].
5. Ability to ensure suitable planning, cost, and motivation structures in relation to the operation as well as to strategic investments related to the transformation into future sustainable energy systems.

The lower distribution temperature (with supply temperatures of ≤70 °C) compared to the previous generations improves the energy efficiency of the system and allows for the integration of low temperature heat sources such as large-scale heat pumps, excess heat from industry, waste heat from cooling production and data centres, waste-fired or biomass-fired CHP plants, geothermal and solar thermal energy. Thanks to thermal energy storage (possibly including seasonal storage) fourth generation district heating can also provide flexibility to electrical grid, for example by absorbing electricity from the grid through heat pumps when there is
excess of electricity production (e.g., from non-dispatchable power production such as wind and solar PV) or providing electricity from biomass plants when the electrical grid requires up-regulation.

A description of how and why many DH companies have transitioned from the 3rd to the 4th generation of DH in the last years in described in Annex 3, while a specific example of a smart and efficiency 4GDH&C system is described in Annex 4.

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[1] https://www.sdu.dk/-/media/files/om_sdu/institutter/iti/forskning/nato+arw/literature/4th+generation+district+heating+4gdh.pdf

[2] Dyrelund A., Bigum F.P., 2020. The four generations of district cooling. https://dbdh.dk/the-four-generations-of-district-cooling-another-great-article-by-ramboll/

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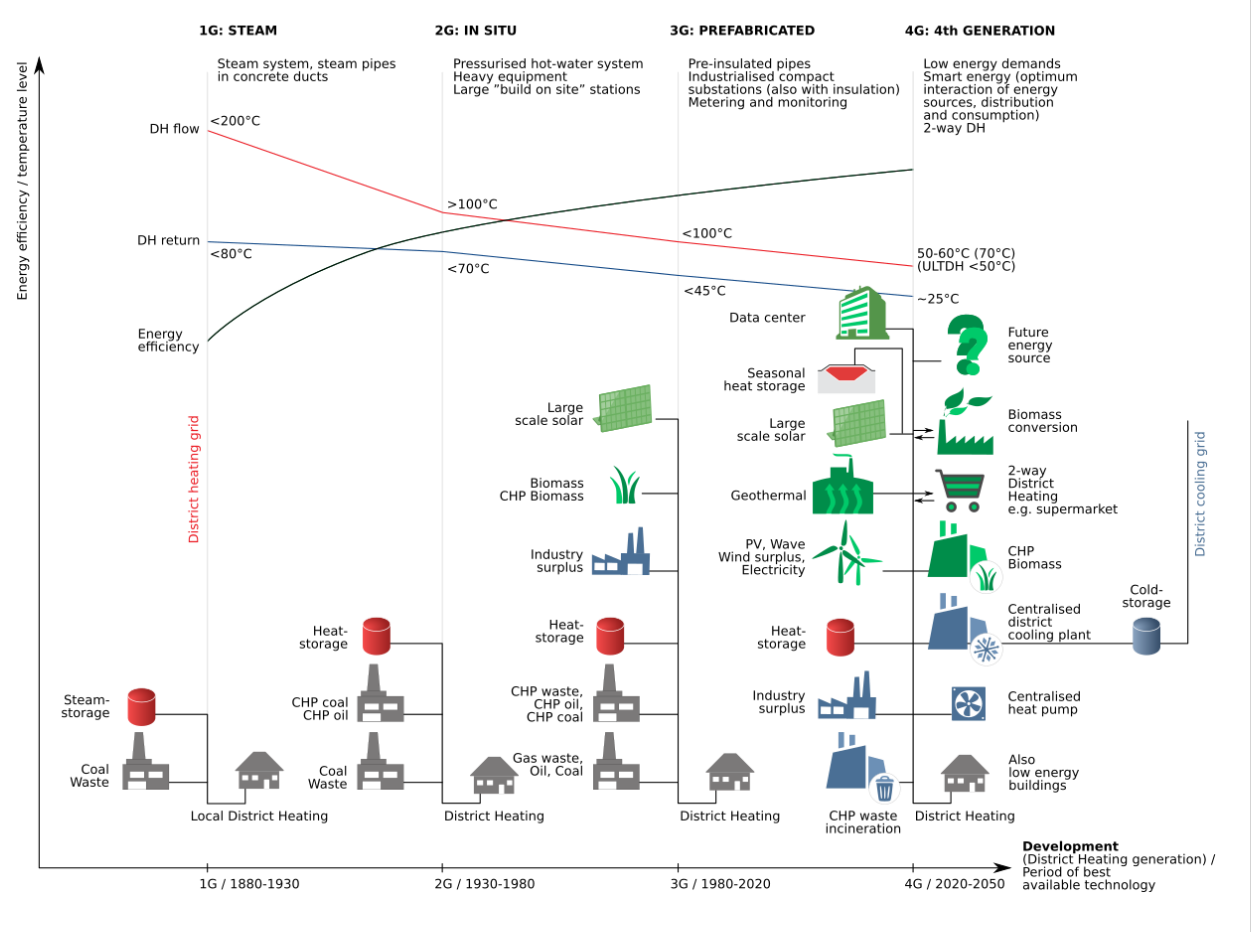

Figure 1 Historical evolution of district heating technology from the 1st to the 4th generation[3].

1.2. Lower temperatures in DH

1.2.1. Challenges of lower temperature in DH systems

From the 1st to the 4th generation of DH, the temperatures have been progressively reduced. So, it seems natural to expect that the next generation of DH would have even lower temperatures than what proposed in the 4th generation. However, reducing network temperatures – especially when these are already quite low - is trickier than one may think.

The limits to DH temperatures are set by customer demands. These demands consist of the possibility of maintaining an indoor air temperature of up to 22 °C and to having access to hot water at a temperature of 40–45 °C.

Supply temperature for space heating systems vary depending on the type of heating system. Modern low-temperature radiators can work with temperatures in the range 45-55 °C, while floor heating systems can make use of water with supply temperature as low as 30 °C.

Despite the comfort-related temperature requirements for domestic hot water being lower, this is usually produced and supplied at higher temperature (55-58 °C) to reduce the risk of Legionella bacteria. However, other ways of avoiding this risk exist, such as chemical treatments, apartment sub-stations, and electric tracing of circulation pipes. If the risk of Legionella can be avoided by means other than higher DH temperatures, the DH supply temperature could be reduced to 50–55 °C, enough to produce domestic hot water at 40–45 °C. The supply temperature could be reduced even further if domestic hot water is prepared using supplementary electric heating. This type of DH is usually referred to as ultra-low-

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[3] https://www.sdu.dk/-/media/files/om_sdu/institutter/iti/forskning/nato+arw/literature/4th+generation+district+heating+4gdh.pdf

temperature DH, and in this case supply temperatures may ideally be as low as 30 °C for areas with low-energy houses equipped with floor heating[4].

While a DH company could – in principle - decrease the supply temperature as low as technically possible while still meeting the customers' requirements, they have much less control on the return temperature of the network, as this will be determined by the return temperature of the customers' heating systems as well as the characteristics of the substation's heat exchanger.

If the supply temperature of a DH system is reduced, without intervening also on the customers' side of the system, the capacity of the DH network will be reduced.
The thermal power carried out by a fluid flowing in a pipe is given by the expression:

$$P_{th} = V \cdot \varrho \cdot c_p \cdot \Delta T$$

where P_{th} is the thermal power [kW]
V is the volume flow rate [kg/s]
ϱ is the fluid density [kg/m^3]
c_p is the fluid specific heat [kJ/kg/K]
ΔT is the temperature difference between supply and return [K]

Therefore, the thermal power which can be delivered by a DH system decreases proportionally with the temperature difference between supply and return (provided that the maximum allowed flow is unchanged).
If the same thermal power is to be transferred with different ΔT, the only option is to increase the volume flow rate V. As the volume flow rate in a circular pipe is given by

$$V = v \cdot D^2 \pi/4$$

where v is the fluid velocity [m/s]
D is the pipe inner diameter [m],

the volume flow rate can be increased either by increasing the fluid velocity v or the pipe diameter D. Increasing the fluid velocity v entails an increase in the frictional losses along the networks. This can pose challenges to meet the hydraulic constraints of a network (minimum differential pressure at the consumers' substations, maximum and minimum pressure allowed in the pipes), as well as entailing higher pumping capacity.
Increasing the pipe diameter entails higher pipe costs as well as higher installation costs.
Therefore, high temperature differences between supply and return of a DH system are desired, especially in cases of high thermal load.

1.2.2. Lower temperature supply – substation level

The baseline of this concept is that there is a main DH network at high-temperature and a nearby neighbourhood, currently not connected to the DH network.

Let us assume that the main DH network must be maintained at high temperature (95 °C supply and 75 °C return), e.g., because of some high temperature consumers. Secondly, let us assume that the buildings in the nearby neighbourhood have heating systems which had been sized to cover the design heat demand (design outdoor temperature of -12 °C) according to the old sizing rules in Denmark, i.e., with temperature levels of 90/70/20. Let us analyse the effect of supplying this neighbourhood with lower DH temperatures.

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[4] Østergaard D.S., 2018. Heating of existing buildings by low-temperature district heating. PhD thesis, Technical University of Denmark. https://orbit.dtu.dk/en/publications/heating-of-existing-buildings-by-low-temperature-district-heating

A scheme of the building substation is shown in Figure 2. As can be seen in the figure, the production of domestic hot water is neglected.

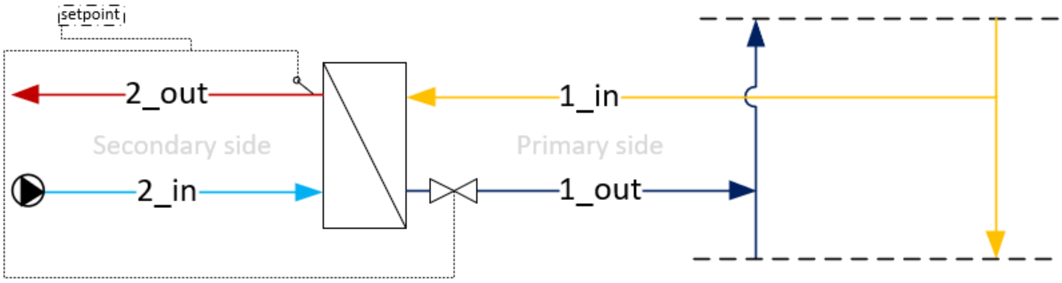

Figure 2 Principle scheme of a building's substation for space heating. "Secondary side" denotes the building side, while "Primary side" denotes the DH side.

Let us assume that a typical building's substation in the considered neighbourhood is characterized by the parameters listed in Table 1 in design conditions.

Table 1: Assumed parameters of a building's substation in design conditions.

Parameter	Unit	Value
Design indoor temperature	°C	20.0
Design outdoor temperature	°C	-12.0
Overall heat loss coefficient of the building	W/K	1300.0
Heat load	W	41600.0
Secondary side inlet temperature ($T_{2,in}$)	°C	70.0
Secondary side outlet temperature ($T_{2,out}$)	°C	90.0
Flow on the secondary side	kg/s	0.50

If the neighbourhood was supplied from the main DH network in design conditions, the substation's heat exchanger would be characterized by the parameters in Table 2.

Table 2: Parameters of a building's substation in design conditions, if supplied at DH network's temperatures.

Parameter	Unit	Value
Design indoor temperature	°C	20.0
Design outdoor temperature	°C	-12.0
Overall heat loss coefficient of building	W/K	1300
Heat load	W	41,600
Secondary side inlet temperature ($T_{2,in}$)	°C	70.0
Secondary side outlet temperature ($T_{2,out}$)	°C	90.0
Flow on the secondary side	kg/s	0.50
Primary side inlet temperature ($T_{1,in}$)	°C	95.0
Primary side outlet temperature ($T_{1,out}$)	°C	75.0
Flow on the primary side	kg/s	0.50
Logarithmic mean temperature difference	K	5.0
Specific heat transfer coefficient of the heat exchanger[5]	W/m²/K	5,668

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[5] For the calculation of the heat transfer coefficient, a flat plate heat exchanger with a hydraulic diameter of 3,4 mm is assumed. The fluid velocity in the channels on the secondary side is assumed to be 0.3 m/s, when the flow rate and temperatures on the secondary side are those listed in Table 1. For different flow rates on both primary and secondary side, the ratio between fluid velocity and mass flow rate is kept constant. The thermodynamic properties of water are evaluated on both sides of the heat exchanger at the average fluid temperature.

Parameter	**Unit**	**Value**
Heat transfer area of the heat exchanger	m^2	1.47

An outdoor ambient temperature of -12 °C is quite extreme for Denmark and is unlikely to occur. An average outdoor ambient temperature of 0 °C is assumed during the colder part of the winter season. If the temperatures on the secondary side were maintained at 90/70 °C, and the inlet temperature on the primary side was maintained at 95 °C, the substation's parameters would change, as shown in Table 3.

Table 3: Parameters of the substation for outdoor temperature of 0 °C, if supplied at DH network's temperatures (Case 0)

Parameter	**Unit**	**Case0**
Design indoor temperature	°C	20.0
Design outdoor temperature	°C	0.0
Overall heat loss coefficient of building	W/K	1,300
Heat load	W	26,000
Secondary side inlet temperature ($T_{2,in}$)	°C	70.0
Secondary side outlet temperature ($T_{2,out}$)	°C	90.0
Flow on the secondary side	kg/s	0.31
Primary side inlet temperature ($T_{1,in}$)	°C	95.0
Primary side outlet temperature ($T_{1,out}$)	°C	73.1
Flow on the primary side	kg/s	0.28
Logarithmic mean temperature difference	K	4.0
Specific heat transfer coefficient of the heat exchanger	$W/m^2/K$	4,481
Heat transfer area of the heat exchanger	m^2	1.47

With constant temperatures on the secondary side, the secondary flow rate decreases proportionally to the heat load. The lower heat load allows both the specific heat transfer coefficient and the logarithmic mean temperature difference to decrease compared to the design scenario, still ensuring the required power across the heat exchanger.

Because the temperatures on the secondary side and the inlet temperature on the primary side are fixed, a lower logarithmic mean temperature difference entails a lower return temperature on the primary side.

Given the much lower heat load in the scenario with 0 °C outdoor temperature, it is likely that heating elements of the building can cover the demand at lower temperatures. In this example we assume a supply and return temperature of 65 °C and 40 °C, respectively.

The much lower supply temperature of the heating system now assumed allows the inlet temperature on the primary side to be decreased too. The effect of the inlet temperature at the primary side on the substation performance is shown in Table 4.

Martin correlation (https://doi.org/10.1016/0255-2701(95)04129-X) is used to evaluate the convective heat transfer coefficients. The thermal resistance of the metal plates of the heat exchanger is neglected.

Table 4: Parameters of the substation for outdoor temperature of 0 °C, at different inlet temperatures on the primary side.

Parameter	**Unit**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Design indoor temperature	°C			20.0		
Design outdoor temperature	°C			0.0		
Overall heat loss coefficient of building	W/K			1,300		
Heat load	W			26,000		
Secondary side inlet temperature ($T_{2,in}$)	°C			40.0		
Secondary side outlet temperature ($T_{2,out}$)	°C			65.0		
Flow on the secondary side	kg/s			0.25		
Primary side inlet temperature ($T_{1,in}$)	°C	90	85	80	75	70
Primary side outlet temperature ($T_{1,out}$)	°C	40.5	40.8	41.3	42.2	44.5
Flow on the primary side	kg/s	0.13	0.14	0.16	0.19	0.24
Logarithmic mean temperature difference	K	6.1	5.9	5.6	5.2	4.7
Specific heat transfer coefficient of the heat exchanger	W/m²/K	2,885	3,017	3,185	3,417	3,808
Heat transfer area of the heat exchanger	m²			1.47		

Comparing the cases in Table 4, it is seen that the outlet temperature on the primary side of the heat exchanger progressively increases, when lowering the inlet temperature. As the temperature difference on the primary side decreases, the corresponding flow rate must increase to cover the same heat load.

For example, when the supply temperature on the primary side (DH side) decreases from 90 °C to 70 °C, the flow rate on the primary increases by 85% due to the lower temperature drop on the primary side of the heat exchanger. This is mainly due to the lower supply temperature (20 K decrease), but to a less extent also to the resulting higher return temperature, which increases from 40.5 °C to 44.5 °C (4 K increase). The overall temperature drop on the primary side of the heat exchanger halves, from 50 K to 25 K.

This example shows that one shall be careful in just reducing the supply temperature without paying attention to the response of the consumers. In order words, it is important for the district heating company to be aware of this response for each consumer by monitoring the performance of the substations.

1.2.3. Lower temperature supply – network level

1.2.3.1. *Shunt from return to supply to reduce the supply temperature from a high temperature system to a low temperature area*

In the proposed concept of *shunt from return to supply*, the low-temperature supply to the considered neighbourhood is achieved by tempering down the temperature from the supply line of the main DH network with some return flow from the neighbourhood itself.

A principle scheme of this concept is shown in Figure 3. In Figure 3 the connection uses a heat exchanger, but it could also be direct. The heat exchanger for hot tap water (not shown in Figure 3) will be connected in parallel with the heat exchanger for space heating.

The temperature in the main district heating network (*DH supply* in Figure 3) is assumed to remain constant at 95 °C, while the temperature on the primary side of the heat exchanger can be equal (case 0 in Table 5) or lower (other cases), depending on the amount of return flow which is diverted through the shunt pipe and mixed with the DH supply water.

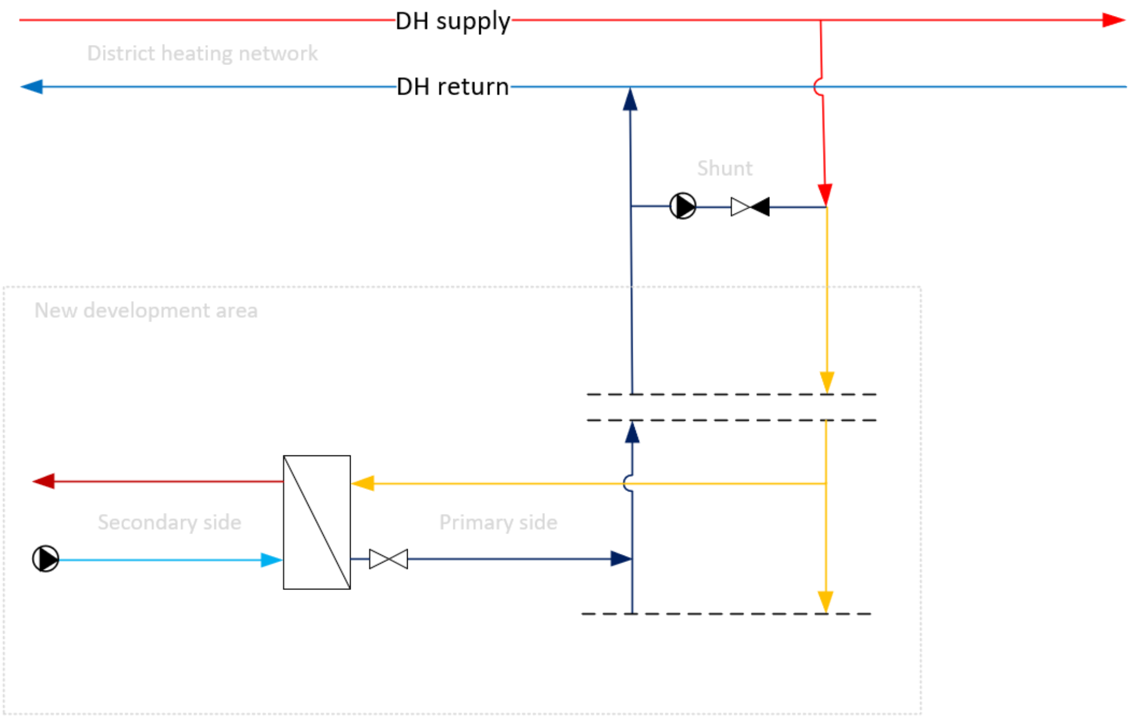

Figure 3: Principle scheme of a low-temperature distribution network supplied by a higher-temperature DH network and a shunt.

The resulting key parameters on the network level are summarized in Table 5 for the different cases investigated.

Table 5: Key parameters on the network level for the investigated cases.

Parameter	**Unit**	***Case 0***	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Primary side inlet temperature ($T_{1,in}$)	°C	*95*	90	85	80	75	70
Primary side outlet temperature ($T_{1,out}$)	°C	*73.1*	40.5	40.8	41.3	42.2	44.5
Flow on the primary side (for 1 building)	kg/s	*0.28*	0.13	0.14	0.16	0.19	0.24
Shunt flow (for 1 building)	kg/s	*0.00*	0.01	0.03	0.04	0.07	0.12
Flow drawn from main DH network (for 1 building)	kg/s	*0.28*	0.11	0.11	0.12	0.12	0.12
Heat losses from supply pipe	W/m	*18.0*	17.0	16.0	15.0	14.0	13.0
Heat losses from return pipe	W/m	*13.6*	7.1	7.2	7.3	7.4	7.9

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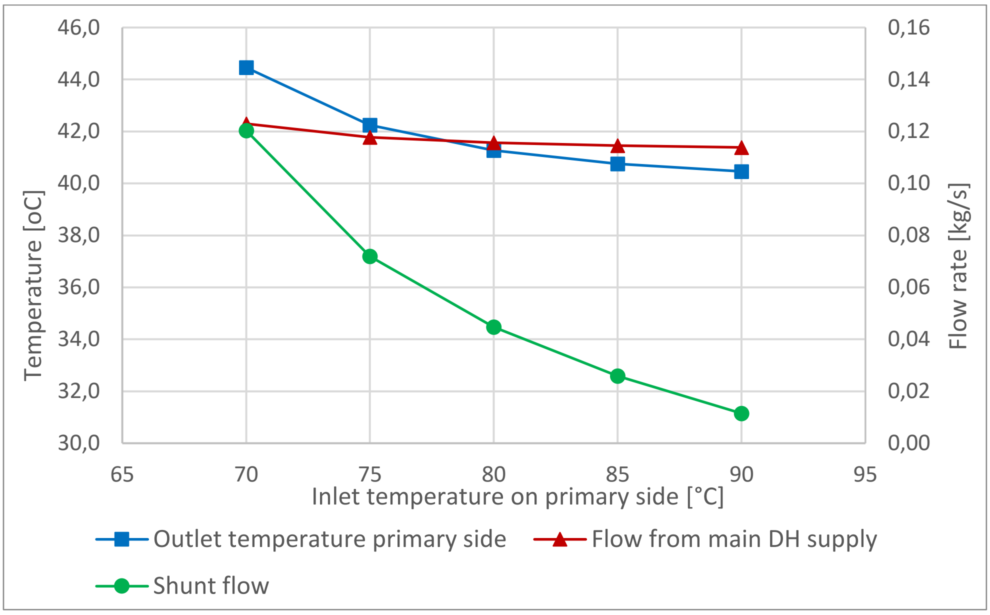

Figure 4: Outlet temperature on the primary side, flow rates from the main DH supply and shunt as function of the inlet temperature on the primary side of the heat exchanger.

Regarding the total flow drawn from the main DH network, the following conclusions can be drawn.
As shown in Table 4 and explained above, lower supply temperatures to the neighbourhood entail higher return temperatures from the neighbourhood (Figure 4). The progressively lower temperature difference between the supply temperature of the main DH network (95 °C) and the return from the neighbourhood causes more flow to be drawn from the DH supply pipe. Additionally, progressively more shunt flow is required to temper the main DH supply temperature to the desired level (Figure 4). Therefore, the pumping energy of both the main pump of the main DH network and the shunt pump increases.

The choice of a lower-temperature supply or a higher-temperature supply should be the result of the best compromise between different instances, such as thermal losses, pumping power, network capacity, etc. However, it can be concluded that a lower supply temperature should be aimed at only after measures have been taken to ensure a decrease in the return temperature too.

Advantages of a low-temperature supply:

- Lower supply temperatures result in lower heat losses from the supply pipes (provided that the heat loss coefficient of the pipe is kept constant, i.e., pipe size and insulation class are not changed).
- Lower temperature differences between supply water and soil may allow for reducing the insulation class of the pipes, so lowering the investment cost.
- Lower supply temperatures may allow for using plastic pipes instead of steel pipes[6].
- Lower supply temperatures result in lower operating costs of CHP and heat pumps
- Lower supply temperatures allow for cheaper and more efficient heat pumps, which are regarded as optimal solution to provide carbon-free baseload to DH networks.

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[6] Although promising to have lower material and installation costs, plastic pipes have not yet been proven significantly more competitive compared to steel pipes even when operating conditions would allow it. Though, future developments may change this. Beside temperature limits and costs, another important aspect to be taken into account when planning to use plastic pipes is the operating pressure of the system. Due to the lower mechanical strength, plastic pipes can tolerate lower pressures compared to steel pipes.

Disadvantages of a low-temperature supply:

- Unless measures are taken on the building side, a lower inlet temperature on the primary side of the heat exchanger increases the outlet temperature on the primary side.
- Higher return temperatures negatively affect the efficiency of heat production units such as heat pumps, condensing boilers, CHP plants, solar thermal, etc.
- Lower temperature difference on the primary side increases the required primary flow, so decreasing the capacity of the network and reducing the ability to transfer base load and peak load capacity to new consumers.
- Higher flow rates entail higher pumping energy and pumping cost.
- Higher return temperatures result in higher heat losses from the return pipes, if the heat loss coefficient of the pipe is kept constant.

If using a low-temperature supply affects the system requirement in design conditions (i.e., extremely low outdoor temperature), the following points should be kept in mind:

- The higher flow rates may require larger - and therefore more expensive - pumps.
- Higher flow rates may require larger pipes and therefore higher investment cost.
- A lower temperature difference between supply and return reduces that capacity of the network.
- Lower temperature difference across the heat exchanger at the building’s substation may require larger and/or more efficient heat exchangers, so increasing their investment cost.

The conclusion is that it is not a simple issue to optimize the supply temperature strategy, as it depends much on all the local conditions, but the following can be summarized:

The life-cycle cost of all investments and operating costs shall be taken into account in the optimization, when aiming at minimizing the NPV of all costs (including cost of CO2). The energy planner and energy manager should at least be aware of the following:

- it is important to understand, measure and monitor the performance of the consumer substations to avoid that lower supply temperatures increase the return temperature too much.
- the market potential for connecting new consumers from existing network has a great impact and can benefit significantly from lower return temperature and higher supply temperature.
- the importance of heat losses depends strongly on the heat generation cost. In case of expensive production, large heat losses are much more critical compared to a scenario with low-cost base-load heat production.
- transfer of maximal cheap base load often is the most important load case, as peak boilers can be distributed
- the optimal supply temperature strategy may change during the year, e.g., lowest possible in some periods and largest in other periods.

Therefore, the conclusion is that the energy planner, the designer and the operator need operational information about the whole system to form the best strategy, which may differ from place to place.

An example of shunt from return to supply is described in Annex 1.

1.2.3.2. Shunt pump (from return to supply) and 3-pipe connection

A principle scheme of this concept is shown in Figure 5.

This concept consists of a shunt pump (from return to supply) and 3-pipe connection to a low temperature area (or low temperature building) to reduce the return temperature of the district heating. The concept was presented in Heat Plan Denmark 2010 as one of measures to reduce the return temperature, and it has been implemented in several cases.

The baseline of this concept is that there is a main DH network or a large consumer at high-return temperature and a low temperature zone, e.g., a large low temperature consumer or a low temperature area, e.g., an urban development area, in which the buildings' heat demand can be covered by low-temperature supply. These heating systems could therefore be supplied by a lower temperature supply compared to the main DH network.

In this concept the return temperature from the main DH network is used as low-temperature supply to the low temperature zone through a *3rd pipe* connection. A dedicated pump is necessary to draw the necessary flow from the return pipe of the main DH network, overcome the pressure drop in the distribution network of the new development area, and inject the return flow back into the return pipe of the main DH network (downstream).

In order to ensure a sufficiently high supply temperature in all load cases, it is necessary install a connection pipe also from the supply pipe. A control valve on this connection pipe opens, if the temperature of the return water is lower than the supply temperature required in the distribution network of the new development area.

The same connection pipe can be used, if the flow required by the downstream consumers is lower than the flow required by the new development area. In this case the difference between the required flows is deviated from the main DH supply line to the new development area through the connection pipe.

A principle scheme of this concept is shown in Figure 5. Here it is assumed that the pressure from the main DH supply pipe is high enough to drive the flow through the connection pipe. If this was not the case, a pump should be installed also on the connection pipe.

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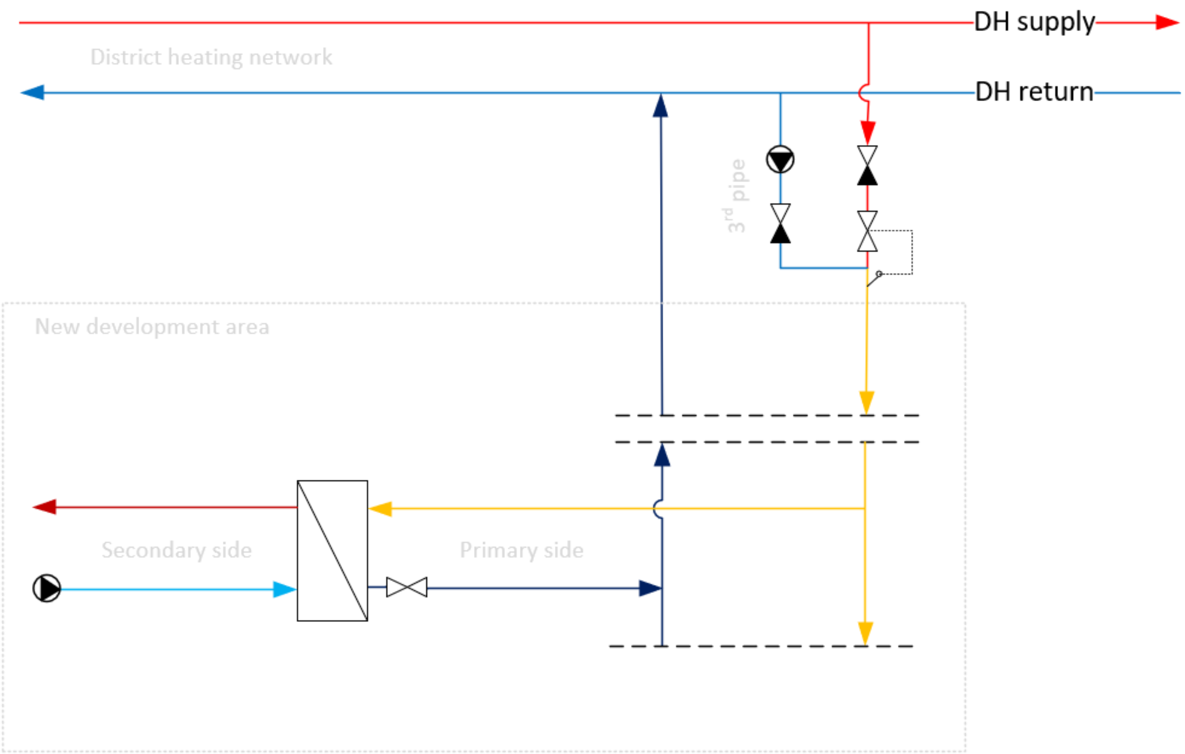

Figure 5: Principle scheme of a low-temperature distribution network supplied from the return flow of a higher-temperature DH network.

Let us assume the same temperature for the main DH network (95/75 °C), as well as the same heat load and substation size as in Section 1.2.2. A summary of key parameters is given in Table 6.

Table 6: Assumed parameters of a building's substation in design conditions.

Parameter	Unit	Value
Design indoor temperature	°C	20.0
Overall heat loss coefficient of the building	W/K	1,300
Heat load for outdoor temperature of 0 °C	W	26,000
Secondary side inlet temperature ($T_{2,in}$)	°C	40.0
Secondary side outlet temperature ($T_{2,out}$)	°C	65.0
Flow on the secondary side	kg/s	0.25
Heat transfer area of the heat exchanger	m^2	1.47
Supply temperature in the main DH network	°C	95.0
Return temperature in the main DH network	°C	75.0

Let us assume that the inlet temperatures on the primary side of the heat exchanger is progressively lowered from 90 °C to 75 °C. The resulting key parameters at a substation and local network level are listed in Table 7.

Table 7: CO2 emissions and other key parameters on the network level for the investigated cases.

Parameter	Unit	Case 1	Case 2	Case 3	Case 4
Primary side inlet temperature ($T_{1,in}$)	°C	90	85	80	75
Primary side outlet temperature ($T_{1,out}$)	°C	40.5	40.8	41.3	42.2
Flow on the primary side (for 1 building)	kg/s	0.13	0.14	0.16	0.19
Flow in 3rd pipe (for 1 building)	kg/s	0.01	0.03	0.04	0.07
Flow drawn from main DH network (for 1 building)	kg/s	0.11	0.11	0.12	0.12
Heat losses from supply pipe	W/m	17.0	16.0	15.0	14.0
Heat losses from return pipe	W/m	7.1	7.2	7.3	7.4

Compared to Table 5, there is no Case 5, as the 3rd pipe connection cannot achieve an inlet temperature on the primary side lower than the return temperature of the main DH network (75 °C in this example).

As also shown in Figure 6, the flow which needs to be drawn from the main DH supply decreases for lower supply temperatures, rather than increasing as for the shunt connection (Figure 4). This happens because the flow from the main DH supply pipe is mixed with flow from the main DH return pipe, rather than with flow from the new development area. The flow from the main DH return pipe is characterized by a significantly higher temperature. Therefore, less flow from the main DH supply is needed to ensure the setpoint supply temperature to the new development area.

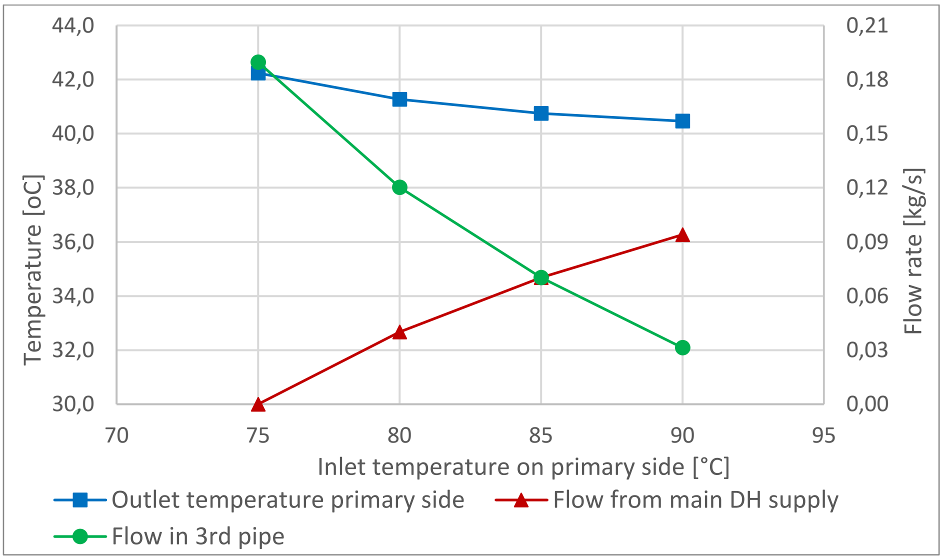

Figure 6 Outlet temperature on the primary side, flow rates from the main DH supply and return pipes as function of the inlet temperature on the primary side of the heat exchanger.

The advantages and disadvantages of supplying a neighbourhood with lower temperatures compared to those used in the main DH network are the same as those already listed in Section 1.2.3.1, except for the reduced capacity of the main network.
However, some differences exist between the two concepts (*shunt from return to supply* in Section 1.2.3.1 and the *3-pipe connection* in the current section). The return of the main DH network will typically have a higher temperature than the return from the new development area with low-temperature DH. If this is true, and assuming all other boundary conditions are the same (supply temperature in the main DH system, flow and temperature requirements in the new development area), a 3-pipe connection will entail that a lower flow needs to be drawn from the main DH supply pipe by the new development area (and in principle this may flow may be as low as null, if the return temperature in the main DH system is the same as the

supply temperature required by the new development area). If a higher flow is drawn from the main DH supply pipe, this means that the main DH plant needs to supply more hot water flow. This may affect the overall efficiency of the DH plant, but also the hydraulic of the DH main network, which now needs to carry a higher flow. If the network was already used close to its limits, it may be a challenge to supply larger flows.
On the other hand, the 3-pipe connection is a bit more complex from a hydraulic perspective, as it requires additional pipe length, and more available space for establishing the pipe connections. This may be relevant if the connection is to be done in an existing station with limited space available.

An example of shunt from return to supply is described in Annex 2.

1.2.4. Effect of lower temperature supply on the heat output from radiators

The heat output from a radiator can be estimated through the two following equations:

$$\Phi = \Phi_n \cdot \left(\frac{\Delta T}{\Delta T_n}\right)^n$$

$$\Delta T = \frac{T_z - T_p}{ln\left((T_z - T_i)/(T_p - T_i)\right)}$$

where Φ is thermal output of the radiator [W],
Φ_n is the nominal thermal output of the radiator determined based on measurements in accordance with EN 442 [W],
ΔT is the logarithmic mean temperature difference between radiator and indoor air [K],
ΔT_n is the logarithmic mean temperature difference calculated for the temperatures used in nominal conditions [K],
n is the exponent characteristic for a given radiator,
T_z is the supply water temperature to the radiator [°C],
T_p is the return water temperature [°C] from the radiator,
T_i is the indoor room temperature [°C].

Typical values of the *n*-exponent are in the range of 1.29-1.36.

To assess the effect of a lower supply temperature to a radiator on its thermal power output, let us consider an actual radiator model available on the market[7]. Based on the above equations, we can calculate the thermal power output, as well as the return temperature from the radiator, as function of the supply temperature, assuming that the flow rate is constant. The results are shown in the figure below.

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[7] The input data used refer to the radiator C 11 with dimensions H=500 mm x L=1000 mm, having a thermal power output of 868 W for operating temperatures 75/65/20 °C. The n-exponent is 1.307. Source: https://www.purmo.com/docs/Purmo-technical-catalogue-radiators-full_PR_01_2014_EN_PL.pdf

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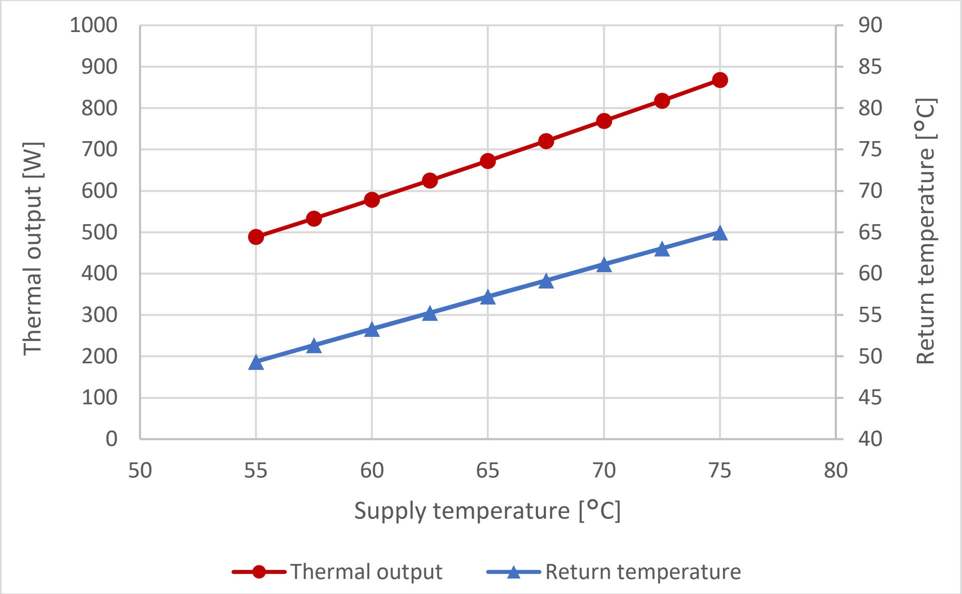

Figure 7: Thermal power output and return temperature from the considered radiator as function of the supply temperature (at constant flow rate).

For this specific radiator, a decrease in supply temperature of about 10 K entails a reduction in thermal power output of about 90 W. If the heating system supply temperature was lowered from 75 °C to 65 °C, the thermal power output would decrease by 23%. If the temperature was further lowered to 55 °C, the thermal power output would decrease by 44%. Increasing the flow rate (even if technically possible), would have a minor impact on the thermal power output. Even assuming a flow rate twice as high as in nominal conditions, a supply temperature of 65 °C instead of 75 °C would still entail a thermal power reduction by 18%; while a supply temperature of 55 °C would entail a reduction by 41%.
Therefore, a reduction of supply temperature to an existing heating system is not a practical solution, unless other measures to reduce the load and/or increase the heat transfer are implemented (see following section).

1.2.5. Efficiency measures at building level

As seen in the section above, a reduction of the supply temperature to a radiator will result in a reduction in its thermal power output. A heating system which has properly sized (i.e., without a significant oversizing margin) will not be able to deliver expected thermal power, if the supply temperature is reduced. This will lead to lower indoor temperatures and decreased thermal comfort, especially during the coldest periods, when the spacing heating demand is highest. At lower space heating demands, the heating system may still be able to ensure the desired thermal comfort even at lower supply temperatures, because the thermal output from the radiators is sufficient to meet the lower heat demand.

Even heating systems in older buildings may be able to cover the design heat load, when run at lower supply temperatures. Since the design outdoor temperature is typically lower than the average minimum temperatures during a typical winter, the heating system is intrinsically “oversized” for most of the heating season, when the temperatures are not as low.
Additionally, because of discrete size at which radiators are available and conservative sizing of the heating elements, the heating elements are usually oversized compared to the minimum size required.
Despite this, existing heating systems may not be able to provide the necessary thermal comfort if the supply temperatures are significantly lowered.
Solutions allowing lower supply temperatures in the space heating system of a building include:

- Replacing the radiators with new ones having a larger heat transfer area
- Upgrading the heating system
- Decreasing the thermal load of the building.

and are further elaborated in the following sections.

The presented considerations come mainly from the Danish experience, but these are applicable to most other contexts.

1.2.5.1. Replacement of the radiators with new ones having a larger heat transfer area

Replacing the radiators with new ones having a larger heat transfer area is often a challenge. Increasing radiator dimensions in newer residential buildings is often a conflict with their architecture. For example, windows often go from the ceiling to the floor (or close to it), to get as much light as possible into the room. This means however that there is only room for low radiators or convectors. The possibilities for increasing the radiator effect are thus limited.

In older construction there may be a conflict between the radiator niche under the window and the desired radiator size. One may even reduce/have reduced the depth of the niche with insulation in connection with a renovation.

Poorly functioning systems can be improved with balancing and perhaps replacement of a few too small radiators. This process will often pay off financially.

1.2.5.2. Upgrade of the heating system

Upgrade from one-string to two string system

In older buildings one-string heating systems can be found. In a one-string system the heating terminal units (typically radiators) in the building connect to one single string (see Figure 8). As the inlet temperature to the radiators becomes progressively lower, the size of the radiators must progressively increase to deliver the same thermal power. One-string systems are usually fixed flow, while the supply temperature must be adjusted based on the thermal load, to minimize the return temperature. The supply temperature is normally controlled by a unit, which takes into account the outdoor temperature.

In a typical one-string system configuration a small diameter pipe (represented by a valve symbol in parallel to the radiators in the figure below) is used to bypass the radiator. This small pipe is sized in such a way that around 1/3 of the flow passes through the radiator and 2/3 of the flow passes through the pipe. The main hydraulic resistance is given by this small bypass pipe and by the thermostatic valve regulating the radiator. The hydraulic resistance of the radiator is negligible.

The return temperature depends strongly on the thermal load of the building (on how many radiators are open), but generally, given the high fraction of flow which bypasses the radiators, the return temperatures of this type of system is higher than in an equivalent two-string system.

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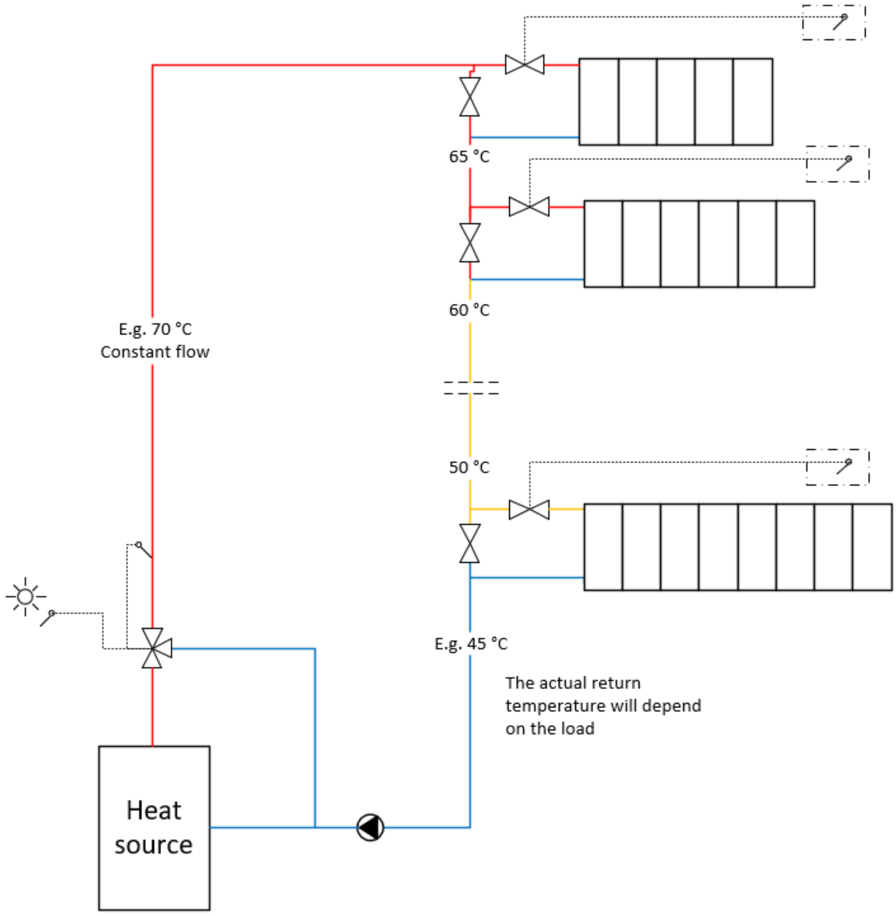

Figure 8 Typical scheme of a one-string systems.

Transitioning from a one-string system to a better functioning two-string system is likely to lead to energy savings and better temperature drop over the overall heating system (and therefore a higher cooling of the district heating supply water).
Poorly functioning systems can be improved with balancing and perhaps replacement of a few too small radiators. This process will often pay off financially.
An overall replacement of the radiator system represents a major renovation project, and it requires a quite large investment, which may not be cost-viable.

Radiant floor heating

Another upgrade of an older heating system is the transition to radiant floor heating. Floor heating is a good solution for a very low-temperature system, i.e., with flow temperature of about 45 °C and return of 40 °C. The return temperature in floor heating systems may not be necessarily lower than for good radiator systems.
Floor heating is not always able to minimize cold precipitation at large / high windows and may require additional heat from radiators in the most exposed places.
In the past, the problem with floor heating was that buildings had too much thermal loss to be able to be heated with floor heating.
The cost of establishing floor heating in existing construction is so high that this renovation measure is only considered in special cases and should also be supplemented by improvements to the building envelope in poorly insulated buildings

Radiators/convectors with built-in fans are in some cases an option, but this solution is rarely seen in residential buildings. Floor convectors can cause problems due to incorrect dimensioning or poorly made convector trenches.

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Building substation

Older buildings substations are likely to benefit from an upgrade - hot water tank, heat exchanger, balancing, control, etc. Besides poor operation in connection to supplying space heating and DHW, poor cooling of the district heating water is often included in the arguments for a renovation.

Older heat exchanger may have insufficient capacity, which may require higher DH supply temperatures and cause higher DH return temperature. In some cases, the exchanger can be cleaned or expanded with additional plates. In other cases, the exchanger is replaced.

1.2.5.3. Decreasing the thermal load of the building.

Regarding the second point, the following interventions are presented:

Facade insulation

In buildings built after the oil crisis (1970s) typically it will not immediately be possible to improve to reduce the heating load within cost-efficient intervention (except for window replacements).

In older buildings, there will be more obvious improvement options, including re-insulation of facades. An exception is cavity wall insulation, which is a relatively inexpensive measure and therefore has already been carried out in the vast majority of places where it is possible.

The addition of insulation can be done externally or internally with respect to the walls. Exterior insulation is often opted out, as it changes the appearance of the building too much. Internal insulation is an option, but is less effective and, if not done properly, can pose a risk of mould. There is not much difference in DKK / kWh heat saved.

Facade insulation also leads to a larger temperature drop across the heating elements, as the load is reduced.

Replacing windows

Windows are replaced several times during the life of a building. One of the reasons for this is that there has been a sharp improvement in the energy efficiency of windows over the last 20-30 years. New windows with 3 layers of glass insulate more than twice as well as older double-glazed windows. In some cases, windows are replaced due to lack of maintenance.

Also, window replacement results in a larger temperature drop across the heating elements, as the load is reduced.

Ventilation

In the past it was common to have one or more exhaust fans connected to the kitchen and bathroom, rejecting indoor air directly outside.

Now balanced ventilation with heat recovery is common. As a ventilation heating surface is included, the load on the radiators is reduced and this means a larger temperature drop across the heating elements.

Though, experience shows that the heat savings due to heat recovery in ventilation systems are small, but in return a better indoor climate is experienced.

Re-insulation of pipe system

Poorly insulated pipes can only in some cases be re-insulated with an economic advantage for the consumers. In fact, in the buildings the pipes are usually hidden in shafts or behind walls and are therefore difficult to re-insulate.

One place where it may make sense is domestic hot water and domestic hot water circulation - especially in unheated areas. In heated areas, an improvement of the pipe insulation will improve the indoor climate during the summer.

Some suggestions:

- To include some existing reference projects for the different DH generations, explaining the main features.

- Do you know any existing installation that has performed the change (evolution) from 3GDH to 4GDH? In that case, it would be great to add a section with such real experience

1.3. The so-called "5th generation DH" (5GDH)

There is still no consensus on what 5th generation district heating is and on whether such generation exists at all[8].

Buffa et al.[9] recognized the lack of a unanimous definition of 5GDH, with several different definitions used to refer to the same concept (such as *Low temperature District Heating and Cooling*, *Bidirectional Low temperature networks*, *Anergy networks*), and some conflict with the definitions linked to 4GDH systems. Therefore, they propose the following definition:

A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium, and hybrid substations with Water Source Heat Pumps. It operates at temperatures so close to the ground that it is not suitable for direct heating purpose. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5GDHC technology enhances sector coupling of thermal, electrical and gas grids in a decentralized smart energy system.

The operating temperatures of the network can have a wide range. In the review of existing 5GDH systems from Buffa et al., 40 systems were considered, and the supply temperatures were found to vary between 0 °C and 35 °C.

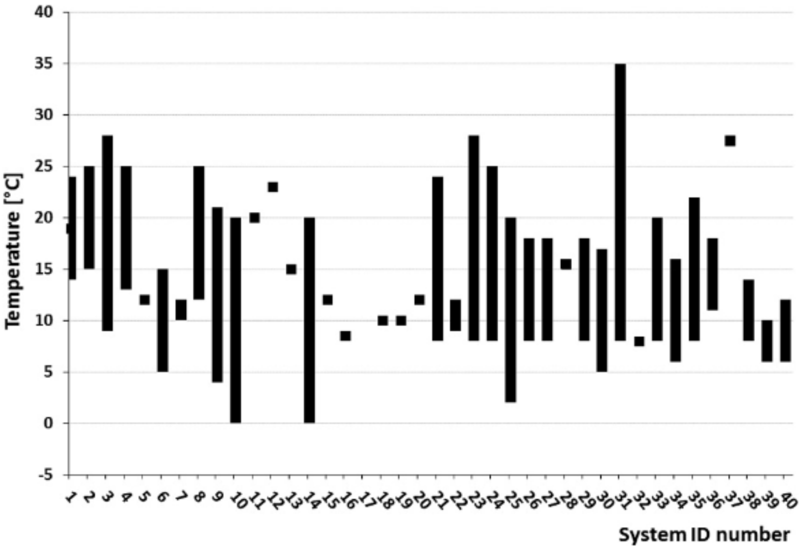

Figure 9 Supply temperature variation of the network for the surveyed 5GDHC systems (Buffa et al.).

Due to the low operating temperatures, uninsulated plastic pipes from the water supply industry can be used. The heat transfer fluid may be either water or a brine (the latter being used if there is risk of freezing).

As mentioned above, there is currently no consensus on whether the above-described DH(&C) system can actually be considered the 5th generation of district heating. The proponents of

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[8] Knutsson H., Holmén M, and Lygnerud K. 2021. Is Innovation Redesigning District Heating? A Systematic Literature Review www.mdpi.com/2411-9660/5/1/7/pdf

[9] Buffa S. et al. 2019, 5th generation district heating and cooling systems: A review of existing cases in Europe, *Renewable and Sustainable Energy Reviews* 104, 504-522. https://doi.org/10.1016/j.rser.2018.12.059

the currently called 5GDHC highlight the fact that the lower temperatures used in 5GDHC systems compared to 4GDH entitle this new concept to be seen as a new generation of DH. After all, decreasing network temperatures have characterized the previous DH generations. On the other hand, those who do not consider 5GDH as an evolution of 4GDH remark that – up to the 4GDH – moving from one DH generation to the next has entailed not only a reduction in temperatures, but – more importantly – also a reduction in cost for the consumers. The economic viability and advantage of 5GDH with respect to 4GDH has not been proven yet.

At least 40 examples of 5GDH systems can be identified in Europe, as listed by Buffa et al. in their review. The majority of these is found in Switzerland (15) and Germany (15).

1.3.1. Expected advantages and disadvantages of 5GDHC with respect to 4GDH

The table below, mainly retrieved by Buffa et al., lists the expected advantages and disadvantages of 5GDHC systems, and is followed by a critical view over these expectations.

Table 8: Expected advantages and disadvantages of 5GDH systems.

Advantages	Disadvantages
1. Allow direct recovering of low-temperature excess heat and include low enthalpy RES 2. Bi-directionality: it provides simultaneously both heating and cooling services throughout the year 3. Modularity, flexibility, and resiliency to a change of boundary conditions (building level efficiency, loads) 4. Negligible thermal losses because of low-temperature difference between the pipes and the ground 5. Pipelines can be uninsulated 6. Pipelines can be made of polymeric materials 7. The ground and the network can be used as thermal storage	1. Substations are more expensive than those in previous DH generations (CAPEX and O&M). 2. The installation of an individual DHW tank is needed 3. Low ΔT between supply and return pipes leads to large pipeline diameter 4. High pumping costs per unit of energy due to small operative ΔT (and therefore higher flows) and higher fluid viscosity 5. Electricity tariffs for decentralized HPs are higher since connected to lower voltage level 6. It may require the upgrade of the local electricity grid 7. In case of simultaneity between high heat demand and bottlenecks on the electricity grid, it can create pressure on the electrical grid

Advantage 1: it should be pointed out that also a traditional DH network can recover low-temperature excess heat through a waste heat HP and/or a heat recovery chiller.

Advantage 4: thermal losses by conduction depends not only on the temperature difference between carried fluid and soil, but also on thermal resistance. If it is true that in a 5GDH system the temperature difference between fluid and soil is much lower compared to a conventional DH system, it is also true that the thermal resistance is much lower, due to the lack of insulation as well as the larger exchange area (due to larger pipes, see Disadvantage 3 and Section 1.3.1.1). On the comparison between thermal losses in a 5GDH system and a conventional DH system, see also Section 1.3.1.2.

Advantage 5: true, but this will limit the extent of Advantage 4. Additionally, the temperature of the soil at low depth (~1 m, where DH pipes are usually laid) is influenced by the ambient air temperature, and therefore it will be colder in winter and warmer in summer. Conversely, a 5GDHC system would work more efficiently with somehow warmer supply temperatures in winter, and colder temperatures in summer, to boost the efficiency of the decentralized HPs. Therefore, the lower the temperature difference between carried fluid and soil, the lower the thermal losses, but the poorer the performance of the heat pumps (see Figure below).
Finally, uninsulated pipes do not have embedded control cables for leak detection, which make the identification of leaks extremely difficult.

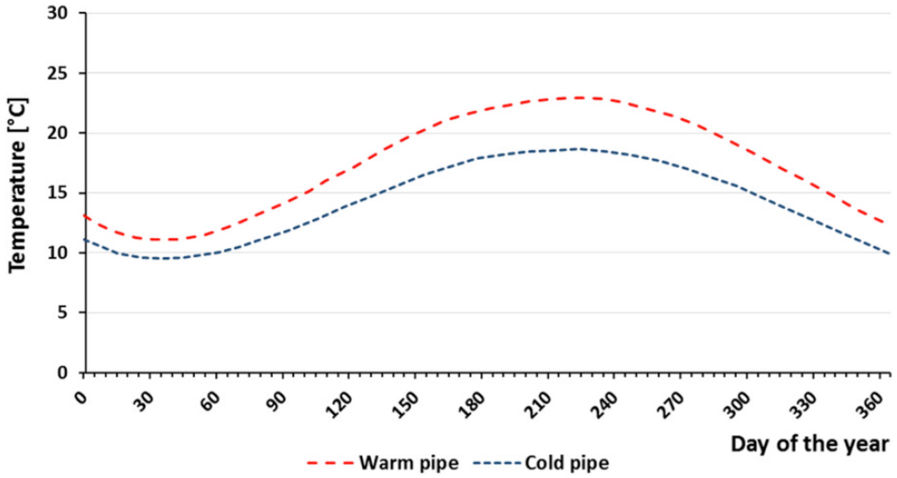

Figure 10: Seasonal temperature variation of the warm and cold pipes in a ground coupled by-directional 5GDHC system (Buffa et al.).

Advantage 6: true, however it is not straightforward that 5GDH networks will necessarily be cheaper than 4GDH ones, as in 5GDH systems pipes are significantly larger than in 4GDH (see Disadvantage 3 and Section 1.3.1.1), resulting in higher excavation costs, which – together with installation costs – represent the larger share of the network costs. Pipe costs are typically a 20% share of the overall network cost.

Advantage 7: in typical geothermal systems where the ground is used as thermal storage the ground heat exchangers consist of deep boreholes (down to 150 meters). At this depth the influence of the ambient air, solar radiation and rainwater is negligible on the energy balance of the geothermal storage. However, pipes buried horizontally at just one meter below ground will not be able to store heat (or cold) in the ground itself, as this will be quickly lost to the surroundings. Additionally, in typical geothermal systems, fluid-to-ground heat exchangers consist of long pipes of relatively small diameter, to increase the heat transfer area compared to thermal power carried by the fluid. Shorter length of bulky pipes will have a much lower heat transfer capacity to the surrounding ground compared to conventional geothermal system.

Disadvantage 1: the substations in a 5GDHC system are more expensive than in a conventional DH system. The main reason for this is that simple heat exchangers are replaced by water-source heat pumps. The CAPEX of the substation is significantly higher for a 5GDH compared to a conventional DH system one; in fact, the turn-key specific cost per unit of power output for a HP is about one order of magnitude higher than that of a heat exchanger, and the lifetime is 2-3 times shorter, which therefore requires much more frequent reinvestments in the substation. Also, the O&M cost are significantly higher for a HP compared to a heat exchanger. Additionally, substations consisting of HP are typically equipped with DHW storage and typically buffer storage for space heating too. This allows to size the HP at a smaller capacity, by shifting in time the heat production with respect to heat utilization. Individual storage has much higher thermal losses and higher specific costs per kWh stored compared to centralized tank TES, typical of conventional DH systems.

Disadvantage 2: thermal storage is strongly affected by the economies of scale, with the specific cost of large-scale storage being much lower than that of individual storage tanks.

Disadvantage 7: as electrification of the heat demand is done at building level, in case of simultaneity between high heat demand and issues on the electricity grid, the capability of covering the heat demand may be compromised. Such an event would be much less critical for a conventional DH system, which usually have a pool of heating plants (possibly including large scale HPs), using different energy sources to operate, as well as backup plants. When present in conventional DH systems, HPs are usually used as baseload technologies due to economic considerations (high CAPEX and low OPEX). Other technologies (such as boilers) are present as peak and backup units. In case of bottlenecks or other issues on the electricity grid, a large-scale HP can be stopped, replaced by other technologies, without compromising the coverage of the network heat load. Achieving the same level of resiliency in a system with decentralized heat pumps would require non-electric backup units at each building, which increases dramatically the investment costs.

Due to limited storage capacity of individual storage systems, electricity will need to be drawn simultaneously with the heating/cooling demand, regardless of the instantaneous electricity prices.

Electrification of the heat demand is often referred to as a way to offer flexibility to the electric grid and to handle the intermittency of non-dispatchable RES electricity production. In this perspective, it is intuitive to understand that centralized and larger scale HPs commonly used in 4GDH systems can more easily participate on electricity markets compared to building-level machines, due to more cost-effective thermal storages, larger capacities, larger energy volumes and they are more likely to get prequalified.

Some of the above advantages and disadvantages of 5GDH systems compared to conventional DH systems are further described in the following sections.

1.3.1.1. Pipe sizing

The thermal power carried by a pipe is given by the expression:

$$P_{th} = v \cdot D^2 \pi/4 \cdot \varrho \cdot c_p \cdot \Delta T$$

where P_{th} is the thermal power carried by a pipe [kW];
v is the fluid mean velocity [m/s];
D is the inner diameter of the pipe [m];
ϱ is the fluid density [kg/m^3];
c_p is the fluid specific heat [kJ/kg/K];
ΔT is the temperature difference by which the carried fluid is cooled down when delivering its thermal power.

From the expression above, we can see that the thermal power depends linearly on the fluid velocity and on the temperature difference between supply and return, while it depends quadratically on the pipe's inner diameter.

Higher velocities allow for smaller pipes, but increase the pressure drop in the network, so requiring more pumping power and pumping energy. Even if additional pumping power is available and more pumping energy is acceptable, there may also be other hydraulic limitations influencing the choice of fluid velocity (as well as pipe diameter), such as maximum and minimum pressure allowed by the network components.

Table 9: Velocity in steel pipes corresponding to 100 Pa/mpipe of pressure drop gradient.

D_N [mm]	Velocity [m/s]	D_N [mm]	Velocity [m/s]
DN15	0.29	DN150	1.29
DN20	0.36	DN200	1.52
DN25	0.42	DN250	1.75
DN32	0.50	DN300	1.95
DN40	0.55	DN350	2.07
DN50	0.64	DN400	2.25
DN65	0.76	DN450	2.42
DN80	0.84	DN500	2.59
DN100	1.00	DN600	2.90
DN125	1.14		

If higher pressure drop gradients are allowed in the pipes, the fluid velocities can be increased. However, pipe manufacturers usually recommend maximum velocities which should not be exceeded irrespective of the resulting pressure drop. An example is given in the table below.

Table 10: Example of maximum speed recommended for DH steel pipes.

Steel pipe diameter	Value, m/s
≤ DN40	1.0
DN50 - DN150	1.5
DN200 - DN250	2.0
DN300 - DN350	2.5
≥ DN400	3.0

Compared to steel pipes, plastic pipes can be considered smooth in terms of surface roughness, therefore they are characterized by a lower friction factor (provided that all other parameters are the same). Therefore, in case of plastic pipes somehow higher velocities than what shown in Figure 10 are acceptable.

Larger pipe diameters allow for lower pressure drops, but increase the network costs, as well as the thermal losses. Given the quadratic correlation between diameter and thermal power, the increase of just one pipe dimension allows for quite an increase in carried thermal power (provided that the other parameters remain the same).

Larger temperature differences between supply and return allows for smaller pipes and/or lower velocities, but – as discussed previously – there are practical limitation on how the supply and (especially) return temperatures can be set.

Typical fluid velocities in DH pipes are given below. The tabled values correspond to fluid velocities resulting in 100 Pa/m of pressure drop gradient along the pipes. Higher velocities may be possible, depending on pumping equipment and hydraulic configuration of the network.

In the table below we compare pre-insulated (Series 1) steel pipes in the context of a conventional DH system against uninsulated HDPE[10] PN16[11] pipes in the context of a 5GDH system.

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[10] High Density Polyethylene

[11] Nominal internal pressure of 16 bar

It is assumed that the pressure drop gradient in both systems is 100 Pa/m, and the heat transfer fluid in the network is water.
The supply (warm) and return (cold) temperatures are assumed to be 80 °C and 50 °C respectively for the conventional DH system, while 15 °C and 10 °C for the 5GDH system. The temperature requirements of the end-consumers are assumed to be 65 °C in supply and 45 °C in return.

The average soil temperature is 8 °C.
During the heating season (high heat load) the heat losses of the conventional DH system are assumed to be equal to 2%.
For the 5GDH system, the COP of the individual water-source HP was assumed to be 3.9, based on the network temperatures and customers' temperature requirements, which have been assumed above.

Table 11: Dimensions and other key parameters of preinsulated series 1 pipes.

D_N	**D_{out}**	**D_{in}**	**Velocity**	**Flow**	**Pipe thermal power**	**End-user thermal power**	**Heat loss coefficient**	**Thermal losses**	**Casing diameter**
mm	mm	mm	m/s	m3/h	MW	MW	W/m_pipe/K	W/m_trench	mm
DN20	26.9	22.9	0.36	0.53	0.0186	0.0182	0.14	16	90
DN25	33.7	29.1	0.42	1.01	0.0350	0.0343	0.18	20	90
DN32	42.4	37.2	0.50	1.96	0.0681	0.0667	0.18	21	110
DN40	48.3	43.1	0.55	2.89	0.101	0.099	0.21	24	110
DN50	60.3	54.5	0.64	5.38	0.187	0.183	0.24	27	125
DN65	76.1	70.3	0.76	10.6	0.370	0.362	0.29	33	140
DN80	88.9	82.5	0.84	16.2	0.563	0.551	0.30	34	160
DN100	114.3	107.1	1.00	32.4	1.129	1.106	0.31	35	200
DN125	139.7	132.5	1.14	56.6	1.97	1.93	0.36	42	225
DN150	168.3	160.3	1.29	93.7	3.26	3.20	0.44	51	250
DN200	219.1	210.1	1.52	189.7	6.60	6.47	0.48	55	315
DN250	273.0	263.0	1.75	342	11.91	11.67	0.45	52	400
DN300	323.9	312.7	1.95	539	18.76	18.39	0.53	61	450
DN350	355.6	344.4	2.07	694	24.16	23.68	0.51	58	500
DN400	406.4	393.8	2.25	987	34.34	33.65	0.54	62	560
DN450	457.0	444.4	2.42	1351	47.03	46.09	0.54	62	630
DN500	508.0	495.4	2.59	1797	62.55	61.30	0.64	72	670
DN600	610.0	595.8	2.90	2911	101.3	99.3	0.74	85	710

Table 12: Dimensions and other key parameters of HDPE PN16 pipes.

D_N	**D_{out}**	**D_{in}**	**Velocity**	**Flow**	**Pipe thermal power**	**End-user thermal power**	**Heat loss coefficient**	**Thermal losses**
mm	mm	mm	m/s	m3/h	MW	MW	W/m_pipe/K	W/m_trench
DN20	20.3	16.1	0.29	0.21	0.0012	0.0016	11.93	107
DN25	25.2	20.2	0.34	0.39	0.0023	0.0031	12.50	113
DN32	32.2	26.0	0.41	0.78	0.0045	0.0061	12.93	116
DN40	40.3	32.3	0.48	1.42	0.008	0.011	12.49	112
DN50	50.3	40.5	0.57	2.63	0.015	0.020	12.76	115
DN63	63.4	51.0	0.67	4.91	0.028	0.038	12.70	114
DN75	75.4	61.0	0.76	7.96	0.046	0.062	13.04	117
DN90	90.5	73.1	0.86	13.0	0.075	0.101	12.95	117
DN110	110.6	89.4	0.98	22.2	0.13	0.17	12.99	117
DN125	125.7	101.5	1.07	31.2	0.18	0.24	12.93	116
DN140	140.7	113.9	1.16	42.5	0.25	0.33	13.08	118
DN160	160.8	130.0	1.27	60.5	0.35	0.47	13.00	117
DN180	180.9	146.7	1.37	83.5	0.48	0.65	13.19	119
DN200	200.9	162.5	1.47	109.7	0.64	0.86	13.03	117
DN225	226.1	182.9	1.50	141.9	0.82	1.11	13.04	117
DN250	251.2	203.4	1.50	175.5	1.02	1.37	13.10	118
DN280	281.4	227.8	1.83	269.1	1.56	2.10	13.08	118
DN315	316.5	256.3	1.98	367.7	2.1	2.9	13.10	118
DN355	356.6	288.8	2.00	471.7	2.7	3.7	13.11	118
DN400	401.8	325.4	2.31	691.7	4.0	5.4	13.11	118
DN450	452.1	366.1	2.49	944.4	5.5	7.4	13.10	118
DN500	502.4	406.8	2.67	1247.4	7.2	9.7	13.10	118
DN560	562.5	455.7	2.87	1682.8	9.8	13.1	13.13	118
DN630	633.0	512.6	3.00	2229.1	12.9	17.4	13.10	118
DN710	713.2	576.2	3.00	2816.5	16.3	22.0	12.96	117
DN800	803.7	643.5	3.00	3512.9	20.4	27.4	12.44	112

The figure below shows the thermal power carried by the conventional and 5GDH system as function of the pipe inner diameter. Because of the much higher ΔT (6 times higher) in case of conventional DH, the thermal power for the same inner diameter is much higher for conventional DH compared to 5GDH. The fact that HDPE pipes allow for higher velocities due to the lower friction factor has an influence (the carried thermal power is 5 times lower instead of 6 times), but not major.

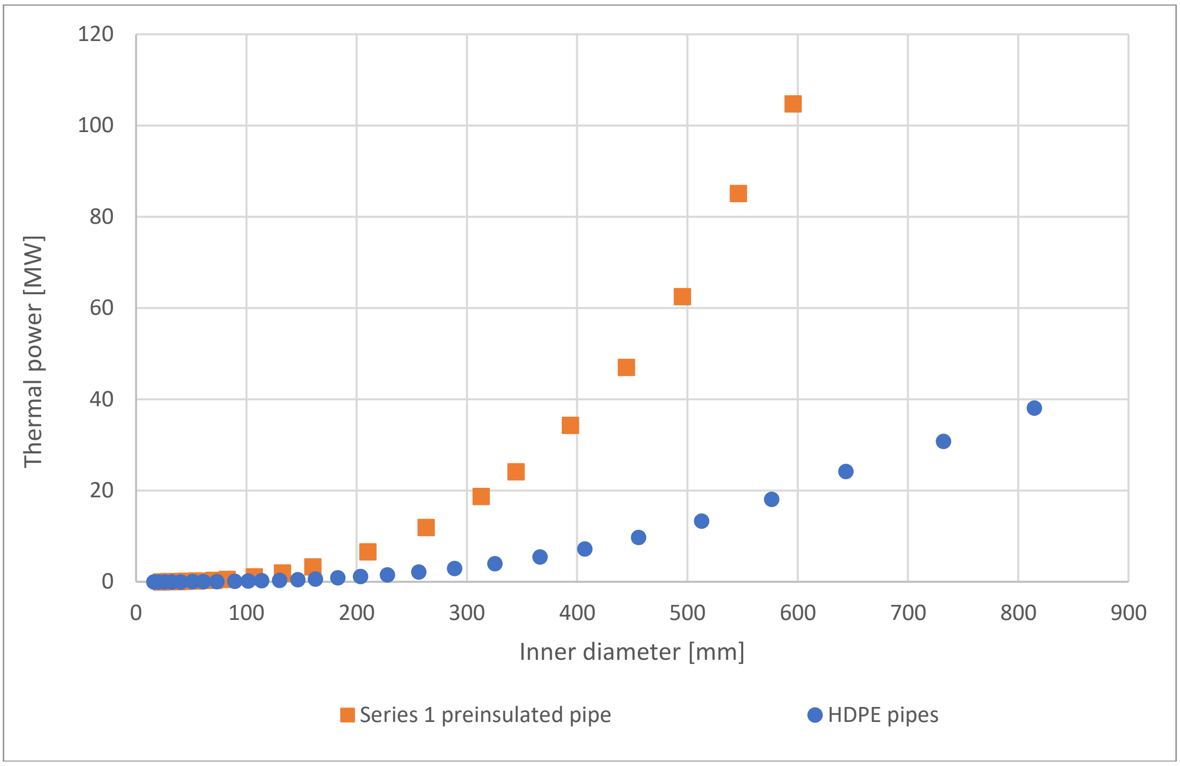

Figure 11: Thermal power carried by carrier pipes in a conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) as function of the pipe inner diameter.

Because in a 5GDH system part of the final thermal energy made available to the consumer is introduced at the substation level by the electricity absorbed by the HP, a 5GDH system will have to carry less amount of thermal power to satisfy the same end-user's demand. Therefore, it is more interesting the compare the two system in terms of end-user thermal power with respect to the pipe diameters (see figure below).

The comparison between conventional DH and 5GDH improves for the 5GDH system, but conventional DH is still able to carry much more thermal power with the same inner diameter thanks to the higher ΔT.

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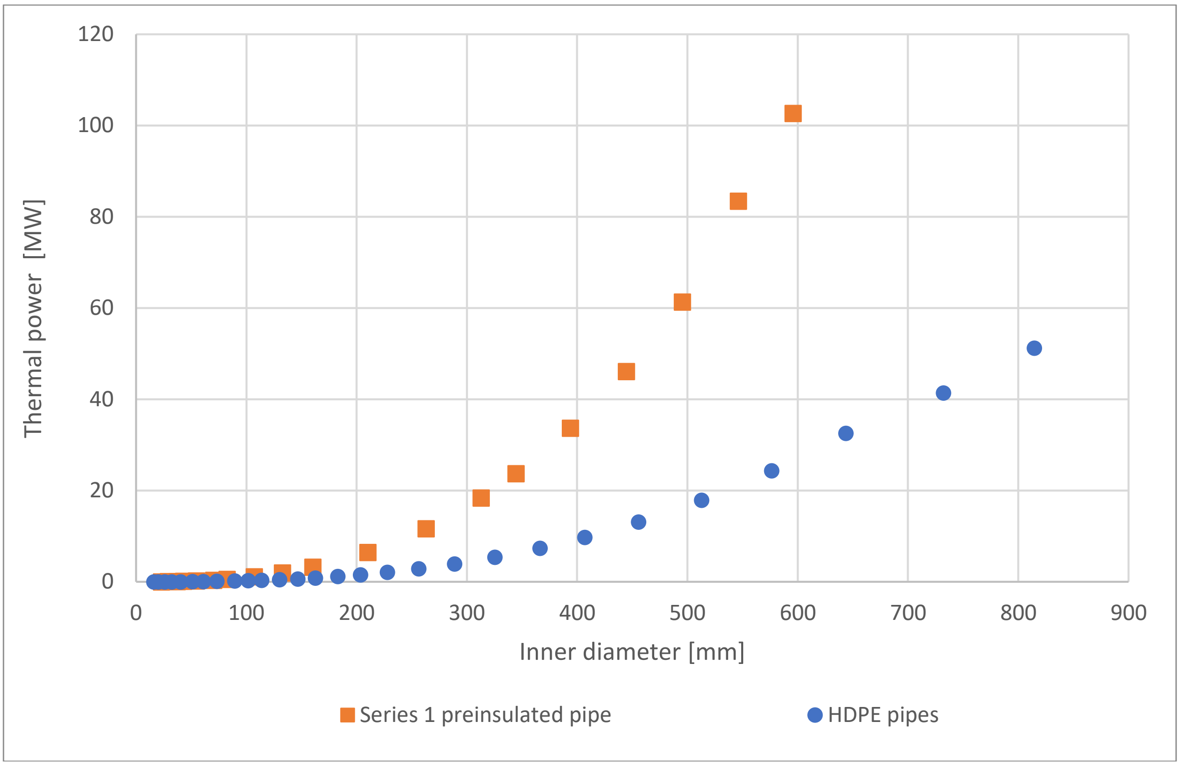

Figure 12: Thermal power made available for the end-user (after the end-user substation) in a conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) as function of the pipe inner diameter.

In this case we see that the end-user thermal power is about 3-3.5 times higher in case of conventional DH compared to 5GDH.

Because the excavation costs are related to the outer diameter (including possible insulation) of the pipe, the figure below shows the thermal power made available for the end-user (after the end-user substation) for both a conventional and a 5GDH system as function of the outer diameter of the pipes (including insulation for pre-insulated pipes).

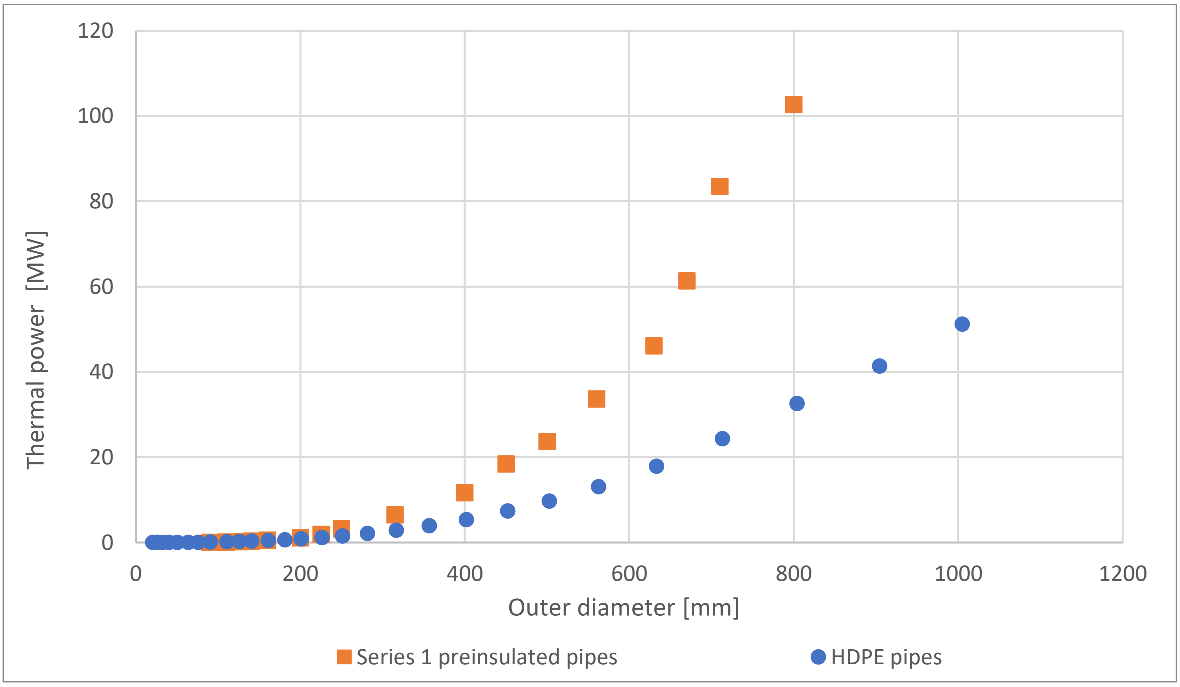

Figure 13: Thermal power made available for the end-user (after the end-user substation) in a conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) as function of the pipe outer diameter (including insulation for pre-insulated pipes).

Also, when the outer diameter is taken into account, a conventional DH system carries a larger thermal power (at end-user level) compared to a 5GDH system, although the factor between the two decreases from about 3-3.5 to about 2-3.2.

Promoters of 5GDHC may argue that a 5GDH system is meant to supply both heating and cooling, therefore rejected heat from the cooling demand will be injected throughout the network into the hot pipe. As heat is provided in multiple points to the network rather than in one or few points (corresponding to the central heating plants), the pipes of a 5GDHC system can be on average sized smaller, which will party counterbalance the gap in carried thermal power shown in the figures above.

However, as the pipes of a district energy system are sized for the peak load conditions (coldest outdoor temperatures), it is unlikely that a significant cooling demand will occur in this situation. Few particular customers (such as data centers, markets, etc.) may require some cooling demand even in these conditions, but this could be easily provided through free cooling (giving the low outdoor temperatures). Few customers with high and continuous cooling demand may also be connected to a 4GDH system via heat recovery chillers, i.e., heat pumps producing simultaneously useful heating and useful cooling on the condenser and evaporator side, respectively.

1.3.1.2. Thermal losses from network

As mentioned above, thermal losses by conduction depends not only on the temperature difference between carried fluid and soil, but also on thermal resistance. If it is true that in a 5GDH system the temperature difference between fluid and soil is much lower compared to a conventional DH system, it is also true that the thermal resistance is much lower, due to the lack of insulation as well as the larger exchange area due to larger pipes.

Based on Table 11 and Table 12, the figures below show the thermal losses per meter of trench as function of the inner and outer diameter (including insulation for pre-insulated pipes) of the pipes, under the temperature assumptions made in Section 1.3.1.1.

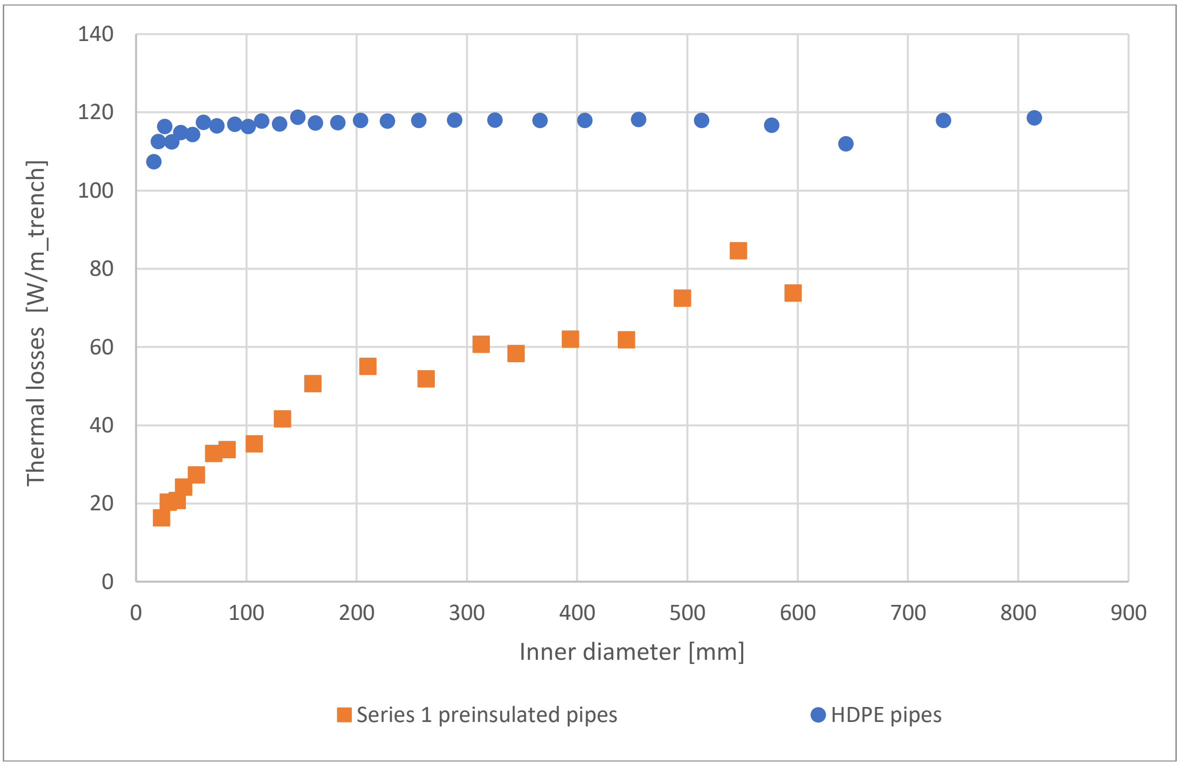

Figure 14: Thermal losses per meter trench in a conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) as function of the pipe inner diameter.

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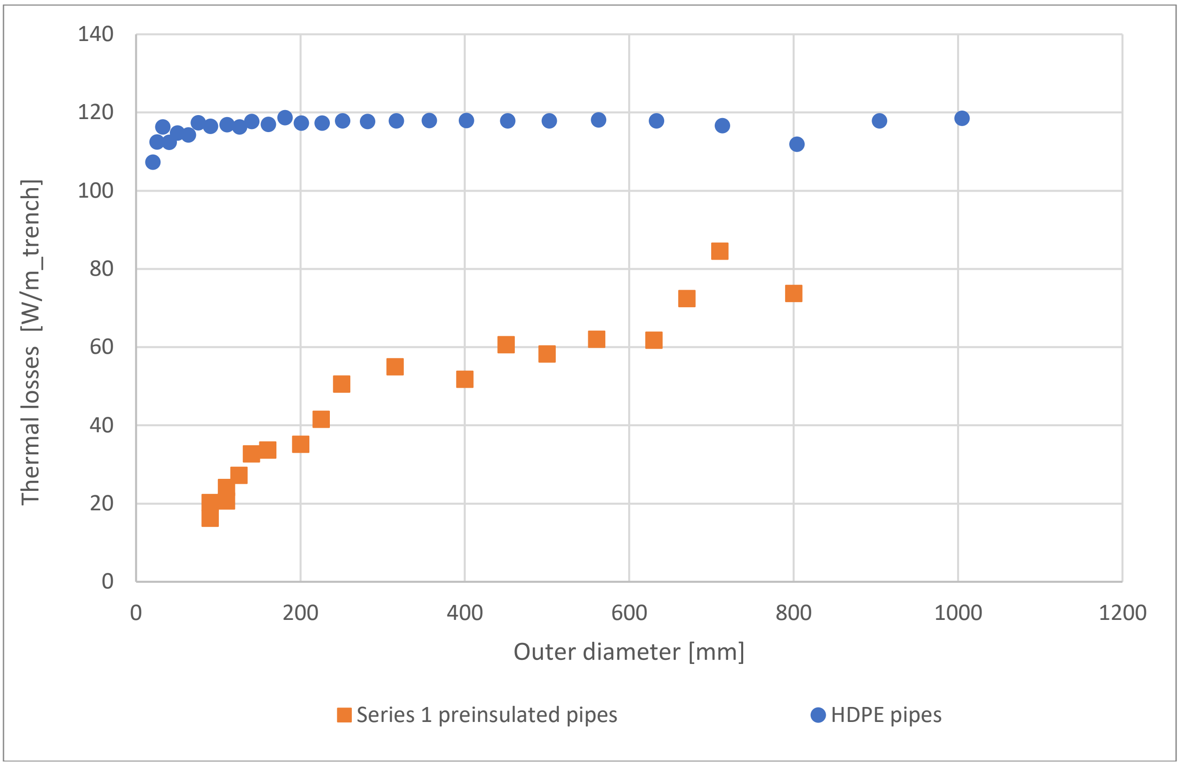

Figure 15 Thermal losses per meter trench in a conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) as function of the pipe outer diameter (including insulation for pre-insulated pipes).

It can be seen that the thermal losses for HDPE pipes are roughly constant with the diameter, as the thickness of the plastic pipes (and therefore its thermal resistance) increases proportionally with the diameter (increasing heat transfer area).

Conversely the thermal losses for pre-insulated pipes increase roughly linearly with the increase of the pipe diameter. This is because the insulation thickness does not increase as much as the pipe diameter, due to bulkiness and cost reasons. Additionally, larger pipes carry much more thermal power (roughly quadratically with the diameter), while thermal losses increase roughly linearly with the diameter. Therefore, when comparing the thermal losses of a pipe to the carried thermal power, larger pipes are more efficient than smaller pipes, despite their higher linear losses.

When comparing the conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) in terms of thermal losses, it is seen that the latter has higher losses, despite what often claimed by 5GDHC supporters. The difference in thermal losses between the two systems can also be seen as function of the end-user thermal power, which is a fairer comparison (see image below).

The comparison in thermal gains of a 5GDH system and a conventional DC system is not shown, but it is reasonable to expect that DC is characterized by lower thermal gains, as the temperature difference between the two pipes and the temperature difference between fluid and soil can be expected to roughly similar for conventional DC and 5GDHC, with the main difference being that DC pipes are pre-insulated, while 5GDHC pipes are not.

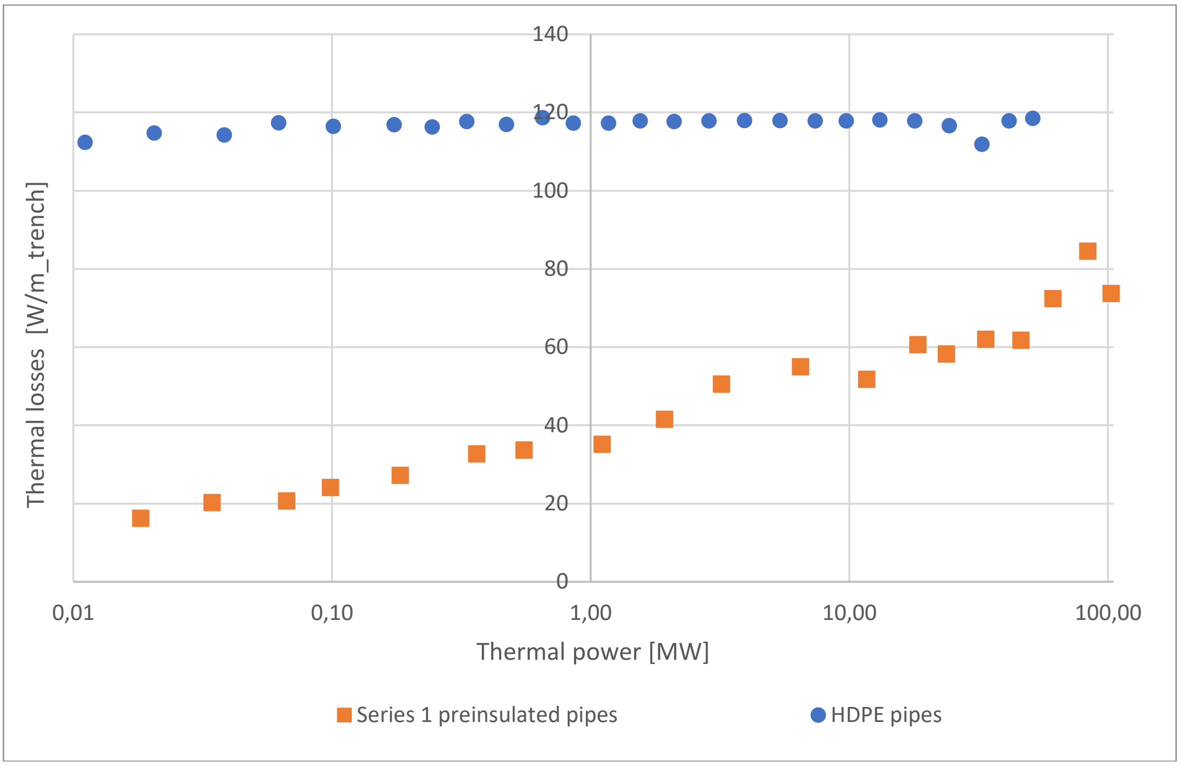

Figure 16: Thermal losses per meter trench in a conventional (series 1 pre-insulated pipes) and 5GDH system (HDPE pipes) as function of the thermal power made available for the end-user (after the end-user substation).

1.3.1.3. Pumping power

Due to higher flow rates required by a 5GDHC system to cover the same end-user heat demand compared to a 4GDH system, the required pumping power is significantly higher. According to the review carried out by Buffa et al., pumping energy consumptions result one order of magnitude higher compared to traditional district heating systems.

The figure below shows the hydraulic power per km of single pipe as function of the thermal power made available for the end-user (after the end-user substation). By hydraulic power we mean the power required to make the heat carrier fluid overcome the friction forces, and it is therefore calculated as the product of pressure drop gradient and volumetric flow rate:

$W_{hydraulic}/L = (\Delta p/l) \cdot V$

where $W_{hydraulic}/L$ is the hydraulic power per unit of pipe length [kW/km],
$\Delta p/l$ is the pressure drop gradient due to friction forces [Pa/m],
V is the volume flow rate [m^3/s].

The figure below refers to the hydraulic assumptions (water as carrier fluid, pressure drop gradient of 100 Pa/m), pipe characteristics (size and velocities) and system characteristics (COP, network efficiencies, temperatures) described in Section 1.3.1.1. The hydraulic power and the thermal power shown in the figure refer therefore to the pipes when operated at a pressure drop gradient of 100 Pa/m. In principle it would most often be possible to increase the flow (and therefore the thermal power) above the stated values (however only to a certain extent), but the pressure drop will increase roughly quadratically with the flow.

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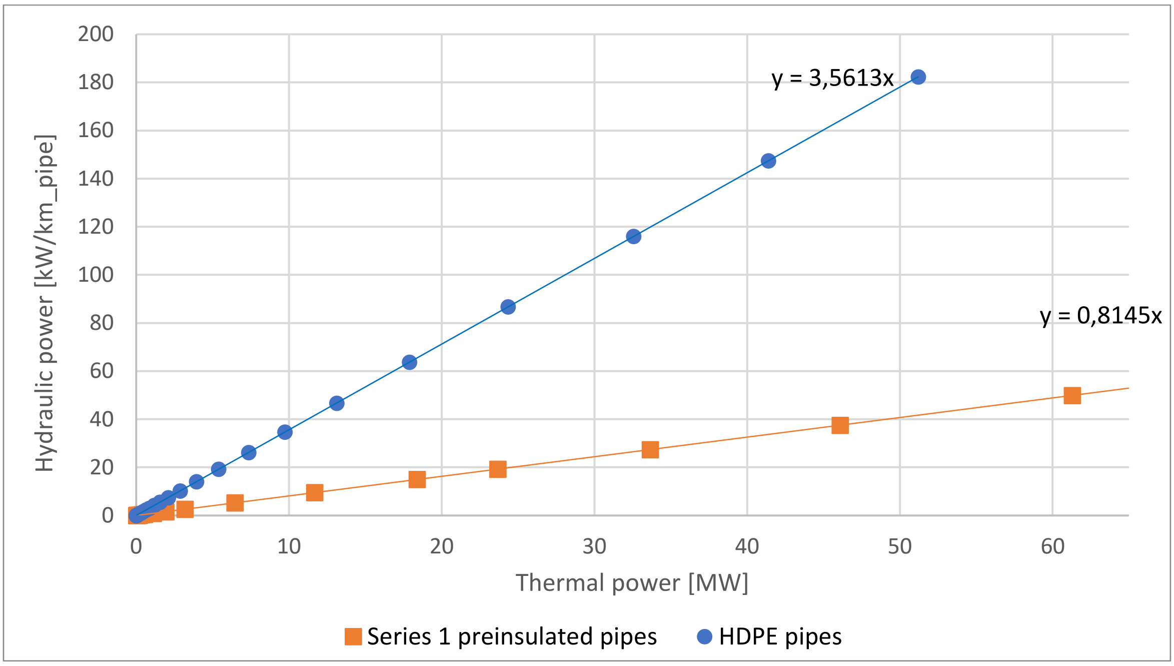

Figure 17: Hydraulic power per km of single pipe as function of the thermal power made available for the end-user (after the end-user substation).

From the figure it is seen that the required hydraulic power in a 5GDH system in full load conditions is about 4.4 times higher than that of a 4GDH system with the used assumptions. It is possible to prove that in first approximation the ratio between the hydraulic powers required by the two systems does not change at lower load (lower flow rates).

If the same pipe network of the 5GDH system used a 25% glycol-water mixture as carrier fluid (as in the 5GDHC system in Bulle, Switzerland), the fluid viscosity would be roughly 4.5 times higher compared to water. Additionally, due to the lower specific heat of the glycol-water mixture, the flow rate (and therefore the fluid velocity) should be 5% higher to carry the same amount of power as what shown in Table 12. The combined effect would result in a hydraulic power 1.5 times higher than in the case using water. In this case the required hydraulic power in the so defined 5GDH system in full load conditions is about 6.5 times higher than that of the 4GDH system.

As a 5GDH system is meant to supply both heating and cooling, rejected heat from the cooling demand will be injected throughout the network into the warmer pipe. As heat is provided in a more “scattered” way to the network, flow rates in a 5GDHC system may be lower compared to a more centralized heat supply, especially in the period with lower heat loads, when the demand for cooling may be higher than during the peak heating period. This would decrease the highest flows in the main pipes, so decreasing the required hydraulic power.

1.3.1.4. Cost of network

Costs of network piping (including installation costs) are quite variable, as these depend on a variety of parameters such as:

- Geographic area
- Type of area (city centre, suburbs, etc.)
- Type of excavated soil (paved/unpaved) and presence of other utilities in the underground (electricity cables, water pipes, etc.)
- Level of experience of the entrepreneur with the task

An example of pipe costs (including installation, covering, project and unforeseen) from 2017 of series 1 steel pipes and HDPE PN16 pipes is shown in the figures below, where the pipe cost per meter trench is shown as function of the inner diameter, of the outer diameter (including insulation for pre-insulated pipes), and of end-user thermal power (after the end-user substation) under the assumptions listed in section 1.3.1.1.

As could be expected, uninsulated plastic pipes are cheaper than steel pre-insulated pipes, when these are compared in terms of pipe diameter. However, because the much higher thermal power carried in a 4GDH system compared to a 5GDH system, when the two systems are compared in terms of thermal power made available to the end-user (after the end-user's substation) (see Figure 20), the cost difference disappears, and a 4GDH network may be even cheaper than a 5GDH one at larger thermal powers.

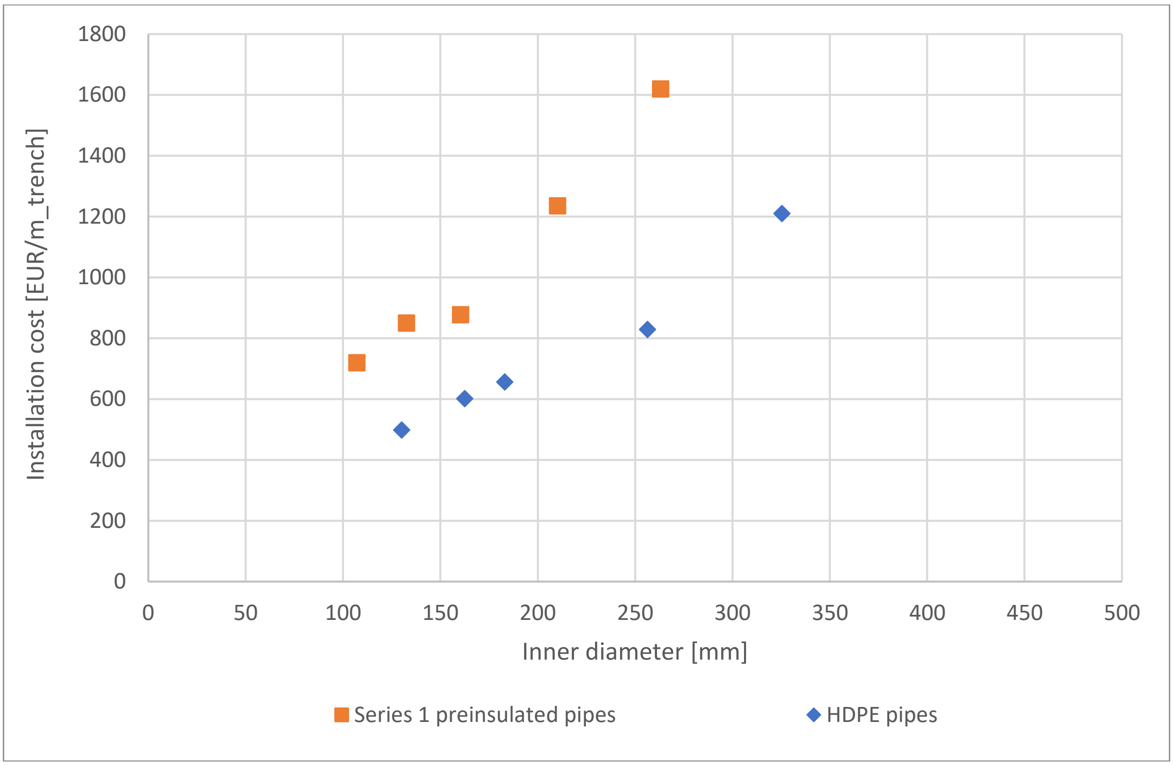

Figure 18: Installation cost per meter trench of series 1 pre-insulated pipes and HDPE PN16 pipes as function of the pipe inner diameter.

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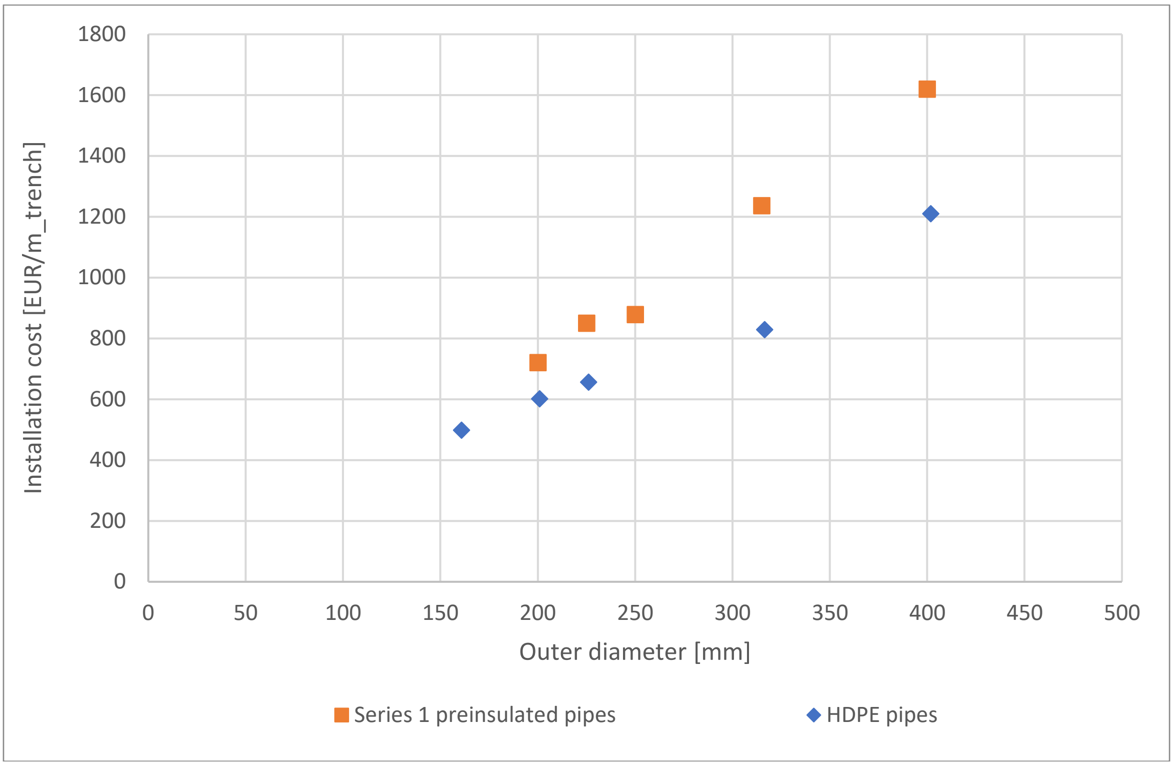

Figure 19: Installation cost per meter trench of series 1 pre-insulated pipes and HDPE PN16 pipes as function of the pipe outer diameter (including insulation for pre-insulated pipes).

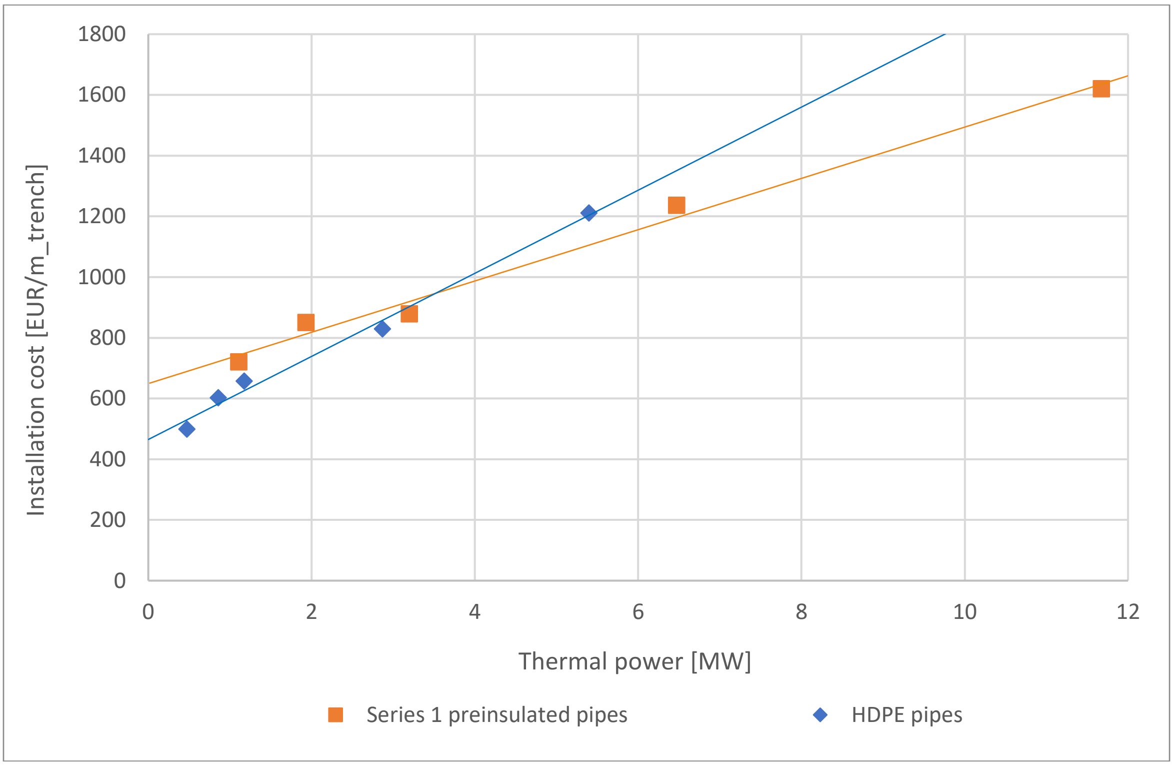

Figure 20: Installation cost per meter trench of series 1 pre-insulated pipes and HDPE PN16 pipes as function of the thermal power made available for the end-user (after the end-user substation).

Under the assumptions made above, the cost of the network is of the same order between 4GDH and 5GDH systems. However, a 5GDH system is meant to provide both heating and cooling, while a 4GDH system provides heating only. To make the comparison fairer, in presence of cooling demand beside heating demand, the costs of a DC network along the 4GDH network are to be included too. If DC pipes are established alongside and

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simultaneously with DH pipes, large saving in the DC installation costs can be expected, as excavation, refilling and covering costs are shared between the two networks.
Another option is to have chillers installed at building level, with the preference between one solution or the other depending largely on the “geographic density” of the cooling demand, and hence on the economic feasibility of the two solutions.

Potential for the cost reduction of 4GDH networks exist, as the lower operating temperatures can allow the use of (insulated) plastic pipes also in this case. A study from Denmark carried out in 2017[12] compared the costs of installing pre-insulated plastic pipes with those of pre-insulated steel pipes, to establish a low temperature small DH distribution system. The pros and cons of the different types of pipes were evaluated. The report concludes that under the assumed conditions, plastic pipes are not as competitive as steel pipes for the DH companies in the analysed case, mainly due to additional thermal losses. Additionally, all project partners see the possibility of using plastic pipes in the district heating distribution in the future, and few changed parameters would make the plastic pipe solution cheaper than the steel pipe one.

Due to the larger water content, a 5GDH network will likely have larger operating costs in terms of feed-in water and water treatment.

1.3.1.5. Costs of substation

The main technological difference between conventional DH and 5GDH is the building level substation. In conventional DH this is typically one or more heat exchanger, used as interface between the network on the supply side and the heating/DHW preparation system on the customer side. Direct connection of the customer’s heating system to the DH network (i.e., without heat exchanger) also exist, but this solution is less common and is not treated in this paper.
A 5GDH system requires the substation to be a water-source HP, in order to rise the network temperature to the temperature level required by the customer.
This technological difference also results in an important cost difference. The figure below shows indicative prices (incl. installation) for DH substation and water-source HP as function of their heat output in the Danish context. Note that the y-axis is in logarithmic scale.
It should be noted that the costs for the HP refer to a “simple” HP, i.e., producing heating only. A HP which needs to operate both as a heat pump and a chiller will probably entail a somehow higher CAPEX, also in consideration of the more complicated control system, managing the production of heating, cooling and DHW.
It can be seen that a 5GDH substation is roughly one order of magnitude more expensive than a conventional DH substation. Additionally, the lifetime of a HP is typically 2-3 times shorter than for a heat exchanger. Therefore, 5GDH substations must be replaced more frequently, requiring more frequent reinvestments.

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[12] Pedersen L.P., Birkbak S.S, Aaen R. 2017. Valg af plast eller stålrør til fjernvarmedistribution (in Danish, ”Choice of plastic or steel pipes for DH distribution”) www.danskfjernvarme.dk/viden-og-v%c3%a6rkt%c3%b8jer/f-u-konto-subsection/rapporter/2016-02-valg-af-plast-eller-staalroer-til-fjernvarmedistribution

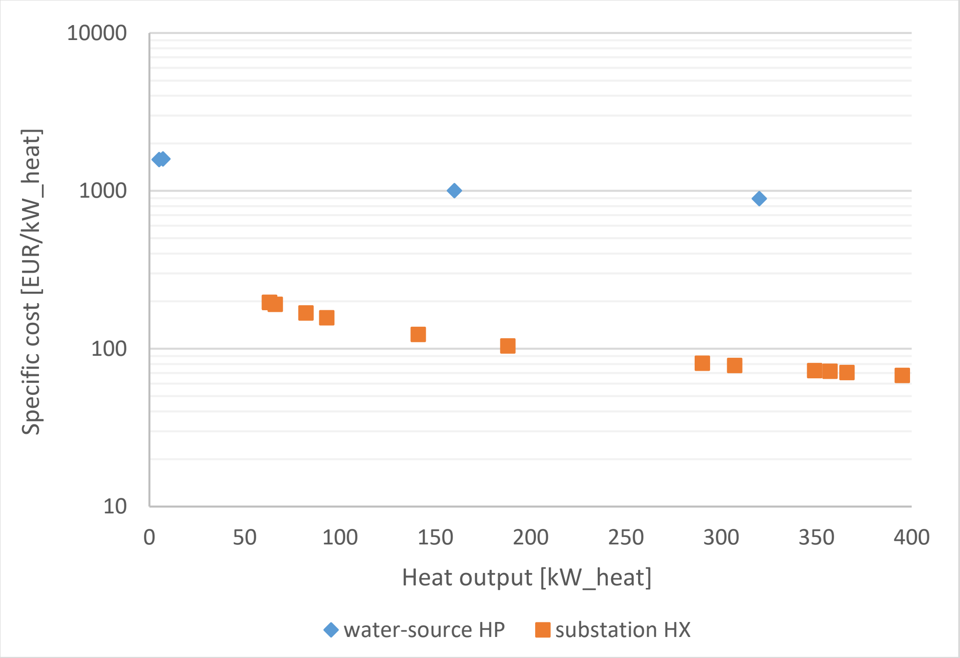

Figure 21: Specific installation cost of conventional DH substation and water-source HP as function of their thermal power output.

Besides CAPEX and O&M, the substations of the two systems differ considerably in terms of marginal cost of operation. A conventional DH substation has basically no marginal cost of operation. On the other hand, the electricity consumption of the HP installed in a 5GDH substation is considerable and equal approximately to one fourth (1/COP) of the end-user's heat demand.

1.3.1.6. Energy prices – electricity

Besides investment costs, electricity costs have an important share in both a 4GDH system using heat pumps as baseload technologies and in a 5GDH system. In this perspective, it is important to consider that utilities using large amounts of electricity and connected to high-voltage grids usually benefit from cheaper prices, compared to low-voltage private consumers. To have a preliminary idea on what price difference we are talking about, one may use Eurostat data[13]. Here indicative electricity prices for non-household and household consumers are continuously updated for the different European countries. As household consumers the Eurostat data refer to medium-sized consumers with an annual consumption between 2,500 kWh and 5,000 kWh, while as non-household consumers they refer to medium-sized consumers with an annual consumption between 500 MWh and 2,000 MWh.

In the second half of 2020 the average electricity price across the EU-27 area for household consumers was 0.21 €/kWh, while the average price for non-household consumers was 0.13 €/kWh.

It is true that some countries, e.g. Denmark, applies reduced taxation on the use of electricity when used for heating purposes, so reducing the gap between the household and non-household tariffs, but this varies from country to country.

1.3.1.7. Energy centre

Another important component of a DH system is the energy centre (or centres, depending on the extent and complexity of the network). In a conventional DH system, the energy centre is where the entire heat production takes place, as the consumers' substations are not equipped with production units, but only with heat exchangers.

The production units are typically distinguished in base load units and peak load units (as well as backup units). The base load units are those which are in operation for most of the hours of the year. Because they operate for a high number of hours, it is important that their OPEX

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[13] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

are relatively low, while their CAPEX may be high. A typical example of baseload production units in 4GDH systems are HPs, which may exploit various energy sources, such as ambient air, geothermal heat, water bodies (rivers, lakes, sea), wastewater, excess heat from industry or cooling production, etc.

If environmental considerations are also included, it is important that baseload units have low emissions factors.

Baseload units may be sized to about 50% of the peak network heat demand and represent about 90% of the yearly heat demand.

The peak load production units are in operation for few hours per year, corresponding to the periods of highest heat demand (coldest periods). Because they operate only few hours per year, it is important that their CAPEX is low, while it is not a critical issue if their OPEX is high. They may also be allowed to have higher emission factors, as their overall emissions will anyway be limited, due to the low use of fuel on a yearly basis. Typical peak load units are boilers running on natural gas or oil (solid fuels are not suitable, due to their typically longer response times, which are not compatible with the fast regulation that is required by peak load units).

Finally, backup units have the same characteristics as peak load units and provide redundancy in case of failure or unavailability of main production units.

An example of how baseload production units and peak load units can cover the heat demand of a DH network is shown in the figure below. In this example, baseload technologies are sized at 50% of the peak load and cover 89% of the yearly heat demand.

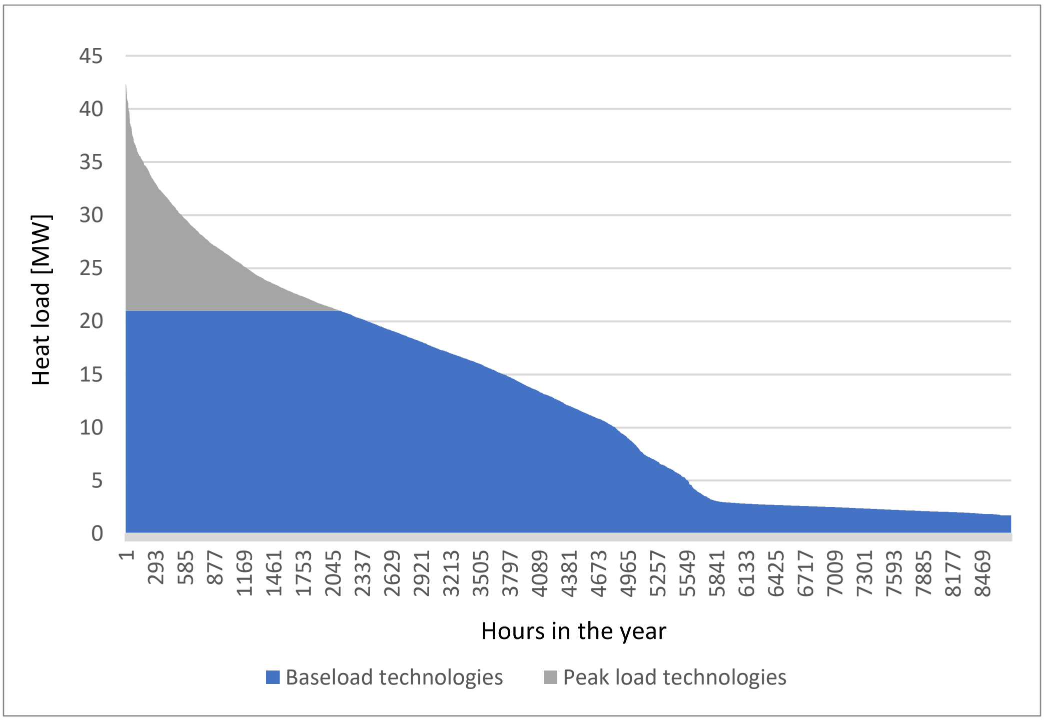

Figure 22: Example of heat load curve and distinction between production from baseload technologies (here representing 50% of the peak load and 89% of the yearly heat production) and from peak load technologies (50% of the peak load and 11% of the yearly heat production).

In a 5GDH system the customers' substations are HPs, therefore they are energy production units themselves. However, a HP still requires a lower temperature heat source to operate. For most of the winter, it is not realistic that the (possible) heat gains of the distribution pipes from the surrounding soil and/or the heat rejected by cooling demand is sufficient to compensate for the heat extracted from the decentralized HPs from the 5GDH network. If sufficient heat was not inputted into the 5GDH network, the operating temperatures would progressively decrease, resulting in lower COP (and therefore higher electricity consumption) of the HPs. If the temperature decreases even further, the HPs may stop operating below a certain evaporating temperature. There would also be risk of freezing of the heat carrier fluid, depending on what is used and in which concentration. If the operating temperatures are expected to be close to or below 0 °C, the heat transfer fluid in the network would need to be a brine (e.g. a glycol/water mixture) rather than water, to avoid freezing. This comes with the drawback of much higher pumping requirement (due to the higher viscosity), higher costs for filling up the system, increased cost related to safety measures to avoid/control/mitigate possible leakages.

Therefore, an energy centre will be required also in a 5GDH system, equipped at least with pumps and a heat exchanger to extract low temperature heat from some kind of low temperature heat source (if available). Otherwise, some kind of heat production unit will be necessary also in this case.

It is true that a 5GDH system is most likely to have lower CAPEX for the energy centre, compared to a 4GDH system, given the lower installed capacity required. However, some costs will be common (and quite fixed) to both a 4GDH and 5GDH systems, such as the cost of the building, SCADA, control system, water treatment, electrical/gas connection.

The cost estimate of the energy centres in the two scenarios depends strongly on the production technologies assumed, their size, redundancy level, etc. and is therefore not treated in this paper.

1.3.2. Other considerations

1.3.2.1. Addition of cooling

We could find only few studies presenting a quantitative economic comparison between a 4GDH and a 5GDH system. Gudmundsson et al. [14] compare a 4GDH system (at two different supply temperatures) against a 5GDH (heating only) systems in Denmark and the UK, taking into account all the main cost components of the different systems. Despite recognizing the uncertainty of some assumptions, the authors conclude that t*he economy of scale obtained by centralized heat generation in LTDH* (i.e., 4GDH) *systems, provides significant competitive advantage over ATDH* (i.e. 5GDH) *systems, which rely on end-user heat generation*. More precisely *in Denmark LTDH systems are 29%-37% more cost efficient for high energy buildings and 42%-46% for low energy buildings compared to ATDH. In UK it is narrower, where LTDH is 7%-14% more cost efficient for high energy buildings and 17%-21% for low energy buildings compared to ATDH.*

Another study[15] compares a 5GDH system (for heating only purposes) with conventional DH for a specific case study consisting of a group of 26 single-family houses in the city of Silkeborg (Denmark). The comparison is done in terms of Net Present Value (NPV) over 20 years period. Conventional DH is evaluated to have a NPV of 134,000 €, while the NPV is negative (-15,000 €) for the 5GDH system.

Other studies investigated the economic feasibility of 5GDH systems, but they compared them with individual solutions only, and have therefore little relevance in our analysis.

What seems to be still missing in literature is an economic comparison between the two systems, when also cooling is considered. It is unlikely that an overall conclusion can be given on the comparison between the two technologies, as this will most likely dependent on the specific conditions of the considered case, e.g. demand of heating and cooling, profile of the demands, number and geographic distribution of buildings requiring both heating and cooling demand compared to those requiring only heating, etc.

However, the following qualitative considerations can be made:

- Adding cooling demand will have a limited impact on a 5GDH system which has been from the start designed for this purpose.

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[14] Gudmundsson O., Schmidt R.R., Dyrelund A., Thorsen J.E., 2021. Economic comparison of 4GDH and 5GDH systems e Using a case study, *Energy* 238 (2022) 121613. https://doi.org/10.1016/j.energy.2021.121613.

[15] Tidmarsh C.A., 2017. Kold Fjernvarme (in Danish, *Cold district heating*). www.danskfjernvarme.dk/viden-og-v%c3%a6rkt%c3%b8jer/f-u-konto-subsection/rapporter/2016-05-kold-fjernvarme

  - In fact, the 5GDH network can be used to supply cooling too, the decentralized HPs are assumed to be able to be operated reversibly both in heating and cooling mode.
  - Ideally a 5GDHC system would be coupled with an aquifer thermal energy storage (ATES), where heat can be extracted in winter and rejected in summer, aiming at having roughly an energy balance on a yearly basis. It should be noted that ATES requires very specific geological and hydrogeological conditions to be established. Even in presence of proper conditions, legislation may prevent (or at least make more complicated) the use of underground aquifers.

    If ATES is not feasible, borehole thermal energy storage (BTES) could be an option. Also, BTES requires some geological prerequisites (although not as stringent as those for ATES) to be effectively established. On the other hand, the CAPEX of a BTES system is typically higher compared to ATES.
  - The energy center may require the addition of a chiller, to keep the network at sufficiently low temperature in summer, to allow for direct cooling of buildings or maintain a sufficiently high COP of the heat pumps in cooling mode.

- In the 4GDH system, the addition of cooling can be handled in different ways:
  - If the cooling demand is sufficiently concentrated (geographically) in one or more clusters of buildings, local DC network(s) can be established. In this context the same central HP can be used to produce simultaneously cooling (on the evaporator side) for the DC network and heating (on the condenser side) for the DH network.

    Beside the additional costs for the chiller/heat recovery chiller, the cost of the DC network is to be added. If DC is established at the same time as DH, then the network costs can be reduced, as the same trench can be used for laying the pipes.
  - If the cooling demand is too scattered or not high enough to justify a DC network, individual cooling machines installed at building level are necessary.
  - A combination of the solutions above is possible, with DC established in areas with high cooling density, and individual solutions for less dense areas.

- The more scattered throughout the network the demand of cooling is, the higher the advantage of a 5GDHC system can be expected to be compared to a 4GDH system + cooling (DC or individual). A widespread and scattered cooling demand will make individual cooling expensive, as many individual small units – each sized for peak capacity – need to be installed. A scattered cooling demand would also make DC an expensive solution, due to the costs of a new network. DC networks are quite expensive due to the low temperature difference (5-10 K) they use, requiring large pipes.

- The fewer and/or more clustered the buildings with cooling demand are, the more likely it is that 4GDH + cooling can maintain its techno-economic advantage compared to a 5GDHC system. Few buildings requiring cooling could simply be equipped with individual chillers. If the buildings with high cooling demand are clustered together, these could justify the establishment of a local and small DC network, supplied by a unique chiller. In both cases, if the investment is justified, the chillers can be heat recovery chillers, where the rejected heat on the condenser side is supplied to the 4GDH network. A 4GDH+DC system would also benefit from the presence of an available ATES, used as heat source for centralized HPs in winter, and as heat sink for centralized chillers in summer.

Currently, in most of Europe, residential buildings are not typically supplied cooling. Therefore, DC networks are much rarer than DH network, and typically limited to small commercial/tertiary sector areas of the cities.
However, cooling also in residential buildings is quite common in the southern part of Europe, e.g. in southern Italy or southern Spain, and it may become more widespread in the future due to climate change.

1.3.2.2. Simultaneous demand of heating and cooling at building level

In the literature we have examined, it is not clearly stated how a potential simultaneous demand of heating and cooling at building level is handled in a 5GDH&C system.
An obvious example of this this could be the demand of DHW and space cooling in summer.
We foresee a number of possible configurations:

1. the decentralized HP work in cooling mode during the day, while at night it operates in heating mode recharging the DHW tank, which is then used during the day. In this configuration, only one HP is required.
2. the DHW tanks are equipped with an electric rod, which is used to produce DHW only during summer. This solution would however entail higher OPEX (due to the lower efficiency than an electric rod, compared to a HP) and slightly higher CAPEX (installation and control of the electric rod). Also, in this case only one HP is required.
3. At building level two HPs are installed, one producing DHW and the other producing cooling. This solution entails higher CAPEX (as more than one HP is needed) but offers a better modulation of the heating production during the heating season.
4. The HP produces simultaneously heating and cooling, based on the larger demand between the two. The excess cooling (or heating production) compared to the demand is either stored (if/until possible) in storage tanks or exchanged with the 5GDH&C network.

1.4. WEDISTRICT concepts and current trends and future developments of DH&C

WEDISTRICT demonstration is established between the 3rd and 4th generation of DH, as the demo sites are expected to operate with DH supply temperatures between 70 °C and 90 °C. However, technologies and prosumer concept would be part of the 4th generation of DH.

1.4.1. Bucharest demo site

The Bucharest demo site focuses on the supply of heating and cooling to a single building (with the possibility of delivering some excess heat to preheat the return of the local DH network). The main thermal source for both heating and cooling is a borehole field, with a reversible heat pump used to reach the required temperature level both for heating and cooling purposes.
Principle schemes and brief descriptions of the system is given below both in heating and cooling mode.

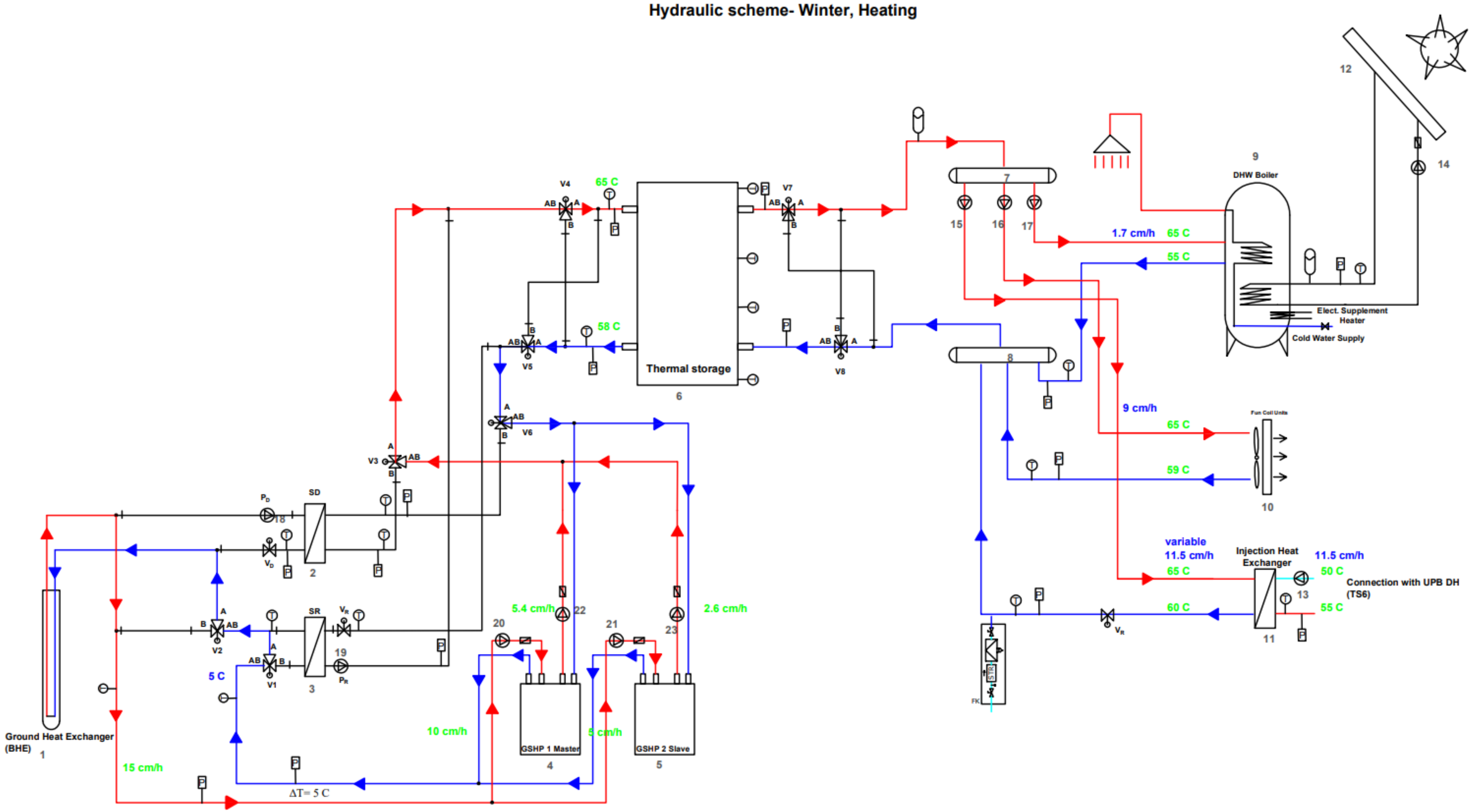

Figure 23*: Hydraulic scheme of thermal subsystem during heating period.*

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°857801

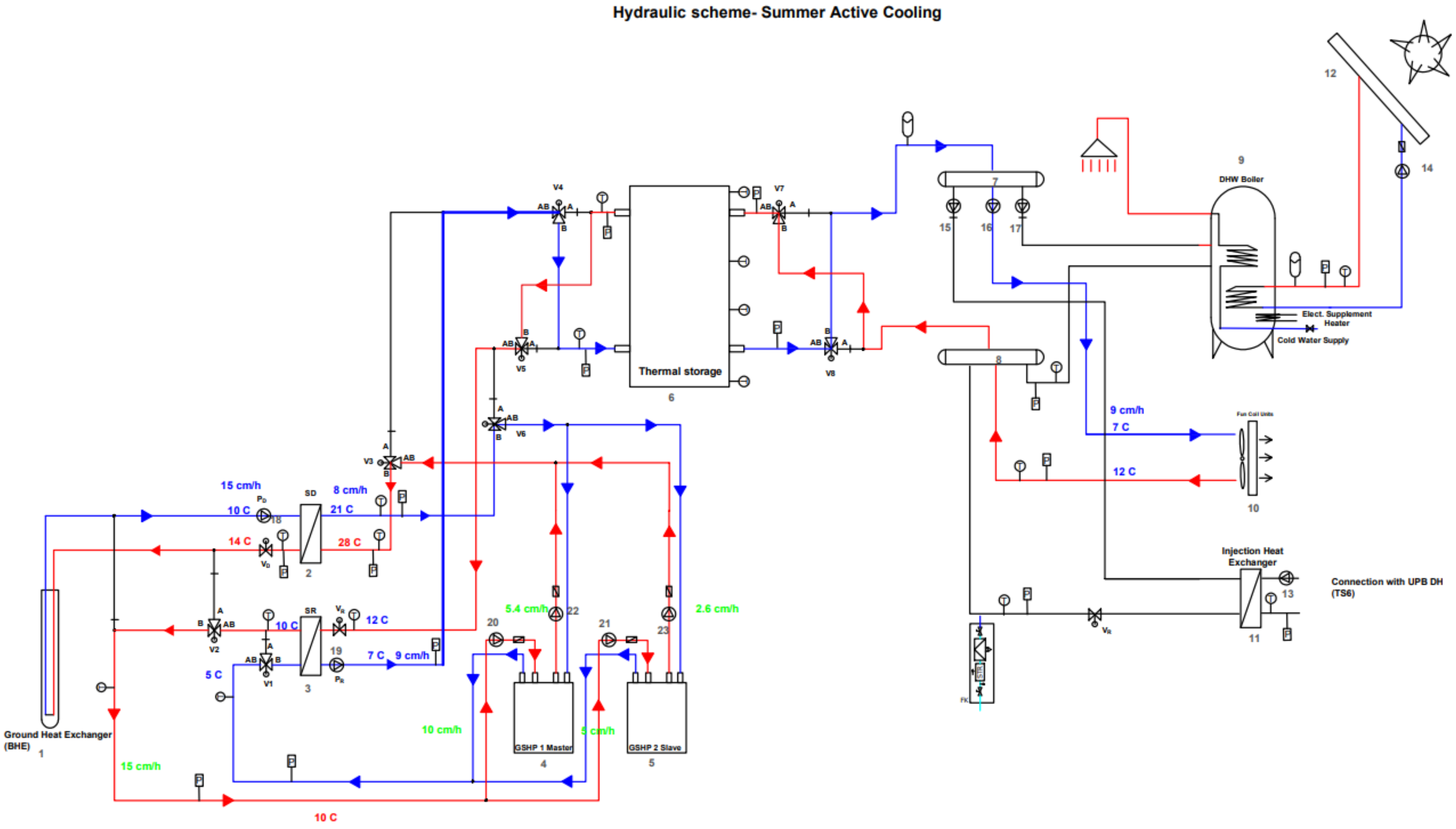

Figure 24: *Hydraulic scheme of thermal subsystem during cooling period (active cooling mode).*

In heating mode (winter) the HPs produce hot water using heat flux from the borehole field (1 in the figures above). The hot water produced on the HPs condenser side is sent to the storage tank (6).
On the demand side, the hot water from the storage tank is sent towards distributor (7), from which it is supplied to:

- DHW tank (9).
- fan coil units (10) [heat distribution system in building].
- injection heat exchanger (11) connected to the district heating system (DH).

In summer, cooling will be ensured mainly by passive cooling, using the cold underground as heat sink for the heat extracted from the building. In the periods when the passive cooling is not sufficient, active cooling will be used.
In active cooling mode, the fluid on the "cold" side of HPs (evaporators) is flowing in closed circuit with heat exchanger SR (3). Cold water produced at the heat exchanger SR (3) is stored in storage tank (6). On the condenser side of the HPs, the hot water produced is sent towards heat exchanger SD (2), from where heat is further transferred towards to borehole field, contributing to the thermal regeneration of the ground.
On the energy demand side, regardless of the cooling mode (active or passive), the cold water from Storage tank 6 is sent towards distributor 7. From here it is distributed through the fan coils units (10), to ensure the building cooling.
The DHW tank (9) is heated by the hybrid PVT panels (and electrical resistance when needed).

Despite its small case and its building-level supply, this demo site is characterized by a concept which, if deployed at larger scale, could be considered a 4th generation DH system, as it meets the requirements specified in Section 1.1.4, such ability to supply low-temperature heat for space heating and DHW (the system is expected to output with supply/return temperatures of 65 °C /58 °C), ability to integrate renewable heat sources such as geothermal heat, ability to be an integrated part of smart energy systems (i.e. integrated smart electricity).
The system is somehow an example of 4th generation district cooling. By 4th generation district cooling it is usually referred to combined production of heating and cooling from a HP system. Despite this is not exactly the case in the Bucharest demo (as hot water in summer is produced by solar thermal), the demo site uses however the same assets (HPs and borehole fields) to cover both heating and cooling in different periods of the year, so reducing the required investment costs.
Making one step further, the Bucharest demo could also be related to a 5GDHC system, as it presents some of the characteristics of this concept, such as:

- Building level HP, operated to cover both heating and cooling demand,
- Possibility of using direct cooling (bypassing the HP),
- Same piping used for both heating and cooling,
- Use of low temperature heat source / sink such as a borehole field.

The fact that the same demo site can simultaneously be related to both a 4GDH and a 5GDHC system is only apparently contradictory. A 4GDH with combined production of heating and cooling through a HP and a 5GDHC system differ mainly in terms of where the HP is located with respect to distribution network and the consumer (see figure below). As the Bucharest demo supply a single building rather than a network, so it is not possible to define a proper "distribution network".

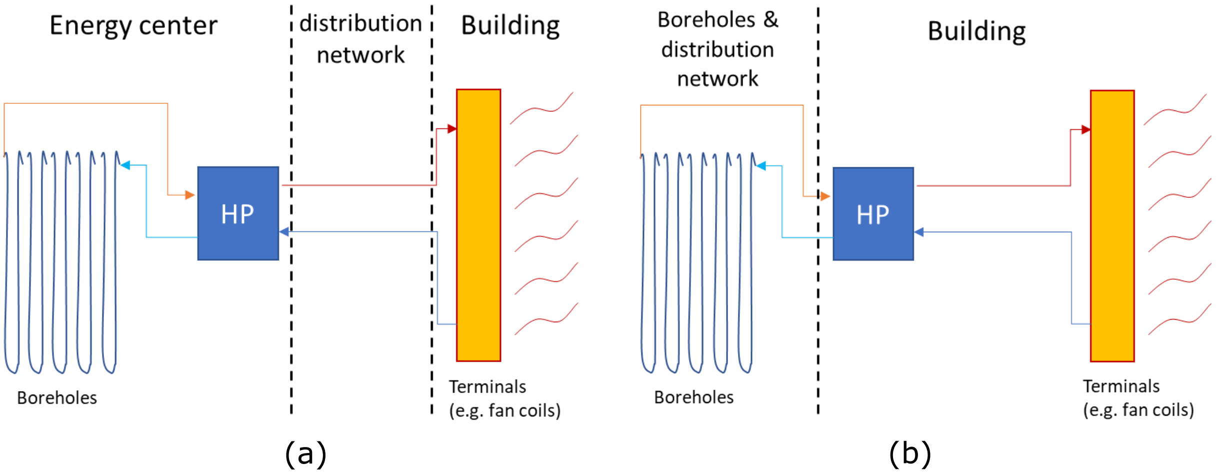

Figure 25: Difference in boundaries between a 4GDH and a 5GDH system.

1.4.2. Lulea demo site

Regarding the Lulea demo site, the envisaged solution is to recover the heat from the fuel cell's exhaust gas to the DH system, with excess heat from partially used to preheat the outside air intake required for the fuel cell process. In this manner the envisaged system is not a solution to transfer low-grade heat from a data centre to a DH system, instead it is a solution to transfer high-grade heat from the fuel cell exhaust gas to the DH-system.

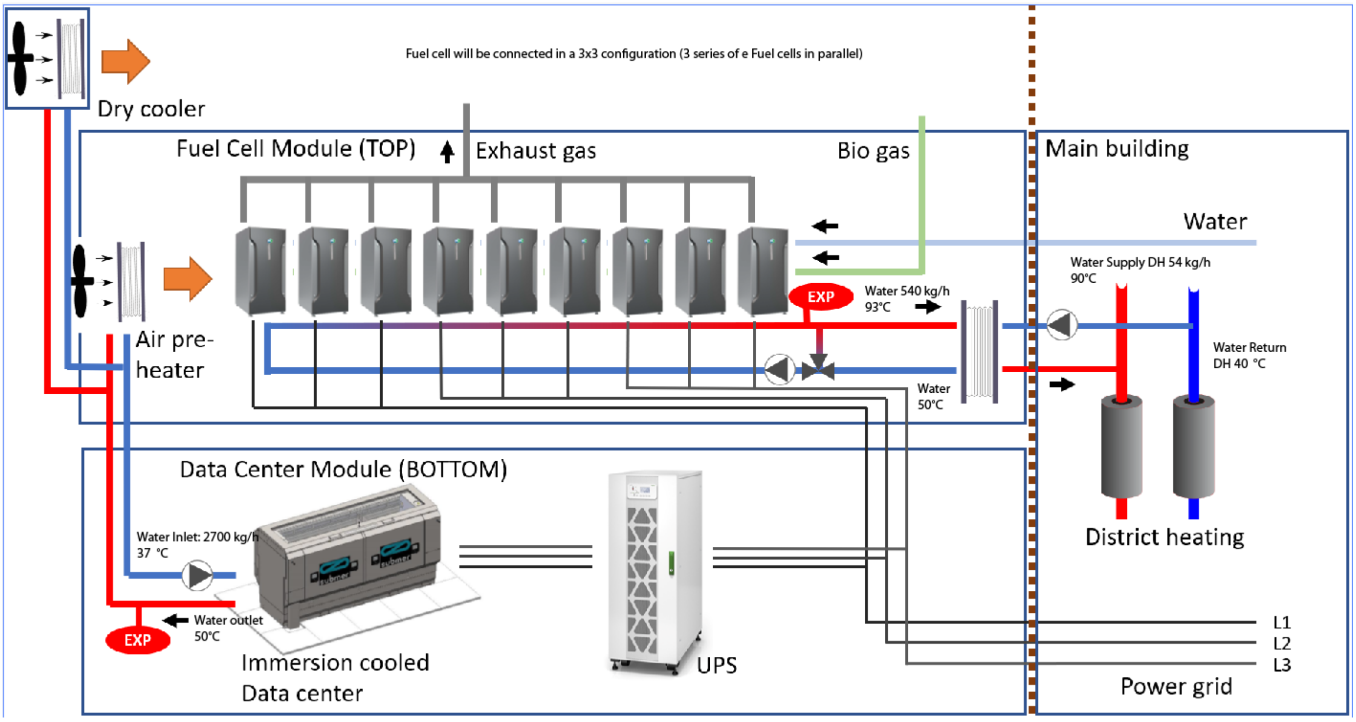

Figure 26: Principle diagram of Lulea demo site

In the above-described configurations, the Lulea demo can be integrated into 4GDH systems (if not even 3GDH systems), as exhaust gas from the fuel cell is characterized by a sufficiently high temperature (~90 °C). However, the lower the return temperature from the DH system, the more low-temperature heat could be directly retrieved from the cooling of the data centre. If a 5GDH system was present in proximity of the data centre, the very low temperature of the 5GDH system allow to recover also the part of the low-temperature heat from the data centre which is currently rejected by the dry cooler (see Figure 26), so to improve the overall efficiency of the system. Additionally, the low temperature of the 5GDH system would allow to recover a larger fraction of the energy content of the exhaust gas, whose temperature out of the stack

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can be reduced. Condensation of the exhaust gas can easily be achieved, but in this case the condensate water should be properly treated before discharge, due to likely high acidic content.

Although the recovery of high-temperature heat from the flue gases is technically possible in connection to a 5GDH system, this comes with a very low energetic efficiency, as high temperature heat is downgraded to ambient level heat. If there are other energy users in proximity who require higher-temperature heat, these would definitely be a better alternative compared to a 5GDH system.

1.4.3. Alcala demo site

The Alcala demo site (see Figure 27) can be interpret as a conventional DH system, where the relatively high supply temperatures make it possible to use the DH supply pipe to run absorption chillers and so produce cooling too. Because a sufficiently high temperature is required to drive the chillers, the configuration of the Alcala demo site poses a challenge if this should be replicated in a context of low temperature DH (e.g., 4GDH with supply temperatures lower than 80 °C).

For the same reason, the Alcala demo is incompatible with the 5GDH concept which is based on low temperature supply.

However, the configuration of the Alcala demo could adopt the decentralization of some production units, typical of the 5GDH concept. As seen in Section 1.4.1 (Figure 25) for the Bucharest demo, also in the case of Alcala the fact that only one building is supplied by the heating and cooling network makes is difficult to draw clear boundaries between the “distribution network” and the building. However, if the Alcala demo site was expanded to supply more buildings, two possible solutions would be possible:

1. Individual absorption chillers located at the building level, supplied heat by the DH network.
2. Centralized absorption chiller located in the main heating plant, producing cooling which is then delivered to the connected buildings through a DC network.

The first solution is somehow similar to the 5GDH concept in the way that individual energy-conversion technologies are installed at the individual buildings and ensure that the right temperature level required by the building is met. This solution also avoids the installation of a dedicated DC network but requires that the DH network is operated at high temperature also during summer.

The second solution is a more classical DH&C solution. Since now the cooling production is centralized and a DC network is established, it is to operate the DH network at a lower temperature compared to the absorption chiller requirements, so reducing the heat losses, especially in summer.

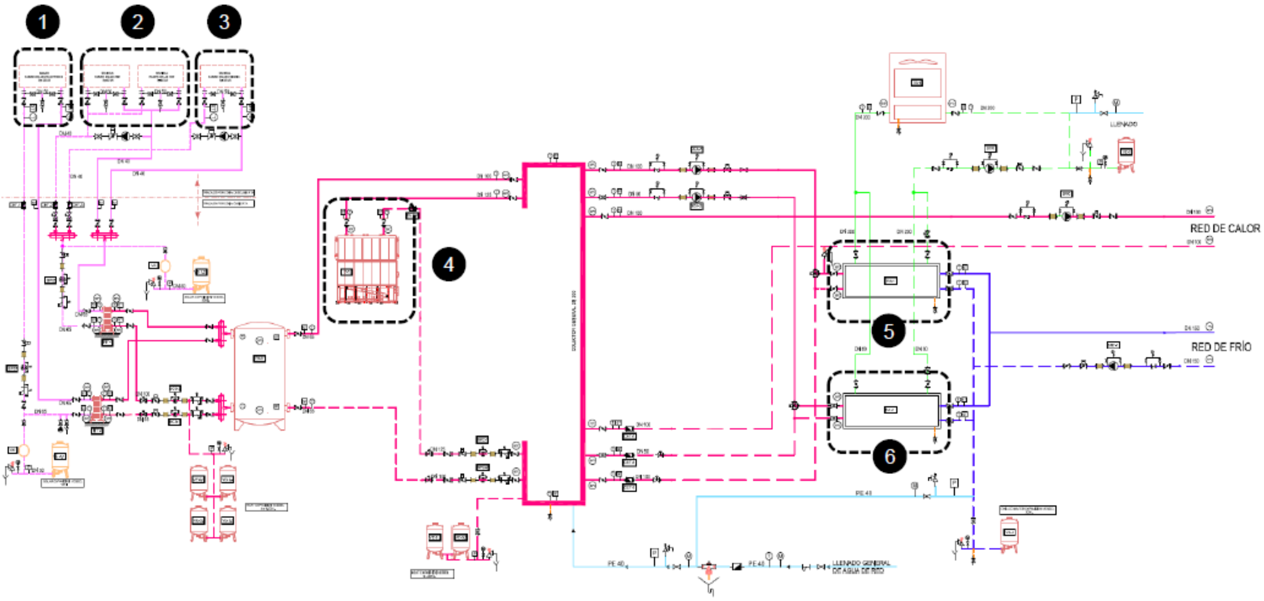

Figure 27: Principle diagram of Alcalá demo site. 1) Tracking Concentrator for Fixed Tilt Collector; 2) Concentrating parabolic troughs; 3) Linear Fresnel solar collectors; 4) Biomass boiler; 5) Advanced absorption chiller; 6) Commercial absorption chiller.

Looking at the single heat-production technologies, the Alcala demo site foresees the following:

- Linear Fresnel solar collectors
- Concentrating parabolic troughs
- Tracking Concentrator for Fixed Tilt Collector
- Biomass boiler

Regarding the solar technologies, despite difference in the range of operating temperatures of these technologies, all of them can supply heat at relatively high temperature. In particular, linear Fresnel and parabolic troughs collectors can deliver heat at very high temperatures (>200 °C), which is higher than any modern DH system. These systems can obviously operate and produce heat at lower temperatures, and examples of these technologies applied for DH applications exist (e.g., in Taars, Denmark[16]).

Because concentrating collectors are characterized by a relatively low optical efficiency, but also very low degradation of the overall thermal efficiency for increasing operating temperatures, they progressively lose their competitive advantage against non-concentrating collectors the lower the required operating temperatures. Almost the totality of solar collector installations in Europe is based on standard flat plate collectors.

For 5GDH application, the temperature requirements at the network level are so low that the use of concentrating collectors (or even non-concentrating glazed collectors) seems unreasonable. In case of a 5GDH system based on geothermal energy (e.g., boreholes or aquifer), where free excess heat is not sufficient to recharge the geothermal energy source before the start of the next heating season, unglazed collectors could be used in summer at this purpose.

The biomass boiler can also supply heat at high temperature, but its efficiency increases al lower DH temperatures, especially if the return of the DH is sufficiently low to achieve condensation of water vapor in the flue gases. Given the lower installation cost of this technology and its dispatchable production, it is more indicated for supplying 4GDH systems compared to concentrating solar technologies seen above.

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[16] https://www.aalborgcsp.com/projects/68mwth-solar-district-heating-system-in-taars-denmark/

The use of a biomass boiler in connection of a 5GDH system is technically possible, but it is realistic to expect that – given the low temperature requirement of 5GDH – a combustion technology will not be used to provide the required heat input.

1.4.4. The Polish demo site

Regarding the Polish demo site, this is currently under re-definition, after the original demo site at Kuznia Raciborska has left the WEDISTRICT project. In any case, the approach in the future demo site is expected to be very similar, with the removal of existing coal boilers and their replacement with new biomass boilers, complemented by a small PV installation for electricity consumption of the thermal station.

As seen in the previous section, a biomass boiler fits quite well in the 4GDH technology. The relatively low return temperature of a 4GDH system would allow the condensation of the water vapor in the flue gases of the boiler, which – in a biomass boiler – represent a non-negligible fraction of the energy input. Modern biomass boilers can reach efficiencies higher than 100% when coupled with 4GDH networks, which do not require high supply temperature and whose low return temperatures allow condensation of the flue gases.

As explained in the previous section, the use of a biomass boiler in connection of a 5GDH system does not seem realistic.

1.5. Conclusions

From the sections above we have seen that, when considering only heating supply, the following considerations can be done:

- The cost of the network for a 4GDH system and for a 5GDH are roughly similar when compared in terms of thermal power delivered to the end-consumer.

- The costs of the substations are roughly one order of magnitude higher for a 5GDH system compared to a 4GDH system.

- The thermal losses on a yearly basis can be estimated to be roughly similar. It is true that the heat losses may be higher for a 5GDH system in wintertime, due to the non-insulated pipes and the non-null temperature difference between pipes and cold soil. However, in summertime, when the soil temperature is higher, the temperature difference between pipes and soil is likely to be negligible, and so the heat losses. Conversely, a 4GDH system will still have high losses also in summertime, due to the considerably higher operating temperature.

- The electricity costs can be expected to be considerably higher (roughly by a factor 1.5-2) for a 5GDH system compared to a 4GDH system using a large-scale as baseload heat production unit, due to the lower electricity tariffs applied to large consumers connected to higher voltage electrical network, compared to individual consumers.

- A 5GDH system is most likely to have a lower CAPEX for the energy center, due to the lower required heat production capacity (as additional capacity is present at each building in form the decentralized HP). The cost estimate for the energy center(s) in the two systems depends strongly on the production technologies assumed, their size, redundancy level, etc. and was therefore not investigated in this study.

- It can therefore be expected that a 4GDH system will be more economically competitive than a 5GDH system, if only heating is supplied. Findings in literature supports this conclusion.

If cooling is also considered, the picture may well change. A 5GDH system could provide cooling also, with limited additional investment costs. The presence of a ATES would be particularly favourable in this context, as the operating temperatures of ATES are very close to those proposed in 5GDHC systems

Conversely, a 4GDH system cannot provide cooling and therefore covering the cooling demand would require some additional investment, e.g., in the form of a DC network, individual cooling machines, or a combination of both.

2. Stakeholders survey

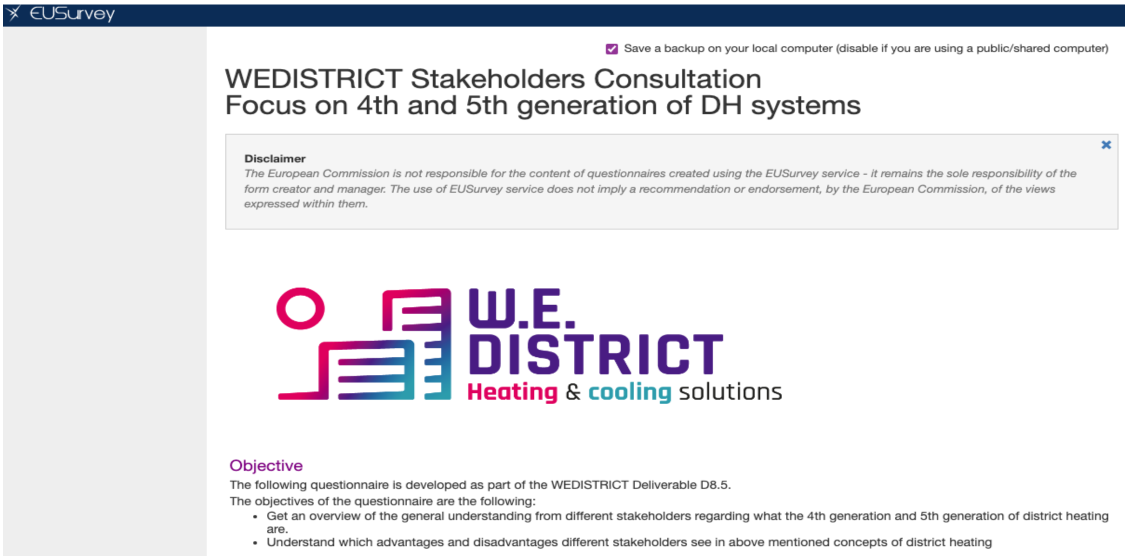
2.1. Stakeholders survey: methodology

Scope of the interview

As presented in this report, WEDISTRICT partners studied the application of 4th and 5th generation of district heating and cooling systems (respectively 4GDH and 5GDH) under different perspectives: the first perspective is the theoretical analysis of the two concepts aiming at explaining the underlying technical specificity of each of the configurations (Section 1). The second perspective presents the simulation work that has been done by the WEDISTRICT simulation group to represent the integration of WEDISTRICT technology in the "future DHC" based on lower energy demand, lower supply temperature (Section 3).
The third perspective, which is reported in the following paragraphs, aimed at investigating the current knowledge of DHC stakeholders and general technical audience in Europe to have, even partially, a preliminary view of the common understanding of 4GDH and 5GDH.

Gathering of participants' feedback

The stakeholders' feedback was collected via a survey including ten open questions that have been shared to the audience using the EU survey platform[17] (the link is available here: https://ec.europa.eu/eusurvey/runner/1_WEDISTRICT4th5thGEN). The full content of the survey is provided in Annex 5.



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WEDISTRICT Stakeholders Consultation
Focus on 4th and 5th generation of DH systems

Disclaimer
The European Commission is not responsible for the content of questionnaires created using the EUSurvey service - it remains the sole responsibility of the form creator and manager. The use of EUSurvey service does not imply a recommendation or endorsement, by the European Commission, of the views expressed within them.

Objective

The following questionnaire is developed as part of the WEDISTRICT Deliverable D8.5.

The objectives of the questionnaire are the following:

- Get an overview of the general understanding from different stakeholders regarding what the 4th generation and 5th generation of district heating are.
- Understand which advantages and disadvantages different stakeholders see in above mentioned concepts of district heating

Figure 28 Image of the WEDISTRICT survey page on the EU survey platform

The answers collected are anonymous and have been collected via two distinct links corresponding to two sub-groups: i) WEDISTRICT partners and their network and ii) the general technical audience.
The respondents of the general technical audience mainly belong to the external advisory board of the project and their network, the WEDISTRICT Market Community (subscribers) and the followers of the project's social media channels. The number of experts in this field is quite limited and therefore the target group has to be specifically addressed. More than fifty direct emails have been sent out to relevant stakeholders from April 2022 to February 2023 and two

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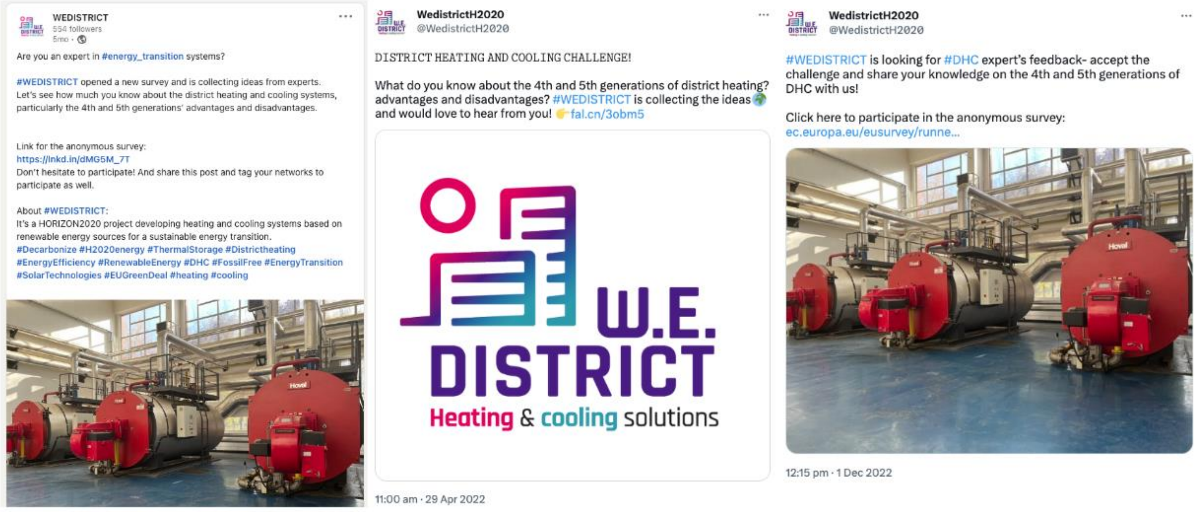
[17] https://ec.europa.eu/eusurvey/dashboard

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

social media campaigns have been organized on LinkedIn and Twitter in April and December 2022[18].



WEDISTRICT
554 followers
5mo ·

Are you an expert in #energy_transition systems?

#WEDISTRICT opened a new survey and is collecting ideas from experts. Let's see how much you know about the district heating and cooling systems, particularly the 4th and 5th generations' advantages and disadvantages.

Link for the anonymous survey:
https://lnkd.in/dMG5M_7T
Don't hesitate to participate! And share this post and tag your networks to participate as well.

About #WEDISTRICT:
It's a HORIZON2020 project developing heating and cooling systems based on renewable energy sources for a sustainable energy transition.
#Decarbonize #H2020energy #ThermalStorage #Districtheating #EnergyEfficiency #RenewableEnergy #DHC #FossilFree #EnergyTransition #SolarTechnologies #EUGreenDeal #heating #cooling

WedistrictH2020
@WedistrictH2020

DISTRICT HEATING AND COOLING CHALLENGE!

What do you know about the 4th and 5th generations of district heating? advantages and disadvantages? #WEDISTRICT is collecting the ideas 🌍 and would love to hear from you! 👉 fal.cn/3obm5

11:00 am · 29 Apr 2022

WedistrictH2020
@WedistrictH2020

#WEDISTRICT is looking for #DHC expert's feedback- accept the challenge and share your knowledge on the 4th and 5th generations of DHC with us!

Click here to participate in the anonymous survey:
ec.europa.eu/eusurvey/runne...

12:15 pm · 1 Dec 2022

Figure 29 Images of the WEDISTRICT social media campaigns on LinkedIn and Twitter

Analysis of the answers

The analysis of the answers firstly included an attentive reading by a sector expert from the WEDISTRICT consortium (Aalborg) able to identify incoherent or meaningless answers.

The following analysis, carried out by R2M, focused on the identification of characteristics more commonly reported by the respondents able to represent relevant and shared knowledge on the addressed sector. The analysis has been done at aggregated level and at sub-groups level, highlighting different interpretations between WEDISTRICT partners and the wider general technical audience in some cases.

This section aims at i) reporting the knowledge shared by the DHC stakeholders that decided to participate in the survey and ii) identifying common understanding without any form of validation by WEDISTRICT consortium.

The conclusion of this analysis summarizes the main aspects of the gathered feedback and also shares WEDISTRICT perspective on the reported vision for 4GDH and 5GDH systems development.

2.2. Answers received to the survey

The survey collected a total of 30 answers, 18 of which were from the WEDISTRICT partners and related network and 12 from the general technical audience. The respondents answered from eight different European countries and from one extra-EU country with the following distribution:

Country	#Interviewees
Spain	9
Denmark	5
Romania	4
Germany	4

Country	#Interviewees
Sweden	2
Italy	2
Latvia	1
Croatia	1

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[18] Links to the social media campaigns:
https://twitter.com/WedistrictH2020/status/1598274477120536578,
https://twitter.com/WedistrictH2020/status/1519964818983333889,
https://twitter.com/WedistrictH2020/status/1516311175524401160
https://www.linkedin.com/posts/wedistrict_wedistrict-stakeholders-consultation-focus-activity-7004038895369662464-1adM?utm_source=share&utm_medium=member_desktop

Chile	2

The respondents have been asked to specify their profile and connection with the DHC sector. Figure 30 shows the diversity of the stakeholders who decided to participate in the survey. Multiple answers were possible.

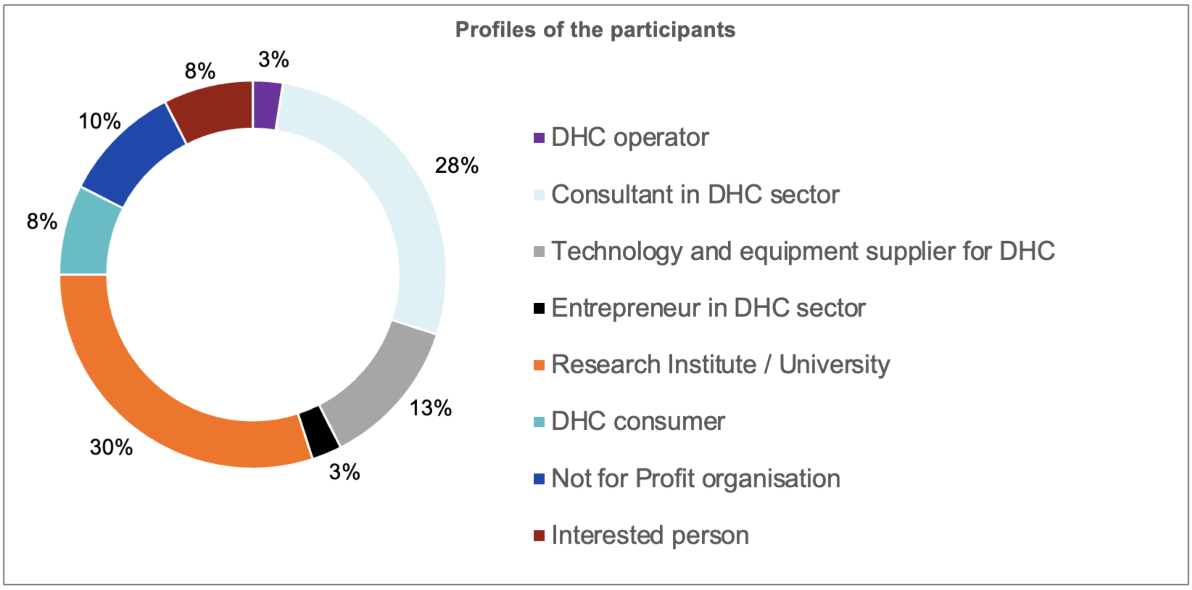

Figure 30 WEDISTRICT stakeholders: typology of profiles

Question 1

- **Based on your current knowledge, how would you describe a 4th generation district heating system (4GDH)?**

Answer 1

All 30 participants answered to this question.
The description of the 4GDH systems given by the participants include specific features which have been reported by more than one participant. The several aspects representing the knowledge expressed by the interviewees have been summarized in the following 10 characteristics and represented in Figure 31:

1-Supply temperature lower than 70°C;
2-Integration of multiple RES technology;
3-Integration of digitalisation and advanced control;
4-Ability to be an integrated part of smart energy systems (contributing to higher grid flexibility and prosumer approach);
5-More cost-efficient than other DHC generations;
6-Characterised by low heat losses;
7-Able to integrate heat reuse from low-temperature sources;
8-Need to be installed where highly efficient terminal heating devices and advanced thermal insulations in buildings exist;
9-More efficient from a technical point of view;
10-Other criteria different from points 1-9.

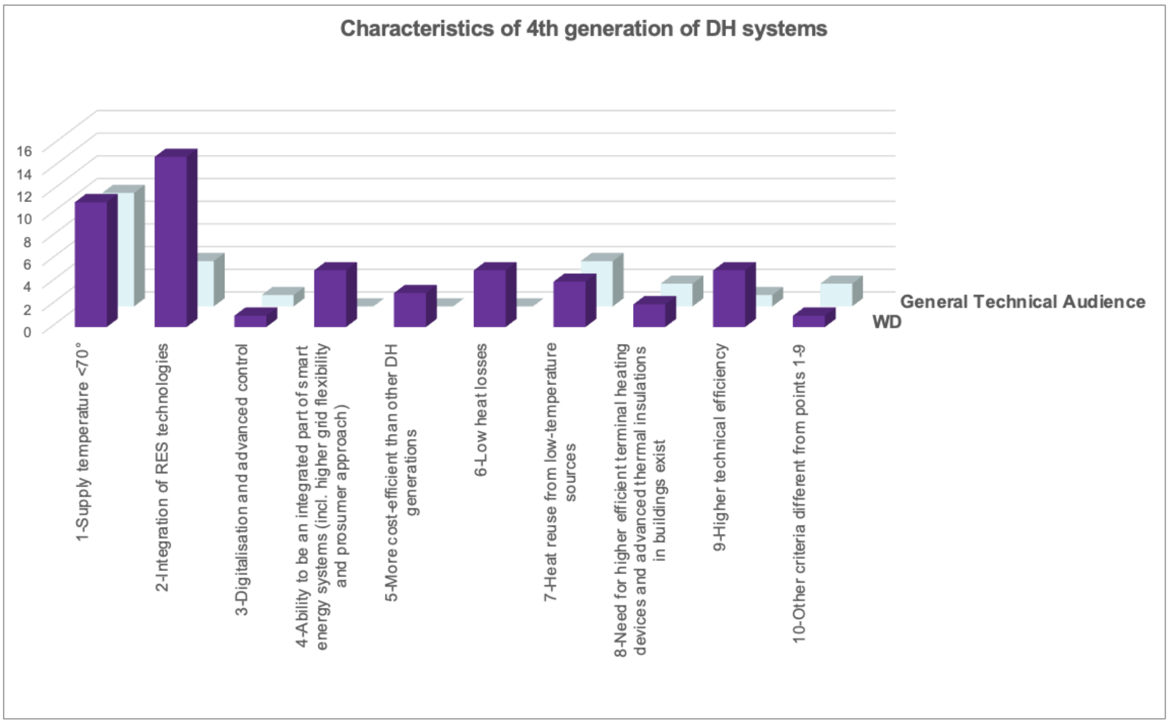

Figure 31 Description of the 4GDH by WEDISTRICT stakeholders

Considering the whole group of interviewees, the two characteristics of *1-Supply temperature < 70°C* and *2-Integration of RES technologies* have been used to describe the 4GDH systems by respectively 70% and 63% of participants, followed by the ability to integrate waste heat recovery, i.e. *7-Heat reuse from low-temperature sources*, answered by 27% of the sample.

The mentioned characterising of 4GDH with both the lower supply temperature and the heat reuse has been highlighted equally by WD partners and by the general technical audience, while the RES technologies integration was reported, in majority, by WD partners (79% of respondents were WD partners).
Three characteristics have been mentioned only by WD partners. These are, in order of percentage of answers:

- *4-Ability to be an integrated part of smart energy systems (incl. higher grid flexibility and prosumer approach), reported by the 17% of respondents;*
- *6-Low heat losses, reported by the 17% of respondents;*
- *5-More cost-efficient than other DHC generations, reported by the 10% of respondents.*

Amongst the WD partners, an additional aspect is highlighted with approx. the same frequency as the above-mentioned bullet point which is the *9-Higher technical efficiency.* As reported by one of the interviewees:

> *“The lower distribution temperature (with supply temperatures of ≤70 ° C) compared to the previous generations improves the energy efficiency of the system, and allows for the integration of low temperature heat sources such as large scale heat pumps, excess heat from industry, waste heat from cooling production and data centers, waste-fired or biomass-fired CHP plants, geothermal and solar thermal energy.*”

Amongst the sub-group of the general technical audience, the 4GDHC system is predominantly connected to the lower supply temperature, reported by the 42% of the sub-group. 8% of the sample also highlighted the following feature: *8-Need for higher efficient terminal heating devices and advanced thermal insulations in buildings* which has been reported by a lower percentage amongst the WD partners sub-group.

One of the interviewees raised an interesting point highlighting the need for additional knowledge vis-à-vis the impact on end-users: *"Will the new generation provide lower costs for consumers?".*

Question 2

- **Based on your current knowledge, how would you describe a 5th generation district heating system (5GDH)?**

Answers 2

All 30 participants answered this question.

The description of the 5GDH systems given by the participants include specific features which have been reported by more than one participant. The several aspects representing the knowledge expressed by the interviewees have been summarized in the following 10 characteristics (three of them are common to 4GDH) and represented in Figure 32:

- 2- Integration of multiple RES technology
- 4- Ability to be an integrated part of smart energy systems (contributing to higher grid flexibility and prosumer approach)
- 6- Low heat losses
- 11- Decentralization / Need for individual heat pumps
- 12- Need for a balance between heating and cooling
- 13- Near-ground or ultra low temperature
- 14- No insulation of the distribution pipes
- 15- Need for well insulated buildings
- 16- 5GDHC is an inappropriate definition
- 17- Low or no knowledge on the topic
- 18- Other

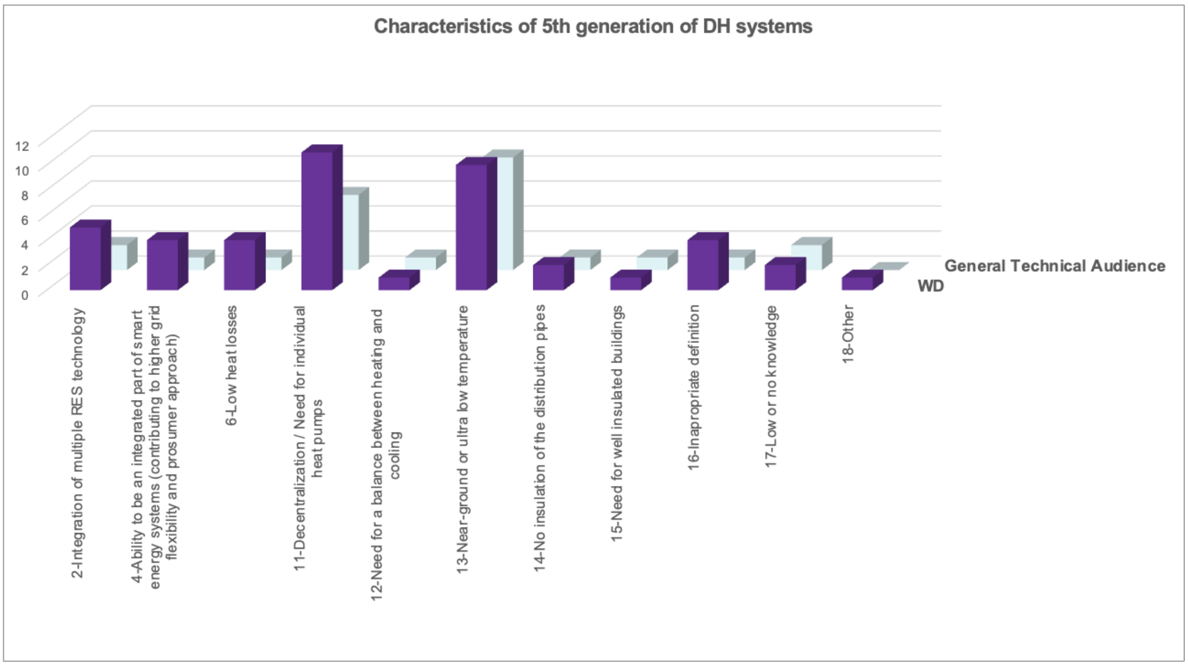

Figure 32 Description of the 5GDH by WEDISTRICT stakeholders

Considering the whole group of interviewees, the two characteristics of *13-Near-ground or ultra low temperature* and *11-Decentralization / Need for individual heat pumps* have been used to describe the 5GDH systems by respectively 63% and 57% of participants, followed by the *2-Integration of multiple RES technology*, answered by 23% of the sample.

The main aspect related to the 5GDH highlighted by the interviewees, meaning *13-Near-ground or ultra low temperature*, has been equally reported by WD partners and by the general technical audience, while the need for decentralized individual heat pumps and the RES technologies integration was reported, in majority, by WD partners (respectively 65% and 71% of respondents were WD partners).

In contrast with the previous knowledge on 4GDH, there are no specific aspects that have been mentioned only by one of the sub-groups.

Amongst the whole group of respondents, the characterization of the so-called 5GDH seems to be more controversial than for the 4GDH generation, with the 17% of interviewees reporting that such generation definition makes no sense or is not really necessary as the 5GDH can be considered as an extreme evolution of the previous one. Some of the interviewees reported the following statements:

> *"In reality there is no such thing as 5G. It is only about moving a heat pump from being centralized to being installed on building level. More accurately, it should be called ambient loop systems."*

> *"It is a mistake to talk about 5th generation DH. It is just warm water at a high of max 35 degrees; not warm enough to be used for anything."*

> *"5th generation district heating and cooling (5GDHC) is a concept in development that represents the most extreme implementation of 4GDHC."*

> *"The main difference with 4th generation is the use of bidirectional exchange of heat and cold between connected buildings, facilitated by seasonal storage."*

> *"It is a form of 4GDH".*

> *"5GDHC has the same goals as 4GDHC (decarbonization and integration with smart energy system) so it is debatable if it should be considered a new generation of DHC or the most advanced concept within 4GDHC."*

Amongst the WD partners, approx. 9% of the participants is aligned with the idea that the definition of 5GDH is not appropriate or needed. This aspect for this sub-group has been expressed with the same frequency as the other two characteristics: *4-Ability to be an integrated part of smart energy systems (contributing to higher grid flexibility and prosumer approach)* and *6-Low heat losses.*

4% of the interviewees have shown no or low knowledge for defining this topic.

Amongst the sub-group of the general technical audience, apart from the predominantly reported aspects of *13-Near-ground or ultra low temperature* and *11-Decentralization / Need for individual heat pumps*, there is no other specific characteristics which has been reported by more than 2 people of the sub-group (equivalent to the 8%). In fact the following aspects have been reported by few interviewees:

- *2- Integration of multiple RES technology*, indicated by 8%;
- *4- Ability to be an integrated part of smart energy systems (contributing to higher grid flexibility and prosumer approach)*, indicated by 4%;
- *6- Low heat losses*, indicated by 4%;
- *12- Need for a balance between heating and cooling*, indicated by 4%;
- *14- No insulation of the distribution pipes*, indicated by 4%;
- *15- Need for well insulated buildings*, indicated by 4%;
- *16- Inappropriate definition*, indicated by 4%;

8% of the interviewees of this sub-group has shown no or low knowledge for defining this topic.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Question 3

- **What do you think are the advantages of a 4GDH system compared to a 5GDH?**

Answers 3

All 30 participants answered this question.
The majority of participants (44%) indicated the choice *A - Easier installation and operations in existing building / low risk,* highlighting the advantage of the 4GDH being more easily adaptable to the existing assets, both in terms of i) existing DH network and in terms of ii) supplied buildings. Regarding point i), the interviewees mainly mentioned:

- the easier possibility to reconvert existing DH networks, reusing the existing facilities, then introducing renewables and optimizing the operation;
- the utilization of the market-available thermal energy production system and established technology correlated with a lower uncertainty and risks;
- the easier and simpler design, investment scheme, and operation.

Regarding point ii), the participants mentioned the advantage of applicability to lower energy efficiency supplied buildings or to districts where renovation is somehow complex or limited, not only in new low-energy buildings or energy-renovated existing buildings.
The second relevant advantage mentioned by the audience (27%) was related to lower costs both in terms of capex and opex (*B - Lower capex and opex involved*). Concerning the operational costs, the perceived advantage is linked to the smaller dependence on multiple heat pumps devices consuming energy (even more in high electricity prices scenarios) and requiring a certain level of maintenance.

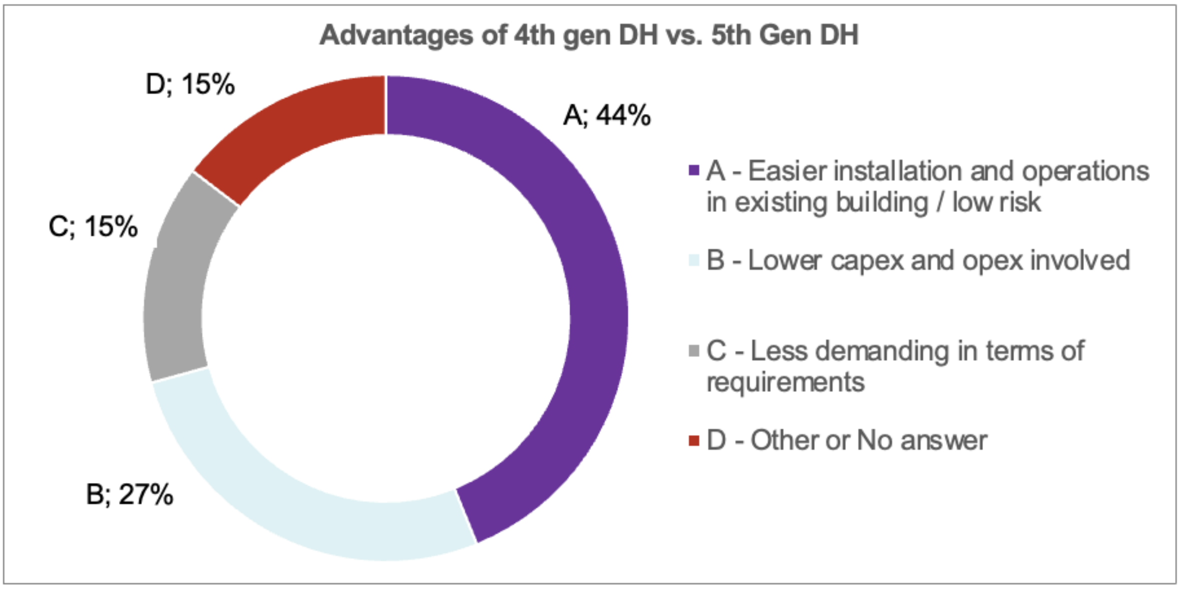

Figure 33 Description of the advantages of 4GDH by WEDISTRICT stakeholders

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Question 4

- **What do you think are the advantages of a 5GDH system compared to a 4GDH?**

Answers 4

All 30 participants answered this question.

The answers for this question were more heterogeneous: 25% of the interviewees considers the 5GDH system more beneficial in terms of CO2 emission cut and energy efficiency opportunity (*G - No fossil fuels used and high opportunity for energy reuse*).

23% of the audience see, as a benefit, the fact that the systems are an appropriate solution when both heating and cooling are needed *(F - Appropriate when both heating and cooling are needed / Same pipe system).*

18% of interviewees indicated that the benefits of the 5GDH system lies on the *H - Minimisation of thermal losses and insulation requirements.*

The overall comments provided by this part of interviewees mainly highlight the opportunity to use the same pipe systems for both heating and cooling demand incorporating also the advantageous use of less expensive pipe types. The interviewed audience link the 5GDH systems to decentralization (e.g., ability to exploit decentralized sources of electricity) and the valorisation of a higher variety of additional sources of waste heat or low temperature heat. Three contacts highlighted also the higher opportunities to exploit sector coupling thanks to the presence of the 5GDHC systems:

> *"It makes interesting the use of geothermal storage and allows opportunities of sector coupling bringing services to the electricity grid."*

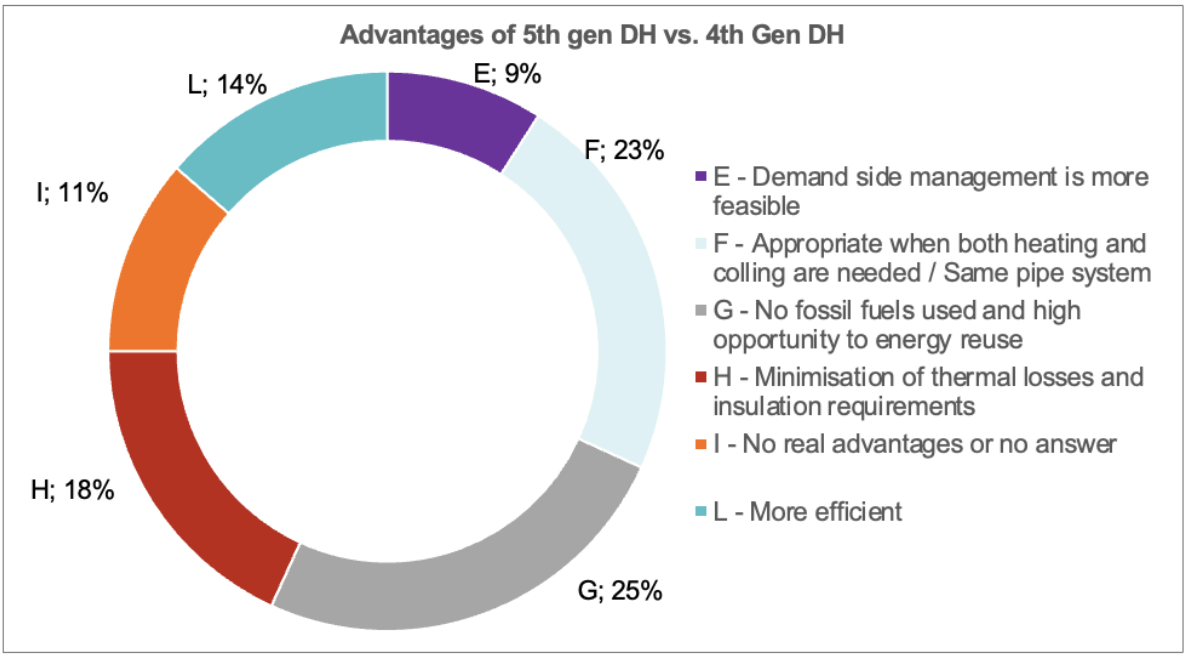

Figure 34 Description of the advantages of 5GDH by WEDISTRICT stakeholders

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Question 5

Where/under which boundary conditions would you think that 5GDH systems have the higher potential for successful deployment?

Answer 5

28 participants answered this question.

The provided answers were extremely variable for this question as shown in Figure 35. 16% of the interviewees indicated the condition to deal with areas in which there is an abundance of low-grade temperature heat sources (e.g., data centres) and decentralization is the preferred approach (*M – Decentralized and low temperature)*.14% of the people consider that areas with a balanced heating and cooling demand have the best potential for 5GDH system deployment (*F – Appropriate when both heating and cooling are needed).*

10% of the interviewees think that 5GDH system successful deployment happens in districts characterized by highly efficient buildings or where renovation is not expensive (*N - Highly energy efficiency buildings or low renovation costs)*. A similar percentage of people (10%) only expressed the condition to be installed in small settlement, characterized by low heat density systems *(T – Small settlement).* 8% of the audience seems not convinced on the real development of 5GDH systems in the current moment (*V – Sceptical on real development).*

All other percentages are shown in the figure below (Figure 35):

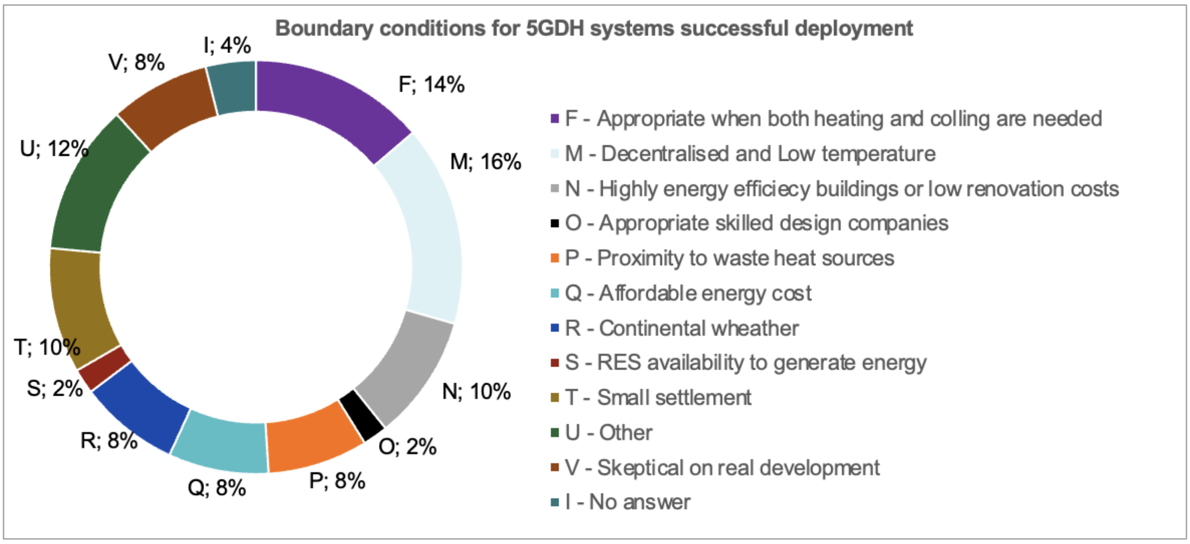

Figure 35 Description of the boundary conditions for 5GDH by WEDISTRICT stakeholders

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Question 6

In your opinion, what are the main obstacles for the deployment of 5GDH systems?

Answer 6

28 participants answered this question.

The main obstacle highlighted by the 23% of respondents is linked to the additional CAPEX that would be necessary in order to deploy 5GDH systems (*AD – Additional collateral investment needed*). The mentioned investments are related to the need for resizing/replacing the network, more complex substations, hybridization of systems, integration of devices not easily available on the market which are more costly.

Two different barriers have been quoted by 12% of the experts, respectively the perceived higher amount of operational costs vs. the 4GDH systems (*AF - High OPEX*) and the low degree of knowledge around this typology of installation (*AI - Scarce knowledge*). In terms of operational costs, mainly the impact of the electricity costs has been highlighted, followed by maintenance charges.

In relation to the limited knowledge, the respondents observe "*a low general knowledge of the technology in the industry"* and "*lack of knowledge of the technology by private customers, the low experience of technicians and political representatives*".

10% of the interviewees indicated the presence of high efficiency buildings as an obstacle due to the current level of energy efficient buildings in the EU stock (in line with the answers provided for Question 5 above).

Many other obstacles have been quoted by the respondents as shown by figure 36 below.

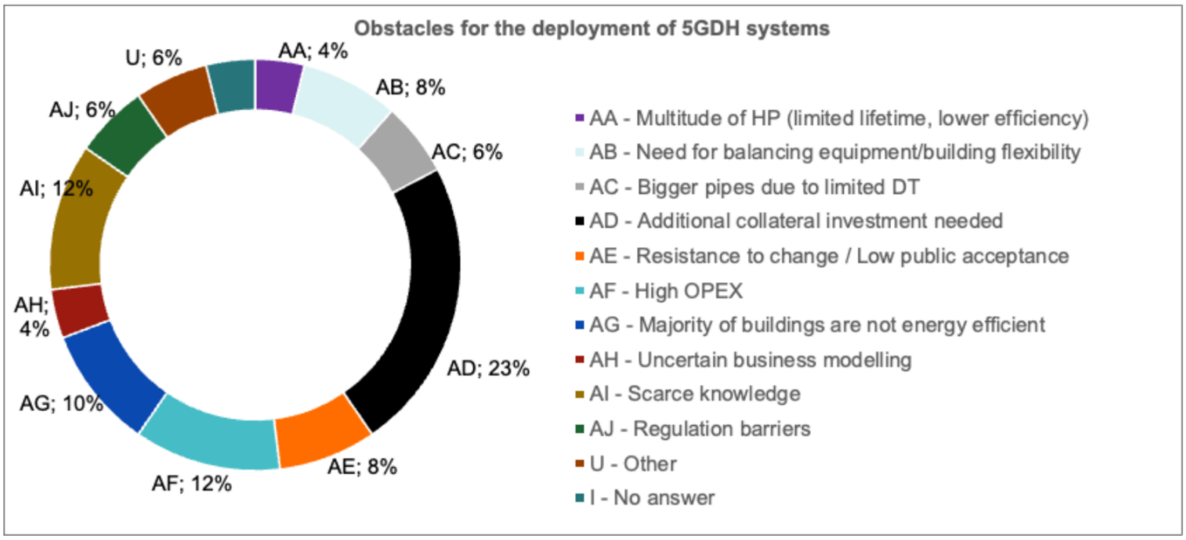

Figure 36 Description of the obstacles for 5GDH deployment by WEDISTRICT stakeholders

Question 7
In your opinion, how do 4GDH and 5GDH systems compare in terms of resilience?

Answer 7
26 participants answered this question.
The answers to this question highlighted that there is not a predominant opinion amongst the respondents and, above all, that the opinions highly differ between WEDISTRICT partners and the general technical audience.
The 33% of WEDISTRICT partners explained that the resilience of the systems really depends on the boundary condition (i.e., presence or not of storage systems, scenarios of changes in demand due to building renovations or climate change, etc.), followed by 28% of them considering the 4GDH systems more resilient than the 5GDH systems. 22% of interviewees do not know the answer and 17% consider 5GDH systems as more resilient.
Amongst the general technical audience 33% of the respondents considers 5GDH systems as more resilient vs. 17% of respondents considering 4GDH systems as more resilient. 33% declared not being able to answer to this point and 17% conditioned their answer to the need to understand the boundary condition of the systems.

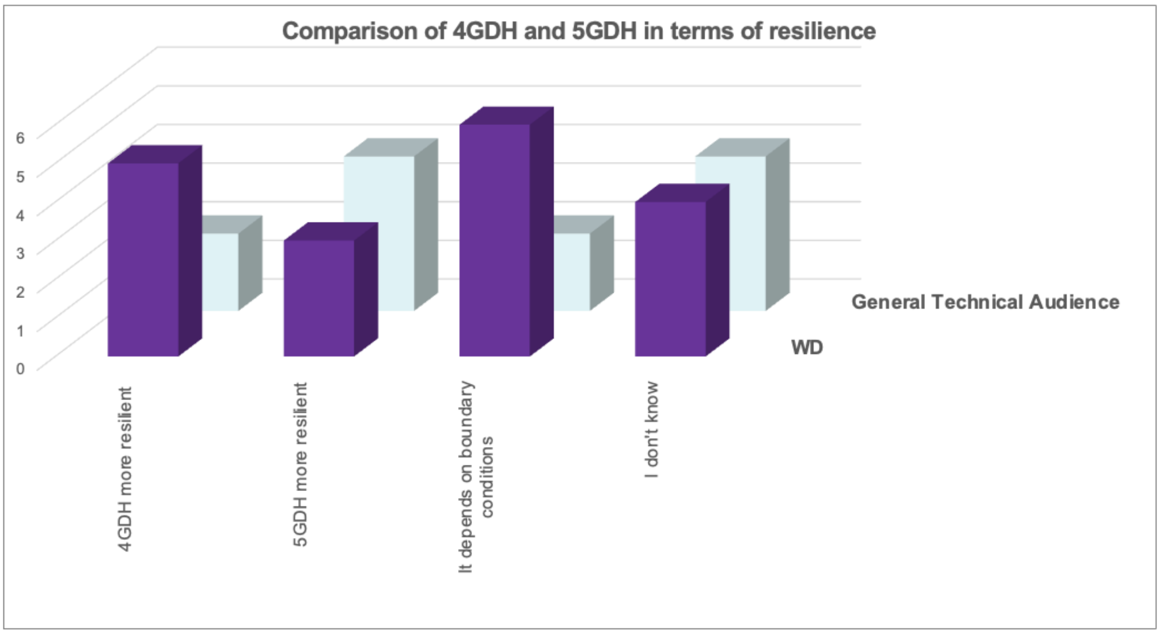

Figure 37 Resilience: comparison between 4GDH and 5GDH by WEDISTRICT stakeholders

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Question 8
In your opinion, how do 4GDH and 5GDH systems compare in terms on impact on the electricity sector?

Answer 8
27 participants answered this question.
As for the previous ones, question 8 is an open question that allows the respondents to share their interpretation of “impact” on the electricity sector. The table below shows which kind of impacts in relation to 4GDH and 5GDH have been mentioned and the frequency of answers:

	4GDH	5GDH	Others
Higher potential to support energy flexibility	■	■■■	
Able to facilitate RES integration into the grid	■■	■■	
More demanding for and depending on the grid		■■■■■■■■	
Able to contribute to sector coupling	■■	■■	
Contribute to save electricity consumption for h/c demand	■	■	
More stressful for the grid		■	
More adaptable to the needs of the electricity sector		■■■	
I don't know or not clear answer			■■
No answer			■■■
More impactful in general	■■■	■■■	

The 5GDH is considered by the respondents as more impactful from at least three axes:

i) The higher potential to support energy flexibility;
ii) The more demanding / more dependent approach vis-à-vis the grid;
iii) Adaptability to the needs of the electricity sector.

Because 5GDH is mostly based on electric devices (e.g., heat pumps and chillers), frequent comments from interviewees highlight the inevitable higher impact (in terms of electricity demand) on the electricity sector, but also the higher potential for flexibility.

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Question 9
What questions would you like to have answered regarding 4GDH and/or 5GDH?

Answer 9
21 participants answered this question.
Several relevant questions have been reported by the respondents; they highlight specific domains for which an increased level of knowledge is needed and should be publicly shared. The most relevant ones are the following:

1. A thorough comparison of 4GDH and 5GDH in different climates, with different energy densities and different demand for respectively heating and cooling.

2. How do EU policies encourage/support the development of 5GDH technologies and the implementation of such systems?

3. The real cost in respect to the use of 100% renewable and their environmental impact.

4. It would be interesting to discuss/establish if 5GDHC is actually a new generation of DH or just an extreme/refined concept of 4GDHC. The goals are exactly the same, contrary to previous generation which had motivations and technological novelties that made the clearly(ish) distinguishable.

5. More shared experience from developed projects in 5GDH, in relation to costs, operational challenges from actual system, hydraulic control of the ambient loop, design criteria for the ambient loop and substation.

6. How regulation would make it easier to rent and use spaces in consumer buildings, for bigger substations and operated remotely.

7. What is the average Capex of both system per kW installed of heat of cold? What is the average Opex of both system per kW consumed? What is the average electricity demand? What is the scale of implementation in terms of power and Ha?

8. Real analysis on the technical economic interest of 4GDH and 5GDH, compared with 3GDH in relation to the EU building stock (age, heating system, energy consumption), the urban density. Based on this, evaluate the real market opportunities and map the area in European cities and small towns where each of the generation of DH should be developed.

9. Can older generations be transformed into 5GDH or is 4GDH the limit? What's the transition pathway in large cities with high temperature district heating?

10. Are any EU standards available for the design of 4GDH and/or 5GDH? Is any EU map available for the different incentives for the construction of new 4GDH and/or 5GDHC in the different member states?

11. How to calculate heat gains from the ground precisely without complex simulation tools

12. How many and which 5GDHC networks are in Europe?

13. Why is 5GDH mainly meant for an urban setting?

2.3. Conclusions

When discussing 4GDH and 5GDH it should be considered that 4GDH has only just begun to be rolled out. Most district heating systems, even in the countries where district heating is the most advanced like Denmark, are still 3rd generation and only provide heating – no cooling. So, 5GDH is still really a theoretical exercise or experimental at best. That does not mean that 5GDH will not be taken into use in the coming years. It would be very smart for companies, when building new housing quarters in cities, to plan for 5GDH from the beginning.

Main aspects gathered from DHC stakeholders participating in the survey

The respondents of the WEDISTRICT stakeholders' survey showed a high participation rate: on average 92.6% of interviewees answered all points of the survey. The aim of the survey was to investigate the current level of knowledge about the 4GDH and 5GDH by WEDISTRICT technical audience. The gathered feedback shows that 4GDH systems are mainly described based on the lower supply temperature and by the integration of RES technologies (topics highlighted by more than 50% of the sample). The 5GDH systems are mainly described by near-ground or ultra-low temperature and by the link to the decentralization approach with the dependency on individual heat pumps (topics highlighted by more than 50% of the sample).

In terms of advantages brought by the two generations of DH systems, the audience highlighted the easier installation and operations in existing buildings for the 4GDH, considering this typology of systems as more applicable to the current existing EU building stock which is, on average, represented by low energy efficient buildings. The respondents clearly perceive 4GDH as less risky compared to 5GDH.

The answers provided for 5GDH advantages are much more heterogeneous and include different aspects such as the higher benefits in terms of CO2 emission cut, energy efficiency opportunity represented by waste heat reuse and appropriate solution when both heating and cooling are needed.

The main obstacles linked to the deployment of 5GDH which were reported by the respondents are mainly linked to the need for higher capital expenditure and operational costs (capex and opex), especially in relation to the electricity consumption of individual heat pumps and also linked to the scarce knowledge on the specific topic. This lack of knowledge, in particular, is also reinforced by the numerous questions proposed by the respondents which show a strong interest of the technical audience on 4GDH and 5GDH.

WEDISTRICT perspective on 4GDH and 5GDH future development

Change hurts, or to phrase it differently: development has costs. Changing from 1st, 2nd, 3rd, or 4th to 5th generation of district heating systems comes with certain requirements: in particular, the forward temperature of the district heating will change; this will probably require new district heating pipes in the network which may mean road works and inconvenience to the commuters, and which will come with some costs. But that also has some positive consequences: due to the low temperature, i) it will be possible to use polymer (plastic) tubes in the district heating network; ii) the need for insulation of the tubes is lowered, maybe entirely unnecessary in some regions; iii) it may be possible to use district heating water directly in the floor heating with the floor heating only needing to be around 5 K (°C) warmer than the desired room temperature, floor heating would be the smart heating solution[19].

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[19] Source of information: https://5gdhc.eu/5gdhc-in-short/

The brilliance is that by generating low temperature heat and relatively high temperature cooling in the network, the heating and cooling loss to the environment is limited.

The network heating and cooling can come from many sources: the sun, waste heat recovery, combined heat and power, and even big heat pumps. All these configurations would be characterised by high efficiency due to the fact that they will deliver heating or cooling with a small temperature difference and with a low heating and cooling loss to the environment.

Then, when the heating and cooling reaches the end user a smaller heat pump can boost the heating and cooling to something closer to 4th generation heating and cooling temperatures but still with a high efficiency and the usual or slightly lower heating and cooling losses for the end user.

5GDHC will be more reliant on the electrical power grid due to the need of individual heat pumps in each substation. Nevertheless, this higher integration of the energy system can also be positive as the building energy flexibility can more easily exploited to absorb power spikes from wind and solar power. Demand side management signal can be issued to the end users to reduce or increase the power consumption, which can be achieved by changing the setpoints of the building (effectively using the building thermal mass) or the domestic hot water storages. Demand side management can also be implemented in 4GDHC, but the impact to the electricity grid can be limited due to the slower dynamics of the district heating network. Nevertheless, 4GDHC can also have flexible generation by using centralized TES and switching between centralized HP or CHP depending on the electricity grid conditions.

5DHC will also rely a lot on waste heat recovery - utilizing a lot of the heat and cooling that is just wasted to the environment today.

Because of the change of district heating pipes to plastic tubes and the advantage of using floor heating, a lot of steel and iron from district heating networks and space heating radiators can be recycled and reused for other purposes. Plastic pipes will also have the advantage that they will not corrode. Conversely plastics tend to embrittle over time, but plastic embrittlement tends to be accelerated by exposure to ultraviolet light and changes in temperature and humidity. Since most district heating and cooling network pipes tend to be kept underground, they will not be exposed to much UV light and only to very limited temperature variation, which means that the pipes should last a very long time assuming that they are not subjected to mechanical stress and strain, e.g., from being dug into.

As also highlighted by WEDISTRICT stakeholders, one of the main advantages brought by 4GDHC and 5GDHC is the heat loss mitigation in comparison with current district heating networks. This will mean a further decrease and optimization of both capital expenditure and operational costs (capex and opex), which in the end will be an advantage for the end users of district heating and cooling systems.

3. Comparison between 3GDH and 4GDHC

3.1. Case study

This work compares a DHC system of the 3rd generation (3GDH) and a system of the 4th generation (4GDHC). For this purpose, a system representative of each generation is designed and simulated in TRNSYS following the methodology explained in Deliverable D5.7. It is assumed that both systems are located in Madrid (Spain).

3.1.1. Demand profiles

The demand profile considers a mix of residential and office buildings located in Madrid, hence accounting for heating, domestic hot water and cooling demand. Figure 38 represents the monthly heating demand. The annual heating demand is 8953 MWh/year. From May to September, there is only hot water demand. Figure 38 shows the load duration curve of heating. The heating peak demand is 2911 kW. A heating installed capacity of 2500 kW covers 99% of the heating demand. The heating demand does not consider the thermal losses of the network to compare same peak power size of both plants (3GDH and 4GDH).

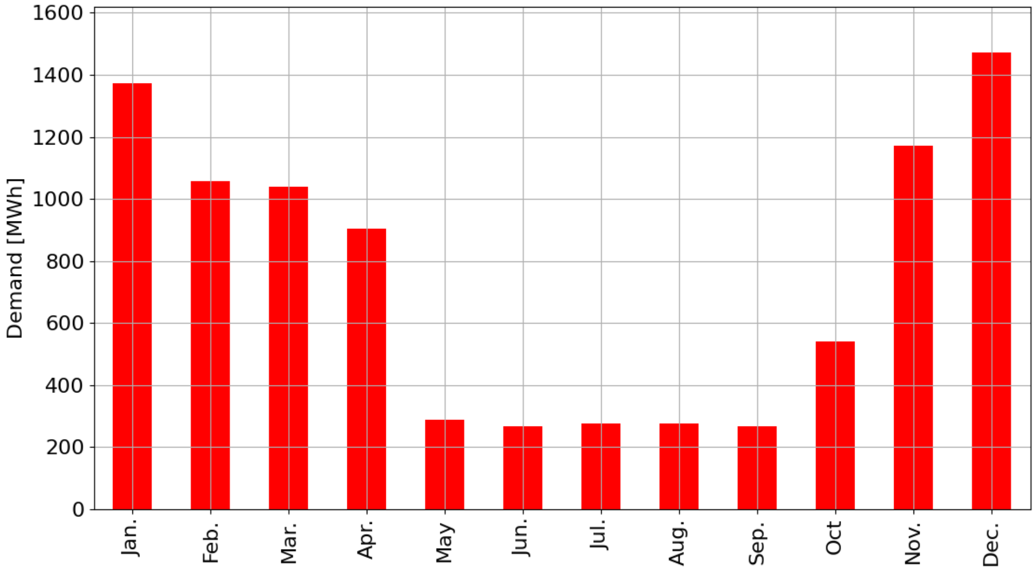

Figure 38 *Monthly heating demand.*

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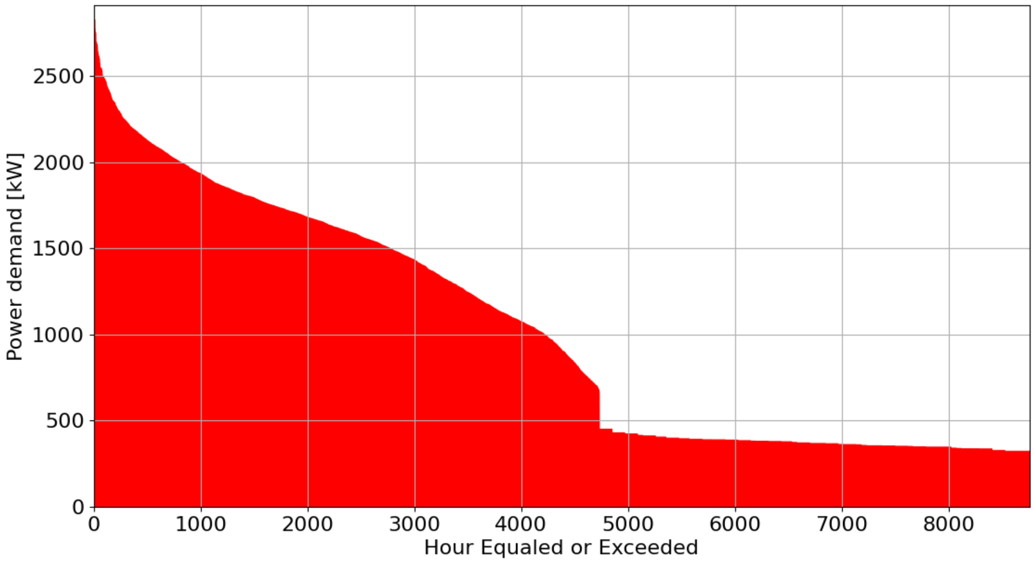

Figure 39 *Load duration curves of heating.*

Figure 40 represents the monthly cooling demand. The annual cooling demand is 3088 MWh/year. It is assumed that cooling demand is only present from April to October. Figure 40 shows the load duration curve of cooling. The cooling peak demand is 2055 kW. A cooling installed capacity of 1900 kW covers 99% of the cooling demand. The cooling demand does not consider the thermal losses of the network in order to be consistent with the aforementioned heating approach.

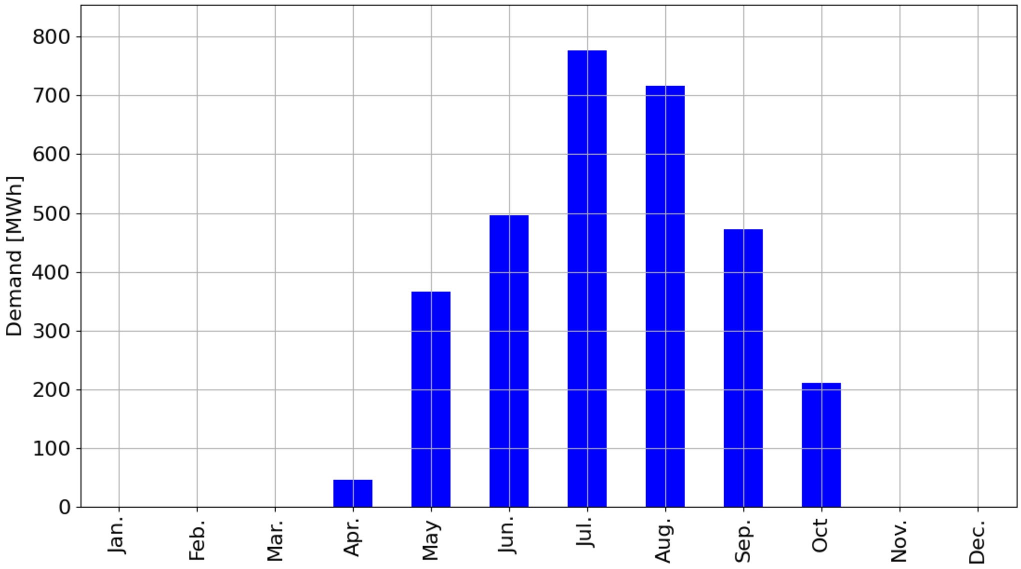

Figure 40 *Monthly cooling demand.*

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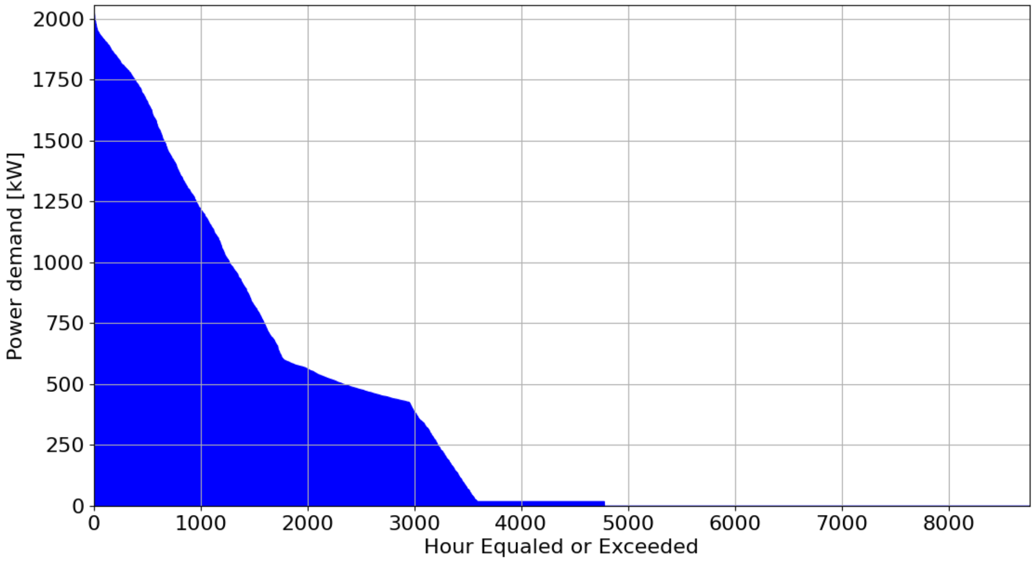

Figure 41 *Load duration curves of cooling.*

3.1.2. Network characteristics

The heating and cooling network are represented on Figure 42. The total length is 4350 m. The nominal pipe size and the length of each section is included on Table 13. The costs of the network are calculated from the data price included in reference[20].

Table 13. Diameters and length of each section of the heating and cooling networks.

Section	Length (m)	DN Heating	DN Cooling
A	400	200	400
B	300	100	200
C	100	50	100
D	100	80	150
E	400	200	400
F	300	80	150
G	300	40	80
H	400	200	350
I	300	125	250
J	100	65	125
K	100	65	125
L	300	80	200
M	100	50	100
N	100	65	150
O	400	125	250
P	150	50	100
Q	100	65	125
R	100	80	150
S	150	125	250
T	150	65	150

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[20] Steel Tubes India https://www.steeltubesindia.net/schedule-40-steel-pipe.html

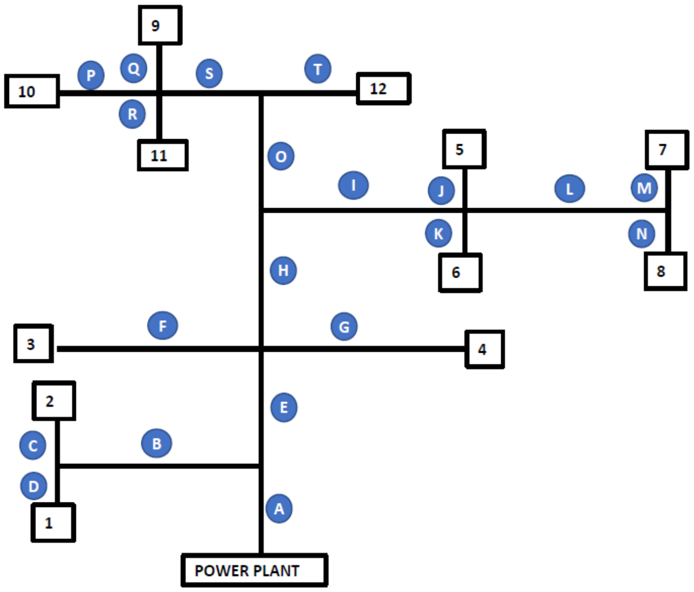

Figure 42. *Layout of the heating and cooling networks.*

The characteristics of network are used to estimate the heat losses and the investment cost. In the case of the heat losses, the network is transformed into an equivalent pipe in the TRNSYS simulation. This has a fixed diameter and a length selected to have an equivalent surface, hence heat losses. The investment cost considers the deployment of a new network, with 3GDH having only the heating piping while 4GDHC also includes the cooling pipes.

3.2. DHC of 3rd generation

3.2.1. System description

Figure 43 represents the layout the system representative of 3GDH. The system consists of a solar field, a water tank, a biomass boiler and gas boiler.

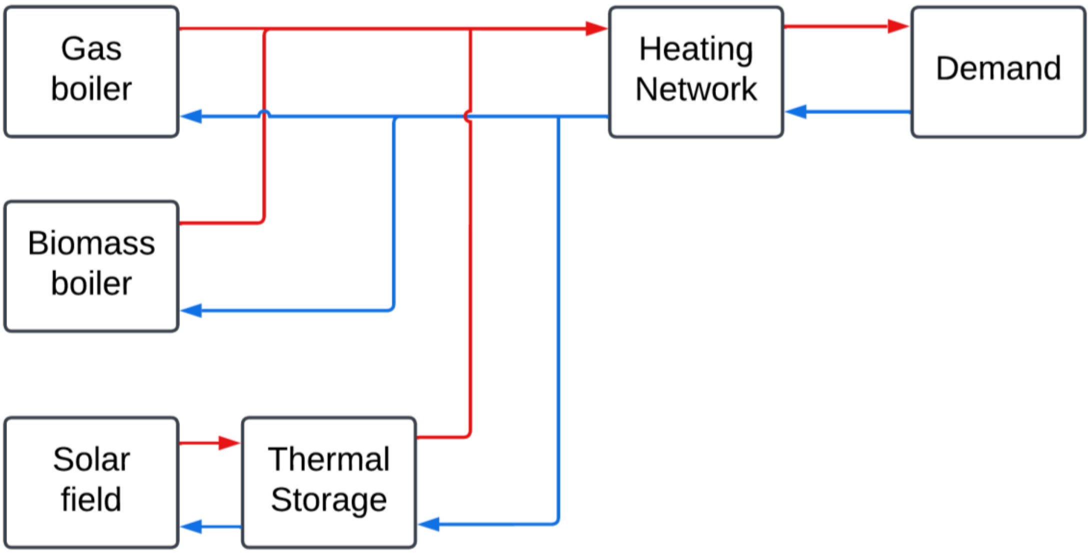

Figure 43 *Layout of 3GDH system.*

The operation of the plant is as follows:

- Parabolic trough collectors capture the solar radiation of the site and transforms it into thermal energy, which is stored in the water tank.

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- Water tank transfers thermal energy to the heated water network at the temperature set points of the facility. If the energy stored does not cover the demand, the boilers are turned on.
- Biomass boiler operates as base demand and not switched ON if the demand is lower than the 30% of its nominal capacity.
- Gas boiler operates as peak unit, supplying the demand not covered by the water tank or the biomass boiler.

3.2.2. Data

The values of the main parameters used on the simulations are summarized in Table 14. The supply and return temperature are 90 ºC and 70 ºC respectively.

Table 14 Parametrization of 3GDH.

Equipment	Capacity
Biomass boiler capacity	1500 kW
Gas boiler capacity	1000 kW
PTC area	4000 m^2
Water tank	320 m^3

Table 15 and Table 16 include the economic data and primary energy factor and CO_2 emission coefficient used. The gas price and electricity price are taken from Eurostat[21]. The primary energy factors and the emissions coefficients are taken from the Spanish Institute for Energy Savings and Diversification (IDAE)[22]. The emission factor for electricity values is updated to the year 2021 according to the value published by the Spanish National Securities Market Commission (CNMV)[23].

Table 15 Economic data for the 3GDH.

Specific capital cost of biomass boiler	250€/kW
Specific capital cost of natural gas boiler	80 €/kW
Specific capital cost of PTC	215 €/m^2
Specific capital cost of water tank	260 €/m^3
Biomass price	25 €/MWh
Natural gas price	104.7 €/MWh
Electricity price	220.2 €/MWh
Lifetime[24]	25 year
Discount rate	7%
Fixed OM	3%

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[21] EUROSTAT https://ec.europa.eu/eurostat

[22] IDAE. (2014). "Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España."

[23] Comisión Nacional del Mercado de Valores https://gdo.cnmc.es/CNE/resumenGdo.do?anio=2021

[24] The same lifetime has been assumed for all the components of the plant.

Table 16 Primary energy factor and CO2 emission coefficient *for the 3GDH.*

Energy Vector	Primary energy factor Non-renewable	Primary energy factor Renewable	Primary energy factor Total	CO_2 emissions coefficient [kg CO_2/MWh]
Biomass	0.034	1.003	1.037	18
Natural gas	1.190	0.005	1.195	252
Solar thermal	0	1	1	0
Electricity	1.954	0.414	2.368	259

3.2.3. Results

Figure 44 represents the Sankey diagram. The diagram only includes the main fluxes on annual basics. The total energy supplied 7659 MWh. The unmet demand is 14.5% because the peak power was sized without considering the network thermal losses (22%). The total heating generated is 10039 MWh. The biomass boiler generates the 58.9%, parabolic collectors generate the 26.8% and the gas boiler generates the 14.3%.

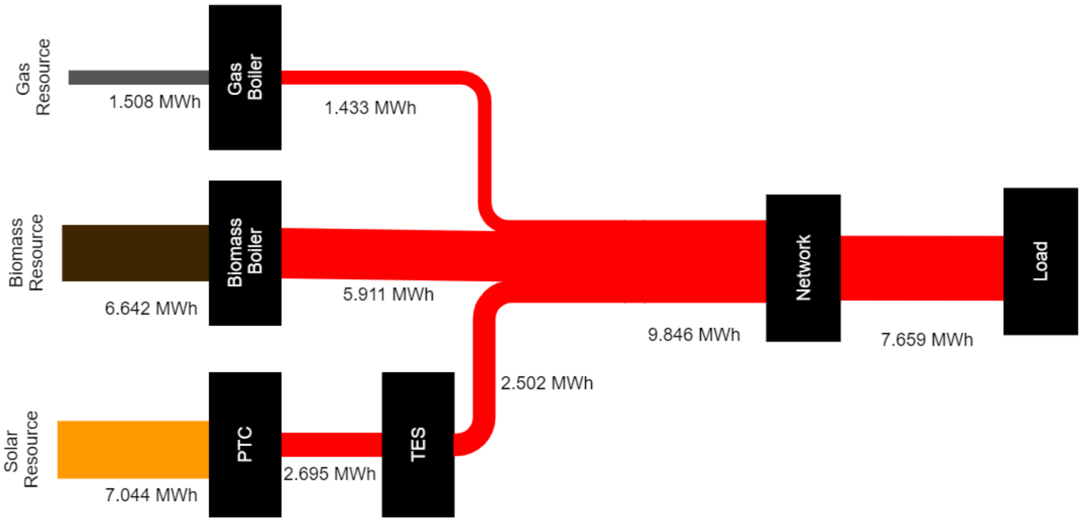

Figure 44 *Sankey diagram of 3GDH.*

Figure 45 shows the monthly heating supplied per technology. In winter, the demand is mainly covered by the biomass boiler. In summer, solar technology covers practically the demand. In summer months, the biomass boiler is switched off because the demand is very low. The gas boiler helps to cover the peaks in both seasons.

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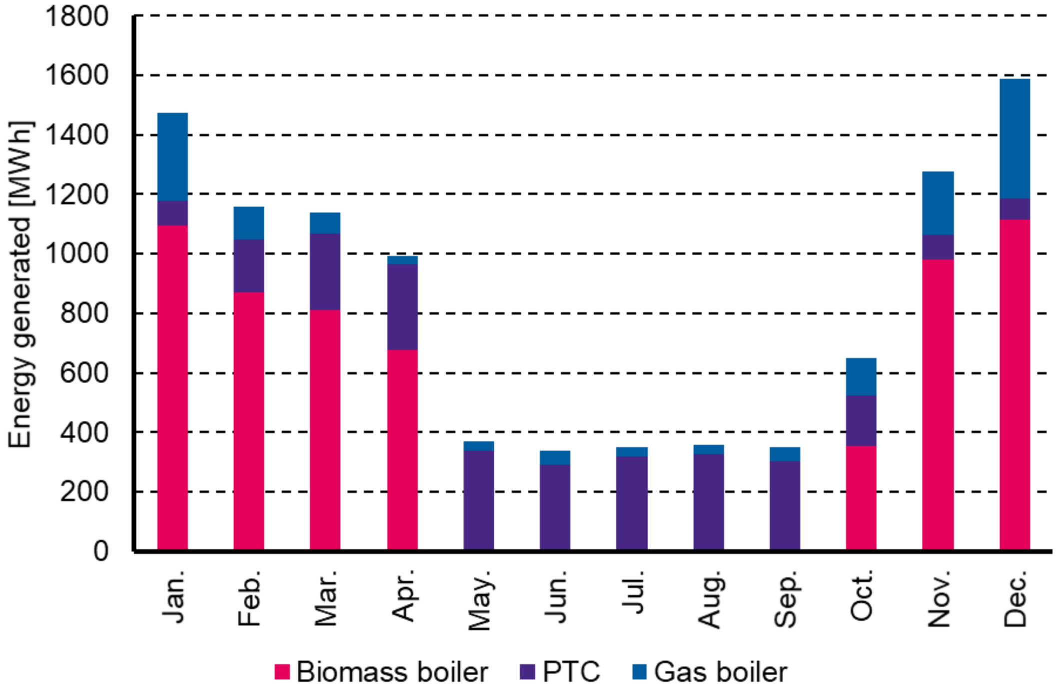

Figure 45 *Monthly energy generated by technology.*

The emissions factor is 75.5 kgCO_2/MWh. The gas boiler produces 66% of the emissions, the biomass boiler produces 21%, and the electricity produces 14%. The renewable energy ratio is 0.79, while the non-renewable primary energy factor is 0.28.

Table 17 presents the economic results for the 3GDH. The CAPEX of the system is approximately 4.7 M€. Equipment CAPEX represents 30.3%, while the network is 70.7%. The biomass cost is 44.1% of the variable OPEX, while the gas cost is 42.0%. The electricity cost is 13.9%. The LCOE of the plant is 122 €/MWh.

Table 17. Economic results for 3GDH.

CAPEX	
PTC	860000 €
Biomass Boiler	375000 €
Gas Boiler	80000 €
TES	83200 €
Network	3373200 €
Total	**4771400 €**
Fixed OPEX[25]	
PTC	25800 €
Biomass Boiler	11250 €
Gas Boiler	2400 €
TES	2496 €
Network	101196 €
Total	**143142 €**
Variable OPEX	
Biomass cost	166042 €
Gas costs	157944 €
Electricity costs	52268 €
Total	**376254 €**

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[25] Fixed OPEX is assumed as a 3% of the CAPEX

Figure 46 shows the CAPEX, fixed OPEX and variable OPEX fraction percentages in the LCOE.

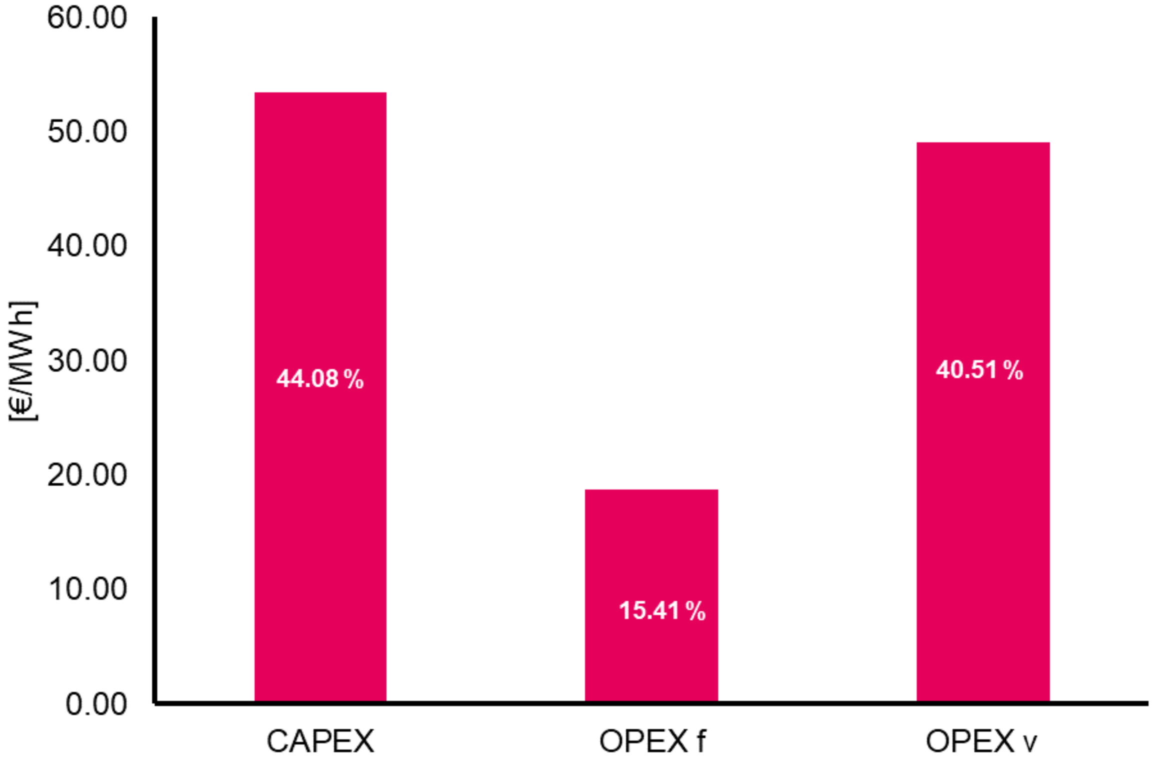

Figure 46 *Comparison between the LCOE breakdown for 3GDH.*

3.3. DHC of 4th generation

3.3.1. Description

Figure 47 represents the layout of 4GDHC system. The system consists in two geothermal heat pumps, a solar technology and waste heat recovery. Moreover, heat is recovered from a fuel cell powered data centre containing 267 fuel cell stacks. Each unit generates 1.5 kW of electrical power and a maximum of 900 W of thermal power.

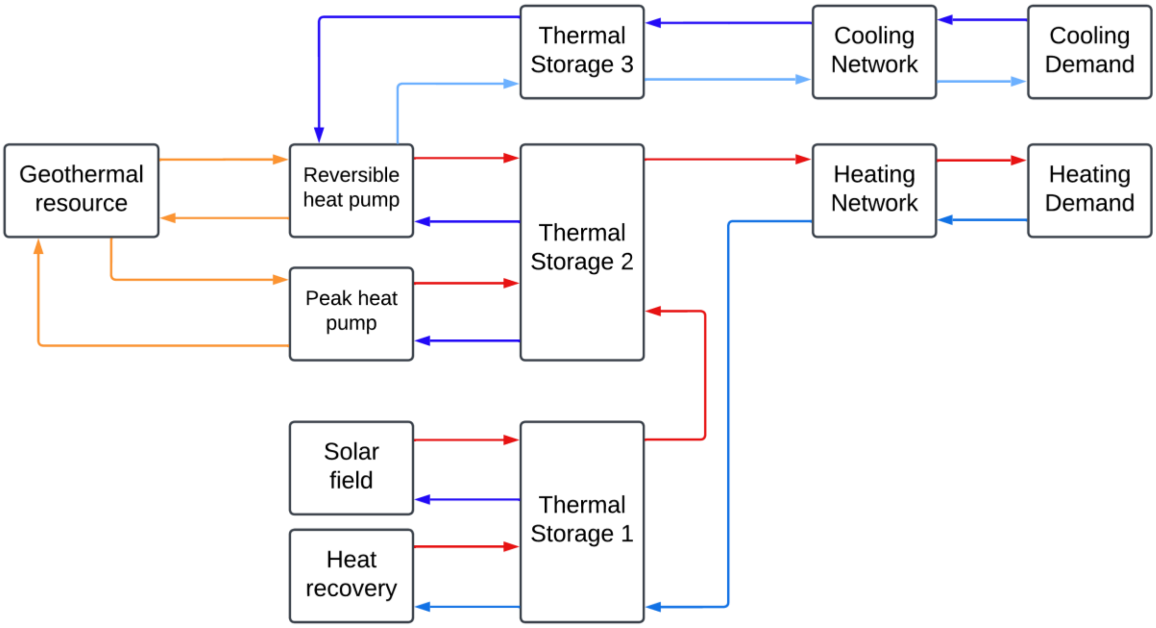

Figure 47 *Layout of 4GDHC system.*

The operation of the system is the following:

- Heating system: The heating demand is covered by the energy storage on two water tanks. The solar technology (WESSUN) and the heat recovery charge the first water tank (Thermal storage 1). The second water tank (Thermal storage 2) is charge by reversible heat pump in winter and by the peak heat pump in summer.
- Cooling system: The cooling demand is covered by the energy storage on a water tank (Thermal storage 3). This tank is charged by the heat pump reversible.

3.3.2. Data

The values of the main parameters used on the simulations are summarized in Table 18. The supply and return temperature for heating network are 60 ºC and 40 ºC respectively. The supply and return temperature for cooling network are 7 ºC and 12 ºC respectively.

Table 18: Main parameters of 4GDHC system

Equipment	Capacity
Peak Heat pump heating/cooling capacity [kW]	2500 kW / 1875 kW
Reversible Heat pump heating capacity [kW]	1000 kW
WESSUN area	4000 m^2
Water tank 1	1000 m^3
Water tank 2	1000 m^3
Water tank 3	1000 m^3
Number of fuel cells	267 units

Table 19 and Table 20 include the economic data, primary energy factor, and CO_2 emission coefficient used. The electricity price is taken from Eurostat. The primary energy factors and the emissions coefficients are taken from the Spanish Institute for Energy Savings and Diversification (IDAE). The emission factor for electricity values is updated to 2021 according to by the Spanish National Securities Market Commission (CNMV). Waste heat recovery is assumed to be 100% renewable. This assumption is based on the fact that the fuel consumption of the fuel cell is independent of whether it recovers heat.

Table 19 Economic data for the 4GDHC.

Specific capital cost of heat pump	100 €/kW
Specific capital cost of WESSUN	164 €/ m^2
Specific capital cost of Boreholes	4000 €/unit
Specific capital cost of water tank	260 €/m^3
Electricity price	220.2 €/MWh
Waste heat recovery	70 €/MWh
Lifetime[26]	25 years
Discount rate	7%
Fixed OM	3%

Table 20 Primary energy factor and CO_2 emission coefficient for the 4GDHC.

Energy Vector	**Primary energy factor Non-renewable**	**Primary energy factor renewable**	**Primary energy factor Total**	**CO_2 emissions coefficient [kg/MWh]**
Solar Thermal	0	1	1	0
Geothermal	0	1	1	0
Electricity	1.954	0.414	2.368	259
Waste heat recovery	0	1	1	0

3.3.3. Results

Figure 48 represents the Sankey diagram on heating mode. The total heating supplied is 8075 MWh. The unmet heating demand is 9.8% because the peak power was sized without considering the network thermal losses (13,7%). The heating generated is 9896 MWh. The heat pumps generate 61.3% (heat pump 1 generates 52.8%, heat pump 2 generates 8.5%), and the solar field generates 26.1%. The heat recovery provides 12.6% of the energy supplied to the system.

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[26] The same lifetime has been assumed for all the components of the plant.

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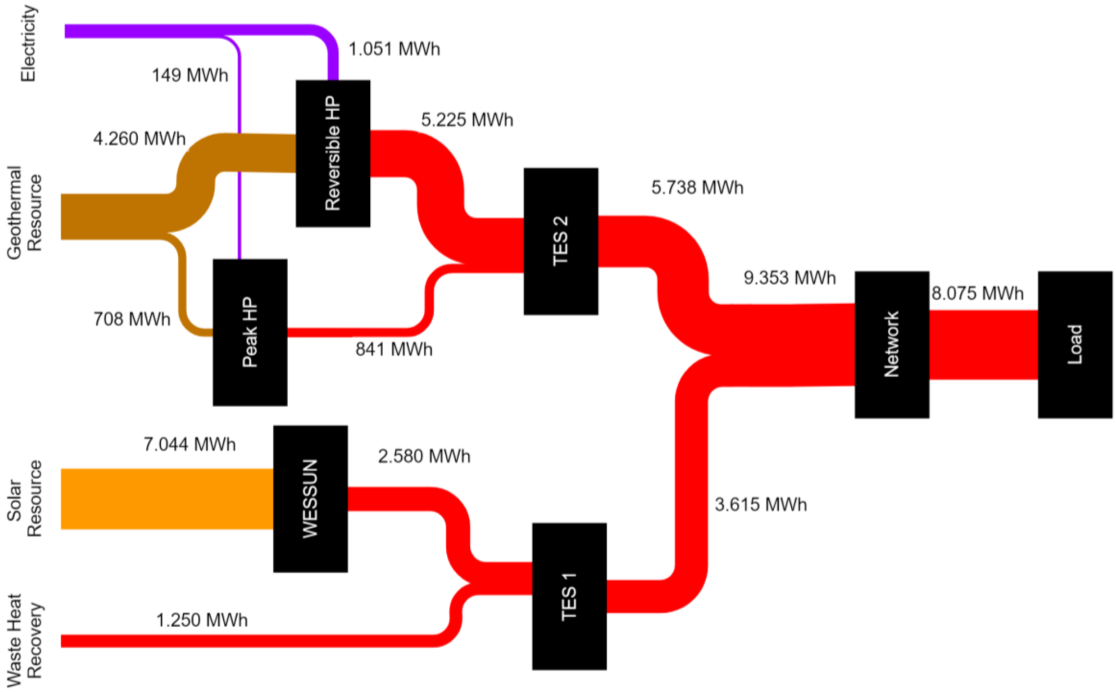

Figure 48 *Sankey diagram of 4GDHC on heating mode.*

Figure 49 shows the monthly heating supplied per technology. In the summer, WESSUN and heat recovery cover most of the demand, while peak heat pump helps cover the peaks. In winter, the reversible heat pump mainly covers the demand. The energy provided by heat recovery is practically constant throughout the year. Heat pumps generate more energy in the winter months than in the summer months. In winter, reversible heat pump is turned ON, and peak heat pump is switched OFF. In the summer, peak heat pump is turned ON, and reversible heat pump is switched OFF, because it operates in cooling mode during those months.

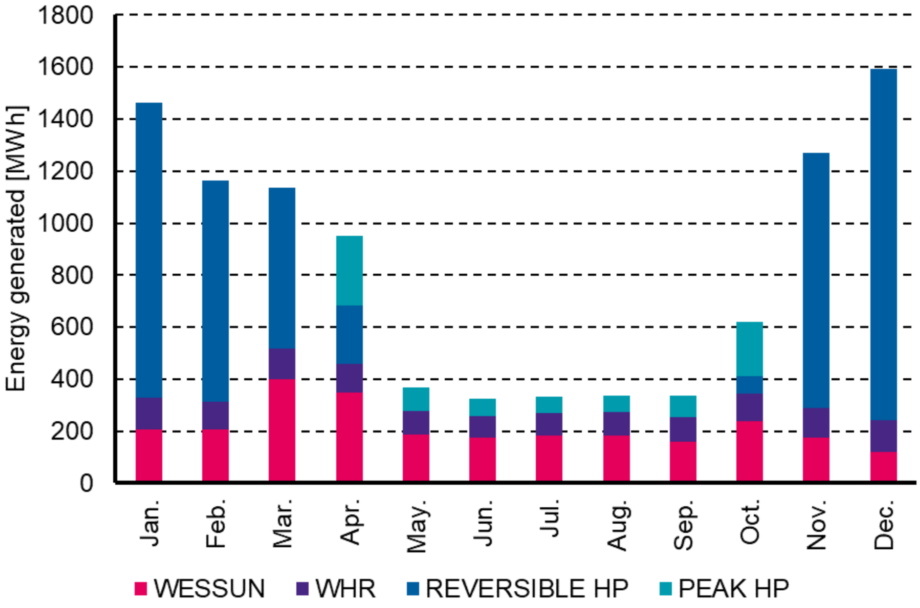

Figure 49 *Monthly energy generated by technology.*

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Figure 50 represents a simplified Sankey diagram of the system in cooling mode. In this case, the demand is covered exclusively by reversible heat pump . The cooling supplied is 2783 MWh. The demand is uncovered a 9.9%. The thermal loss of the cooling network is 13.1%.

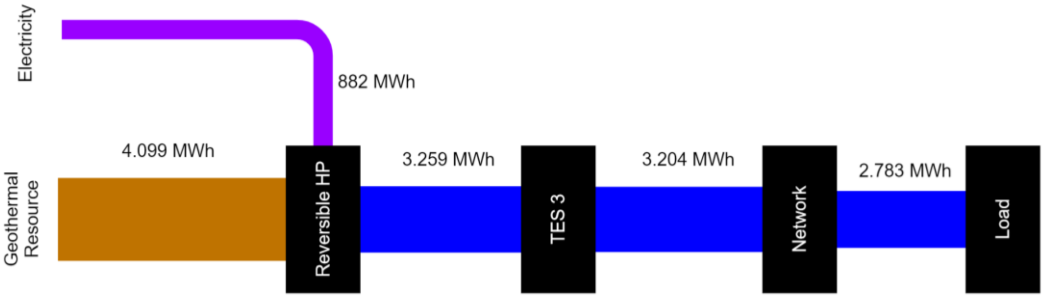

Figure 50 *Sankey diagram of 4GDHC on cooling mode.*

The emissions factor is 60.55 kgCO$_2$/MWh. The heating and the cooling emissions factors are 49.10 kg CO$_2$/MWh and 93.80 kg CO$_2$/MWh respectively. These emissions factors are directly correlated with the electricity emission factor. The renewable energy ratio is 0.85, while the non-renewable primary energy factor is 0.46.

Table 21 presents the economic results for the 4GDHC. The CAPEX of the system is approximately 11.3 M€ (5.9 M€ heating and 5.4 M€ cooling). The CAPEX of equipment represents 28.8%, while the CAPEX of the network is 71.2%. In heating, the CAPEX of equipment represents 42.6%, while the CAPEX of the network is 57.4%. In cooling, the CAPEX of equipment represents 13.9%, while the CAPEX of the network is 86.1%. The electricity cost is 86.5% of the variable OPEX and the waste heating recovery is 13.5%. In heating, the electricity and the waste heating recovery costs are 79.4% and 21.6%, respectively. In cooling, there is only electricity cost as a variable OPEX. The LCOE of the plant is 180.4 €/MWh. The heating LCOE is 136.8 €/MWh, and the cooling LCOE is 306.8 €/MWh.

Table 21 Economic results for 4GDHC.

CAPEX			
	Total	Heating	Cooling
Heat Pumps + Boreholes	1824000 €	1323526 €	500474 €
WESSUN	656000 €	656000 €	0 €
Water tanks	780000 €	520000 €	260000 €
Networks	8071799 €	3373200 €	4698599 €
Total	**11331799 €**	**5872726 €**	**5459073 €**
Fixed OPEX			
	Total	Heating	Cooling
Heat Pumps + Boreholes	54720 €	39706 €	15014 €
WESSUN	19680 €	19680 €	0 €
Water tanks	23400 €	15600 €	7800 €
Networks	242154 €	101196 €	140958 €
Total	**339954 €**	**176182 €**	**163772 €**
Variable OPEX			
Waste heat recovery	87524 €	87524 €	0 €
Electricity costs	558519 €	336766 €	221754 €
Total	**646043 €**	**424289 €**	**221754 €**

Figure 51 shows the CAPEX, fixed OPEX and variable OPEX percentages in the LCOE. In heating mode, the CAPEX represents 45.63%, while the variable OPEX represents 38.42%. In cooling mode, the CAPEX is 54.85%, while the variable OPEX is 25.97%.

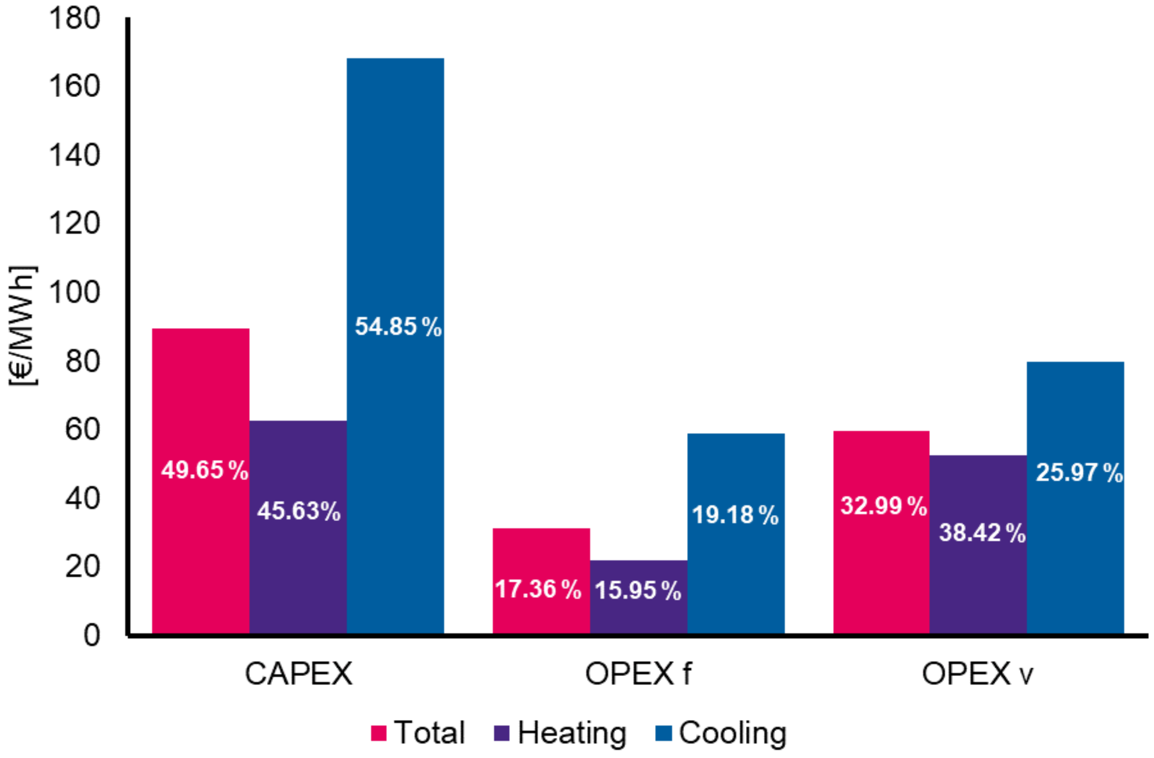

Figure 51 *Comparison between the LCOE breakdown for 4GDHC.*

3.4. Comparison between 3GDH and 4GDHC

Table 22 include the key parameters calculated for 3GDH and 4GDHC. The thermal losses of the heating network in the 4GDHC are 41.6% lower than in the 3GDH. This reduction is due to lower supply and return temperatures.

3.4.1. Total performance

Renewable energy ratio is higher for the 4GDHC. However, non-renewable primary factor is lower for the 3GDH. These results are conditioned by the inputs used in their calculation. These are obtained from the RITE ("Reglamento instalaciones térmicas en los edificios"). This document is the official reference for primary energy factors in Spain. The values of the primary energy factors have not been updated since 2014. It is important to note that the values for electricity are based on an energy mix with a minor contribution of renewable energies than at present. Despite this limitation, the 4GDHC system presents a higher renewable energy ratio, and the non-renewable primary energy factor is very close to the 3GDH.

Table 22 Key parameter for 3GDH and 4GDHC.

Parameter	3 GDH	4 GDHC
Thermal losses [MWh]	2187	1278 (heating) 421 (cooling
Unmet demand [%]	14.45%	9.9% (heating) 9.8% (cooling)
Renewable energy ratio factor [-]	0.79	0.85

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Non renewable primary energy factor [-]	0.28	0.46
Emission factor [kg CO_2/MWh]	75.51	60.55
LCOE [€/MWh]	121.27	180.35

The emission factor of 4DGCH is 20% minor than the emission factor of 3DGHC. The emission factor of both systems is greatly influenced by the emissions factor of the biomass and the electricity. These values vary greatly depending on the electricity mix and the type of biomass. Figure 52 shows the biomass and electricity emission factors that make both systems have the same emissions. Only if the biomass emission factor is very low or the electricity mission factor is very high, the 3GDH system will have lower emissions than the 4GDHC system. On the extreme situation when the biomass emission factor is null, the electricity emission factor must be less than 244.76 kg CO_2/MWh.

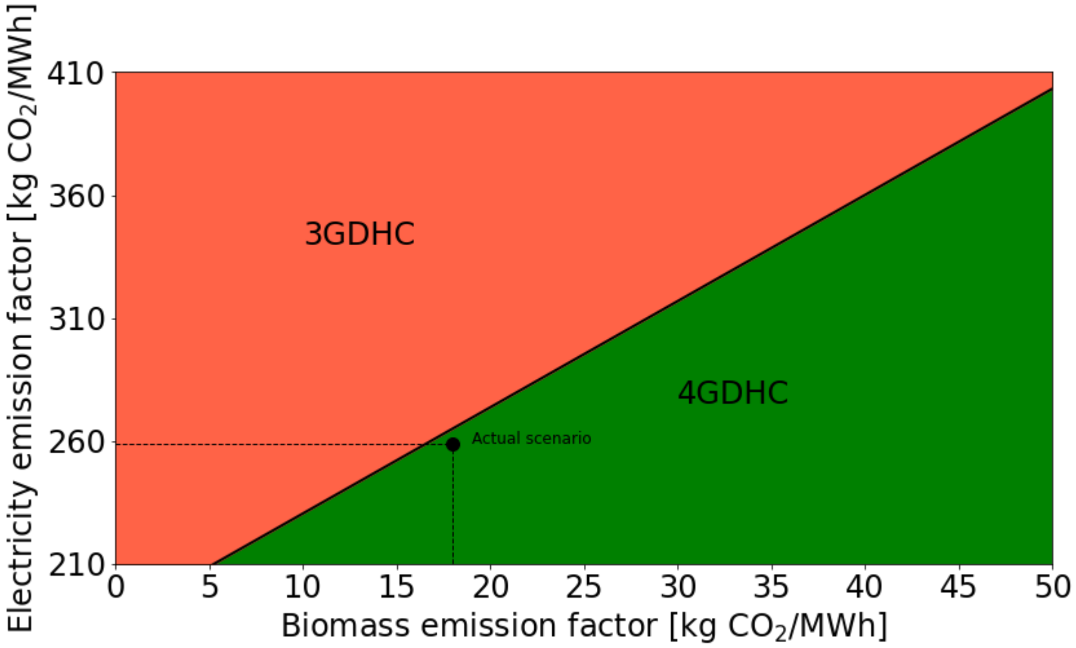

Figure 52 *Biomass and electricity emission values that make equal the emission factor of 3 GDH and 4 GDHC.*

Table 23 includes the total LCOE for the 3GDH and 4GDHC systems. This means that in 4GDHC we include the heating and cooling demand while in 3GDH only the heating demand is included. The LCOE of 3GDH is a 32.75% lower than the LCOE of 4 GDHC. On one hand, the lower price of the biomass respect to electricity explains this difference, but on the other hand because 4GDH also covers the cooling demand, the impact of which will be shown in the following section. The electricity price (220 €/MWh) is approximately 9 times higher than biomass price (25 €/MWh). Figure 53 shows the biomass and electricity prices that make both systems have the LCOE (gas price is fixed) With an electricity price of 220 €/MWh, the price of biomass needs to be 93 €/MWh in order to have the same LCOE.

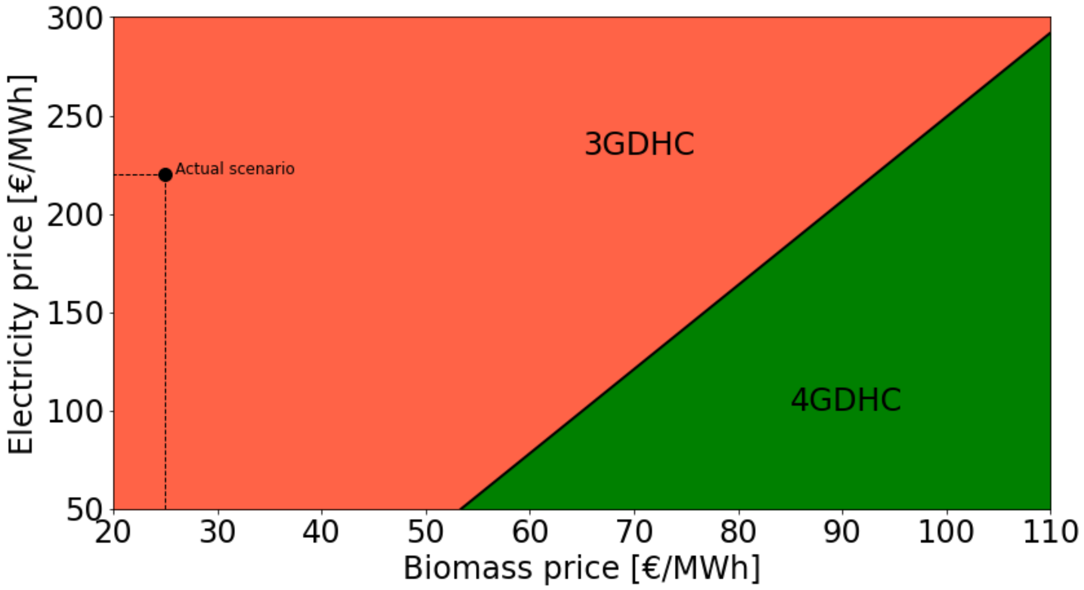

Figure 53 *Biomass and electricity prices values that make equal LCOE of 3GDH and 4GDHC.*

3.4.2. Heating performance

Table 23 includes the key parameters 4GDHC heating and 3GDH. The emission factor of 4GDHC heating is 35% lower than 3GDH. The renewable energy ratio of the 4GDHC is 20% higher than the value for 3GDH. The LCOE of 3GDH is 12% lower than LCOE of 4 GDHC. The sum of levelized CAPEX and OPEX for the third generation is 16% lower while the energy generated by the 4th generation is 5.4% higher.

Table 23 Key parameters for 3GDH and 4 GDHC on heating mode.

	3 GDH Heating	**4 GDHC Heating**
Emission factor [kg CO_2/MWh]	75.51	49.10
Renewable energy ratio factor [-]	0.79	0.95
Non renewable primary energy factor [-]	0.28	0.37
LCOE [€/MWh]	121.27	136.76
CAPEX [€]	4771400	5872726
Fix OPEX [€]	143142	176182
Variable OPEX [€]	376254	424 289
Energy supplied [MWh]	7659	8075

Figure 54 shows the biomass and electricity prices that make both systems have the LCOE. If the electricity price is 220 €/MWh and biomass price is 42.87 €/MWh, both systems present the same LCOE.

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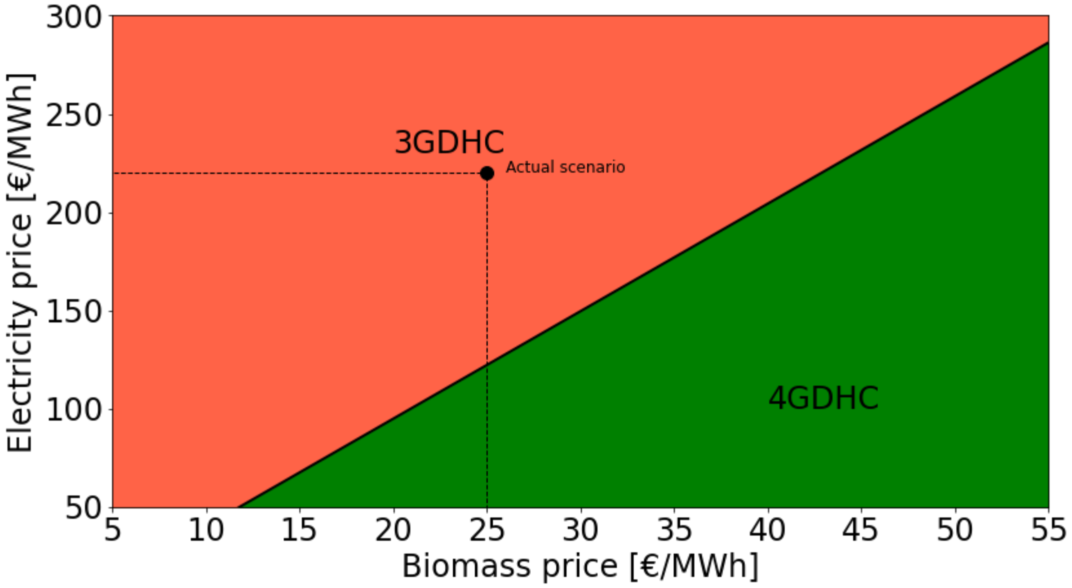

Figure 54 *Biomass and electricity prices values that make equal LCOE of 3GDH and 4GDHC (heating).*

3.4.3. Cooling performance

The 3GDH does not cover the cooling demand. In this case it is assumed that individual equipment covers cooling demand. Hence, the emission factor and LCOE are calculated taking account the following assumptions:

- The demand is covered by individual units of 5 kW with a COP of 3.
- The electricity consumption of the chiller represents 51% of the total electricity of the system[27].
- The capacity installed is oversized un 20%.
- The electricity price is 335 €/MWh. This is the price published in Eurostat for household consumers.
- The emission factor is 259 kg CO_2/MWh.

Table 24 includes the key parameters 4GDHC cooling and individual. The emission factor of 4GDHC cooling emission factor is 80.4% lower than individual equipment. However, the LCOE of 4GDHC is 24.1% higher than individual equipment. It should be noted that for the individual equipment system only the cost of the units has been considered, the necessary auxiliary equipment has not been included on the cost's estimation.

Table 24 Key parameters for 3GDH and 4GDHC on cooling mode

	Individual Equipment	**4 GDHC Cooling**
Emission factor [kg CO_2/MWh]	169.28	93.8
LCOE [€/MWh]	247.27	306.83

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[27] Jungbauer, J., Serrano Garcia, D., Wallisch, A., Dalin, P., Terouanne, D., & Wirgentius, N. (2011). Measurements of individual chiller systems compared to district cooling solutions. In ECEEE Conference Proceedings, Toulon.

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3.5. Conclusions

The following conclusions can be drawn from the present study:

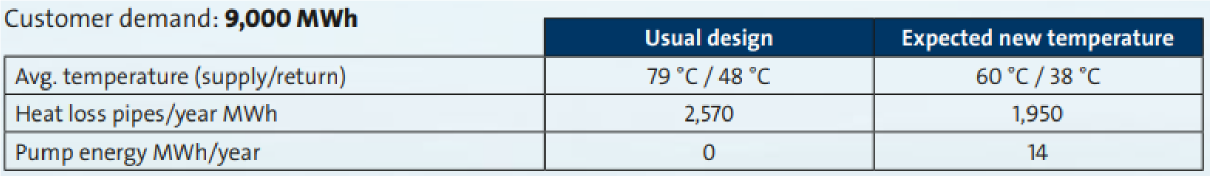
- In 4GDHC, heat losses in the networks are lower due to supply and return temperatures. This allows better coverage of the demand.
- The 4GDHC emissions are strongly influenced by the electricity mix.
- The 4GDHC system generates lower CO_2 emissions. Only if the biomass emission factor is very low or the electricity mission factor is very high, the 3GDH system will have lower emissions than the 4GDHC system.
- The LCOE of the 4GDHC is greatly penalized by the cooling mode. The cooling mode has much larger LCOE than the heating mode.
- If the electricity price decreases or the biomass price increases, there are some scenarios where the 4GDHC has lower LCOE.
- The advantages of 4GDHC stand out more when comparing its heating mode with 3GDH.

Annex 1. Example of shunt from return to supply in Gentofte (Denmark)

Gentofte and Gladsaxe District Heating Company serves a mix of housing blocks, public buildings, and single-family homes. A solution with a shunt from return to supply (see Section 1.2.3.1) was installed to reduce the average supply temperature from 79 °C to 60 °C in a part of the network.

Thanks to this solution the DH company is now able to deliver the exact heat energy required by all the different buildings in this area, but supplied at much lower temperatures, even during peaks.

This is expected to reduce heat losses by up to 25%, with a return on investment of the total project in just 3 years.



Customer demand: **9,000 MWh**

	Usual design	Expected new temperature
Avg. temperature (supply/return)	79 °C / 48 °C	60 °C / 38 °C
Heat loss pipes/year MWh	2,570	1,950
Pump energy MWh/year	0	14

Figure 55*: Calculated impact of the shunt solution in the considered case*[28].

Figure 56*: Installation of shunt connection in Gentofte (source: Grundfos)*[29].

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[28] Grundfos. Grundfos iGRID solutions. https://api.grundfos.com/literature/Grundfosliterature-6400907.pdf

[29] Grundfos. https://www.grundfos.com/solutions/learn/cases/gentofte-case

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Annex 2. Examples of three-pipe connection on the return pipe

Three pipe connections on the return pipe at Herlev New Hospital (Denmark)

An example of three-pipe connection on the return pipe comes from Herlev New Hospital, located some 12 km north-west of Copenhagen (Denmark).
In the aerial photo below, we see the old hospital from 1970 in the northern part with the tower. The heating system is a poor high temperature system, which is supplied from the DH DN500 main pipe in the curved ringroad.
This network has supply temperatures between 110 °C and 125 °C, while the return temperature is around 55 °C due to poor building installations.

To the south we see the new part of the hospital (round buildings are part of it). These are designed for 60 °C supply temperature and 35 °C return.

Figure 57: *Herlev New Hospital (Denmark)*

Three-pipe connection of renovated DH network to local area in Høje Taastrup (Denmark)

Sønderby is a district in the municipality of Høje Taastrup, some 18 km west of Copenhagen (Denmark) (see picture below).
The DH network and building substations in this district is renovated and the strategy is now to operate this system with around 55 °C supply to each one-family house.
The district is connected via a three-pipe connection on the return pipe from a nearby old apartment block, which has quite high return temperature.

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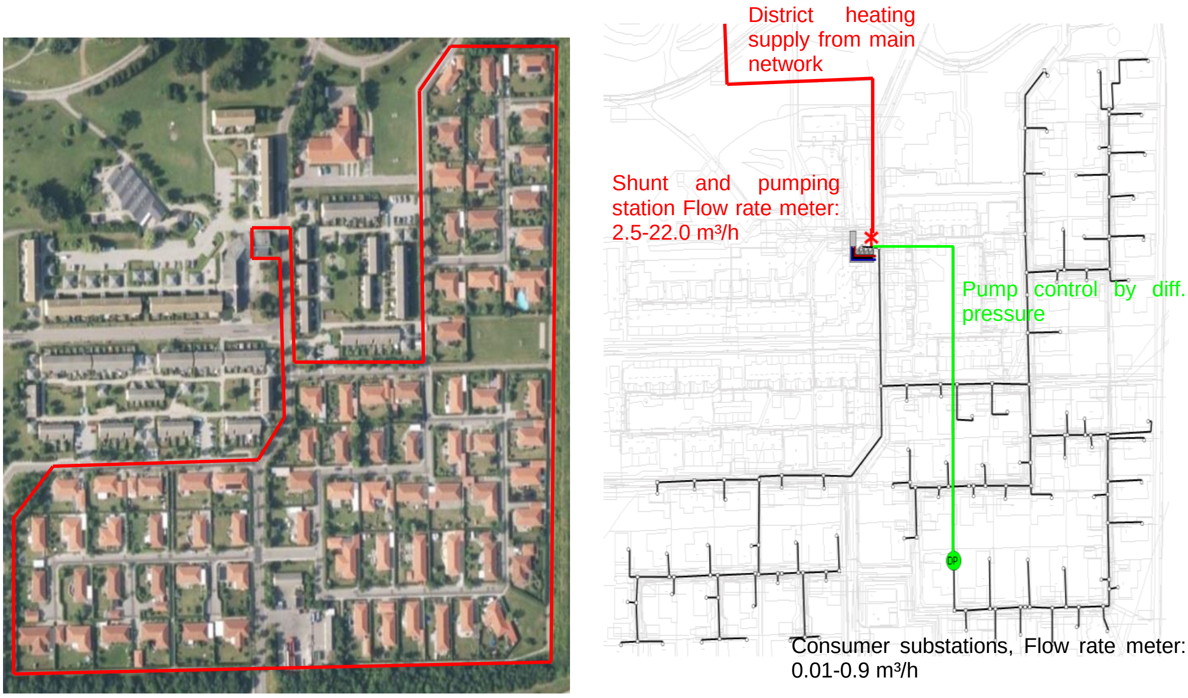

Figure 58*: Sønderby district in Høje Taastrup*

Three-pipe connection of an industry to the supply pipe

Vestforbrænding network (north of Copenhagen) supplies heat to an industry (a chocolate factory). A gas boiler boosts the supply temperature, if necessary.

The return temperature is quite high (around 60 °C).

The operator of Vestforbrænding network considers distributing heat from this substation to a large consumer next in line by using a 3-pipe connection.

It could be by letting the supply temperature go through the heat exchanger to the industry and then back to the same supply line (see Figure 61 below), or it could be a three-pipe connection on the return pipe.

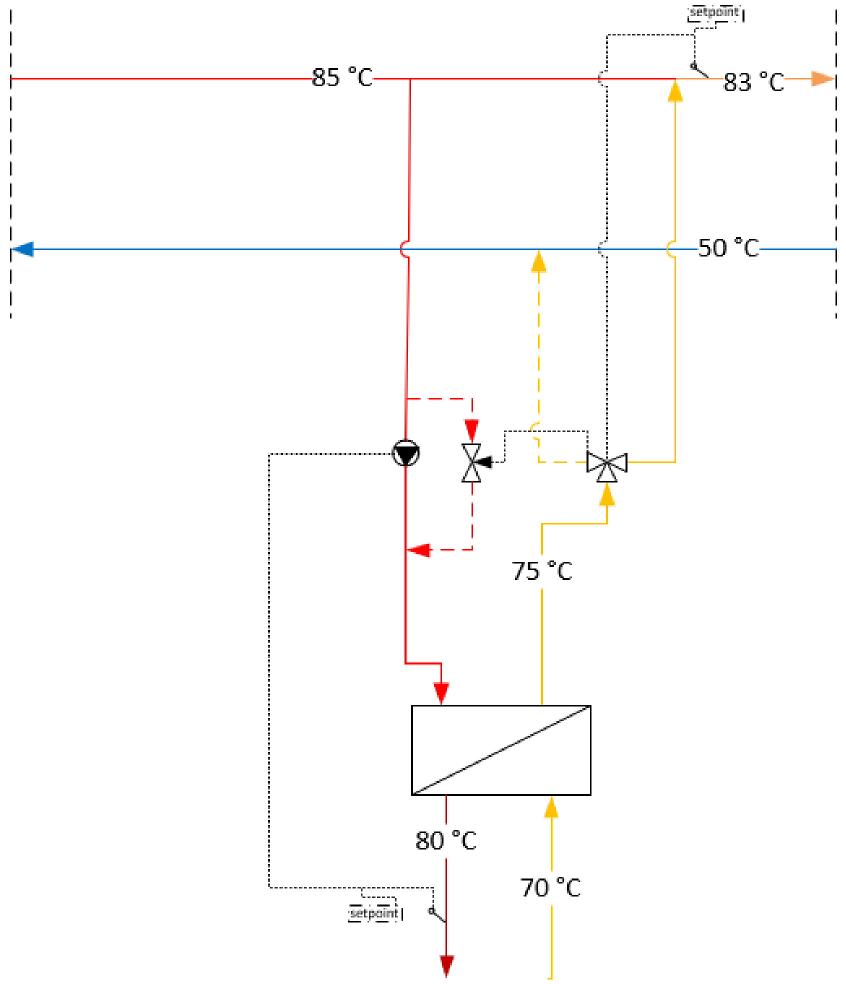

Figure 59*: Principle scheme of a high-temperature consumer whose supply and return are both connected to the supply line of the main DH network.*

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Annex 3. Conversion from 3 GDH to 4GDH

Many Danish DH companies have been using for many years now cubic meters of water consumption for billing for heat demand, rather than kWh. At the same time, motivation tariffs have been used to give incentive to the consumers to reach low return temperatures.

Recently the electricity tax for supply of heat was cancelled in Denmark. Therefore, many companies have invested or are investing in electric boilers and/or electric heat pumps, supplement the gas engine and the thermal storage.
According to the definition given above (Section 1.1.4), these can now be considered 4GDH networks.
Also the large DH companies are in principle 4GDH as they use the heat pumps for combined heating and cooling and electric boilers, whenever it is cost effective.

The network of Fjernvarme Fyn in Odense (Denmark) is probably the largest and most remarkable, having the following characteristics:

- 70,000 consumers and no heat exchangers at building level (direct connection).
- Very low return temperature
- 75,000 m3 thermal storage
- Waste and biomass CHP (coal will stop now)
- Around 40 MW heat pump from a data centre
- Around 20 MW heat pump from a wastewater plant
- Heat pumps for combined heating and cooling in progress.

This system will be described in more detail in an upcoming report from EU.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Annex 4. Taarnby 4G District heating and cooling system

Circulating water is a vital part of the infrastructure for energy and environment in the sustainable cities, in particular district heating and cooling.

Figure 60*: Heating plant in Taarnby District heating and Cooling system.*

In a new urban development in Taanrnby, north of Copenhagen Airport a unique project has been established, which according to Ramboll seems to be the smartest district heating and cooling system in the world.

The plant, which is established at the waste-water treatment plant, includes a heat pump installation of 4.5 MW in cooling and 6.5 MW in heating, and a 2,000 m^3 chilled water tank. The heat pump generates cooling to the storage tank, and from the tank the cold water is pumped to the district cooling grid which supplies all buildings in a new business district including the nearby Copenhagen aquarium “Blue Planet”.

All heat from the warm side of the heat pump is pumped into the district heating system at a temperature as low as possible and not more than 70-75 ˚C. This water is mixed with water at a higher temperature on cold days to meet the demand for larger temperature for some consumers.

Most of the year there is available cooling capacity, which is utilized to extract heat from the treated wastewater. The treated wastewater is pumped from the outlet to a heat exchanger in the energy plant.

In the next stage ground water will be pumped up from a cold well to deliver first priority cooling in summer and in winter it will be pumped up from the warm well to deliver ambient heat to the heat pump (an ATES system). This will reduce production of heat in summer and insure, that the heat pump can deliver maximal heat load in winter.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°857801

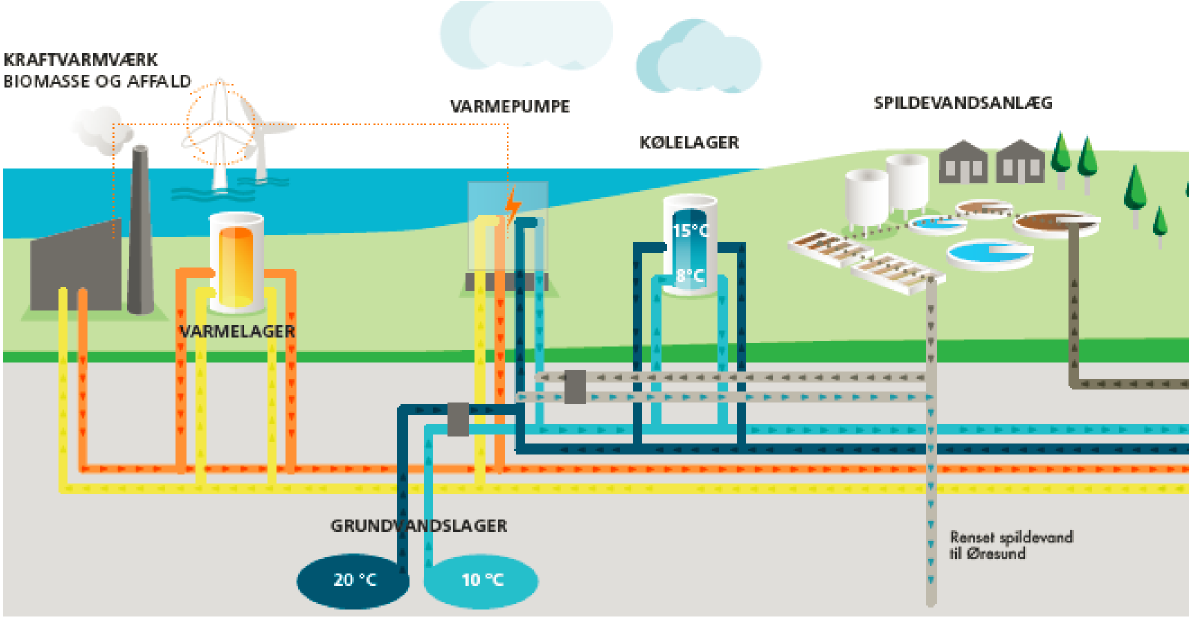

Figure 61: *Principle scheme of Taarnby District Heating and Cooling system.*

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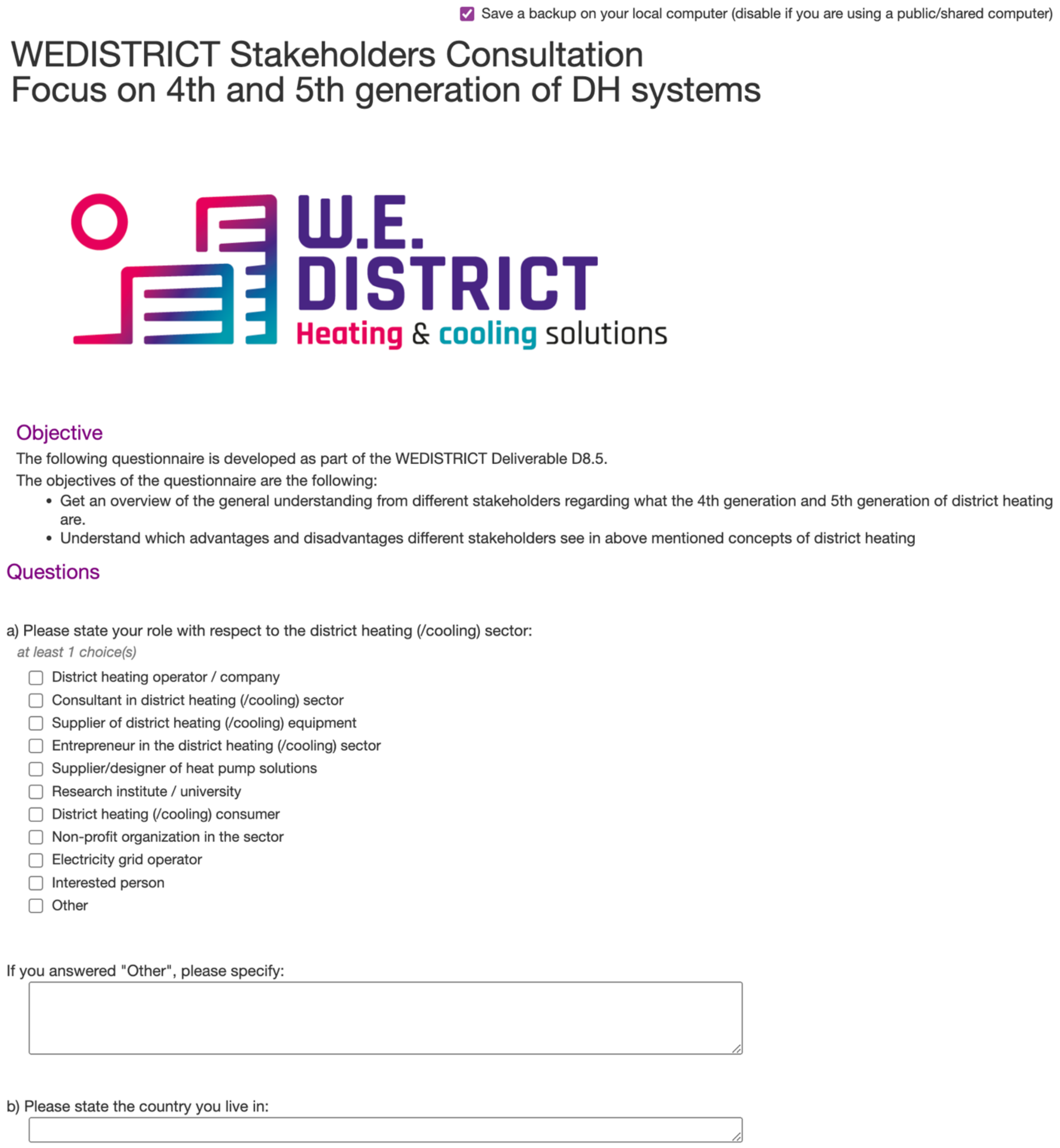
Annex 5. WEDISTRICT stakeholders survey

WEDISTRICT stakeholders survey available on EU Survey platform



☑ Save a backup on your local computer (disable if you are using a public/shared computer)

WEDISTRICT Stakeholders Consultation
Focus on 4th and 5th generation of DH systems

Objective

The following questionnaire is developed as part of the WEDISTRICT Deliverable D8.5.

The objectives of the questionnaire are the following:

- Get an overview of the general understanding from different stakeholders regarding what the 4th generation and 5th generation of district heating are.
- Understand which advantages and disadvantages different stakeholders see in above mentioned concepts of district heating

Questions

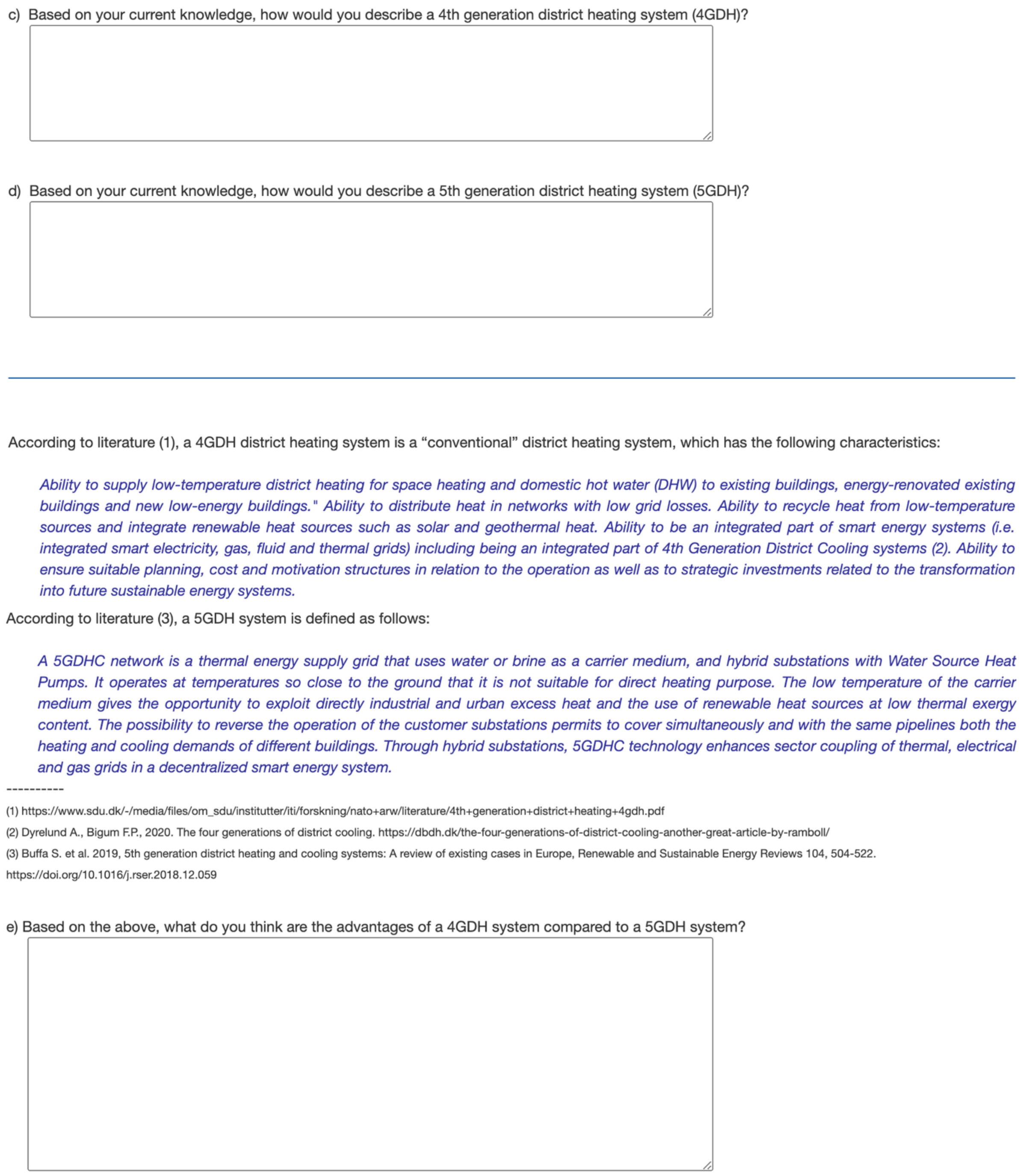
a) Please state your role with respect to the district heating (/cooling) sector:

at least 1 choice(s)

☐ District heating operator / company
☐ Consultant in district heating (/cooling) sector
☐ Supplier of district heating (/cooling) equipment
☐ Entrepreneur in the district heating (/cooling) sector
☐ Supplier/designer of heat pump solutions
☐ Research institute / university
☐ District heating (/cooling) consumer
☐ Non-profit organization in the sector
☐ Electricity grid operator
☐ Interested person
☐ Other

If you answered "Other", please specify:

b) Please state the country you live in:



c) Based on your current knowledge, how would you describe a 4th generation district heating system (4GDH)?

d) Based on your current knowledge, how would you describe a 5th generation district heating system (5GDH)?

According to literature (1), a 4GDH district heating system is a “conventional” district heating system, which has the following characteristics:

> *Ability to supply low-temperature district heating for space heating and domestic hot water (DHW) to existing buildings, energy-renovated existing buildings and new low-energy buildings." Ability to distribute heat in networks with low grid losses. Ability to recycle heat from low-temperature sources and integrate renewable heat sources such as solar and geothermal heat. Ability to be an integrated part of smart energy systems (i.e. integrated smart electricity, gas, fluid and thermal grids) including being an integrated part of 4th Generation District Cooling systems (2). Ability to ensure suitable planning, cost and motivation structures in relation to the operation as well as to strategic investments related to the transformation into future sustainable energy systems.*

According to literature (3), a 5GDH system is defined as follows:

> *A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium, and hybrid substations with Water Source Heat Pumps. It operates at temperatures so close to the ground that it is not suitable for direct heating purpose. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5GDHC technology enhances sector coupling of thermal, electrical and gas grids in a decentralized smart energy system.*

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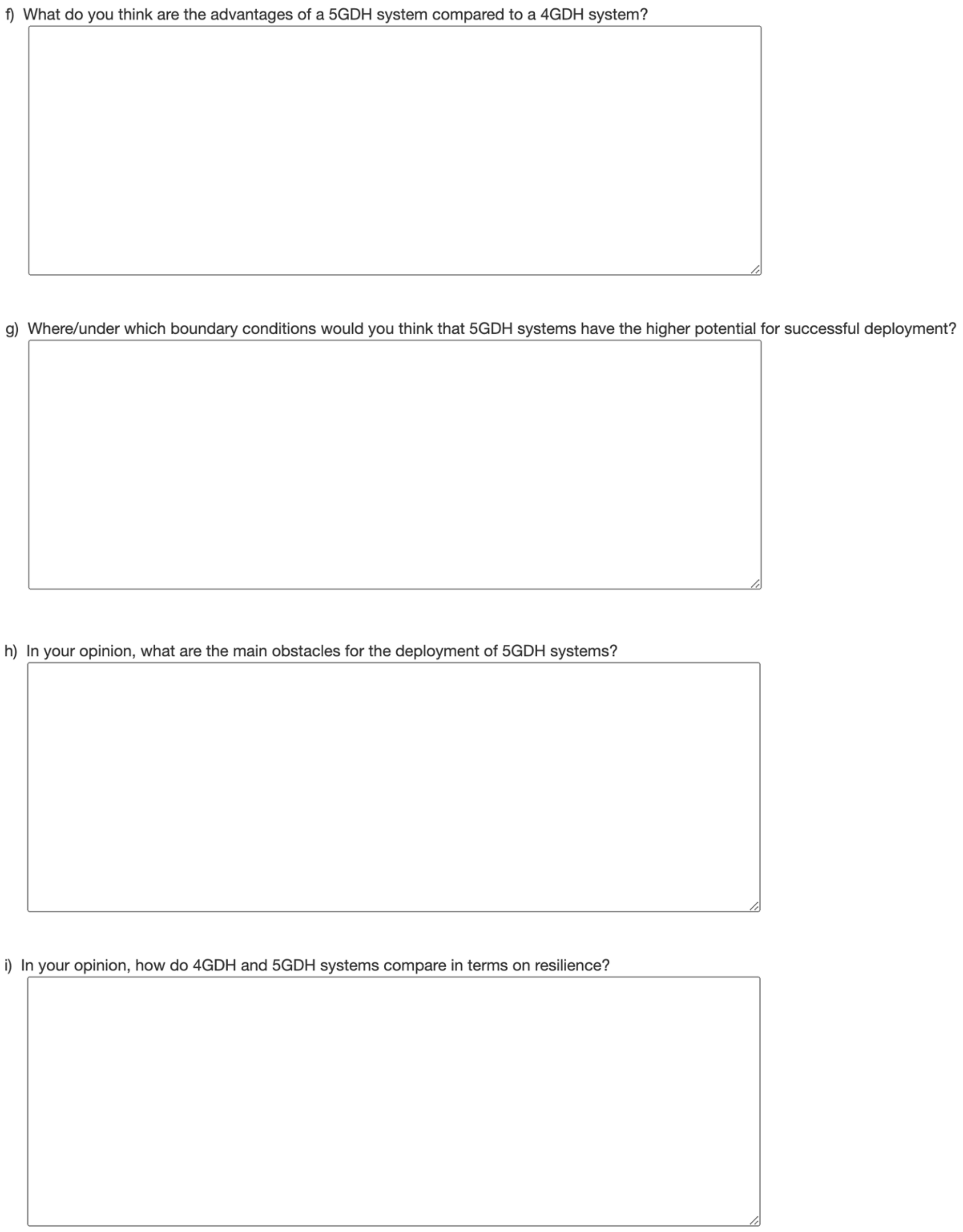
(1) https://www.sdu.dk/-/media/files/om_sdu/institutter/iti/forskning/nato+arw/literature/4th+generation+district+heating+4gdh.pdf

(2) Dyrelund A., Bigum F.P., 2020. The four generations of district cooling. https://dbdh.dk/the-four-generations-of-district-cooling-another-great-article-by-ramboll/

(3) Buffa S. et al. 2019, 5th generation district heating and cooling systems: A review of existing cases in Europe, Renewable and Sustainable Energy Reviews 104, 504-522. https://doi.org/10.1016/j.rser.2018.12.059

e) Based on the above, what do you think are the advantages of a 4GDH system compared to a 5GDH system?



f) What do you think are the advantages of a 5GDH system compared to a 4GDH system?

g) Where/under which boundary conditions would you think that 5GDH systems have the higher potential for successful deployment?

h) In your opinion, what are the main obstacles for the deployment of 5GDH systems?

i) In your opinion, how do 4GDH and 5GDH systems compare in terms on resilience?

j) In your opinion, how do 4GDH and 5GDH systems compare in terms on impact on the electricity sector?

k) What questions would you like to have answered regarding 4GDH and/or 5GDH?

THANK YOU!

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