Brno’s review of practices: Smart Thermal Grid

Jiří Pospíšil, Jan Fiedler, Pavel Charvát, Libor Kudela, Jiří Hejčík, Zdeněk Skála

September 2018

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 731198. The sole responsibility for the content of this document lies with the RUGGEDISED project and does not necessarily reflect the opinion of the European Union.

Contents

Nomenclature

DH	district heating
NOx	nitrogen oxides
PMx	particulate matter of particles with x micrometres in diameter
CHMI	Czech hydrometeorological institule
AC	absorption cooling
EPBD	Energy Performance of Buildings Directive
DC	district cooling
CHP	combined heat and power
HP	heat pump
LTDH	low temperature district heating
4GDH	4th generation of district heating
RES	renewable energy sources
CO2	carbon dioxide
HTDH	high temperature district heating
LTC	low temperature customer
COP	coefficient of performance
DHW	domestic hot water
PHA	private housing association
PS	Spitalka plant
PV	photovoltaic

1 Short summary of the study's content

The systems of the district heating have a long history in the Czech Republic. In spite of this, due to technological, economic and legislative changes, central heating has reached the limit of sustainability. However, the concept of district heating offers a number of benefits that are irreplaceable for urban agglomerations, although economically difficult to quantify. In this context, it is important and appropriate to properly assess the possibilities of implementing the Smart Thermal Grid concept. The future operation of heating networks requires changes that respect the current situation and the new demands of both the consumers and potential heat energy producers.

Based on the aforementioned reasons, the presented research was composed to introduce the current trends and innovative solutions in district heating and cooling systems. Selected pilot projects and interesting prospective studies are presented here. For heat supply in Brno, the presented material describes and assesses the possibilities of transferring examples of pilot projects and the potential use of innovative solutions. A specific design of heat supply is presented for the Spitalka development site located in the central part of Brno.

2 The current importance of heat supply

The heating industry is an energy sector that ensures, in particular, the production, supply and distribution of heat energy. Historically, the heating industry has developed in line with rising demands for heat supply due to the growth of urbanisation and industrialisation. From the original local heating in small boiler houses for individual houses or a group of houses and industrial boiler rooms, they gradually moved to centralised district heat (DH) supply systems. Using several central sources connected by the distribution system of heat, different district heating plants and industrial consumers are supplied at a distance. In central heat sources, both thermal and electrical energy is produced, which is also referred to as cogeneration.

The development of the current heating industry is the result of a number of market, technological and legislative parameters. From the customer's point of view, there is a market offering various available technologies that can deliver heat with the required comfort. However, the individual technologies differ regarding economic parameters and impacts on the environment. In this sense, it is necessary to consider and plan the conceptual utilisation of the heating network under the given conditions.

Heat industry is a one way of reducing the negative effects of using energy sources on the environment, especially by saving primary fuels compared to separate production of electricity and heat. This fact is indisputable, but it does not in itself guarantee the economic advantage of operating a heating network. With regard to air purity in urban areas, another obvious positive feature of district heating plant is the absolute reduction of pollutants by centralisation of combustion sources and subsequent cleaning of discharged combustion products with an assumption of better output emissions monitoring. The central sources emit the flue gas into the higher levels of the atmosphere, making it possible to reduce the air pollution in the inhabited ground-level of the atmosphere.

On the other hand, there is now a modern trend of getting the customer closer to the source and minimising losses in heat distribution. This trend leads to the construction of decentralised heat supply systems, whereby thermal energy is produced at the point of consumption, thus eliminating the need for transport and heat distribution. A source of heat can be any heat source, including combustion devices for any fuel (fossil or biofuel). From an environmental point of view, however, different fuels for decentralised sources in urban areas are not suitable. This is due to the pollution of the site because of scattered emissions from low chimneys and insufficient ventilation of the ground air layer.

In this context, attention is currently paid to the emission of particulate matter, fine particles leaving the combustion processes (particulate matter), NOx and polyaromatic hydrocarbons. Fine particles with a size of fewer than 10 microns are now very often discussed with regard to their health impacts. The emissions of these particles in the urban atmosphere come mainly from local heaters and road transport.

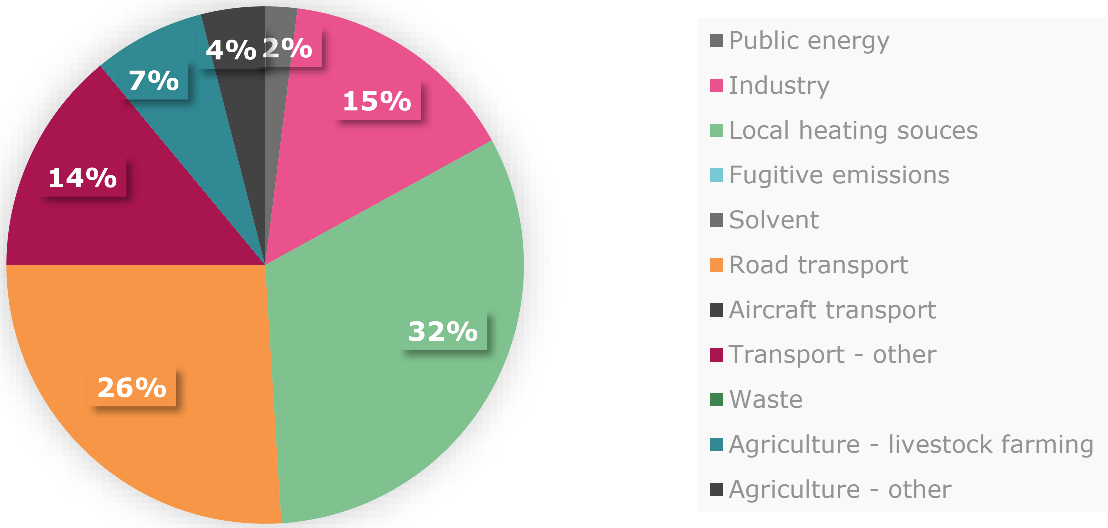

Fig. 1 Emission balance of PM2.5 fine particles in the South Moravian Region in 2015 (Source: CHMI)

In addition, however, there are local sources of heat that do not emit any pollutants at the site, so they are environmentally friendly and fit into locations that are subject to increased pollution loads in much the same way as DH. These are all sources based on electricity heating (heaters, accumulators, hybrid sources), and more recently HPs.

The current situation of heat supply is based on a wide range of available resources, with the anticipation of the integration of a larger number of smaller sources and unstable renewable sources. In this area, in the future, there is a great room for the application of new management and monitoring technologies in the field of Thermal Smart Grids.

The demand for heat supply is influenced by the thermal and technical properties of buildings and the manner of their operation. From this point of view, there is a long-term trend towards reducing the energy performance of buildings, which leads to a reduction in heat demand requirements. The heating networks become excessive during this development, which reduces their economic efficiency and ultimately leads to an increase in the price per unit of heat. This enhances discussion over DH's meaningfulness and can lead to subsequent disconnection of customers.

Development, however, does have not only a side of energy consumption but also a side of energy production. In the case of the joint production of electricity and heat, many heating plants have long-term contracts for the provision of system services in power generation. These contractual relationships affect the operation times of heat sources that do not have to meet the heat demand requirements. In this case, the heating systems are supplemented by suitable storage technology for the preservation and subsequent release of heat energy. Heat accumulation is used in heating systems in recent years for direct water heating by electric energy (electrode boilers) at moments of surplus electricity in the transmission system. Heat sources and systems are also used in some cases for the subsequent production of cold using absorption cooling (AC). These systems can be complemented by a cold-water distribution, made with cold water at temperatures of 6 °C/12 °C.

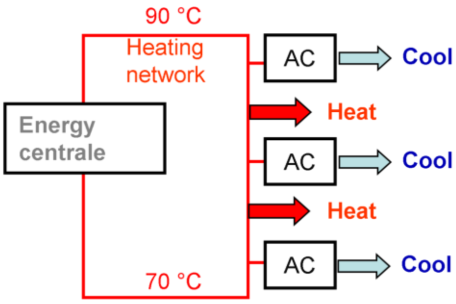

Fig. 2 Heat distribution diagram complemented by the production of cold

At present, in the Czech Republic, if we also count domestic boiler rooms, roughly 49% of the population is supplied with heat from a source outside the apartment. This heat is made by roughly two thirds of coal, the remaining third is gas. For the future, we plan to balance these two resources. It is assumed that for sources that only serve as heating plants, the price of heat will increase with the rising cost of fuel. On the contrary, for cogeneration sources, the rising fuel price could be compensated by selling electricity at a higher price. Heat sources are therefore prospective in terms of heat prices in the future. The serious danger of the economy of centralized heat supply systems is loss in distribution and the cost of building and maintaining heat distribution. Incorporating these costs into the final heat price causes the resulting price to be close or even higher than local heat sources. Further development of the heating industry is closely related to other energy sectors (e.g., system services). Gas (and cycle gas) heat sources are valued for their ability to regulate power at fluctuations in the power grid. The situation in the heating industry is also dependent on breaking the mining limits in the Most basin area.

Renewable sources are currently playing a major role in the heating industry. The Czech Republic has pledged to produce 20% of gross electricity in the combined production in 2020. In 2011, the share of combined energy production was 12.8% of total gross production in the Czech Republic. In the coming years, therefore, the objective is to increase the production of electricity from cogeneration. This is also due to a significant increase in the efficiency of primary fuel consumption compared to separate heat and power generation.

From the overview above, it is clear that the operation and further development of the heating networks is a complex issue and it is necessary to judge the individual cases in relation to a particular location. The conceptual decision should be made on the basis of a comprehensive study with clarification of the preferences. A good source of developmental suggestions may be examples that were implemented in other cities, which must always be considered with regard to regional specifics, and their application is only possible after detailed technical consideration with circumspect modification to the local situation. This work contributes to this aim, summarising the current state of the heating plant development. The study also presents examples of the implementation of innovative heat technology acquired from available literary sources. At the end of the study is presented the proposal of an innovative way of supply of heat for location Spitalka, Brno.

3 Trends in the world and Europe in centralized supply of heat and cold

3.1 Decreasing heat demand

The Czech Republic's energy management legislation is increasingly influenced by the European Union's common policy in this area. The first version of the Energy Performance of Buildings Directive (EPBD) 2002/91/EC was approved in 2002. Following this directive, changes have been made to national regulations. The most significant changes in the Czech Republic were the introduction of an energy performance certificate for buildings and regular inspections of boilers and air-conditioning units. After its redesign in 2010, the Energy Performance of Buildings Directive introduced even more stringent requirements for reducing primary energy consumption in buildings. Under Article 9 of this directive, EU Member States are to ensure that *"by 31 December 2020, all new buildings are nearly zero energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings."* Zero energy consumption is related to the non-renewable primary energy consumed for the operation of the building (heating, cooling, ventilation, hot water). Almost zero consumption of primary non-renewable energy is to be achieved by the thermal resistance of building structures and the integration of renewable energy sources. Buildings with near-zero energy consumption have significantly lower primary energy consumption than the current average use of existing buildings. It can be expected that the implementation of these regulations will reduce the average energy consumption per unit floor area. On the other hand, reducing energy consumption per unit of floor space allows the use of low-temperature heating systems. Low-temperature heating systems in buildings allow the use of heat from return heating networks of DH.

3.2 Extension of DH in Europe

[1] dealt with the issue of the primary energy factor in DH in the Member States of the European Union. Primary non-renewable energy consumption is used in the EU to assess the energy performance of buildings. The heat source type for DH has an impact on the energy performance of buildings using heat from DH. In the EU, there are significant differences in both the number population using heat from DH and in determining the primary energy factor in DH. According to the data presented, over 60% of the population in Latvia, Denmark, and Estonia use DH while in the United Kingdom, Belgium, and Luxembourg it is less than 5%. Regarding the determination of the primary energy factor, the authors consider an inappropriate way of using one fixed value of the primary energy factor for all DH systems. Such an approach does not take into account heat sources in individual DH systems or waste heat utilisation, and thus does not create incentives for DH system owners to reduce primary energy factor.

3.3 Evolution of electricity, heat, and cold consumption in the EU

[2] conducted an analysis of the need for electricity, heat, and cold in 28 EU countries. In 25 out of 28 countries, heat consumption is currently higher than electricity and cold consumption. The need for heat outweighs the need for cold in all 28 countries and therefore also in mild-temperate countries such as Spain, Italy, Croatia, Greece, Malta, and Cyprus. The author, based on various literary sources, expects that the need for electricity will gradually increase, while the need for heat will decrease. The cold consumption in Europe is currently low and can be expected to increase as the population's demands on the thermal comfort of the buildings increase.

3.4 Low-temperature DH systems

[3] presented a study of 18 houses in Denmark built in the 1980s. The study included simulation using IDA ICE tool and verification of data from four houses. The houses were heated by heat from a central heat supply network with heating medium with a temperature of up to 45 °C for most of the year. An existing heating system with radiators heated the houses. DH heating and electric heating were used to heat hot water. The authors concluded that there is considerable potential for combining existing

heating systems with radiators and low-temperature central heat supply. In the study, the average annual heating water temperature in the heating system was 44 °C and the return water temperature was 31 °C.

3.5 Analysis of cold supplies

[4] carried out an analysis of cold supply to service buildings in twenty central cold supply systems in eight countries in Europe. Based on these data and other assumptions, he estimated the energy performance of cooling commercial and residential buildings in individual countries in Europe. In the case of the Czech Republic, the need for cooling of buildings in the service sector 64 kWh/m^2 per year and, in the case of residential buildings, 26 kWh/m^2 per year.

3.6 Development of central cold supply

[5] addressed the potential cooling demand in Europe. Energy consumption for cooling in buildings (mainly residential) increases faster than total electricity consumption or heat consumption. Nevertheless, it is significantly lower than the US. The authors used several assumptions in their analysis. One of them was that under the same climatic conditions the cooling requirements would be approximately the same. This comparison was based on data for the US, where residential cooling is widespread, and assumed that in the future cooling requirements in Europe could be close to US requirements under the same climate conditions. The analysis was carried out for all 28 EU member states. In the case of the Czech Republic, the expansion of cooling to 54.8% of residential buildings was estimated, which would represent an increase in cooling energy by 2.23 TWh per year. Since all air-conditioning systems in residential buildings are powered by electricity, additional power sources have to be installed and power transmission systems enhanced. In the case of the Czech Republic, additional installed power generation output was based on 1.14 GW. The authors also addressed the possibility of centrally supplying cold, which could reduce the demand for both power generation and distribution. The European Union devotes considerable attention to the use of DC. There is no need to use electricity to produce cold with DC, but other energy sources, including waste heat from industrial processes, can be used. The contribution of DC depends on the percentage of the population living in urban areas, which changes significantly in the EU, from almost 100% in Malta to about 70% in Belgium to about 11% in Romania and Slovakia.

3.7 Heat and cold supply in Sweden

[6] published an overview of central heat and cold supply in Sweden. The first DH system was put into operation in Sweden in 1948 and the first DC system was created in 1992 in connection with the ban on the use of freon refrigerants. The author states that DH's market share in heat supply was 55% in 2014, with DH's biggest competitor being HPs with a share of about 25%. In 2014, in Sweden, 93% of dwellings in apartment buildings were connected to DH. In 13 percent of cases, homes connected to DH also used heat from local HPs. As far as DH heat sources are concerned, there has been a significant shift from fossil fuels in Sweden over the last 40 years. In 2015, 46% of the heat came from biomass burning and 24% of the heat came from waste incineration. The proportion of fossil fuels was only 7% and was lower than the excess heat from industrial processes, which was 8%. For the central supply of cold water in many cases water from great depths in the sea and lakes was used. Other sources of cold were AC using heat from waste incinerators. Returning heated water in the DC system is sometimes used as a heat source for HPs. In Sweden, DC is much smaller than DH (3.6 PJ vs. 175 PJ in 2014). A big challenge for the future for DH in Sweden is the high proportion of biomass and waste used as fuel in heat sources. In the field of biomass use, the demand from the chemical and petrochemical industries is expected to increase and the development of sorting and recycling of waste will reduce the amount of waste intended for incineration.

3.8 Multi-source DH implementation perspective

[7] dealt with the thermo-economic analysis of district heating systems in the near future. The authors assumed that in the EU, shortly, a variety of suppliers could supply heat to a single central heat supply network, and this would put a strain of price-setting on the part of both suppliers and consumers. It will be necessary to consider not only the amount of heat but also the quality and energy needed to transport the heat transfer medium. Buildings with low-temperature heating systems reduce the return water temperature and thus contribute to the higher efficiency of heat sources.

3.9 Smart thermal grids – Future 4th generation of district heating and cooling systems (4GDH)

The most agreed underlying principle for future district heating (DH) systems is lowering the temperature in the distribution networks. It leads to significant increase of thermal efficiencies in supply side and distribution side of the system. Heat supply becomes more efficient with respect to combined heat and power (CHP) production, flue gas condensation, heat pumps (HP), geothermal heat extraction, low temperature excess heat and heat storage. Lower temperatures also allow use of plastic pipes instead of steel pipes, which reduces construction costs. Decreasing the temperature in DH network will be allowed by the fact that new buildings will have lower heat demands (new buildings in Europe are required to be nearly zero-energy by 2021). The Heat Roadmap Europe studies [8] indicated that with low temperature district heating (LTDH) the Europe's objective to lower greenhouse gas emission by 80 % in 2050 compared to 1990 levels could be achieved at lower total cost for heating and cooling than without LTDH. For many previous years, the concept of smart grids was exclusively associated with smart electricity grids, while other grids such as gas or thermal have been neglected. The definition of 4GDH is based on [9] and it is as follows: *"**Smart thermal grid** is a networks of pipes connecting the buildings in a neighborhood, town center or whole city, so that they can be served from **centralized plants as well as from a number of distributed heating and cooling producing units** including individual contributions from the connected buildings. The concept of smart thermal grids can be regarded as being **parallel to smart electricity grids**. Both concepts focus on the integration and efficient **use of potential future renewable energy sources** as well as the operation of a grid **structure allowing for distributed generation**, which may involve **interaction with consumers**."*

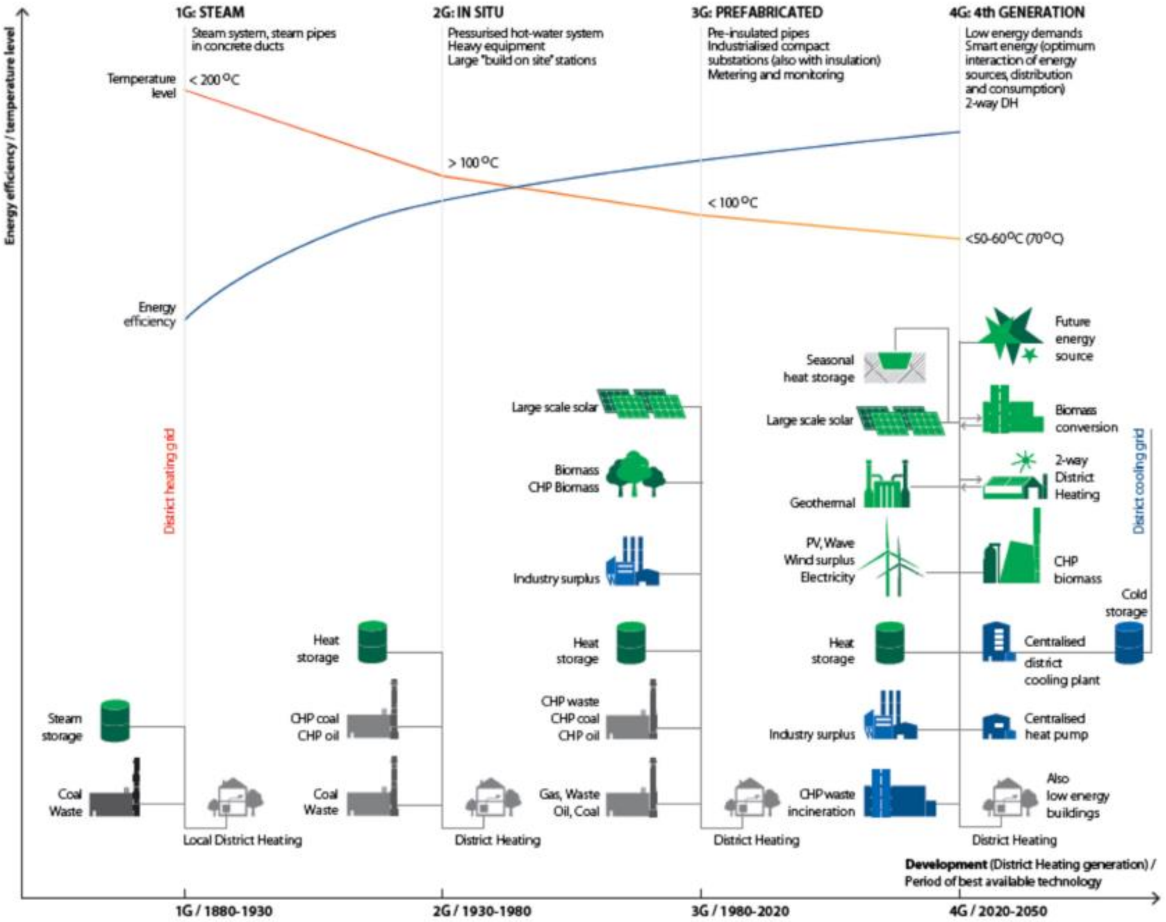

Fig. 3 The development and future of centralised heating [9]

Successful implementation of low-temperature thermal energy sources like renewable energy sources (RES) into future sustainable energy systems is dependent on the ability of the whole system to deal with their fluctuations. The harvested energy must be either immediately used or stored until it is going to be used. Sometimes it is stated that renewable energy is not feasible without the capability to store energy. The problem is that it is very often focused only on electricity storage while neglecting all the other technologies. It has been shown that other storage technologies are more financially viable and have much fewer conversion losses and therefore should be part of the future solution.

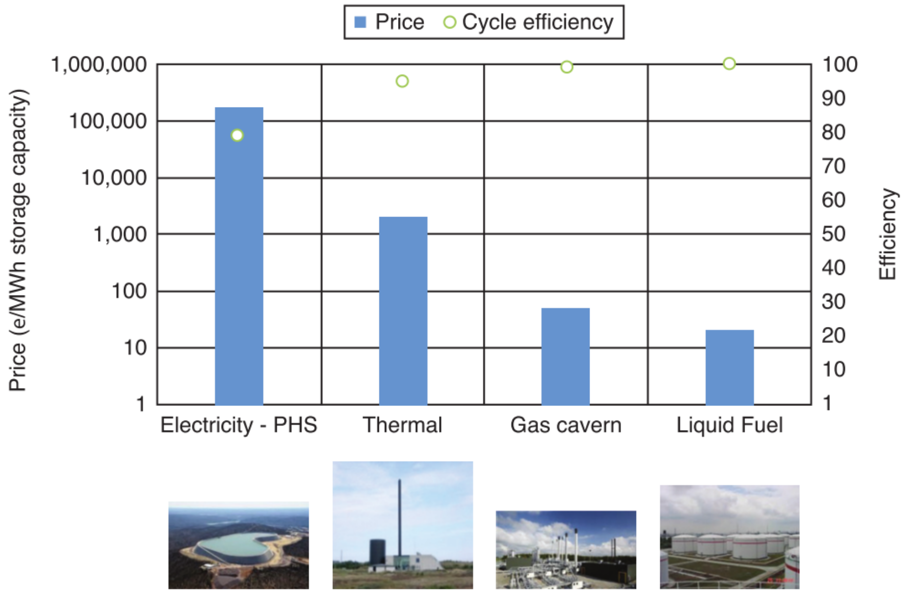

Fig. 4 Investment cost and efficiency of different storage technologies [10]

In the case of thermal storage, it has been pointed out that the relative price per unit of stored energy significantly decreases with the increasing volume of the thermal storage. It leads to a conclusion that distributed domestic storages are a lot less financially viable than big volume community thermal storage, even when the additional heat losses caused by added connection pipes are accounted for [10]. Appropriately insulated high volume thermal storage can be used as seasonal storage which allows transfer of accumulated heat from summer season to the winter season and similarly transfer of accumulated cold from winter season to the summer season.

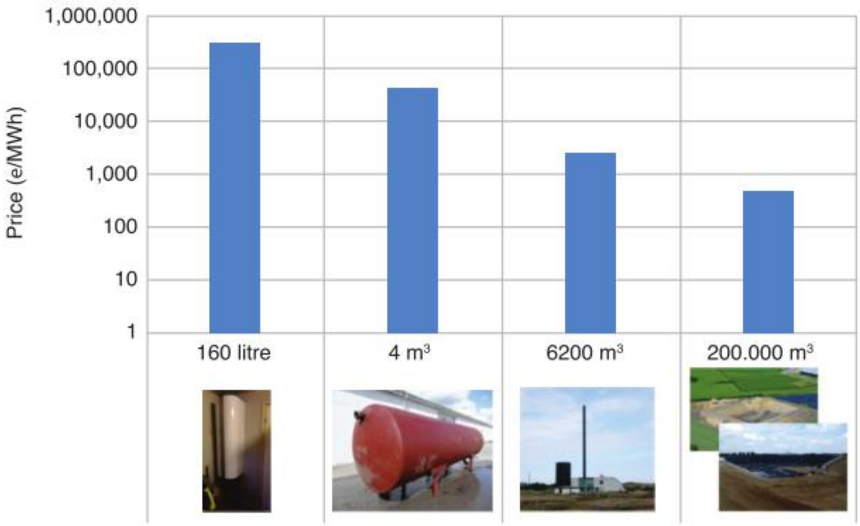

Fig. 5 Investment cost of different sizes of thermal storage technologies [10]

3.10 DH with a significant proportion of heat pumps

[11] in their paper discuss the use of surplus electricity in Sweden for central heat supply. The structural surplus of power began to occur in the 1980s when a number of nuclear power reactors were put into operation. As the possibilities for exporting electricity were limited, they were looking for the possibility of using surplus electricity within Sweden. One option was to centrally supply heat,

using electricity for large electric heaters and large HP. The authors list nearly 20 electric heaters with outputs over 30 MW that were in operation in 1986. The authors also state that in 1987 155 large HPs with a total heat output of 1330 MW (not all HP connected to DH) were in Sweden. Based on these past experiences, the authors see a great potential for the conversion of electricity to heat in connection with increasing electricity production from the sun and wind.

[12] addressed the possibility of using large HPs within DH in Sweden. The installed power of large HPs since the 1980s in DH systems reaches 1.5 GW. The conversion of heat to DH within short time intervals of low electricity prices due to high production from renewable sources offers a number of advantages over the local use of these surpluses. The cost per unit of power or heat capacity unit for heat and cold production and storage systems is lower in the case of a small number of large devices than a large number of small devices. For large HPs, it is also possible to use strategic heat sources.

3.11 Model assessment of DH contribution to air purity – replacement of local gas heating (USA)

[13] analysed the cost of reducing greenhouse gas emission through central heat supply in the northeast of the United States (New York State and New England State). In the beginning, the authors state that while some European countries are investing in the development of central heat supply, the benefits of DH in North America are not yet fully exploited, even in climate conditions with year-round heating requirements. Analysis of the DH benefit was done using computer simulations. Two basic cases were analysed. The first case was gas-fired areas, where local gas supplies were replaced by central heat supply with combined heat and power generation. The second case was the natural gas distribution area, where local biomass sources and DH fuel oil with cogeneration were replaced. Both residential and commercial buildings were considered. The analysis has been carried out for cities with a population of more than 5,000. The authors have observed that for most of the analysed sites, replacement of local DH sources would lead to a significant reduction in CO2 production.

3.12 Model assessment of the integration of the solar thermal system into DH (Finland)

[14] compared the benefits of centralised and distributed integration of the solar thermal system into an existing central heat supply system under conditions in Finland. The comparison was carried out using computer simulation for two cases: a high-temperature system with an inlet temperature of 115-80 °C, depending on outdoor conditions and a low-temperature system with a supply temperature of 65 °C. Higher cost per unit of installed power was considered for the distributed system than in the case of central integration. The central thermal solar system showed 3 to 5 times higher heat production at the same total installation costs. Underinvestment costs in the lower range of the price spectrum, the return on the central solar system was 10 to 11 years.

3.13 Model assessment of possible DH development scenarios (Denmark)

[15] compared five scenarios (in the context of Denmark which could be to some extent considered as demonstrative for Europe in general) of five different temperature levels in LTDH network using cost/benefit analysis. The studied scenarios might be considered as individual steps in the direction of reducing the temperature levels. The studied scenarios could be described as bellow (short names in brackets).

1. **Heat Savings (Save)** – The buildings are thermally improved, but the temperature levels in DH system stay at the current levels (80 °C/40 °C). The reduction in heat demand is a prerequisite for the feasibility of LTDH.
2. **Low return temperature (Return)** – The buildings are improved in such way that the reduction of return temperature is achieved. The supply temperature stays the same (80 °C/25 °C). It allows the study of the relevance of the return temperature reduction.
3. **Low temperature (Low)** – Both supply and return temperatures are reduced to the lowest possible levels for which a booster for hot domestic water is not necessary (55 °C/25 °C).

4. **Ultra-low temperature with el. booster (Ultra)** – The supply temperature is further reduced, and therefore the domestic hot water temperature booster is necessary (45 °C/25 °C). In this scenario, direct electric heating of the hot domestic water is applied.
5. **Ultra-low temperature with HP booster (HP)** – The supply and return temperature are further reduced, and the temperature of the hot domestic water is boosted by micro HP (35 °C/20 °C).

The scenarios are analysed in **EnergyPLAN**, which is advanced energy system analysis tool for large-scale system dynamics developed in Denmark. The tool focuses on the integration of various energy sectors and allows simulation of one full year on hourly bases. In the presented study, the tool is modified to account for changing COP of the HPs because the supply and return temperatures are also changing in hourly bases.

The study concludes that from a socioeconomic point of view the reduction of temperature levels in DH is feasible strategy towards a renewable energy system. The reduction of the temperatures to the lowest possible level in which booster for hot domestic water is not necessary (**Low** strategy) gives an annual reduction of socioeconomic cost about 100 M€ /year (in Danish context). Further reduction of the supply and return temperatures (**Ultra** scenario) is questionable and relies on low prices of the boosting units. The scenario with micro HPs (HP strategy) is beyond realistic feasibility even though it might be economically acceptable for specific areas.

3.14 Combination of high and low-temperature heat distribution

To achieve reasonable transformation from high-temperature district heating (HTDH) to future LTDH, it is necessary to go through a transition phase. Such a phase is characterised by new/upgraded buildings (low-energy buildings) and old buildings (high-energy buildings) being connected to the same distribution grid at the same time. That creates a need for different supply temperature levels for each type of building. The low-energy objects are best when supplied with low temperatures while the high-energy object cannot operate if they are supplied at low temperature due to a high heat loss through walls, windows and so on. The transitions phase can be solved by cascading. The HTDH network is used for heating in the high-energy object, and the return temperature from those is then used as supply temperature for low-energy objects.

3.15 Cascade of heat distribution (Vienna)

[16] studied the options for one case in Vienna. The thermo-hydraulic mathematical models are developed in **Modelica/Dymola** (tool for dynamical simulation of various complex physical systems). The tested scenarios could be described in the following way.

- **Reference scenario (status quo - 0)** – The low-temperature customers (LTC) are not connected. Heat demand is about 2 400 MWh, and the maximum peak load is about 830 kW. The supply temperature is controlled between 63 and 90°C. The average supply temperature through the year is 65.7 °C. The average return temperature is 53.5 °C.
- **The standard connection of LTC to the grid (1)** – The heat demand increases to 3 030 MWh. Maximum peak load is about 1000 kW. Supply temperature is not changed. The return temperature is reduced to 52.8 °C. The average flow rate increases by 18%.
- **The LTC is connected to return line of the grid (2a)** – According to Austrian laws, the minimal supply temperature must be 63°C because of the preparation of domestic hot water which must be stored at 60°C. (3 °C difference for heat exchanger). The right value is guaranteed by three-way mixing valve, which boosts the temperature by water from the supply line. The return temperature decreases to 52.8 °C.
- **The LTC is connected to return line of the grid (2b)** – This scenario is similar to the previous one. The difference is in the method of preparation of domestic hot water. In this case, the hot water is instantaneously heated when needed. There is only a small buffer for smoothing the demand peaks. Because the hot water is not stored, it is possible to use

lower supply temperature (60 °C – no legionella risk). The average return temperature is about 51.7 °C. The average flow rate increases by 8 %.

- **The LTC is connected to the grid by 3-pipe-system (3)** – The pipe connected to return line is used for space heating, and the pipe connected to supply line is used prepare the hot domestic water. The third pipe is returned to the DH system. The average flow rate increases by 13 % and the return temperature are decreased to 52.1 °C.

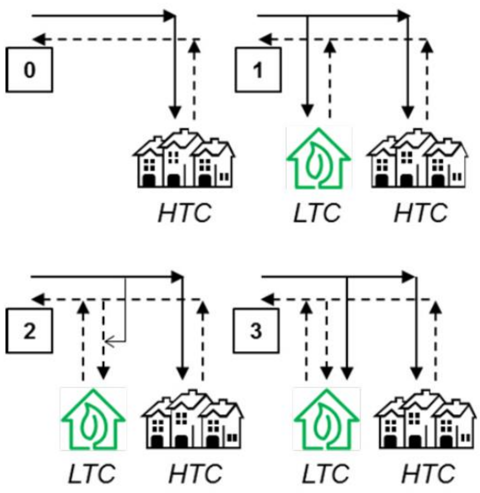

Fig. 6 Connection schemes for the scenarios [16]

The result of the study is that the HTDH networks with high potential of reduction of return can allow very efficient implementation of low-temperature sources. It is necessary to take appropriate measures (for example mixing water from return line of the main grid with high-temperature water from the supply line of the main grid) for establishing the security of hot domestic water generation for LTC (in the case without additional booster). For the effective implementation of the proposed solutions, it is required to develop new business model and tariffs for LTC and possible suppliers to the return line.

4 Introduction of selected implemented pilot projects

4.1 Drake Landing Solar Community – Okotoks, Canada

The Drake Landing Solar Community is a neighbourhood of 52 two-story energy efficient houses, which use solar thermal energy for heating. The living areas of the houses are from 139 to 155 m^2. The hot domestic water is provided by a stand-alone solar system installed in each house, and it covers from 50 % to 60 % of the annual hot water demand. The rest of the demand is backed-up by the gas-fired water heater. Average supply temperature is 40 °C and average return temperature is 32 °C.

Fig. 7 Photos of Drake Landing Solar Community (energy centre at the upper-right corner of the pictures) [17]

The community space heating system includes stratified short-term thermal storage placed at the energy centre and seasonal borehole thermal storage placed outside. Net-zero electricity for pumping power is achieved through the use of photovoltaic solar electricity generation (18 kW). Solar thermal energy is collected by 798 plate solar panels, which are placed in four rows at the roofs of the apart standing garages. The total area of the panels is about 2 293 m^2. Heat collected in the panels is sent to the community energy centre through underground pipes using the water-glycol solution as a heat carrier. The heat is then transferred into the stratified short-term thermal storage (240 m^3) through a heat exchanger. This short-term storage acts as a buffer between the collector loop, the district heating loop and the long-term borehole thermal storage. It helps the system to deal with peaks in heat demands and peaks in solar power generation since it can charge and discharge in much higher paste then the seasonal storage. The collected heat is either stored or immediately send to the houses.

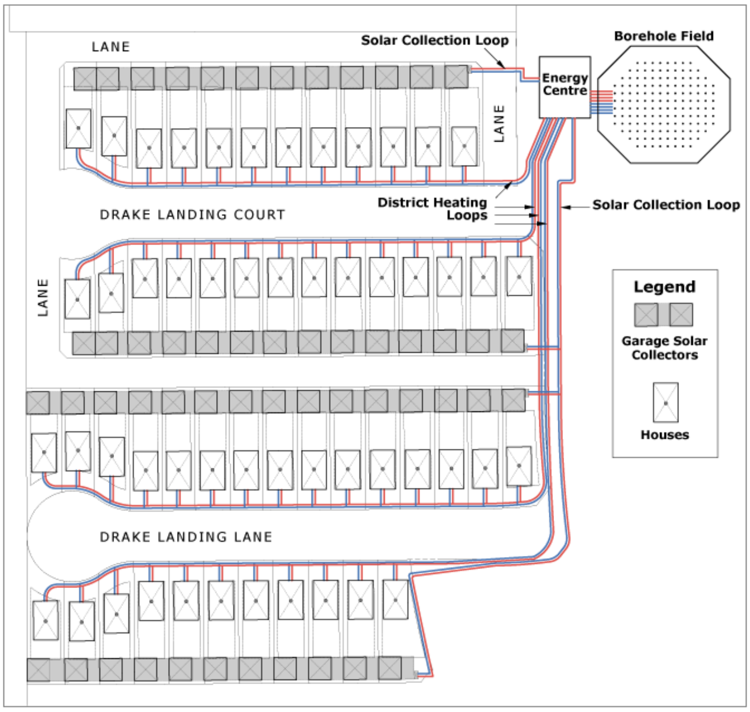

Fig. 8 Drake Landing Solar Community – site plan [17]

The seasonal thermal storage comprises of 144 boreholes, which are 35 m deep and in which there is a U-shaped pipe. Those are connected into groups of six in such way that the temperature is higher closer to the core. When the heat is being stored the hot water is pumped into the core and cools down as it reaches the outer edges and when it is extracted the cold water is pumped into the outer edges and heats up as it reaches the core. It was calculated that it would take three years to charge the storage (80 °C) fully. In the energy centre, there is also backup gas boiler. The houses have installed an air handler with a heat recovery unit, which preheats the cold incoming fresh air and a water-to-air heat exchanger, which transfers the heat from LTDH to the inner environment. The system has a consistent record of fulfilling more than 90 % of requirements for space heating by the solar system even though it operates in extremely cold climate (more than 5000 heating degree-days).

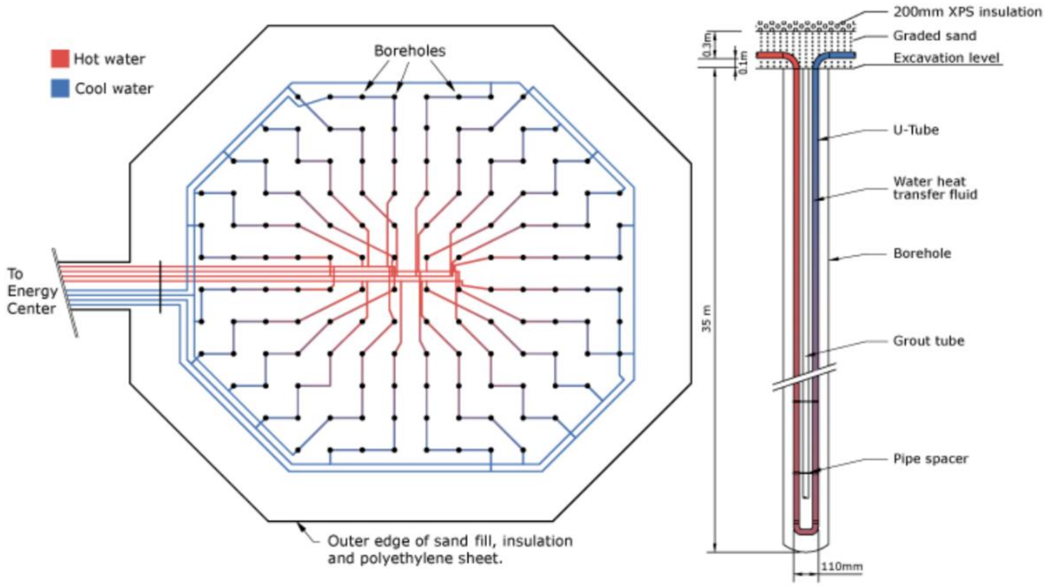

Fig. 9 Drake Landing - The seasonal borehole thermal storage [17]

4.2 Solar district heating – Ackermannbogen, Munich, Germany

The case in Munich consists of 13 residential buildings with 319 apartments in them. The total living area of the apartments is 28 550 m^2. The hot domestic water is provided through the district system. The heat sources of the system are solar panels (total area of 2 761 m^2) and an absorption HP (550 kW of thermal power and 230 kW of chilling power). The coefficient of performance (COP) of the absorption HP is about 1.7. There is also district heating backup-system, which is also used as a high-temperature source for the absorption of HP. The fraction of useful heat provided by the solar panels is about 45 %. Average supply temperature is about 59 °C. The concept was developed using simulation tool TRNSYS.

Fig. 10 Ackermannbogen - The seasonal borehole thermal storage [17]

The system includes stratified seasonal thermal storage (5 700 m^3) build from precast concrete segments, which have stainless steel lining from the inside of the storage. There is thick insulation from outside of the storage to reduce heat loss. To create the appearance that is more natural looking and to reduce the heat loss further, the storage was covered by soil. The capacity of the storage is

480 MWh (at 90 °C where 15 °C is considered as completely discharged) and its designed annual heat loss is about 80 MWh.

Fig. 11 Ackermannbogen - The stratified seasonal storage from inside (left) and from outside (right) [18,19]

The absorption HP is used as a temperature booster of water from storage. The high-temperature source used for evaporation of refrigerant (lithium-bromide) in the HP’s generator is water from centralised district heating plant (130 °C – 80 °C) of the city of Munich. The residual heat contained in the high-temperature water outgoing from HP is then used as a supplement as well. This mode is not used for the whole year, but it is used in a situation in which it is a most efficient choice. Sometimes it is most reasonable to use direct supplementation from the district heating plant directly. The use of heat from district heating plant only is considered as a backup plan.

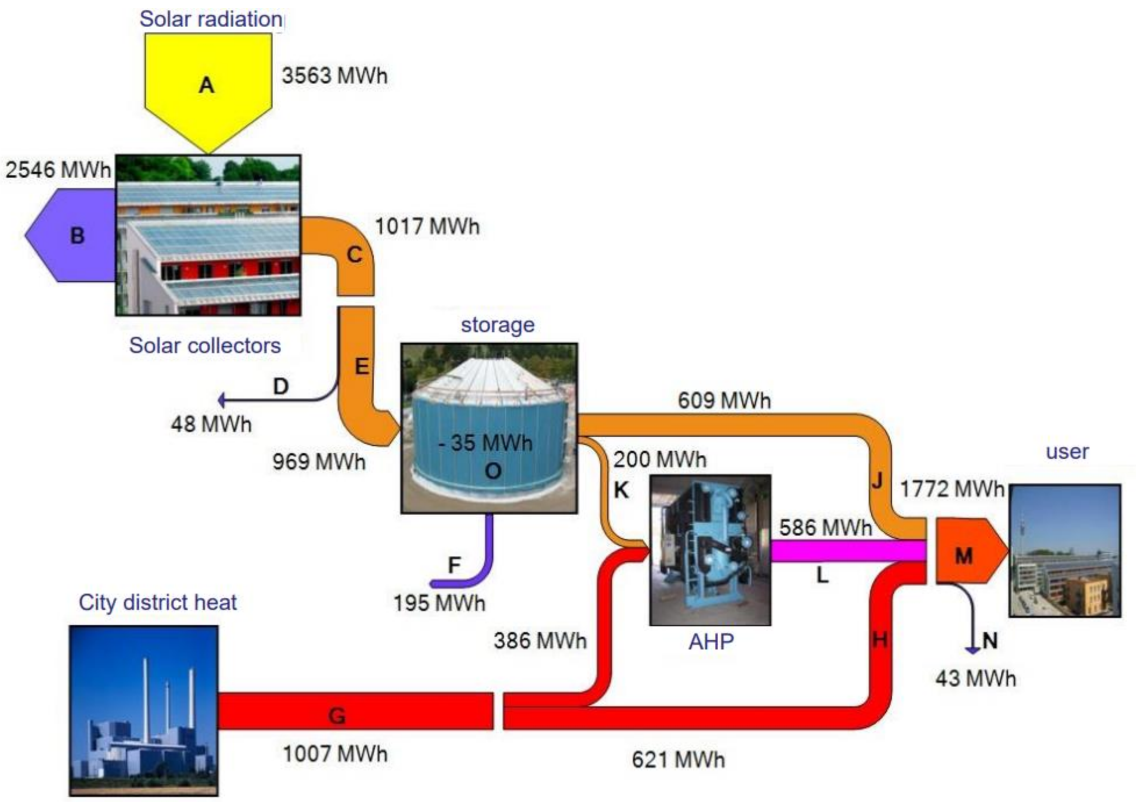

Fig. 12 Ackermannbogen – Energy flow chart 2008/2009 [19]

In hot water installations, flow type heater is used. The hot domestic water does not circulate. All the apartments have individual heat meter. The space heating installations in the apartments are of three types. Direct floor heating, direct floor heating with radiators and indirect floor heating (plate heat exchanger). The overall distribution loss of the system is under 3 % due to the low temperature in the network.

4.3 Lystrup, Denmark

The example in the city of Lystrup comprises of 40 low-energy terraced houses, which were built in October 2009 [17]. The living areas of the houses vary from 87 to 110 m^2, and the total heated area of the site is about 4,115 m^2. Radiators heat the houses with designed supply temperature of 55 °C and return temperature of 25°C. This results in room temperature of 20°C. The area uses twin-pipes instead of single pipes for all network parts. After first two years of operation, the average supply temperature was about 52°C. The reduction of heat loss was almost 75 % compared to the traditional approach with supply and return temperatures of 80°C and 40°C (relative heat loss is high due to a very small amount of energy used in the houses).

4.4 Summary

Name	Year	Temp. Supply/Return °C	Temp. Outdoor °C	Heat supplied/sold GJ	Relative distribution heat loss %	Area land/building m^2
Drake Landing, Okotoks, Canada	2007	40/32	3,9	2 705/2 564	5	29 500/7 650
Munich, Ackermannbogen, Germany	2006	59/33	9,6	6 534/6 379	2,4	23 000/28 550
Lystrup, Denmark	2009	52/34	8	986/790	19,9	unknown/4 115

5 Planned implementation in Partner cities

5.1 Rotterdam

Expansion of the heating network by connecting selected "large" customers (Exhibition Centre, Congress Centre, Arts building, and swimming pool) to the central heat supply system. There will be heat/cold distribution. By using the distribution system, it will be possible to exchange heat/cold between the connected objects and the central sources. The system will be complemented by a rock accumulator for long-term storage of heat energy. The accumulator will be charged during the summer period with excess heat production and will be discharged during the heating season.

The use of the thermal energy of wastewater within a single building will be realised by using wastewater heat from the showers of the local pool to preheat domestic hot water. At the level of the central heat supply system, the thermal energy leaving the wastewater from the residential area will be used to supply heat to the heat supply system.

Use of hard surfaces as a heat exchanger to capture heat in summer. Heat exhaust from the layer under the hard surface of the sidewalks and roads cools the surfaces during the summer period, which has a favourable effect on the durability of the paved surfaces and the microclimate in urban areas. In the winter, hard surfaces are heated, which effectively solves the maintenance of the surfaces (snow-free sidewalks).

5.2 Umeå

The heat accumulator in the heat distribution system will be built as a deep (geothermal) heat accumulator for seasonal and operational heat accumulation. A heat supply management system will be developed which would take account of the building heat accumulation and the current heat supply needs throughout the entire monitored heat supply system. The management system will be developed and applied to a set of campus buildings.

A business model will be created to monitor the production of renewable energy sources and the current demand for energy supply to buildings. In conjunction with a functional heat supply management system, it will be possible to create conditions for the efficient use of energy produced from renewable sources. This will allow the effective integration of RES, which in the future may lead to a 100% share of RES.

5.3 Glasgow

Create a business model that allows organising sales of thermal energy surpluses between subjects of all categories and sizes, including the private sphere.

6 Description of potential opportunities for Brno within Smart City Context

6.1 Current state and outlook for Brno

In addition to existing fossil sources in the Brno heating plant and block boilers, the City of Brno in the SMART THERMAL GRID area will intensively use local clean, renewable energy sources and waste heat (for production of electricity, heating, and cooling). From this point of view, it will be necessary to complete and transform the services offered. Otherwise, there is a threat in the form of disconnection of existing DH customers operated by the Brno heating plant. However, support of renewable energy is also in line with Directive of the European Parliament and of the Council 2010/31/EU of 19 May 2010 about energy performance, which defines the concept of a building with almost zero energy consumption.

The energy consumption of such a building should be covered to a large extent from renewable sources. It is, therefore, necessary, regarding the concept of central heat supply, to count on this fact and to prepare the societal development also in this direction. Another aspect is the assessment of the energy performance of buildings using the energy performance tool, where the share of renewable energy sources is defined and states the non-renewable primary energy factor. This assessment has an impact on new construction and also affects the value of existing properties.

Another area of the SMART THERMAL GRID vision for Brno is the support of island systems and promotion of energy accumulation in buildings. These strategies require innovative solutions that can be found in cooperation with universities and research institutions as pilot projects.

Heat generation and combined heat and power generation are carried out in Brno within the premises of Brno heating plant, but also within the SAKO incinerator plant. The operation of the incinerator will be extended by the 3rd boiler, which will be able to increase the incineration to 380,000 tons of municipal waste. This increase will have an impact on the current operation of the Brno heating plant. It is a question of whether there will be a reduction in the operation of the Brno heating plant or there will only be a reduction in the performance of individual plants or other measures.

From the heat distribution point of view, the Brno heating plant is switching to the change of steam distribution to hot water. This will result in reduced heat loss of the conveyed medium. This step is in line with the global trends of DH transformation.

6.2 Future challenges facing the city of Brno

Distorted non-market prices of inputs for fuels, energy, and subsidised investments caused by nonconventional subsidy policy currently favour some types of heating over others.

According to this, the heating industry must behave as a whole. Otherwise, its uncontrolled disintegration will occur. At present, customers who take heat for heating and domestic hot water (DHW) are offered a wide range of options. Not only in the decentralised systems of house and block boiler rooms and individual heating systems of family houses. It is no longer the rule that the original panel housing estates historically connected to DH have no alternative and have to take heat from a monopolistic supplier, which on the contrary can be sure of a guaranteed offtake.

Whole blocks of panel buildings owned by a private housing association (PHA) with dozens of apartments are looking for an alternative to DH. The city of Brno, as the owner of the Brno heating plant, must carefully consider whether and how to prevent obtaining a building permit for the change of the heating method (according to the Constitutional Court, it cannot be legally prevented).

Why are customers being disconnected? In addition to state making the form of non-systemic subsidies to selected heating methods attractive (this is, of course, beneficial for the suppliers of alternative heating systems), it is mainly freedom of citizens to decide on the way of heating.

Connection to the DH system is perceived in residential buildings as a historically given dependency, which suddenly may have an alternative. This feeling cannot be expressed in money. If the operators of DH and heating plants fail to grasp this fact, they will still be able to access their customers from their power of "natural" monopoly supplier. And as we can see, it is no longer true. Therefore, here is an opportunity for the Smart Thermal Grid and utilisation of its benefits and possibilities.

It is always necessary to look at the specific location, the character of the use of the building, the state of the heating system and, in particular, to determine the resulting objectives of the comparison (technical, operational, economic). For economic comparisons, that the potential investors are interested in, the type and price of the fuel used for the DH are always crucial. We are still talking about apartment buildings connected to existing DH systems, especially in housing estates, and not about family houses or new buildings.

The heating company must accept the coexistence of multiple heating modes. Deciding on the way of heating of apartment buildings must always be based on the complete undistorted information. For economic reasons, some parts of the large city-wide DH networks may become loss-making in the future due to the disconnecting of extensive groups of large apartment buildings, in particular after their complete revitalisation. This is the reality of the current conditions in the Czech Republic.

6.3 What needs the city of Brno be ready for in the area of Smart Thermal Grid?

1. Actively offer new alternative ways of decentralised heating and, in particular, other services of a maintenance nature. Otherwise, it may lose its long-term customers. In some cases, the uncontrolled disintegration of DH systems may occur. This can be prevented, primarily, by maintaining a competitive heat price for the end customer in the given location even at the cost of restructuring the inefficient systems (Resolution No. 362/2015 on the State Energy Concept of the Czech Republic of 18 May 2015). Which means, to minimise the heat losses in the networks, even at the cost of disconnecting lossmaking branches and converting them to local heating. In addition to the condition of efficiency, this must also be the case for not increasing or even reducing emissions (HP) at a given location.
2. The decrease of the temperature level in the hot water network after a complete transition from the steam system.
3. Cogeneration units used in local systems or block boiler rooms. The output must be tied to continuous operation (DHW sizing) or peak operation of the CHP unit in the high accumulator tariff zone.
4. High-efficiency cogeneration with a contribution to CHP production: - Heat machinery operations (turbines, motors): Maximize supported electricity generation (10% prime energy savings), Offering system service (secondary frequency regulation and minute back-up - depends on the type of machine). The purchase price of electricity from gas is not worth it - it is necessary to monitor developments in the EU.
5. Prepare the conditions for the integration of heat supplies from decentralised sources and the tools for the reciprocal omnidirectional heat sales between all categories of DH related entities.

6.4 Minimizing of IoT security risks

- Restoration of completely outdated technologies and their reduction to lower performance.
- Reconstruction of networks, pre-insulated piping, steam transition – hot water.
- Flexibility in resources, including accumulation and new small high-end resources.
- Cogeneration units based on combustion engines up to 1 MWe (CHP production support).
- Reconstruction of older steam turbines to other parameters (power, counterpressure, suppressed condensation) and sampling steam turbines with the possibility of summer operation in condensation mode.
- Diversification of fuel base sources – lower dependence on one fuel.

- Source decentralisation – an opportunity for suppliers of small condensation, gas, and biomass boilers, HPs and solar panels.

7 Solution proposal for Spitalka site

This solution focuses on the design of the real possibility of an innovative way of supplying the thermal energy of a new development project in the central part of the city. The thermal energy source for the considered location can be operated in the variant a) Spitalka plant (PS), which is in the immediate vicinity of the site considered.

7.1 The current state of Spitalka plant

The PS is equipped for the production of heat in a combined way with the simultaneous generation of electricity in backpressure steam turbines. Because of historical links, the source is a natural operational and control centre of DH Brno with the connection to all the main steam lines to the steam distributors of PS. The generated heat is supplied in the form of steam and hot water. Electricity is supplied to the distributor's grid.

The fuel for PS is natural gas, the connection of which is led via the main gas valve and the measuring path to the gas control station where the gas is regulated to the operating pressure. From there it is transported by a medium-pressure industrial gas pipeline to the individual gas connections of the boilers: K28, K29, K25 and K01.

The field of the heating economy includes combustion sources: steam boiler K 25, K 28, K 29 and steam boiler K 1 with the possibility of operating on two levels of overheated steam parameters of 9.4 MPa and 510 ° C or 6.4 MPa and 420 °C. In total, PS has a heat input of 442.4 MWt and thermal output of 411.0 MWt.

PS provides steam delivery at 0.9 MPa, 200 °C to the DH network. Maximum steam output in the winter is 150 MWt. The PS further provides hot water supply with 120/80 °C heating water for the Brno-Julianov and Brno-city locations, with an output of about 35-40 MWt in the peak winter season. The maximum output of the heat exchanger station is 68.5 MWt. During the summer shutdown of the source, DH steam is collected for the heating of the hot water network at the heat exchanger station.

For the production of electricity, the following devices are installed: Turbochargers TG 20, TG 22, TG 26, TG 27, TG 28. The total power of PS is 80.6 MWe. The PS is connected to the distribution substation of E.ON Distribuce, a.s. The produced electricity is consumed for its use and supplied to the grid. In the shut-down, electricity is taken from the distributor's grid.

By progressively rebuilding the steam network to hot-water, the heat output from the steam network is transferred to the hot water network. In 2018, 14.4 MW will be transformed into hot water. In the following years, the rebuilding will continue with approximately the same connected inputs; the summer of 2022 is expected to be the end, and the last steam customers will be switched. Reconstruction of the steam network to hot-water will be mainly realised in the area of the Brno-city hot-water pipeline, to which the PS and Cerveny Mlyn will supply the thermal energy. Areas in the south of the city as well as in the western part of the Old Brno and BVV areas will also be connected.

After the conversion of steam/hot-water (after 2022), the output is expected to be: 20 – 100 MW

- supply of heat in hot water up to 100 MW,
- operation technology must be highly flexible with a regulation power range.

The Spitalka location, with the inclusion of a mix of different uses with a share of opportunities for housing, work, service, and recreation, can be easily and directly connected to the newly constructed hot water distribution networks that continue to the city. The immediate proximity of both sites is advantageous regarding minimising the heat losses of the pipelines and the possibility of a prospective connection of the backup electricity network. It will be suitable both regarding project and technology to incorporate these possible connections into the plans for rebuilding the steam into the hot-water system and to modernise the PS operation now.

7.2 The proposal of innovative heat supply to Spitalka - Specifications of the solution

In the area, the mixed building is anticipated, which includes buildings for housing, work, service, and recreation, with the prevailing function should be housing. However, the actual form of the housing development is not known at present and will result from the urban and architectural competition.

It is evident that the new building will already be fully subject to Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, which is implemented by Act No. 406/2000 Coll., on energy management and related implementing regulations. Buildings in the area will thus have to meet the requirements for almost zero-energy buildings, which are in Act 406/2000 Coll. defined as "buildings with very low energy performance, whose energy consumption is largely covered by renewable sources." Specific requirements for buildings with near zero-energy consumption are defined in 78/2013 Coll. Under this Directive, a building with nearly zero-energy consumption must meet the two criteria which are the average heat transfer coefficient and primary non-renewable energy consumption. Primary non-renewable energy consumption is not limited by the maximum allowable value, but it is required to reduce the consumption of non-renewable primary energy relative to the reference building, which is a relatively benevolent approach with regard to the choice of a heat source for heating and DHW heating.

The construction of the new "Smart neighbourhood" should fully comply with the idea of sustainable development, particularly in the area of minimising the production of greenhouse gases associated with the building's operation. This should be achieved through the use of a smart heat/cold building system that should minimise heat/cold production from non-renewable sources and its efficient distribution to the point of consumption. The basic service requirements provided by the smart grid are as follows:

- heat supply for building heating - due to building requirements it is possible to cover the heat demand even at lower temperatures of the heating medium at 40-55 °C,
- heat supply for DHW preparation - current legislation requires a DHW outlet at a temperature of 50 to 55 °C,
- storage of "cheap" heat/cold energy, produced using renewable energy sources, or at an economically advantageous moment,
- cold supply - if required, provide cold for cooling water with input parameters of 6-10 °C,
- ensure the thermal stability of the network, in particular, to balance out the production and consumption.

These requirements can be met using 4GDH where the temperature of the heat transfer medium is in the range of 50-60 °C. With regard to the favourable distance between the PS and the Brno heating plant, the following three variants of the heating network solution are offered in the area:

1. Central heat and cold production
2. Central heat production, local cold production
3. Local heat and cold production

7.3 Central heat and cold production

This is a variant of the SmartEnCity project built in Estonian Tartu. Heat and cold production take place centrally in PS and heat, and cold are fed to individual buildings using a 4-pipe system (2 heat pipes + 2 cold pipes). Heat generation is ensured all year round by connecting to the back-flow of the hot-water distribution system of the existing heat supply network. For the production of cold, according to the economic evaluation, either the compressor cooling can be used, which uses the electricity produced from cogeneration or electricity from RES, or AC using the heat produced. After evaluating the environmental impacts, water from nearby Svitava river could also be a temporary source of cold. Heat storage would take place within the heat supply network. Cold storage would need to be solved within PS.

The advantage of this solution is the use of a nearby heat source that produces it in combined heat and power mode. Connection to the return branch of regular distribution network will help reduce the return water temperature to a heat source, which is desirable in the case of PS.

The disadvantage of the solution is the need to build a more complicated infrastructure (4 pipe distributions), relatively small use of RES for the heating of buildings and the need to deal with storage of cold.

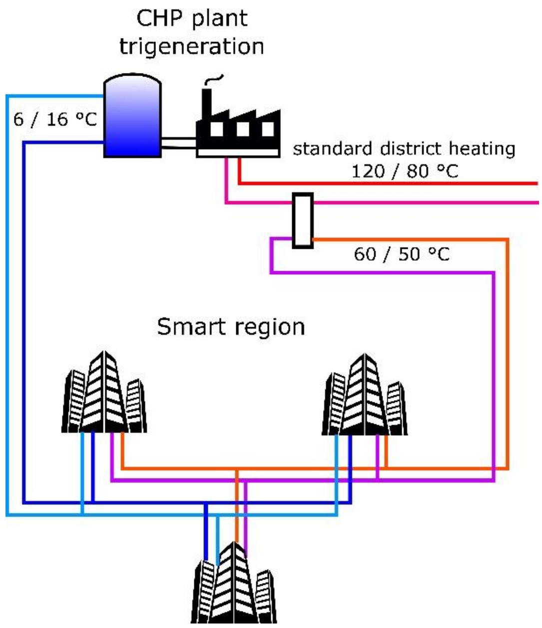

Fig. 13 First variant with centralised heat and cold production

7.4 Central heat production, local cold production

The smart neighbourhood has its thermal network built, which is connected via the exchanger to the return branch of the standard DH system, which thus serves to supply heat in the winter and to stabilise the parameters in the summer season. Cooling takes place directly at the point of consumption (building) with a compressor cooling device. The power consumption of the cooling device is partially (or completely) covered by its power production from the PV system installed on the building. Waste heat generated during cold production will be used to produce hot water in the building, and any surplus will be diverted to the "smart neighbourhood" heating network. The issue of cold storage is solved locally in the building. Heat storage takes place only within the DH system of Brno.

The advantage of the solution is to increase the use of RES and the use of heat surpluses from one building in another building (Smart Grid). The disadvantage of the solution is the deterioration of the efficiency of production of cold due to the requirement for a higher condensing temperature (about 65 °C) related to the preparation of the TV and the supply of excess heat to the heating network.

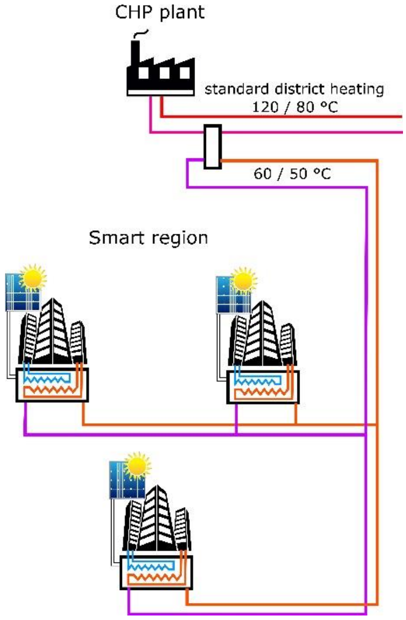

Fig. 14 Second variant with centralised heat production and local cold production

7.5 Local heat and cold production

"Smart neighbourhood" has its heating network, which is operated at low temperatures (8 – 20 °C/4 – 16 °C), which serve as heat/cold sources for HPs (boosters) located in individual buildings. Part of this network is also a heat accumulator, consisting of drills under individual buildings and energy stilts of individual buildings.

HP in buildings is used either to produce cold in the building and to supply heat to a thermal network or as a heat source for heating or DHW heating when it is removed from the heating energy network. For the drive of HPs, energy is powered by PV panels integrated into buildings is used. Heat/cold production takes place according to building requirements. Energy storage occurs in the form of low-potential heat, which is stored in a distributed accumulator.

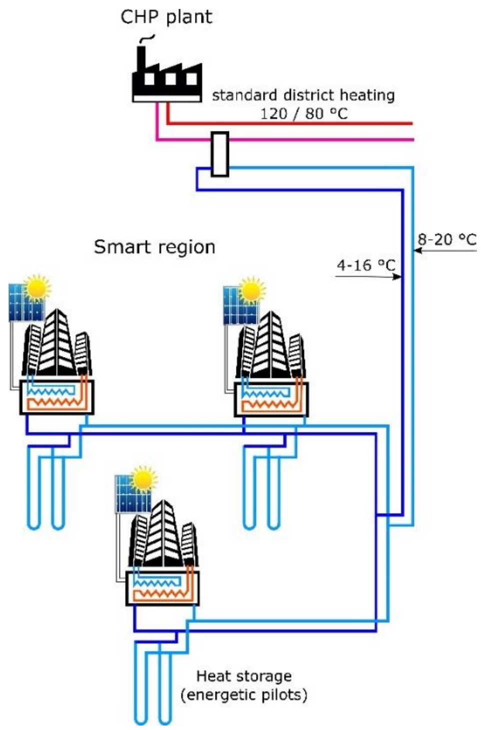

Fig. 15 Third variant with local heat and cold production

The smart neighbourhood heating system is connected to the return branch of the DH system, which is used as a heat source in the winter months and for the regeneration of the distributed heat accumulator in the summer months. The advantage of the solution is a low-temperature heating network that minimises the heat loss of the distribution system. Keeping energy in the form of low-potential heat allows utilising virtually any renewable source. The disadvantage of the solution is the need for HPs (boosters) which are used to produce heat or cold. Although it is modified water to water HP, this device is not common on the market and has to be custom-made.

8 Final summary of the report

The presented report deals with the implementations and concepts of the Smart Thermal Grid with a focus on the utilisation under the conditions of the city of Brno. The report includes a research section presenting the implemented solutions on an international scale. Subsequently, the specifics of centralised heat supply in Brno are presented, and the possibilities of further development are assessed.

The problem analysis shows that the heating networks have to be adapted to meet the new conditions and requirements to fulfil their function further and to be socially and economically justifiable. The field of remote heat supply is, by its very nature, very conservative and the implementation of the changes always takes place over a significantly long stretch of time. For this reason, it is necessary to pay increased attention to strategic decisions in this field and to review the current status regularly and to keep track of changes in the field.

The new trends in the heating industry, which must be respected in the present time, are devoted mainly to:

- Decreasing water temperature in grids,
- Utilisation of gas sources to solve 5-minute backups,
- Utilisation of battery storage for 1-minute backups,
- Increasing the possibilities of heat accumulation in the system,
- Involving decentralized heat sources,
- The predictive methods of controlling the heat system,
- Utilisation of controlled electricity consumption in the heat industry,
- The use of alternative sources in the heat industry,
- Introducing a system of direct heat sales between different entities within a single system.

The Brno heating plants respect and partly apply a number of trends mentioned above. It is advisable to make these trends a subject of further research to correctly quantify their potential impact and to assess economic parameters. In this context, it is suitable to use modern SW tools to model the behaviour of the heating network. The model evaluation allows the assessment of different operating variants. Furthermore, numerical models are useful for testing the algorithms of heating network operation and resources management including the possibility to optimise operating parameters.

9 References

[1] Latõšov E, Volkova A, Siirde A, Kurnitski J, Thalfeldt M. Primary energy factor for district heating networks in European Union member states. Energy Procedia 2017;116:69–77. doi:10.1016/J.EGYPRO .2017.05.056.

[2] Connolly D. Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries. Energy 2017;139:580–93. doi:10.1016/J.ENERGY.2017.07.037.

[3] Østergaard D, Svendsen S. Space heating with ultra-low-temperature district heating – a case study of four single-family houses from the 1980s. Energy Procedia 2017;116:226–35. doi:10.1016/J.EGYPRO .2017.05.070.

[4] Werner S. European space cooling demands. Energy 2016;110:148–56. doi:10.1016/J.ENERGY. 2015.11.028.

[5] Jakubcionis M, Carlsson J. Estimation of European Union residential sector space cooling potential. Energy Policy 2017;101:225–35. doi:10.1016/J.ENPOL.2016.11.047.

[6] Werner S. District heating and cooling in Sweden. Energy 2017;126:419–29. doi:10.1016/J.ENERGY .2017.03.052.

[7] Verda V, Caccin M, Kona A. Thermoeconomic cost assessment in future district heating networks. Energy 2016;117:485–91. doi:10.1016/J.ENERGY.2016.07.016.

[8] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, et al. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. doi:10.1016/J.ENPOL.2013.10.035.

[9] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.

[10] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy Storage and Smart Energy Systems. Int J Sustain Energy Plan Manag 2016;11:3–14. doi:10.5278/IJSEPM.2016.11.2.

[11] Averfalk H, Ingvarsson P, Persson U, Werner S. On the use of surplus electricity in district heating systems. Proc. 14th Int. Symp. Dist. Heat. Cool., Stockholm: 2014.

[12] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 2017;79:1275–84. doi:10.1016/J.RSER.2017.05.135.

[13] Björnebo L, Spatari S, Gurian PL. A greenhouse gas abatement framework for investment in district heating. Appl Energy 2018;211:1095–105. doi:10.1016/J.APENERGY.2017.12.003.

[14] Rämä M, Mohammadi S. Comparison of distributed and centralised integration of solar heat in a district heating system. Energy 2017;137:649–60. doi:10.1016/J.ENERGY.2017.03.115.

[15] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective. Int J Sustain Energy Plan Manag 2017;12:5–18. doi:10.5278/IJSEPM.2017.12.2.

[16] Köfinger M, Basciotti D, Schmidt R-R. Reduction of return temperatures in urban district heating systems by the implementation of energy-cascades. Energy Procedia 2017;116:438–51. doi:10.1016/J.EGYPRO .2017.05.091.

[17] Rosa D. IEA DHC Annex X report:Toward 4th Generation District Heating Experience and Potential of Low-Temperature District Heating n.d.

[18] Eichhorst O. Solar District Heating 2014. www.ikt.de/wp-content/uploads/2014/10/18-06-eichhorst-solar-district-heating.pdf (accessed May 11, 2018).

[19] Reuß M. Solar District Heating - an Innovative Approach of an Established Technology 2016. energia.fi/files/822/Solar_District_Heating_-_Reuss_-_Mikkeli_24.08.2016.pdf (accessed May 11, 2018).