# D2.1 - REWARDHeat planning schemes - Handbook

Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

REWARDHeat

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Lead beneficiary: UNIZAG FSB, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

Josip Miškić, UNIZAG FSB

Tomislav Pukšec, UNIZAG FSB

Zvonimir Guzović, UNIZAG FSB

Nastia Degiuli, UNIZAG FSB

Neven Duić, UNIZAG FSB

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# 1 Summary

REWARDHeat is an Horizon2020 research project dealing with next-generation district heating and cooling (DHC) networks. The goal of the project is to demonstrate low-temperature thermal networks and recovery of available urban waste heat and renewable energy. This Handbook presents a shorter version of the deliverable D2.1 REWARDHeat planning schemes database and it is part of WP2 - Design of low-temperature networks with multiple energy sources which has an objective of developing a database of solutions for next-generation DHC networks and develop REWARDHeat predesign tool.

This document D2.1 REWARDHeat planning schemes database – Handbook and presents a shorter version of D2.1. It contains key takeaways from it. It offers a short literature review and best practice examples for next generation DHC networks, i.e., ultra-low (ULTDH) and neutral temperature (NTDH) DHC networks. The Handbook is divided into several Sections.

Section 2 provides an overview of urban and renewable thermal sources that can be used in next-gen DHC networks. The emphasis is especially on the integration into the next-gen DHC networks. Section 3 provides an overview of Supply technologies that can be combined with next-gen DHC networks. In Section 5, an overview of thermal energy storage technologies In Section 7, an Overview of existing next-gen DHC networks thermal sources was made. In Section 6 the overview of the next-gen DHC networks is carried out. Furthermore, in Section 8, a SWOT analysis is presented for individual components of the DHC network and different versions of the network. In Section 9, an economic, energy, and environmental analysis of next-gen networks was carried out. Finally, in Section 10, the PESTLE analysis of next-gen networks is presented.

This Handbook contains key takeaways about the next-gen DHC networks which filter information presented in D2.1 – REWARDHEAT planning guidelines and provides quick literature and general information overview. This Handbook can serve for knowledge transfer and dissemination.

The full version of the D2.1 REWARDHeat planning schemes database is available at the following link.

# 2 Introduction

Conventional district heating (DH) networks are characterized by high temperatures of water in the system and the use of fossil fuels as heat sources. These two characteristics cause dependency on foreign countries that export fossil fuels, excessive emissions of $CO_{2,}$ and high heat losses in the thermal network. So, to reduce these negative effects, or even to eliminate them, new next-gen DHC networks are being developed. They are usually named ultra-low (ULTDH) and neutral temperature (NTDH) DHC networks. Operating temperatures of these networks are much lower than in conventional DH networks which enables the incorporation of low-temperature renewable energy and waste heat sources in the thermal network.

The main difference between mentioned DH networks is the supply network temperatures and end-user substation type. In ULTDH up to 50°C and NTDH up to 35°C. Depending on the temperature of the network, different consumer substations for space heating (SH), space cooling (SC), and domestic hot water (DHW) preparation are used. A general definition of these networks is as follows:

- ULTDH networks achieve network temperatures up to around 50°C. These temperatures are high enough to satisfy consumer SH needs, but the DHW preparation booster unit is needed to prevent Legionella growth. Different technologies could be used to raise temperature such as heat pumps (HP), electrical heaters, solar collectors, boilers, etc.
- NTDH networks have such low temperatures (up to 35°C) which are not high enough both for SH and DHW preparation. So, every consumer substation is equipped with booster HPs to rise temperatures to levels needed for SH and DHW preparation. Due to the low-temperature regime, these networks also offer the possibility of SC. Furthermore, these networks can enable bidirectional energy exchange between supplier and customer.

ULTDH and NTDH networks are considered the 5th (5DH) or next generation of district heating. From Figure 1 it can be noticed that every next generation follows supply temperature reduction and increase of energy efficiency, due to lower heat losses [1].

To become next-gen DHC networks several criteria need to be satisfied:

- Ability to supply low-temperature DH for SH and DHW.
- Ability to distribute heat in thermal networks with low thermal losses.
- Ability to recycle heat from low-temperature and integrate renewable energy sources.
- Ability to be an integrated part of the smart energy system.
- Ability to ensure suitable planning, cost, and motivation structures concerning the operation and investment.

HPs are mentioned as a crucial part of the system due to several reasons. HP coefficient of performance (COP) is increased with thermal network supply temperature reduction. HP enables power and heating sector coupling and offers more opportunities to rise the flexibility of these networks. For example, if HPs are used in combination with thermal storage, electricity from variable renewable energy sources, when there is not a high enough demand, can be used for thermal energy production, allowing more flexible electro-energetic and DH networks. Furthermore, next-gen DHC networks can potentially have interconnection with the gas sector. For example, biomethane could be used as a back-up boiler or integrated with DHW production in multi-purpose HP. Also, if used in combination with thermal storage, it can offer great flexibility [2].

Supply temperature reduction improves the performance of renewable heating technologies, either by direct utilization (e.g., solar thermal collectors) or by use of HPs. Furthermore, temperature reduction has a positive influence on central heat supply units, such as cogeneration and heat-only boilers. Finally, it gives a possibility for decreased heat losses in distribution networks [3], [4].

On the other hand, low-temperature DH networks have a lower temperature difference between supply and return lines. Thus, it is subject to increased investment and pump operation due to the larger volume flow rate for fixed heat delivery. Besides this, there are additional aspects that should be considered when developing ULTDH and NTDH networks, such as additional investments needed for substations and decentralized heat booster technologies [5], [6].

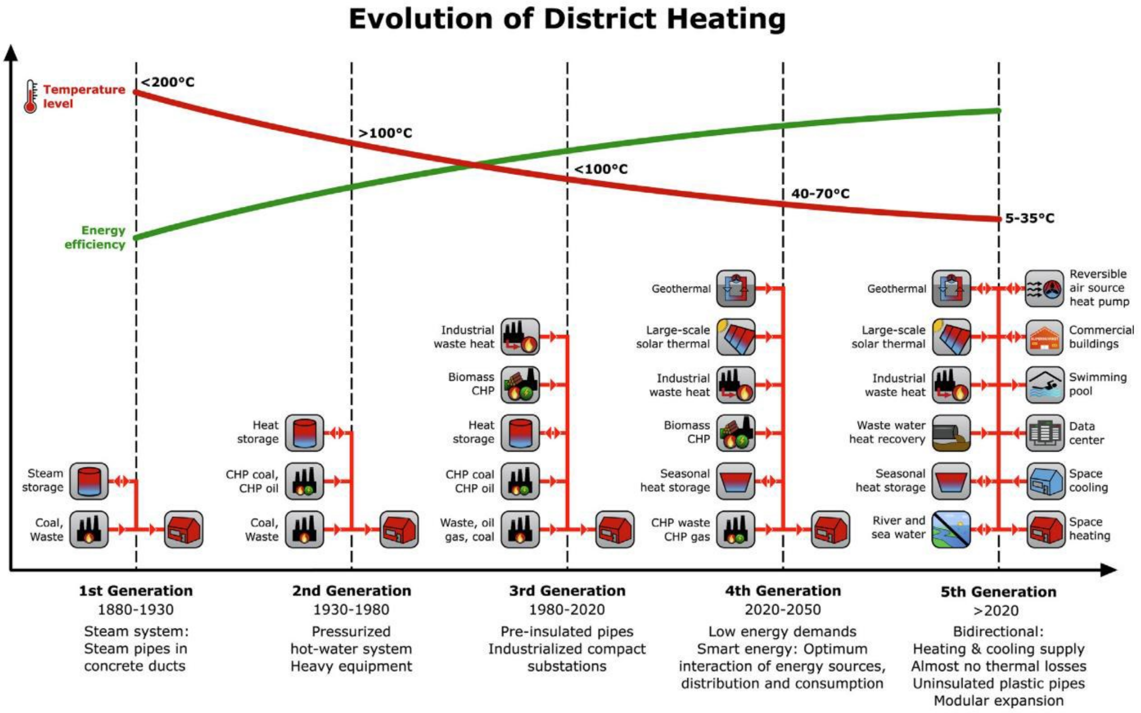

*Figure 1 Evolution of district heating networks* [1]

# 3 Thermal sources

One of the main parts of every DH system are heat sources. The number of heat sources varies in each network. More heat sources mean that the heat supply will be more continuous and more reliable. Reduction of supply temperature enables integration of additional low-temperature thermal sources. In this section, the focus will be put on natural and urban waste heat sources which are often utilized in ULTDH and NTDH networks.

## 3.1 Natural thermal sources

### 3.1.1 Groundwater

Groundwater is commonly used in NTDH networks since it provides a relatively constant temperature due to the high thermal large thermal capacity of the source. Groundwater is usually utilised through ATES (aquifer thermal energy storage) and it can transfer energy directly to the thermal network, as in NTDH networks, or it can serve as the heat source/sink for the HP, as in ULTDH networks. More about ATES can be found in Section 5.3.4. The ATES used in NTDH networks can provide the service of cooling. The heated groundwater is injected back into the aquifer to create heat storage. In the winter season, the flow direction in the system is reversed such that the heated groundwater is extracted to provide heating and create cold storage.

### 3.1.2 Ground

Ground as a natural thermal source is already well known and its potential is already being widely exploited. The ground is a very stable and reliable source of heat energy and offers the possibility to serve as a heat storage tank [7]. Tubes can be installed in the subsurface vertically or horizontally. At a depth of two meters in the ground, the temperature is above 10°C even in winter. Such temperature stability without large variations during the year allows the use of the ground for heating during the winter period and for cooling during the summer period [8]. The most common way to use the ground as a thermal source is as Borehole Thermal Energy Storage (BTES). More about BTES can be found in Section 5.3.3.

### 3.1.3 Superficial water bodies

Besides groundwater, superficial water resources (lakes, rivers, and seas) can also be utilised [9]. However, such heat sources have temperature variations which are usually correlated with ambient temperature. To limit this issue, preheating can be used by using different sources such as cogeneration, heat-only boiler, etc. There are also limitations to the exploitation of superficial water bodies, however not as rigorous as groundwater. The energy exploitation of surface water is thus generally favoured if compared with underground water, since the first allows a higher temperature variation between inlet and outlet flows, with a consequent reduction of water flow rate at constant heat exchange (thus reducing pipeline diameter, heat exchanger size, etc.). Typical temperature increases can be up to 10-15°C, water mixing is then needed to reduce temperature.

## 3.2 Urban thermal sources

### 3.2.1 Urban water networks

Paper [4] proposes utilisation of urban water bodies for utilisation in DH networks, such as sewage water and water treatment plants. Although sewage water is always available in cities, where heating demand density is relatively high, the flow ratio is an important factor when assessing sewage waters as a heat source. Sewage water has a constant temperature, which is relatively high, around 25°C. Due to this, it is an excellent heat source for HP operation in ULTDH.

### 3.2.2 Supermarket's refrigeration and HVAC networks

Supermarkets are an essential part of any larger city. The increase in supermarkets is followed by the constant increase in their surface area [10]. To ensure quality, sanitary regular, and fresh food, in supermarkets three types of refrigeration units are used: stand-alone, condensing, and centralized. Refrigeration takes a large part in the energy consumption of the supermarket. Average annual energy (electricity) consumption is between 327 and 600 kWh/m$^2$ and refrigeration covers between 35% and 50% of that consumption [10]. To ensure the necessary conditions in the refrigerators, the excess heat is released through chillers and cooling towers. The temperature level of the released heat may vary from 50 to 120 °C, which depends on the type of refrigerator used. The integration of excess heat can be achieved in two ways, directly (when the temperature of the excess heat is higher than the temperature regime of the network) or indirectly (when the temperature regime of the network is higher than the temperature of the excess heat). In the case of indirect integration, it is necessary to install a booster HP that will ensure a high enough temperature to integrate the excess heat into the network. In this case, the cooler represents the heat source, and the DH network represents the heat sink.

### 3.2.3 Shopping malls and supermarkets HVAC networks

Heating, ventilation, and air conditioning networks (HVAC) in supermarkets and shopping malls can be easily observed as identical networks. HVAC purpose in both objects is to ensure optimal thermal comfort. Average annual electricity consumption is between 327 and 600 kWh/m$^2$ for supermarkets and between 118 and 300 kWh m$^{-2}$ for shopping malls [10]. The energy consumption is directly related to the average ambient temperature. The main waste heat potential in HVAC networks represents heat discharge in coolers. Thermal comfort is maintained in the temperature range between 22 and 26°C for most of the stores in shopping malls. There are three fundamental ways of designing HVAC networks. The most used is a combination of Variable Refrigerant Volume (VRV) and Ventilation Air Mounted (VAM). The purpose of the VAM is to secure fresh air in combination with VRV's room unit. Those networks are located on the roof, and they contain everything that is needed for appropriate air conditioning. Even though they can recover some part of the waste heat, the efficiency of those networks is still very low.

### 3.2.4 Data centres

With the increasing digitalization of services data centres are becoming important worldwide and it is expected that the role of data centres in the future will be significant. Raise in the number of data centres, due to the raising demand, has necessary effects on electricity consumption. Two main electric energy consumers in data centres are Information Technologies (IT) networks, used for processing and storage of data, and HVAC networks [11]. The HVAC system needs to ensure a working environment in a set range for the proper functioning of IT equipment.

There are three main cooling techniques in data centres: air-cooled networks for small conventional data centres providing low-quality waste heat, water-cooled networks for mid- and large-scale data centres providing high-quality waste heat, and two-phase cooled networks for large-scale data centres providing high-quality waste heat. Most used are air-cooled networks that provide waste heat with a temperature level of about 45°C.

To capture waste heat from data centres there are two most common techniques: waste heat recovery from hot aisle returns or on the chiller condenser. Waste heat recovery in the return hot aisle is usually implemented in CRAH (Computer Room Air Handler) cooling networks since the hot air streams in IT facility rooms are gathered at relatively high temperatures (about 45°C) and delivered in a common duct to the air-handling units [12], [13]. Another solution to utilize waste heat is to capture heat from the chiller condenser. For heat recovery from the chiller condenser of CRAH networks, a water-to-refrigerant heat exchange is installed in parallel with the condenser of the chiller. The temperature can reach a higher temperature level (about 50°C). The warmed water is fed into a heat exchanger or HP and integrated into the DH network [13].

### 3.2.5 Power substations

Power substations are an important part of electric power networks (EPS), they are a segment of transmission and distribution networks that includes electric energy sources and electric energy consumers. These parts are crucial in every EPS. Power substations are steady electromagnetic devices that with help of electromagnetic induction convert alternatives currently in currents on different stages with the same frequency. The main parts of substations are an iron core, primary and secondary winding, insulation, housing, construction reinforcements, and a cooling system. Substations have a high efficiency of up to 99.8%, and the losses in substations are usually divided into energy dissipation due to no-load losses which are related to using iron core, and losses due to the load which is related to using copper wiring.

The temperature level in the substation depends on the load of the substation, but usually, those temperatures are low (about 35°C) [14]. The direct utilization of the waste heat is possible when the outlet temperature on the transformer site is above the supply temperature of the DH area. This case is rare, and it is possible only in low-temperature DH networks. If no direct utilization is possible, an HP will be used to provide the temperature lift to make possible integration of the waste heat in DH.

### 3.2.6 Metro stations

Metro networks consume a large amount of electric energy for different purposes. Most of the consumed electric energy is transformed into heat energy. The heat energy in metro networks causes a rise in the temperature, and in this, part HVAC networks have an important role. Through HVAC networks, heat is dissipated and ensured that the temperature in metro networks stays at a level acceptable in sense of thermal and humidity level for people and equipment. Discharge of this amount of heat causes a rise in the operational cost of metro networks and can cause thermal pollution. Recovering heat from metro networks through heat exchangers and HPs directly linked to the tunnel body is already shown viable. Typical waste heat temperature in metro networks is between 20°C to 35°C [15], [16], [17]. The HP is used to upgrade the temperature of recovered heat ad may be located either at the decentral unit (Shaft head house) or at the central unit (Energy Centre). The rising temperature level of recovered heat is making heat suitable to use in the DH network.

### 3.2.7 Wastewater treatment plants

Wastewater treatment plants (WWTP) produce significant quantities of waste heat energy and show great potential for usage. Wastewater has a high heat capacity, and density, and it can provide a concentrated source of heat. Wastewater heat could be used in heating and cooling residential, social, and administrative buildings on a narrower scale or in DH on a larger scale [18]. Wastewater is available in large quantities throughout the whole year, and temperature variations throughout the year are small. Throughout the heating season average temperature is about 10°C, while during the cooling season average temperature is about 22°C [19]. Another advantage is that summer wastewater has a lower temperature than the outdoor temperature, while during winter it has a higher temperature than the outdoor temperature enabling the usage of the HPs for cooling and heating buildings. Waste heat can be utilized using a heat exchanger or HP. There are three different techniques for extracting heat with a heat exchanger from WWTP: Sewer-integrated heat exchanger – heat exchanger placed directly inside the sewer tunnel, Sieved wastewater sewer-integrated heat exchanger – the raw wastewater flowing in the sewer is first fed to a sieving stage in which solids are separated, then the wastewater is passed through the heat exchanger and then returned to the sewage system, Collecting shaft heat exchangers – collecting shaft heat exchangers to ensure continuous heat transfer can be installed [20]. There are two types of heat utilization from wastewater through HPs: Indirect type (wastewater to circulating water) and direct type (wastewater to the refrigerant) [21].

# 4 Supply technologies

In this section, different supply technologies are presented, with a focus on their role in the energy transition from conventional to ULTDH and NTDH networks. The impact of temperature reduction on the technology characteristics is presented.

## 4.1 Cogeneration

Cogeneration, or combined heat and power (CHP), is a technology that can simultaneously produce heating and electrical energy. There are two types of CHP, back-pressure, and extraction CHP. In the back-pressure CHP, heating and electrical load are directly correlated, i.e., there is no flexibility in plant operation. Back-pressure CHP is working only if there is a DH load. The flexibility of the back-pressure CHP can be increased if thermal storage is installed. Extraction CHP is relatively flexible since electricity production does not necessarily follow the heating load. Extraction CHP can for the same level of heat production produce more electricity, even for lower DH supply temperature. The correlation between CHP efficiency and DH network temperature presents an essential element for DH networks in the energy transition. The temperature reduction of the DH network connected to CHP can have a negative effect on overall system efficiency. Because of that CHP networks are rarely directly connected to ULTDH or NTDH networks. Next-gen DH networks are usually linked to CHP units through a shunt valve connection. More about shunt valve connection can be found in Section 4.3.

## 4.2 Solar thermal collectors

Solar thermal collectors can produce thermal energy with a wide variety of temperatures, depending on thermal load and collector type. Generally, solar thermal technology can be divided in two main groups: flat plate collectors (FPC) and evacuated tube collectors (ETC) [22]. FPC has a relatively simple design constituting flow pipes that are placed inside the absorber. On the other hand, ETC has flow pipes located inside vacuum tubes, thus reducing thermal losses due to conduction and convection which presents the main drawback of FPC. The transition from high temperature to ULTDH and NTDH networks has a significant impact on collector efficiency. Temperature reduction can cause an over 30% efficiency increase. One important aspect when using solar energy is that it should be coupled with thermal storage to store heat when there is an excess of it and use it when there is high demand [23].

## 4.3 Existing DH networks connection

LTDH and ULTDH networks can be integrated into larger DH networks by using various connection technologies. This enables the creation of low-temperature subnetworks which can easily be integrated into existing DH networks. This could be achieved by using a heat exchanger, HPs, or direct connection. In the case of the direct connection of LTDH or ULTDH, a mixing shunt or 3-pipe connection can be used [24].

### Heat exchanger solution connection

ULTDH can be connected to a high-temperature DH network by using a heat exchanger system. The heat exchanger area is directly related to the temperature difference between networks – the higher the temperature difference, the lower the heat exchanger area, i.e., investment. In this case, ULTDH networks, and heat booster units are installed in end-user substations for DHW preparation.

- Mixing shunt connection

Mixing shunt is a direct connection of existing DH and secondary subnetwork where the supply coming from existing DH is mixed with the return flow of the secondary subnetwork. The performance of the mixing loop is controlled by a temperature sensor in the main supply pipe in a low-temperature network. This is a relatively simple technical solution since a secondary network can be easily established.

- Three pipe connection

Three pipe connection is a solution similar to a shunt valve. However, in this case, the primary network supply and return flow are mixed to provide the supply flow of the secondary network. The primary heat source comes from the return line of medium-temperature DH. When the temperature of the return line is not sufficient, water from the supply line of medium temperature DH is mixed with return water to achieve desirable supply temperatures of the subnetwork. Therefore, the system consists of two pipes: two supply pipes and one return pipe [25]. This system enables the expansion of the network without the need to increase network capacity [24].

- Heat pump connection

Next-gen DH subnetwork can be connected to the existing DH network via HP to reduce the energy consumption of the pumping system. For example, the return water from the primary DH network at 40°C passes through the HP condenser after which the temperature is risen to 55°C, i.e., it serves as the heat sink. It becomes the supply temperature of the secondary DH network. Return water from the secondary network passes through the evaporator and serves as the heat source. By doing so, it is cooled before it is returned to the primary DH network [23].

## 4.4 Central heat pumps

HP is a technology that enables transferring heat from a lower temperature (heat source) to a higher temperature (heat sink) employing mechanical input through the compressor. The Coefficient of Performance (COP) of the HP depends on the temperature lift, which is defined as the temperature difference between the heat source and heat sink. The lower the temperature lift, the higher the COP. In other words, lower DH network temperatures (heat sink) cause an increase of HPs COP, for the same heat source type. HPs are used on the heat supplier side to utilize available heat sources to provide thermal energy for the DH network, i.e., heat sink. In ULTDH and NTDH networks, HPs are also used as booster units located in customers' substations. Booster HP has a smaller thermal capacity than central units and different operating conditions.

The feasibility of ULTDH with central HP depends greatly on various factors such as plot ratio (ratio of building and total land area), space heating share, and linear heat density. It has been shown that ULTDH based on excess heat (at 40°C) HP is economically better than classical LTDH networks only for high SH shares and for medium- and high-density urban areas. ULTDH with air source central HP is economically feasible only for the densest regions with a high plot ratio and high SH shares.

# 5 Thermal storage technologies

Thermal energy storage (TES) is a technology that enables the storage of thermal energy and its utilisation in periods when is needed. They can be used to store thermal energy on different levels of temporal scale such as: hourly, daily, weekly, or seasonal. As such, they differ in size, temperature levels, or technology. In this section, the focus is put on characteristics of TES which are primarily used in low-temperature DH networks.

## 5.1 Thermal storage overview

*Table 1 General characteristics of thermal storage technologies* [26]

| Type | TTEA | PTS | BTES | ATES |
|---|---|---|---|---|
| Storage medium | Water | Water (gravel water) | Soil surrounding the boreholes | Groundwater in aquifers |
| Specific capacity [kWh/$m^3$] | 60-80 | 60-80 (30-50 for gravel-water) | 15-30 | 30-40 |
| Water equivalents | 1 $m^3$ TES= 1 $m^3$ water | 1 $m^3$ TES= 1 $m^3$ water | 3-5 $m^3$ TES= 1 $m^3$ water | 2-5 $m^3$ TES= 1 $m^3$ water |
| Geological requirements | Stable ground conditions<br>Preferably no groundwater<br>5-15 m deep | Stable ground conditions<br>Preferably no groundwater<br>5-15 m deep | Drillable ground<br>High heat capacity<br>High thermal conductivity<br>Low hydraulic conductivity<br>Groundwater flow <1 m/s<br>30-100 m deep | High yield aquifer |
| Application | Short-term/diurnal TES, buffer TES | Long-term/seasonal TES for production higher than 20.000 MWh/year<br>Short-term TES for large TES | Long-term/seasonal TES for DH plants production higher than 20.000 MWh/year | Long-term/seasonal heat and cold TES |
| Storage temperatures [°C] | 5-95 | 5-95 | 5-90 | 7-18 |

| | | | | |
|---|---|---|---|---|
| Specific investment cost [€/$m^3$ water equivalent] | 110-200 €/$m^3$ (if > 2.000 $m^3$) | 20-40 €/$m^3$ (if > 50.000 $m^3$) | 20-40 €/$m^3$ (if > 50.000 $m^3$ water equivalent including buffer tank) | 50-60 €/$m^3$ (Cost depends on charge capacity rather storage capacity) |
| Advantages | High charge/discharge capacity | High charge/discharge capacity<br>Low investment cost | Most underground properties are suitable | Provides heat and cold TES<br>Many geologically suitable sites |
| Disadvantages | High specific investment cost | Large area requirements | Low charge/discharge capacity (potential need for a buffer tank) | Low temperatures and temperature differences |

## 5.2 District heating network as a thermal storage

The storage capacity is determined by the temperature difference in the network and the medium's properties. Water has the highest storage capacity, while glycol mixtures have lower. Currently is shown that the network has not sufficient storage capacity, but it could be used for peak shavings. Despite that, the network should not be dimensioned for such a purpose [27].

## 5.3 Storage types

Before storage planning, it is essential to consider whether is more feasible to store at lower temperatures (lower investment cost because there is no need for extensive insulation and availability of low-temperature surplus heat) or higher temperatures (higher energy density and thus smaller storage for the same capacity) [27].

### 5.3.1 Tank thermal energy storage (TTES) – centralised daily storage

TTES is usually made as a cylindrical steel tank. They are mostly used as daily storage, but they can also be used as seasonal storage where solar thermal plants are used for heat production. They can be underground or above the ground. If they are underground, the area above them can be utilised. Figure 2 shows underground TTES. The specific capacity of these storages is around 60 to 80 kWh/$m^3$.

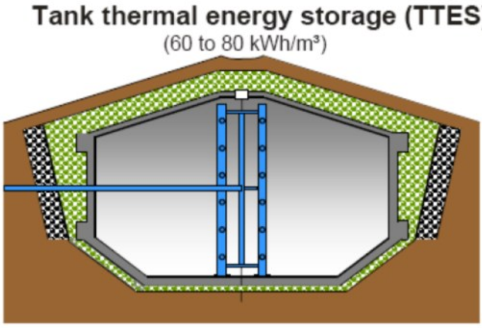

*Figure 2 Tank thermal storage overview*

Thermal storage temperature is mainly chosen to provide the supply temperature for the network. The temperature stratification in the tank is managed with a pipe system. Hot and cold temperature layer mixing is being avoided keeping storage efficiency as higher as possible.

### 5.3.2 Pit thermal energy storage (PTES) – centralised daily to seasonal storage

PTES are usually connected to solar thermal plants. They consist of a pit excavated in the ground with the plastic membrane on the bottom and at the walls (with low slope) of storage to prevent storage leaking. The pit is covered with a lid to reduce heat losses. To keep thermal stratification, a pipe system, like the ones in TTES is utilised [27]. An example of PTES is illustrated in Figure 3.

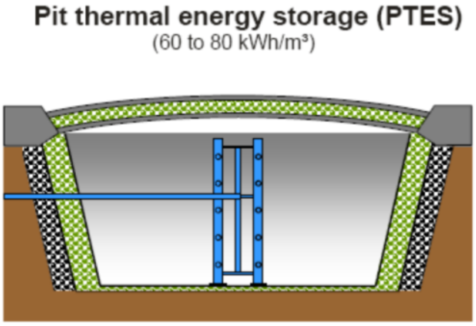

*Figure 3 Pit thermal storage overview*

The specific capacity of these storages is around 60 to 80 kWh/m$^3$, which is like the capacities of TTES. Storage heat losses depend on temperature levels, lid insulation, volume to surface ratio, storage use, and whether HP is used for storage discharge. Storage efficiencies are in the range of 80% to 95%, but they are lower for single-cycle seasonal use.

### 5.3.3 Borehole thermal energy storage (BTES) – centralised daily to seasonal storage

BTES consists of boreholes in the grounds in which pipes are placed. The whole system is usually covered on top with insulation to prevent heat losses. When recharging, hot water runs through the pipes, and it heats the surrounding soil, and when storage is discharging, cold water runs through the pipes, and the soil transfers heat to it. In this case, the storage medium is soil surrounding boreholes, and water is the heat transfer medium. The cross-section of one borehole storage system is shown in Figure 4.

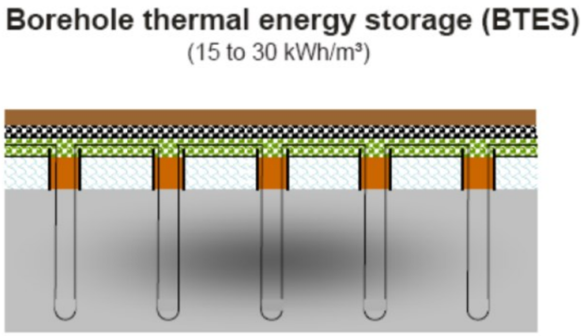

*Figure 4 Borehole thermal storage overview*

BTES can consist of one or more boreholes and to utilize heat from BTES an HP is needed to raise the temperature level of the medium to satisfy the supply temperature. BTES are mainly used for covering the baseload of DH networks. The specific capacity of these storages is around 15 to 30 kWh/m$^3$.

The most important aspect of BTES is that it could be used in DHC simultaneously by using seasonal (periodic) heating and cooling cycles [27]. During the winter season, warm water is supplied from BTES, thus reducing the temperature of the boreholes. During summertime, cooled BTES is used for cold water extraction and district cooling. In this process, BTES is heated up and prepared for the winter season, thus completing the periodical cycle.

### *5.3.4 Aquifer thermal energy storage [ATES] – centralised daily to seasonal storage*

ATES consists of two (or multiples of two) separate wells drilled into an underground groundwater reservoir (aquifer), as shown in Figure 5. The specific capacity of these storages is around 30 to 40 kWh/m$^3$.

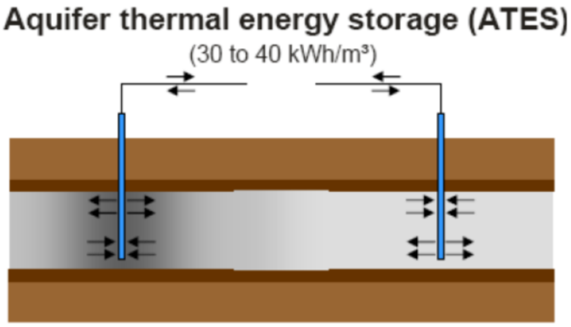

*Figure 5 Aquifer thermal storage overview*

One of the wells acts as heat storage, while the other acts as cold storage. In winter, water is pumped from the warm well for heating purposes, thus being cooled down. It is then injected into the cold well. The reverse process happens in summer where water from a cold well is used for cooling purposes, and after it is heated, it is injected into a warm well. It is essential to notice that ATES is a closed system. This storage type is usually used only for cooling, making this system feasible, even without heating. Typical temperatures for cold wells are in the range of 7-16°C and for the warm wells 10-18°C.

# 6 Thermal networks

In this section, the focus will be put on ULTDH and NTDH thermal network topologies. The emphasis is put on design guidelines, piping, temperature, and pressure levels, including losses.

Table 2 shows a general overview of ULTDH and NTDH networks. The main difference between them and 4th generation, or LTDH, networks need booster heating units to provide temperatures needed for SH and DHW demand.

*Table 2 General overview of ULTDH and NTDH networks characteristics* [28], [29]

| | ULTDH | NTDH |
|---|---|---|
| Definition | Ultra-low temperature DH system which needs booster heater in consumer substation to deliver DHW with suitable temperature level. | Neutral temperature DH system which needs booster heaters in consumer substation to deliver SH and DHW with suitable temperature levels. |
| Temperature | Network supply temperature up to 50°C with a return of 20-35°C | Network supply temperature up to 20°C with a return of 8-15°C |
| Heat carrier | Water-based brine in closed loop | |
| SH production | Floor heating or low-temperature radiator in a secondary loop (30-40°C). Network temperatures are high enough to provide low-temperature heating. | Floor heating or low-temperature radiator in a secondary loop (30-40°C). Network temperatures are not high enough to provide low-temperature heating, i.e. booster heating units in the customer's substation are needed. |
| DHW production | DHW temperature should be increased up to 60-65°C to prevent Legionella growth. To achieve this temperature, booster heating units are needed. | |
| Cooling production | Not possible | Supply network temperatures enable cooling for end customers. |
| Bidirectional energy exchange | Not possible | Customers and NTDH network suppliers can exchange thermal energy, thus achieving a bidirectional thermal grid. In the ideal case, heating and cooling demands in the network are balanced, thus no additional heating or cooling sources are needed. |

The thermal network should be connected to the thermal source, i.e., supply technology. There are different connection types between heat producers and networks: [23].

- Extraction from the return line and feed into the supply line (R/S) – Heat medium is extracted from the return line of the DH network, heated by the source, and then released in the supply line of the network.

- Extraction from the return line and feed in into return line (R/R) – Heating medium is extracted from the return line, then heated, and then released back into the return line of the network.
- Extraction from the supply line and feed into supply line (S/S) – Heat medium is extracted from the supply line, heated, and then returned to the supply line.

## 6.1 ULTDH networks

### 6.1.1 Temperatures

ULTDH networks are DH networks with a low-temperature regime that varies from 35-55°C in the supply line and 30-40°C in the return line. Low supply/return temperatures result in relatively small temperature differences in the network of 15-20 °C. The use of low-temperature regimes in the network usually results in larger pipe diameters for the same level of peak capacity, but at the same time, the insulation class can be reduced due to a smaller temperature difference concerning the environment. However, defining optimal supply temperature depends on numerous boundary conditions such as ambient temperature, thermal source temperature, supply technology, linear heat demand density, etc. It can be stated that supply temperature varies during the season, and it should be defined on the case study level by using detailed analysis.

ULTDH networks are mostly based on solar thermal, as expected for such temperature regimes. Sources for ULTDH networks could also be existing high-temperature DH networks or geothermal heat sources. ULTDH can use existing DH for heat source if they are connected with the supply/return line via shunt or heat exchanger.

### 6.1.2 Layout

There are two most common ULTDH network layouts:

- ring layout
- tree (mesh) layout.

Both layouts have some specific features. The most widespread network layout is a tree structure network where it is necessary to install balancing valves to equalize the flow and pressure at the entrance to consumer substations. Tree layout also uses network street circulation bypasses to keep network temperature above the minimum temperature setpoint. They simply mix water from the supply line into the return line. The result of them has increased return temperature which then causes increased heat losses.

To avoid valve installation and hydraulic imbalances when they are applied, a ring structure is used. To achieve hydraulic balance each consumer, have an equal length of pipes. The supply line begins with the heat source and ends with the last consumer in the network. The return line, in this network topology, begins with the first consumer and ends with a heat source. In this network typology, both supply and return flow have the same direction. Ring layout can achieve significant energy savings when supply water can flow through the whole network. On the other side, negative effects are higher pumping power (because of the increase of differential pressure), longer pipes, and installation of additional valves and pumps to balance flow in the network. Despite all that, heat savings are significant compared to tree layout.

### 6.1.3 Thermal and pressure losses

Losses of the thermal network losses depend on many factors, such as commissioning year, heat demand density, and temperature regimes. Furthermore, it depends on the pipe type and diameter, as well as insulation thickness and the temperature gradient between the pipe and the surrounding ground. Considering all the above, it is estimated that heat losses in ULTDH networks are usually lower than 10%. On the other side, pressure losses are higher.

Due to low supply and return temperatures, the temperature difference is rather low. Such temperature regimes demand an increased mass flow rate to establish the same level of thermal load. An increase in the mass flow leads to a velocity increase. This results in a high-pressure drop, leading to the higher pumping power needed which causes higher operational costs.

### 6.1.4 Substations

ULTDH networks are suitable for low-temperature SH, such as floor heating. However, they are too low for DHW production. Due to this, the ULTDH substation always includes a direct heat exchanger for SH purposes and a booster heater unit to provide temperature regimes that are suitable for preventing *Legionella* bacteria in the DHW system.

The development of ULTDH substations is the topic of many research studies. There are numerous reports dealing with the analysis of the most suitable ULTDH substations and there are many solutions that are proposed. There are four most installed ULTDH substations:

I. Solution based on booster HP combined with DH storage unit.

II. Solution based on micro booster HP.

III. Solution based on booster air-water HP.

IV. Solution based on booster boiler unit (electric, gas, or biomass boiler).

All the proposed solutions have similar common-basic characteristics:

- SH can be covered directly by using a direct heat exchanger, while DHW demand should be covered via a booster unit or additional heater.
- Substations must use boosting technology such as an electrical heater (simple solution) or booster HP (more com)
- Substation design is more complex since it includes DHW booster technology.
- Investment is increased due to booster technology.
- Bi-directional energy exchange with a thermal network is possible but limited.

## 6.2 NTDH networks

### 6.2.1 Temperatures

NTDH networks are DH networks with a low-temperature regime that varies from 12-20°C in the warm pipe and 8-16°C in the cold pipe. Due to this, NTDH can satisfy both the heating and cooling demands of the final customer. In the case of heating demand, the circulation pump of the building withdraws water from the warm line, uses it in an HP to reach temperatures suitable for SH and DHW, and then discharges the cooled water to the cold line. In the case of cooling demand, the system works in the other direction. It takes water from the cold line, heats it, and discharges it in a warm pipe. Due to this, the control of the system is rather complex. It is important to notice that booster heating devices are needed both for SH and DHW production. NTDH network is used as an HP source (in the evaporator) for heating and DHW or HP sink (condenser) for cooling. In case of low temperatures in the grid, cooling can be used directly, thus increasing the efficiency of the system. NTDH networks are mostly based on the ground, groundwater, and waste heat as the thermal source, as expected for such temperature regimes.

### 6.2.2 Layout

The NTDH network is divided into primary and secondary circuits to avoid direct heat exchange between the heat source and end-users. NTDH network can handle the different thermal loads of users at the same time:

- When a consumer uses a network for cooling purposes
- When a consumer uses a network for heating purposes
- When a consumer uses a network for both cooling and heating purpose.

Furthermore, the secondary circuit in the NTDH grid offers pre-heating, e.g., during the winter season when the thermal source temperature is too low. In this case, it is assumed that heating and cooling loads are in equilibrium. If this is not the case, it is necessary to integrate the loop with a heat rejecter (i.e., cooling tower or geothermal heat exchanger), heat supplier (i.e., boiler or geothermal heat exchanger), or energy storage. The important aspect to be considered is the number of final customers. The higher the number of simultaneous requests for heat and cold the greater the possibility to limit the temperature variation of cold ring water.

### 6.2.3 Thermal and pressure losses

Thermal losses of NTDH are smaller than in ULTDH networks. For the network operating at 10°C, they are about 2% of the supplied energy. The additional advantage is that NTDH networks require lower piping insulation, which reduces investment costs. Reduced thermal losses are one of the most important aspects of using NTDH networks. This enables the reduction of operational costs and enables savings which could be used for additional investments needed in the grid.

### 6.2.4 Bidirectionality

Bi-directional thermal energy exchange between final customers and the network is the most important advantage of NTDH networks. It allows thermal energy recycling and minimizes external energy supplied to the network. Bi-directional NTDH networks provide a cost reduction (investment and operational cost) and could cause less $CO_2$ emission compared to the individual HVAC networks. Bi-directional NTDH networks have complex and challenging control which finally enables lower electricity consumption due to the higher COP values. The important aspect to model control networks for bi-directional NTDH is the ratio of heating and cooling demand. The ratio of heating and cooling demand is important for the planning of the network.

Bi-directional NTDH networks are excellent for networks with similar heating and cooling demands. In that case, the network can be used for demand balancing. Also, it is worth mentioning that the utilization of all available waste heat sometimes is not profitable since it raises network temperature and diminishes the cooling capacity of the network. It has been shown that cooling towers are an economically feasible option since they increase the flexibility of the system.

### 6.2.5 Reservoir network

Another specificity that NTDH networks can offer is that they use only one pipe in their network, such networks are also called reservoir networks, which enable simultaneous heating and cooling. The biggest advantage of reservoir networks is that they need only 50% of the pipe length. For this reason, it is economically feasible to increase pipe diameter. Although there will be an increase in the diameter of the pipe, the reduction in the length of the pipeline will still have an economic advantage and the targeted effect will be achieved.

### 6.2.6 Potential issue

The physical and chemical water properties of the NTDH network are a crucial issue, especially when the thermal source is circulating directly in the network. For this reason, secondary and primary circuits in NTDH networks should be used. High levels of hardness and/or contaminant concentration may result in a high risk of clogging and/or damage to the pipeline components, like valves or heat exchangers.

One of the challenges in bidirectional networks is managing complicated hydraulics. Bi-directional networks have specific control challenges such as pump-to-pump interaction. The problem also occurs in the case of prosumers of different sizes – large prosumers affect mass flow through small circulate pumps of other prosumers. This can sometimes reverse flow, freezing damage in HPs, or even cavitation in the circulation pumps.

### 6.2.7 Substations

NTDH substations must be capable of providing temperature boost both for DHW and SH. The most common technology used is a water-to-water booster HP in different configurations. Besides SH and DHW, NTDH networks can also supply space cooling and substations should also be designed in that manner. Space cooling can be covered directly via a heat exchanger from a cold pipe or by using a booster HP and NTDH network as a heat sink.

There are three most used NTDH substations:

I. Solution – water-to-water booster HP is connected to the thermal network to provide heating and cooling.

II. Solution – redundant heat exchanger used between thermal network and booster HP.

III. Solution – the most complex solution and involved two diverter 3-way valves on the primary loop. This enables to rejection of separately hot water in the warm pipeline and cold water in the cold pipeline, avoiding thermal mixing within the network.

All the proposed solutions have similar common-basic characteristics:

- Both SH and DHW demand cannot be covered directly due to low-temperature regimes in the thermal network. Boosting technology, such as HP is needed.
- Substations are usually based on water-water HPs with relatively high COP due to small temperature differences between the heat source and heat sink.
- Substations are relatively complex, resulting in high investment.
- Operation is relatively complex, and the thermal network operator usually must be responsible and is the owner of the equipment.
- Low operational cost due to high COP of HP

- Possible to cover the cooling demand.
- Bi-directional energy exchange with the thermal network is possible.

NTDH substations are more complex and bigger than traditional DH networks. First, they require booster technology, usually an HP. Secondly, due to low-temperature regimes, the temperature drop across heat exchangers is relatively low which requires a high heat exchange surface area for the same level of heat demand. Thirdly, these networks usually need cold and/or hot water thermal storage. All of this can become a crucial issue since additional space in the building should be reserved. This is quite problematic for existing buildings that are connecting to the NTDH network.

# 7 Overview of existing next generation DHC networks

For this deliverable, 124 existing DH networks have been analysed concerning thermal source type and temperature regimes. The database [30] is publicly available on the Zenodo platform, on this link.

An overview of thermal sources used in NTDH networks is shown in Figure 6. The most used sources in NTDH are ground and groundwater is the most used. However, temperature regimes of the network allow large-scale utilisation of waste heat sources. Around 20% of the studied existing networks are utilising waste heat sources. Besides ground and groundwater, solar is also one of the most frequently used renewable energy sources.

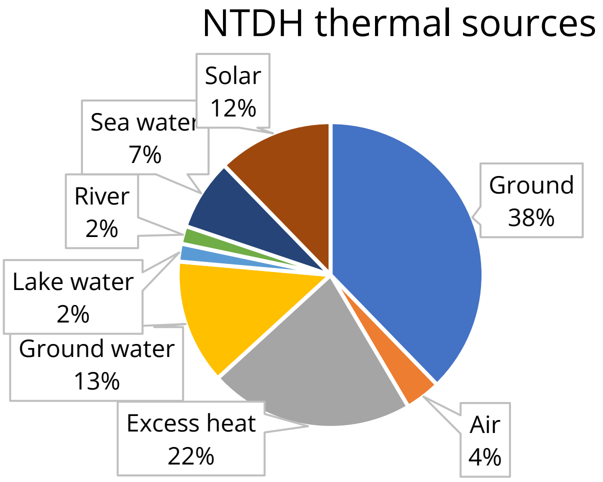

*Figure 6 Overview of thermal sources in existing NTDH networks*

Figure 7 shows the most used thermal sources. ULTDH networks are mostly based on solar thermal collectors with a 60% stake in total analysed ULTDH networks. This is expected considering UTLDH temperature regimes. Then follows geothermal energy (with a 20% stake) and existing DH as a heat source (with a 20% stake).

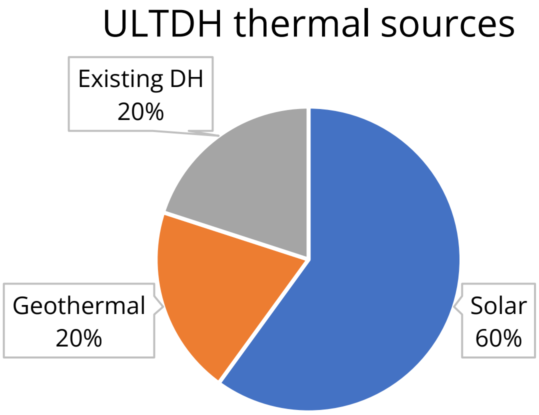

*Figure 7 Overview of thermal sources in existing ULTDH networks*

# 8 SWOT analysis

In this section, different system components are analysed and discussed by using SWOT analyses. System components that are observed:

- DHC End-user substation – End-users substation is component which is usually located in the building of the final user. Substation is used to connect primary (thermal network) and secondary (building) thermal circuit. End-user substations are used to cover space heating (SH), domestic hot water (DHW) and space cooling (SC) demand. The type of end-user substation is directly related to temperature regimes in the thermal network. Due to this, in this analysis three substation types are defined: LTDH, ULTDH and NTDH substations. Additional details on end-user substations can be found in deliverables D4.1 - Configuration and sizing of Package Substations and D4.2 - Prefabricated skids. In this Handbook eight different types of end-user substations are presented, four for the ULTDH networks, and four for NTDH networks.
- DHC network topologies - A DHC system can have different DHC networks topologies. In this Handbook four most used topologies are presented.
- DHC sub-networks – DHC system can have several subnetworks which have different temperature regimes correlating connected final customers. In that case, we are talking about thermal sub-networks. In this Handbook, two different DHC sub-networks are presented.

These system components can be combined in numerous different ways and for every possible combination the SWOT analysis is carried out and presented. System components schemes and different types of coupling can be found on the Zenodo platform, on this link.

## 8.1 End-user substations

*Table 3 SWOT analysis for different types of the end-users substations*

| ULTDH substation – booster heat pump and district heating storage unit | ULTDH substation – micro booster heat pumps | ULTDH substation – other booster technology (e.g., air heat pump) | ULTDH substation – other booster technology (e.g., boiler) | NTDH substation – BHP for DHW and SH, SC directly | NTDH substation – BHP for DHW and SH, SC as a heat source for DHW BHP | NTDH substation – reversible heat pump for SH/DHW and SC | NTDH substation – booster heat pump for SH/DHW and heat pump for SC |
|---|---|---|---|---|---|---|---|
| Strengths<br>Single HP per building<br>Flexible and central DHW production<br>Reduced cost (BHP economy of scale)<br>Weaknesses<br>Space demanding (building substation)<br>Lower booster HP COP due to higher temperature in TES needed<br>Opportunities<br>Easily replaceable with different technology | Strengths<br>Low-temperature lift, due to low water stagnation, results in high COP<br>Low-space consumption<br>Weaknesses<br>Every apartment needs booster HP<br>Investment cost intensive<br>Opportunities<br>Low operational cost and low vulnerability to electricity tariffs<br>Threats<br>Difficult to replace | Strengths<br>Simpler system planning<br>Utilisation of well-established technologies<br>Weaknesses<br>The thermal network is not utilised as a heat source (lower system COP)<br>DH connection and additional supply technology are needed (high investment)<br>Opportunities<br>Booster technology could also serve as a back-up technology if the DH network is under retrofit | Strengths<br>Simpler system planning<br>Utilisation of well-established technologies<br>Local energy tariffs could be utilised (e.g., if biomass is locally available)<br>Weaknesses<br>The thermal network is not utilised as a heat source (lower system COP)<br>DH connection and additional supply technology are needed (high investment)<br>Opportunities | Strengths<br>Single BHP for DHW and SH<br>Space cooling directly<br>Weaknesses<br>A low temperature of return is needed for direct space cooling<br>Return temperature must be low enough to cover direct cooling<br>Opportunities<br>Simultaneous heating and cooling is possible (however rarely used) | Strengths<br>Heat recycling on-site<br>Building-level system COP is relatively high<br>Only one BHP needed<br>Weaknesses<br>Space cooling is possible only with DHW production<br>DHW BHP performance is reduced since the heat source is at a lower temperature than the network<br>Opportunities - The space cooling system could be easily upgraded | Strengths<br>High COP both for heating and cooling - Network serves as a heat sink and heat source<br>Weaknesses<br>Not possible to cover heating and cooling simultaneously - Reversible HP needed<br>Opportunities<br>TES could be added to increase flexibility<br>Threats<br>DHW operation is needed throughout the whole year, this | Strengths<br>The most flexible NTDH substation - High COP for both BHPs<br>Weaknesses<br>High investment cost<br>Additional space requirements<br>Opportunities<br>Suitable for large facilities with different simultaneous demands<br>High level of bi-directionality in the network<br>Threats |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Flexible production could utilise low electricity tariffs<br>Threats<br>Water stagnation (high temperature needed)<br>DH network reduction influences BHP COP | | Threats<br>Operational cost depends on the booster heat source (on the other hand DH temperature regimes are guaranteed) | Booster technology could also serve as a back-up technology if the DH network is under retrofit e.g.<br>Easily replaceable with other technology<br>Threats<br>Operational costs depend on the energy tariffs of the used fuel (e.g., natural gas) | Could be upgraded from existing ULTDH<br>Threats<br>Booster HP COP could be reduced due to network temperature constraint | with additional BHP if needed<br>Threats<br>DHW and SC demand should be simultaneous and balanced | could represent an issue | No on-site recuperation<br>High O&M costs (2 BHPs) |

## 8.2 Thermal networks

*Table 4 SWOT analysis for different types of thermal networks*

| Thermal network – 2-pipe "traditional" network | Thermal network – 4-pipe network for SH/SC and DHW | Thermal network – 6-pipe network for SH, SC and DHW | Thermal network – 1-pipe network for SH, SC, and DHW (reservoir network) – the research phase |
|---|---|---|---|
| Strengths<br>Only two pipes<br>Simple operation and regulation<br>Weaknesses<br>Issues for networks with different users (different temperature regimes)<br>Cooling is possible only with NTDH networks, or if there is no DHW during the summer<br>Opportunities<br>Temperature regime reduction is relatively easy if follows building refurbishment trends<br>Threats<br>Potentially high thermal losses | Strengths<br>Flexible<br>Reduced thermal losses<br>Heating and cooling modes possible<br>Weaknesses<br>Increased investment<br>Pressure losses issues if heating and cooling demands are not appropriately planned<br>Opportunities<br>System upgrade is relatively easy since DHW is separated<br>Threats<br>System operation could be challenging<br>Network refurbishment could be costly | Strengths<br>The most flexible network<br>Booster units can be optimised for each thermal demand<br>Weaknesses<br>High investment<br>Spacing in the ground needed<br>Opportunities<br>Suitable for all users, network expansion is relatively easy<br>Threats<br>Refurbishment could be expensive | Strengths<br>Reduced investment<br>Suitable for all thermal users<br>High prosumer capabilities<br>Weaknesses<br>Pressure issues (prosumers)<br>Grid operation is relatively complex, the grid operator is „balancing" thermal needs<br>All users need booster units<br>The network is in the research phase<br>Opportunities<br>User-grid interaction is increased<br>If users are balanced, there is little-to-no energy supply needed<br>Threats<br>The grid is still only in the research phase<br>Users should be relatively balanced |

## 8.3 Thermal sub-networks

*Table 5 SWOT analysis for different types of thermal sub-networks*

| Thermal sub-network – traditional DH system serves as a heat source for LTDH/ULTDH/NTDH network | Thermal sub-network – NTDH serves as a heat source for LTDH/ULTDH network |
|---|---|
| Strengths<br>High-temperature DH networks are almost always available<br>Heat supply is possible without booster units between the networks<br>Weaknesses<br>Temperature regimes should be carefully selected<br>Networks should operate simultaneously<br>Opportunities<br>Several subnetworks can be developed and expanded at the same time, depending on the available thermal network capacity<br>Threats<br>Shunt connections are relatively complex and could cause pressure issues in the grids | Strengths<br>Reduced thermal losses for ULTDH/LTDH customers - No booster substations needed for LTDH network - Higher COP for BHP in ULTDH networks<br>Weaknesses<br>Planning the network is challenging<br>Thermal networks must be balanced<br>Central BHP must be carefully selected<br>Operation of the grid is challenging<br>Opportunities<br>Simultaneous user expansion for NTDH and LTDH/ULTDH users<br>Threats<br>Grid expansion could be a challenge since network capacities must be aligned |

# 9 Economical, energetic, and environmental analysis

This analysis is given a short overview of NTDH, ULTDH, and LTDH networks, as well as their main components. Also, it shows the techno-economical calculation of assessing the cost and benefits of these networks. Next-gen DH networks are expected to supply lower temperatures to increase system efficiency and enable the exploitation of renewable heat sources. To answer whether it is beneficial to lower DH temperatures below the level where it is still possible to supply DHW directly, the economic feasibility of ULTDH and NTDH concepts have been analysed and compared to LTDH networks. The possibility of SC was also considered during the analysis.

For this purpose, building plot ratio and SH share were varied together with different system topologies. The different solutions were compared based on the levelized cost of heat, primary energy factor, and carbon emission factor. This analysis showed that NTDH and ULTDH are suitable for relatively high SH shares and high plot ratios, which are characteristic of urban areas with high energy-effective buildings.

The modelling used in this analysis is based on the paper [31]. The method has been upgraded to calculate $CO_2$ emissions and primary energy factor (PEF) as shown in the master thesis [32]. The used model is publicly available on the Zenodo platform, on this link.

Different scenarios and their characteristics regarding network type, heat source, utilization unit of central heat source, DHW, SH, and SC substations in the building were analysed. Source temperatures for groundwater were 12°C – 7°C. Excess heat cases had 40°C, 30°C, and 20°C supply temperatures which were cooled to 10°C in the central unit. Air was considered an infinite heat source that does not change the temperature in the HP. DHW temperature is always needed to be raised to 60°C, from 20°C portable water.

## 9.1 Economic analysis

Different scenarios regarding SH share and Plot ratios through LCOE are analysed. In this deliverable, the results for medium energy efficiency buildings (SH share equal to 0.45) and medium density cities (Plot ratio equal to 1) are presented, as shown in Figure 8. Other scenarios can be found in the full version of the D2.1 REWARDHeat Planning schemes and at the Zenodo platform, on this link.

From Figure 8, it can be concluded that the most inconvenient option in this scenario is the use of the ULTDH network in combination with micro HPs, ULTDH_Micro_ASHP. Particularly unsuitable are networks that use HPs in the central units whose heat source is outside air. In decentralized units, such networks use heat exchangers for heating, while micro HPs are used to heat DHW. The amount of LCOE for ULTDH with micro HPs is 147 €/MWh. In contrast, NTDH networks that utilize waste heat at a temperature level of 30°C have proven to be the most suitable option in this scenario, especially NTDH_Booster_EH2HEX_cooling. In the central unit, these networks have a heat exchanger since the temperature of the source is higher than the temperature of the DH network, and in the central unit, they use a booster HP for SH and preparation of DHW. The LCOE for NTDH_Booster_EH2HEX_cooling is 51 €/MWh, most of this cost is coming from investment costs (CAPEX) in the network of this decentralized unit, i.e., booster HP.

In general, it can be noticed that the most unfavourable option is the networks used in the central units as a source of outdoor air or groundwater to operate the HP, while the decentralized units use micro-HP. It turned out that such networks have high investment costs (CAPEX) in central and decentralized units, but also high operating costs (OPEX) in these units. NTDH networks appear to be the most favourable option, especially networks that utilize waste heat in central networks using heat exchangers. In the decentralized unit, such networks use a booster HP to achieve a temperature suitable for heating and preparing DHW.

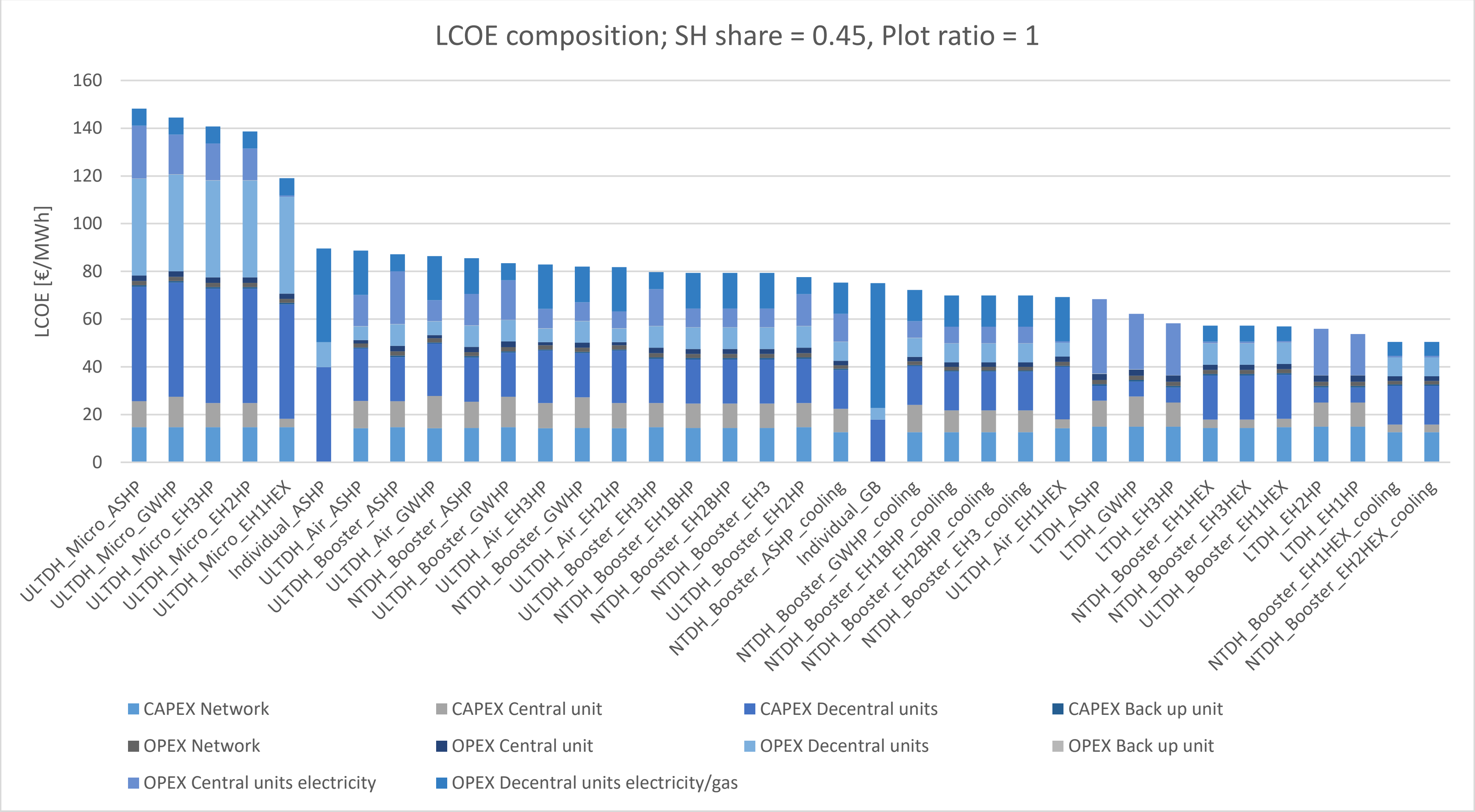

*Figure 8 LCOE composition for NTDH, ULTDH, LTDH, SH share = 0.45, Plot ratio = 1*

## 9.2 Energetic and environmental analysis

The PEF and CEF analysis were performed, as well as the LCOE analysis, for the different SH share and Plot ratio scenarios. In this Handbook the results for medium energy efficiency buildings (SH share equal to 0.45) and medium density cities (Plot ratio equal to 1) are presented, as shown in Figure 9. Other scenarios can be found in the full version of the D2.1 REWARDHeat Planning schemes and at the Zenodo platform, on this link. Analysis of the primary energy factor has been conducted for each DH configuration (for different central sources) and each central heat source in different network configurations. The figures show how CEF monitors PEF, and it can be concluded that if we consume more primary energy, more $CO_2$emissions are released into the atmosphere. All networks have lower $CO_2$ factors than individual gas boilers $CO_2$ factor. As in previous analyses, each system configuration is evaluated for different central units. Also, each central unit is analysed for different system configurations.

Figure 9 shows that the individual gas boilers and networks that use HP in the central unit whose heat source is outside air proved to be the most unsuitable networks with the highest amounts of PEF and CEF. The maximum amount of PEF and CEF for individual gas boilers will be 1.2, i.e., 0.23, which is in line with expectations since gas has a higher carbon emission factor than electricity. LTDH_ASHP networks follow with PEF 0.62 and CEF 0.090. The most suitable networks proved to be the NTDH and ULTDH networks which show low amounts of PEF and CEF. The reason for this lies in the fact that they use waste heat whose temperature class is above the DH network temperature, which enables the use of heat exchangers, thus reducing the use of electricity, which reduces the amount of PEF and CEF. The most suitable solution is NTDH_Booster_EH2HEX_cooling whose PEF is 0.088 and CEF 0.012. This system utilizes waste heat at a temperature of 30°C using a heat exchanger in the central unit, while the decentralized unit uses a booster HP to heat the heating water and DHW. This system also enables the realization of the cooling effect.

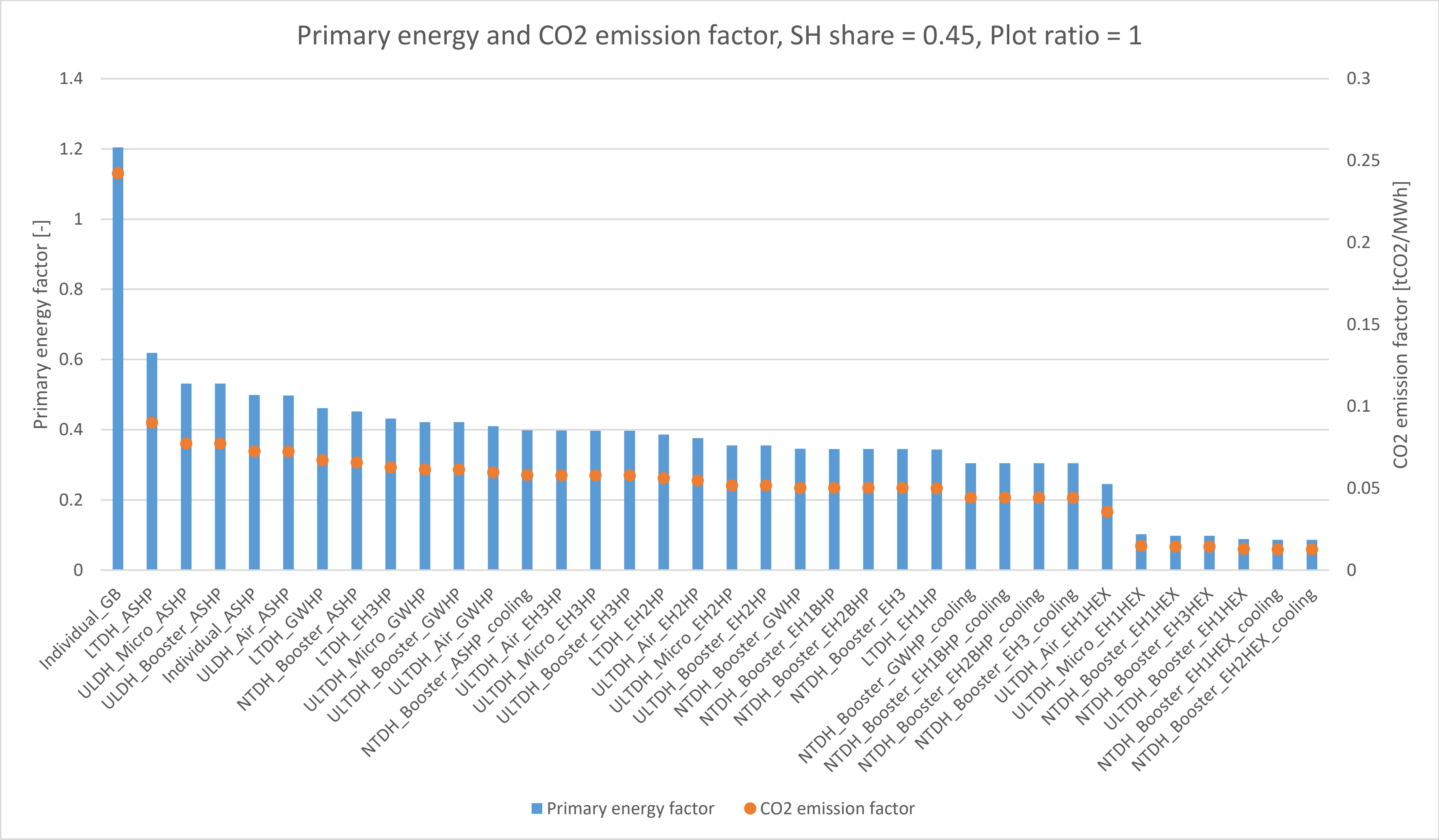

*Figure 9 Primary energy and CO2 emission factor for NTDH, ULTDH, LTDH, SH share = 0.45, Plot ratio =*

# 10 PESTLE analysis

The following can be said as a summary of this analysis. In terms of Policy, next-gen DHC networks such as ULTDH and NTDH have a strong foothold in plans and strategies at the EU level, but also at national levels.

There is strong Political will on the EU level which support decarbonisation of DH and cooling networks, implantation of low-temperature networks, and integration of available waste heat. Usually, this also translates to national energy plans and strategies. This means that ULTDH and NTDH networks are a technology that has political support. However, national-level DH strategies are usually focused on the decarbonisation and refurbishment of existing high-temperature DH networks.

Economic analysis of ULTDH and NTDH prove to be cost-effective options with low LCOEs, subject to two essential conditions. The first condition is that ULTDH and LTDH networks are suitable for areas with high population density with high heat needs, while on the other hand, the buildings of such areas have good energy characteristics, which is also the second condition. Economically comparing ULTDH and NTDH networks, NTDH networks prove to be better due to lower LCOE because of lower investment and operating costs and lower PEF and CEF.

From the Social point of view, the problem of insufficient information and lack of knowledge about the advantages of ULTDH and NTDH stakeholder networks was recognized. NTDH differs in the sense that society does not recognize the potential or does not know about it that such networks can be used for centralized cooling.

Technical analysis has shown that the technology for the application of ULTDH and NTDH networks exists and is already used for various purposes. ULTDH and NTDH networks in central stations can use heat exchangers or HPs depending on the heat source. On the other hand, ULTDH and LTDH substations differ significantly although they both use heat exchangers and HPs. The main difference is the additional subsystem in NTDH networks due to the possibility of cooling. The main technical problem of ULTDH and NTDH networks is buildings with poor energy performance. Since ULTDH and NTDH are characteristic of urban areas that are mostly old in Europe, before the application of these networks it is necessary to renew and adjust the stock of buildings ULTDH and NTDH networks.

Analysis of the Legal documents shows that before the wider application of ULTDH and NTDH, it will be necessary to regulate property legal relations in terms of rights and obligations related to substations, i.e., who will oversee maintaining and managing more complicated designs of thermal substations.

Environmental analysis has shown that ULTDH and NTDH networks reduce PEF and CEF, which shows that these networks are in line with environmental policies at the EU level, but also at national levels. These networks will contribute to reducing the need for primary energy, which will result in a reduction in pollutant emissions. The reason for this is that such networks use less carbon-intensive energy sources, i.e., electricity. By comparing ULTDH and NTDH networks, NTDH networks showed better results in PEF and CEF amounts although the differences in amounts are small.

# 11 Conclusions

This Handbook was developed as part of WP2 - Design of low-temperature networks with multiple energy sources and it represents a shorter version of the D2.1 – REWARDHeat planning schemes database which can be found on the link. The Handbook serves as the knowledge database for next generation DHC networks, i.e., ULTDH and NTDH networks which can be found on the following link.

The Handbook provided s short literature overview of research papers and best practice examples related to ULTDH and NTDH networks while focusing on thermal sources, supply technologies, thermal networks, and end-user substations. Then, the overview of existing next-generation networks has been presented and analysed with the respect to temperature regimes and used thermal sources. Based on the carried-out literature review and existing cases, the database of NTDH and ULTDH system components has been developed: end-user substations, thermal networks, thermal source, and thermal source connection configuration. SWOT analysis of different components has been carried out and a comparison with "traditional" low-temperature DH networks has been provided. Afterward, more than 30 ULTDH and NTDH system topologies have been defined and analysed concerning energy performance, total cost, and carbon emissions. Different boundary conditions, such as plot ratio and space heating share, have been considered. Obtained results have been ranked and compared with traditional LTDH networks and individual solutions such as air-source HP and natural gas boilers. For this purpose, already mentioned Excel-based calculation tools have been used. It has been shown that ULTDH and NTDH networks have lower costs than individual solutions in dense urban areas (high plot ratio) and lower carbon emissions, including the primary energy factor. Finally, PESTLE analysis of ULTDH and NTDH networks has been carried out and presented concisely.

This Handbook serves for quick literature and general information overview and it may serve for knowledge transfer and dissemination of next-gen DH networks.

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