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Transition to the 4th generation district heating - possibilities, bottlenecks, and challenges

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Abstract

The 4th generation district heating (DH) will be available in the coming years. However, the transition from the current 2nd or 3rd generation DH is a challenging task. This article reviewed the technical issues associated with the transition: supplying low temperature to buildings, integrating various heat sources and thermal storages, and developing smart DH systems. Possibilities, bottlenecks, and challenges of the transition were discussed. The conclusion was that the transformation should be conducted carefully and gradually. Comprehensive consideration such as the energy status, system conditions, and operation customs must be taken into account.

Keywords: 4th generation distrcit heating, transition, challenges, low temperature district heating, various heat sources, thermal storage, smart district heating system;

1. Introduction

District heating (DH) is an energy service, which moves the heat from available heat sources to customers. The fundamental idea of DH is to use local fuel or heat resources, which would otherwise be wasted, to satisfy local customer heat demands, by using heat distribution networks [1].

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In historical development of DH, three generations of DH developed successively. The 1st generation DH systems used steam as the heat carrier. Typical components were steam pipes in concrete ducts, steam traps, and compensators. Almost all DH systems established until 1930 used this technology. The 2nd generation DH systems used pressurized hot water as the heat carrier, with supply temperatures mostly higher than 100℃. Typical components were water pipes in concrete ducts, large tube-and-shell heat exchangers, and material-intensive, large, and heavy valves. These systems emerged in the 1930s and dominated all new systems until the 1970s. The 3rd generation DH systems still use pressurized water as the heat carrier, but the supply temperatures are often below 100 ℃. Typical components are prefabricated, pre-insulated pipes directly buried into the ground, compact substations using plate stainless steel heat exchangers, and material lean components. The systems was introduced in the 1970s and took a major share of all extensions in the 1980s and beyond [2].

The direction of development for these three generations has been in favor of lower distribution temperature, material-lean components, and prefabrication. On the basis of the trends identified above, the future DH technology should include lower distribution temperatures, assembly-oriented components, and more flexible materials [1]. The revolutionary temperature level, with supply temperature below 50~60℃, will become the most important feature of the 4th generation DH. The energy supply system, end users, and occupants will benefit from the low temperature level. A brief summary of those benefits are shown in Table 1.

Table 1. Major advantages with lower distribution temperatures.

Objects	Advantages	References
Flue gas condensation from combustion of biomass and waste	Higher output capacity (25~40%) from direct condensation of the fuel moisture in biomass fuels and waste	[1]
Geothermal energy and industrial residual heat with medium temperature	Higher output capacity (50~100%) from available medium-temperature (70~100℃) water flow	[1]
Solar energy	Higher output capacity from connected solar heat collectors	[1]
Steam based combined heat and power (CHP) plant	Higher power-to-heat ratios in the same CHP plant design, results more electricity generation at the same heat demand	[1]
Heat pump (HP)	Higher coefficient of performance, since both pressure and temperature can be lower in the HP condenser	[3]
Heat storage	Increased capacities in water-based heat storages managing both supply and demand variations, reduce heat losses from thermal storage units	[1, 3]
Network	Higher distribution efficiency due to less heat loss from the network	[3]
Network	Lower risk of pipe leakages due to thermal stress, and the corresponding maintenance costs are reduced as well	[3]
Network	Possibility to use plastic pipes in distribution areas with low pressures	[3]
Network	Lower risk of water boiling in the network, which means lower risk of two-phase-flow in pumps and fast moving water walls	[3]
Building	Better match the future building heat demand and heat temperature requirement	[3]
Occupant	Eliminate the potential risk of scalding human skin due to water leakages	[3]

In addition, the 4th generation DH will take advantage of various heat sources, different level thermal storages, modern measuring equipment, and advanced information technology, to make itself more flexible, reliable, intelligent, and competitive.

This article reviews the technical issues associated with transition to the future DH. The studies on transition to the low temperature DH (LTDH) systems are summarized in Section 2.1. The knowledge of integrating various heat sources and thermal storages are presented in Section 2.2 and Section 2.3, respectively. The idea of smart DH system is shown in Section 2.4. Further, some facing challenges and possible solutions for the future DH are discussed in Section 3. Finally, the conclusions for transition to the future DH are proposed in Section 4.

2. Transition to the future district heating

Characterized by low temperature, various heat sources, thermal energy storage (TES), intelligent management, and integration with smart energy system, the 4th generation DH will be available in the coming years. However, the transition from the current 2nd or 3rd generation DH to the future 4th generation DH is a challenging task. This section reviews the following technical issues associated with transition to the 4th generation DH: suppling low temperature to new and existing buildings, integrating various heat sources including renewable sources and recycled sources, different TES technologies, and smart DH systems. In addition, the bottlenecks and challenges of the transition are presented together with potentials solutions.

2.1. Transition to the low temperature district heating system

2.1.1. Temperature level of the current system

For the DH system using pressurized hot water as the heat carrier, the water is heated up to the supply temperature at the heat supply units, and cooled down to the return temperature at the customer substations. The supply temperature is decided by the heat provider, while the return temperature is the aggregated result from all cooling processes at the customer substations. The supply and return network temperatures are not standardized, they will depend on the local conditions [1].

An overview of annual average temperature level of 142 Swedish and 207 Danish DH systems is provided in Fig. 1 [4]. Fig. 1 shows that Swedish and Danish DH systems can be regarded as the 3rd generation DH system with respect to their temperature levels. The average network temperatures in Sweden and Denmark are compared with six other European DH systems in Fig. 2. Fig. 2 shows that the temperature levels of Riga, Warsaw, and Poznan DH systems are similar to the Swedish and Danish systems and they can be also classified as the 3rd generation DH system. However, for Geneva and Brescia systems, the temperature level are relative high, with annual average supply temperatures close to or above 100°C, and with return temperatures range from around 60°C to 80°C. Therefore, these systems may be regarded as the 2nd generation DH system [5].

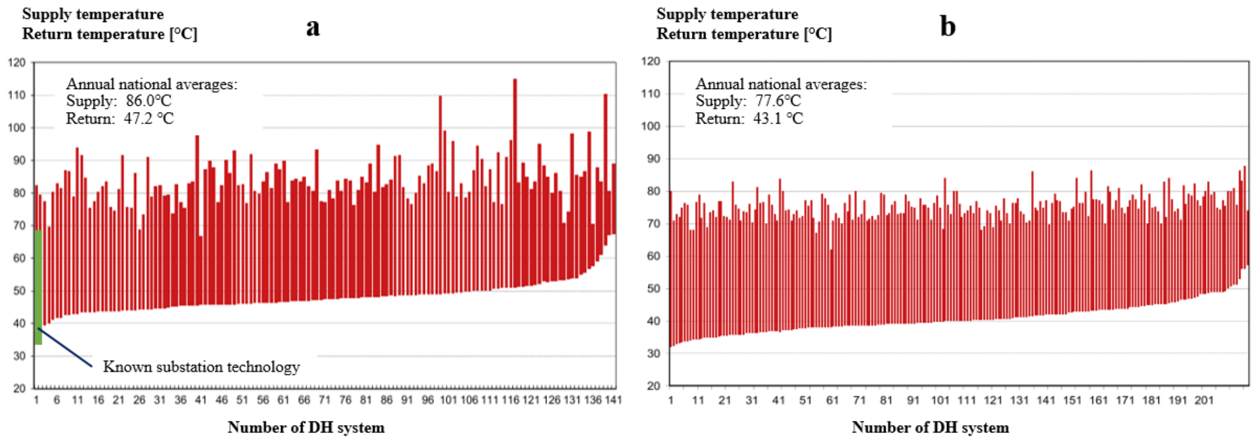

Fig. 1. Overview of heat distribution temperatures in different DH systems. (a) 142 Swedish DH systems, (b) 207 Danish DH systems [4]

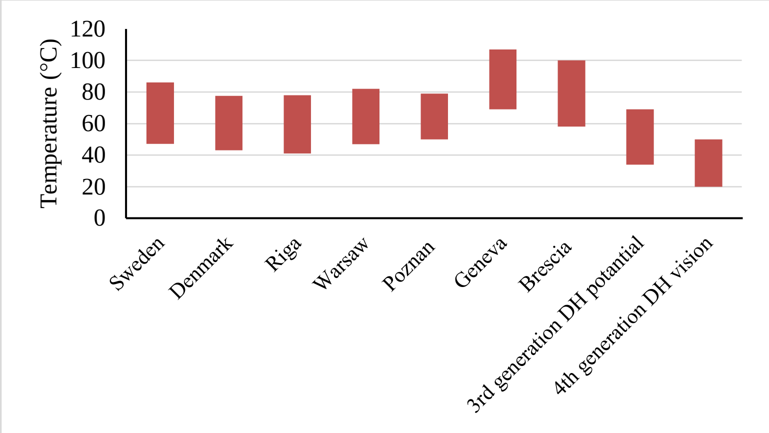

Fig. 2. Typical distribution temperatures for various systems

2.1.2. Transition to the low temperature district heating system

The possibilities to achieve lower temperature level are summarized in the final report of International Energy Agency Technology Collaboration on District Heating and Cooling including Combined Heat and Power (IEA DHC) Annex XI - Transformation Roadmap from High to Low Temperature District Heating Systems [5] . In this report, the transition processes to the low temperature DH are explained in two steps. In the first step, the temperature potential of the current DH system will be fulfilled, with the measures of eliminating system errors and improving system control. In the second step, the temperature level will be further reduced, by the means of enhancing the heat transfer performance of heat exchangers, and improving the design of substations. The renovation of buildings will be conducted along the two steps when it is necessary. These necessary actions for the transition are explained in the text below.

Eliminating system errors and improving system control is a highly important task to reduce the temperature in a DH system. The green bar at the left of Fig. 1 (a) shows the theoretical annual supply and return temperatures of 69 and 34°C for a typical error-free substation with the current substation technology [1]. During 2009, the Marstal DH system in Denmark had an annual average supply and return temperature of 74 and 36°C, very near to the theoretical temperature level. The Marstal DH management has thus proved that it is possible to operate a DH system very near to the theoretical supply and return temperatures [1]. However, Most Swedish DH systems have substantially higher return temperature than their potentials, especially the systems located to the right of Fig. 1 (a). The causes and possible solutions for the difference between actual and theoretical return temperature are summarized in Table 2.

Table 2. Causes and possible solutions for the difference between actual and theatrical return temperature.

Causes		Possible solutions	References
Short-circuit flows	Intentional short-circuit flows to maintain a minimum supply temperature, or to avoid network work freezing	Suitable controlled by thermostatic valves, or introduce innovative systems to avoid bypass flow	[1, 6]
	Unintentional short-circuit flows from remnants of construction, or from the connection mistake	Improve the construction quality	
Low supply temperature	Substation control with high flows to compensate the low supply temperature	Apply intentional short-circuit flows, or use three pipe system with two supply pipes and one return pipe	[1, 5]
Errors in customer heating systems	Missing thermostatic valves in space heating (SH) system, missing hot water circulation in domestic hot water (DHW) system, and using three-way diverting valves in the SH system	Add thermostatic valves in SH system, put the temperature sensor of DHW near or in the heat exchanger, and replace three-way diverting valves with two-way valves	[1, 5]

Causes		Possible solutions	References
	Too small heat emitting surfaces in SH, ventilation and DHW system, which results in a large flow and low cooling	Choose suitable heat emitting surfaces	
Errors in customer substations	Set point errors, sometimes the secondary set point temperature is higher than the primary supply temperature, giving full primary flow	Intelligent control which can ignore impossible control situations	[1, 4, 7]
	Malfunction errors, such as leaking valves, defective valve motors, and malfunctioning temperature transmitters, fouled heat transfer areas for heat exchangers	Use high quality equipment, apply fault detection technology, and regular maintenance	
	Design errors, such as too large valves, wrongly assembled temperature transmitters, and wrong valve motors chosen, parallel flow installations for heat exchangers, and wrong heat exchanger size chosen, deviations from recommended substation configurations	Improve the design quality, apply the prefabricated equipment	

Domestic hot water (DHW) preparation requires certain temperature levels and thereby influence the substation layout and component sizes. The Number of Thermal Units (NTU) indicates the heat transfer ability of heat exchangers. With a fixed heat exchange capacity, larger NTU allows a heat exchanger to operate with lower temperature difference. Meanwhile, larger NTU implies an increased heat exchanger area, which leads to an increased investment cost. For a heat exchanger for DHW preparation, the NTU value is 3.2, with the primary and secondary inlet/outlet temperature as 60°C/25°C and 10°C/50°C, which are recommended by Euroheat and Power [8]. For the low temperature systems with the primary and secondary inlet/outlet temperature as 50°C/20°C and 14°C /47°C, the NTU value should be doubled to 7.6 [5].

For the ultra-low-temperature DH systems, whose supply temperature can be 46°C most of the year, supplementary heating devices are recommended to guarantee comfortable and hygienic DHW [9-11]. Some examples for such application are shown in Fig. 3. In Fig. 3 (a), the DHW is stored in the storage tank and used directly. The DHW is preheated by the DH and further heated by the electric heater. The layout difference between Fig. 3 (a) and Fig. 3 (b) is that Fig. 3 (b) has a heat exchanger after the storage tank, and the DH water is stored in the tank. In Fig. 3 (c), the DHW is preheated by DH through a heat exchanger. The temperature could be comfortable for taking a shower, but considering the requirement for hotter DHW for washing purposes in the kitchen, an instantaneous electric heater is installed on the DHW pipe to the kitchen taps. Fig. 3 (d) has the same layout as Fig. 3 (c), except that an electric heater is used to heat up the total DHW flow. In Fig. 3 (e), a micro HP and a storage tank are installed before the heat exchanger, and one stream of the DH supply is used as the heat source for the HP.

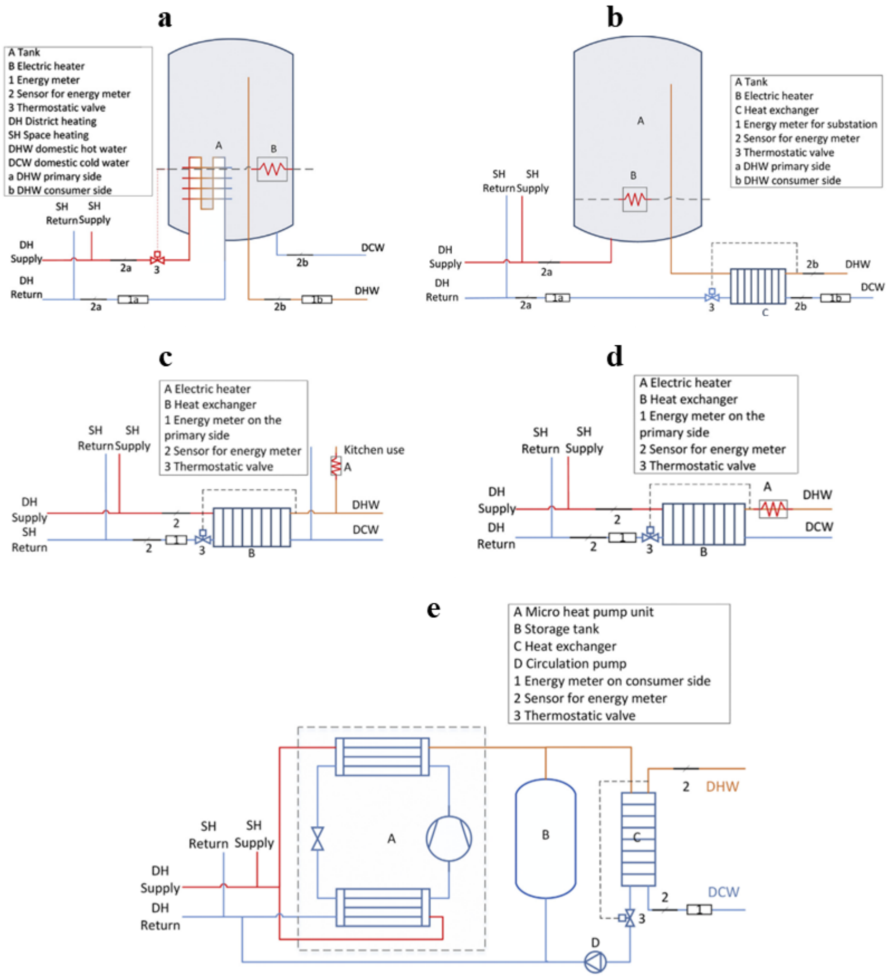

Fig. 3. Different layouts of substations for DHW with supplementary heating devices. (a) substation with tank, (b) substation with tank and heat exchanger, (c) substation with heat exchanger and supplementary heater for kitchen use, (d) substation with heat exchanger and supplementary heater for the total DHW flow, (e) substation with HP, tank and heat exchanger [10].

Building space heat (SH) demand will change in the future and thereby the temperature requirements will change. For newly built buildings and future buildings, 50°C supply temperature to the SH system is enough, with floor heating or low-temperature radiators, and there is still the option to boost the supply temperature during the coldest periods. In fact, the DH supply temperature can be even lower, but it needs supplementary heating system to heat up DHW as explained previously [12].

Low-energy buildings comprise only a small share of the building stock, while the majority are older buildings with considerably higher heat demand. The older buildings will continue to make up a large share of the building stock for many years (for Denmark and Norway, the share will be about 85-90% [13] and 50% [14] in 2030, respectively). Existing buildings are usually equipped with SH systems designed with supply temperatures around 70°C or higher and thereby a reduction of the supply temperature would be expected to cause discomfort for the occupants [12]. However, studies show that houses from the 70s or 80s without any renovation are possible to be heated with the low supply temperature of 50°C most of the year, and only limited time the supply temperature has to be above 60°C. If original windows of the houses are replaced, it is possible to decrease the supply temperature below 60°C for almost the entire year. Further, when the renovated houses replace their SH systems with low-temperature radiators, they may be supplied year around with the supply temperature of 50°C [12, 15].

2.2. Integrating various heat sources into district heating system

There is a huge potential to supply DH systems with heat from various renewable sources, such as industrial waste heat (IWH), solar thermal energy, and geothermal energy. The main advantage of LTDH system is its easier integration and higher efficiency when utilize renewable energy and waste heat (REWH). When the temperature of REWH is higher than the return temperature of a DH system, the resource can be used directly, otherwise the temperature must be upgraded with a HP [16].

Availability is one critical aspect of REWH. Some resources, such as solar and wind, are intermittent and not dispatchable. The hourly and seasonal distribution of those resources may be counter to the distribution of heat demands. In addition, some resources, such as IWH, may be subject to interruptions due to the operating hours of industrial facilities [16]. One common solution is to combine REWH with TES and dispatchable heat sources [1, 17-19].

2.2.1. Methods for heat sources feed-in

There are mainly three ways to feed-in heat sources into DH grids: 1) extraction from the return line and feed-in into the supply line, 2) extraction from the return line and feed-in into the return line, and 3) extraction from the supply line and feed-in into the supply line. The features, advantages, and disadvantages of those variants are summarized in Table 3 [14].

Table 3. The features, advantages and disadvantages of various connection variants.

Connection variants	Features	Advantages	Disadvantages
Extraction from the return line and feed-in into the supply line	The temperature difference is dependent on operating conditions and grid operator. The pressure difference is high, and depends on the actual location in the grid	The return temperature is unchanged, which avoids temperature the strain on return pipes, and the influence of heat extraction efficiency of other heat sources	High energy demand for the mandatory feed-in pumps
Extraction from the return line and feed-in into the return line	The temperature rise is commonly set by the DH operator, the pressure difference is relatively low	It is preferable for heat sources with high efficiencies for lower temperatures	The return temperature is raised, which increases the grid heat loss, and influence the efficiency of other heat sources
Extraction from the supply line and feed-in into the supply line	The temperature increase is prescribed by the grid operator, the pressure difference is relatively low	—	The supply temperature is raised, which increases the grid heat loss, and influence the efficiency of other heat sources

2.2.2. Heat recycling from industrial processes

Recycling heat from industrial processes represents one of the main strategic opportunity for DH, in line with the basic idea of using heat that would otherwise be wasted. In Sweden, recycling of IWH makes up around 6% of the total energy supply to DH networks in 2010. For Danish DH systems, the proportion is about 2%~3%. The DH system in Gothenburg, Sweden, obtains 1112 GWh waste heat from two oil refineries. This gave approximately 27% of heating demand in 2010 [1].

The IWHs are heterogeneous and of various grades. The high-grade IWHs, such as steam and combustible gas, mostly be exploited within the factory, for power generation. However, the low-grade IWHs, with the temperature mostly between 30°C and 200°C, are likely discarded into the environment. There are several technical issues for recycling IWH for DH use: the long distance delivery of IWH to end users, and peak load-shaving of DH system [20].

Long distance delivery for waste heat: Industrial plants are usually far away from DH users, the recommended radius for IWH based DH is 5~10 km for a small-scale town and 20~30 km for a large-or-medium-scale city, due to the investment of transmission network and heat loss during the transmission. However, such a radius might vary with different economic conditions [21].

To decrease the energy use of distribution pumps and thereby the distribution losses, the temperature difference between the supply and return temperature should be increased. As the advantages of LTDH, the reasonable solution is to reduce the return temperature. Several potential techniques to obtain higher temperature difference are shown in Fig. 4, which includes cascade heating technology, absorption heat pump (AHP) technology, and HP technology.

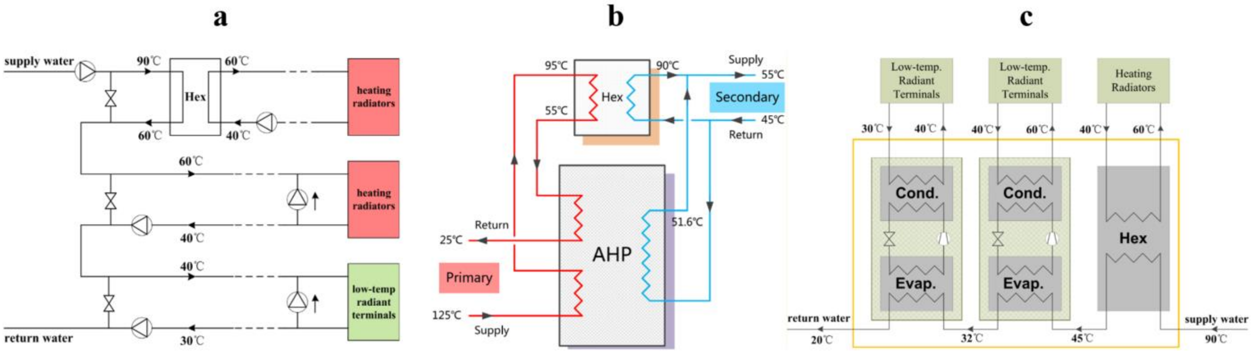

Fig. 4. Scheme of different IWH transition techniques. (a) typical cascade heating system, (b) substation/building entrance AHP system, (c) substation/building entrance electrically driven HP system [20].

In Fig. 4 (a), cascade heating technology supplies heat to the indirectly connected radiators, directly connected radiators, and directly connected low-temperature heating terminals (e.g. floor heating), in sequence. Commonly, the return temperature can be reduced to 30°C or even less by this technology. In Fig. 4 (b), water on the primary side firstly flows into AHP to drive the machine, AHP extracts heat from return water of heat exchanger. After AHP, the water go through the heat exchanger and AHP successively. The final return water can be 25°C. The limitation of this technology is the supply temperature should be high enough to drive AHP. In Fig. 4 (c), supply water firstly transfers heat to heating radiators through a heat exchanger, afterword, the water provides heat to several low-temperature heating terminals by HPs, until the final return temperature become 20°C or even lower [21].

Peak load-shaving in DH systems: An IWH based DH system is complex with respect to the coordination between IWH productions and DH heat demands. Waste heat from industrial processes is constantly fluctuating, and may even come to a temporary stop, depending on the production schedules [21]. However, the heat demand of a DH system changes continuously and smoothly according to the weather conditions [21] and the occupant behaviors [22].

For the above reason, IWH can never serve as the sole heat source, specific control and peak load-shaving strategies should be applied, as shown in In Fig. 5. In Fig. 5 (a), IWH is able to serve the maximum heat load, and cooling towers (CTs) have to operate all the time except the coldest days to release heat to the environment. Opposite, in Fig. 5 (c), IWH serves as the base load. Thus, the peak load-shaving strategies have to be implemented to make up the difference between the total load and the base load. Fig. 5 (b) illustrates a case between these extremes, in which both the CTs and peak-shaving strategies are necessary. To achieve a high IWH recovery ratio, it is appropriate for the IWH to serve as the base load as in Fig. 5 (c). Fig. 5 (d) shows an ideal operation strategy, which takes the fluctuation of IWH into consideration. In this case, IWH together with other heat sources provide the base load, and the peak load-shaving strategy works at the coldest time in winter [21].

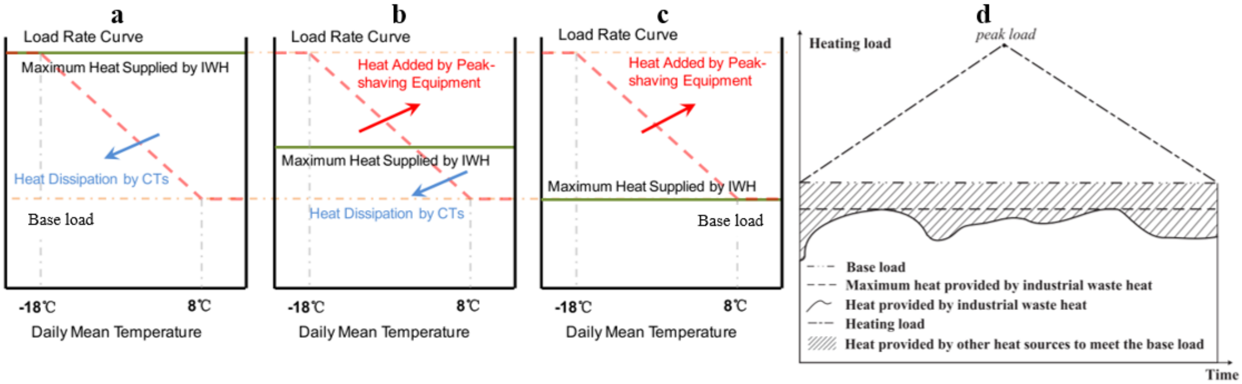

Fig. 5. Regulation and peak load-shaving of IWH based DH system. (a) IWH is able to serve the maximum heat load, (b) a moderate operation strategy with both the peak load-shaving equipment and CTs, (c) IWH serves as the base load, (d) an ideal operation strategy taking the fluctuation of IWH into consideration [20].

2.2.3. Solar district heating

In an international context, solar DH is still in development stage, and it is difficult to ascertain its long-term prospects. There have been interesting developments in a number of countries in Europe, especially in Austria, Denmark, Germany, and Sweden. Recently, companies from these countries have succeeded in contracting for large plants in Asia [1].

The contribution of solar heat to the total heat load can be various from system to system. A large solar thermal plant can be used as a preheater with solar fraction up to 5%. A 100%-coverage of the summer heat load is usually reached with a solar fraction of about 15% on an annual basis. Solar fraction of up to 50% of the annual heat load have been demonstrated for systems using large seasonal heat storages, charging the summer solar heat for the heating period in winter [23].

Solar DH can be provided in a centralized manner with a large array of ground-based collectors, or in a decentralized manner with rooftop-mounted collectors on the buildings that are connected to a DH network, mixed alternatives are also possible, depend on the situation of the projects [1, 19]. Several typical applications of solar DH are presented in Table 4.

Table 4. Typical applications of solar DH.

Location	Solar fraction/ Solar capacity (%/MW_{th})	Other heat sources	DH supply/return temperature (°C)	Thermal storage	Type of integration	Reference
Vallda Heberg (Sweden)	10~20/ 0.2~2	Wood-pellet boiler	—	Buffer storage tank	Centralized	[23]
Crailsheim (Germany)	20~50/ 2~20	Main DH system	65/40	Inter-seasonal borehole heat storage	Centralized	[23]
Gothenburg (Sweden)	100/ 0.2~2	Main DH system	65~100/-	No heat storage	Decentralized	[23]
Büsingen (Germany)	15~20/ 0.5~50	Biomass boiler	75~80/50	—	Centralized	[23]
Braedstrup (Denmark)	10~50/ 0.5~50	CHP, HP and electro-boiler	70~75/30	Multifunctional heat storage	Centralized	[23]
Wels (Austria)	10/ 0.5~10	Main DH system	70~120/-	No heat storage	Decentralized	[23]
Marstal (Denmark)	30/ 13	Oil boiler	—	Two small and one large buffer storages	Centralized	[1]

Location	Solar fraction/ Solar capacity (%/MW_{th})	Other heat sources	DH supply/return temperature (°C)	Thermal storage	Type of integration	Reference
Lyckebo (Sweden)	-/ 3	Biomass boiler	—	Rock cavern hot water storage	Centralized	[1]

The major technical limitation for solar DH is the low energy production density, which means the large areas for placing the solar collectors. In the future, solar thermal energy will continue to be a complementary option [23]. However, the developing technology will bring some possibilities for DH. In the decentralized solar DH systems, there is a possibility that buildings can be either 'importers' or 'exporters' of solar heat energy, or both, depending on the time of the year. Flexibility in this respect offers a prospect for maximizing the use of solar energy, but makes its management difficult. There is another possibility that a large, inter-seasonal storage can be combined with the decentralized solar energy, so that in the summer season all (or most) connected buildings act as 'exporters'.

2.2.4. Geothermal district heating

Geothermal energy has enormous potentials; meanwhile, utilization of geothermal energy produces minimal environmental impact. To varying degrees, exploitable geothermal energy is available all around the world. In spite of the impressive size of this energy source, it currently accounts for only a small fraction of the word energy supply. Intensive initial cost, exploration risk, and human-induced earthquakes are the major obstacle to utilize geothermal energy. In addition, there is also the resource problem- once a geothermal well is set up at a given location, the amount of extracted heat tends to decay gradually, makes it felt to a significant degree after one or few decades, while the DH network is still functioning [1].

Deep geothermal systems use heat from 500~5000 m depth; shallow geothermal systems provide heat from less than 300 m depth. High temperature geothermal energy can be used in conventional ways for electricity generation and for direct heat utilization. Ambient heat stored at shallow depths, and aquifer thermal energy stores in ground water layers can be extracted with ground source heat pump (GSHP) and applied for SH and DHW [24].

Several typical applications of geothermal DH are presented in Table 5.

Table 5. Typical applications of geothermal DH.

Location	Type of system	Geothermal fraction /Geothermal capacity (%/MW_{th})	Other heat sources	Geothermal or DH temperature (°C)	Reference
Paris (France)	1.5~1.8 km depth wells	-/ 250	Fossil fuel boilers	Geo: 70	[25]
Ferrara (Italy)	1 km depth wells	80/ 14	Waste-to-energy plant, backup stations, solar heating station, thermal storage, and organic rankine cycle electricity generation	Geo: 100~105	[25]
Beijing (China)	3 km depth wells	100/ -	No other heat source	Geo: 75	[25]
Ontario (Canada)	213 m depth boreholes	—	—	—	[26]
Malmö (Sweden)	90 m depth wells	-/ 1.3	GSHP, boiler	—	[26]
Bucharest (Romani)	70 and 170 m depth wells	100/ 0.39	GSHP	DH: 40/35	[26]

2.3. Thermal energy storages in district heating system

TES can be divided into inter-seasonal storage and short-term storage. Inter-seasonal storage is still in a development phase, while, short-term storage can be made with well-proven technology. However, the dividing line is not sharp; the largest facilities used for short-term storage in large networks could provide inter-seasonal storage in small systems [1]. In addition, as the end users of DH systems- buildings can also function as TES, due to their thermal inertia. Sometimes, building inertia TES is able to moderate short-term daily net load variations to the same degree compared with hot water tank, while, with much lower investment cost [27].

One purpose of short-term storage is to shift loads away from peak demand hours to lower demand hours. Another purpose is to provide rapid heat or cold supply to meet sudden load changes, which is not capable for heat generating equipment, or to avoid losses associated with quick starts and stops of the generating equipment. A further function of short-term heat storage is to allow for boosted electric power output from some type of CHP plants, which are characterized by a reduced output at increased heat extraction [1, 28].

The objective of inter-seasonal storage is usually either to store collected solar heat for winter heating, or to act as the heating and cooling source as well as thermal storage for GSHP [29].

There are three available technologies for TES: sensible heat storage, latent heat storage, and chemical storage. Sensible heat storage is a comparatively mature technology that has been implemented and evaluated in many large-scale demonstration projects. Latent heat and chemical storage have much higher energy storage densities than sensible storage, and seldom suffer from heat loss problems. However, the latter two technologies are currently still in the stages of material investigations and lab-scale experiments [30]. The detail comparison of those three technologies are shown in Table 6.

Table 6. Comparison of the three available technologies for TES [30].

	Sensible	Latent	Chemical
Storage medium	Water, gravel, pebble, soil...	Organics, inorganics	Metal chlorides, metal hydrides...
Type	Water, rock, and ground based system	Active and passive storage	Thermal sorption and chemical reaction
Advantage	Environmentally friendly, cheap material, relative simple system, easily control, and reliable	Higher energy density than sensible heat storage, and provide thermal energy at constant temperature	Highest energy density, compact system, and negligible heat losses
Disadvantage	Low energy density, huge volumes required, self-discharge and heat losses problem, high cost of site construction, and geological requirements	Lack of thermal stability, crystallization corrosion, and high cost of storage material	Poor heat and mass transfer property under high density condition, uncertain cyclability, and high cost of storage material
Present status	Large-scale demonstration projects	Laboratory-scale prototypes	Laboratory-scale prototypes
Future work	Optimization of control strategy to advance the solar fraction and reduce the power consumption, optimization of storage temperature to reduce heat losses, and simulation of ground based system with the consideration of affecting factors	Screening for better suited phase change material materials with higher heat of fusion, optimal study on store process and concept, and further thermodynamic and kinetic study, noble reaction cycle	Optimization of the particle size and reaction bed structure to get constant heat output, optimization of temperature level during charging/discharging process, screening for more suitable and economical materials, and further thermodynamic and kinetic study, noble reaction cycle

2.4. Smart district heating system

The transformation toward the future renewable energy system poses challenge for all the sub-systems. Facing the challenge, all the sub-systems should benefit from the use of modern information and communication technologies, and uprated themselves to become smart systems [31].

The smart DH system consists of three essential parts: physical network (PN), internet of things (IoT), and intelligent decision system (IDS). PN includes pipes, heating equipment, local meters, and control devices. IoT is the network of sensors, data collecting and transmission devices, and other items, which enables these objects to be connected and exchange data. IDS makes the optimal decisions based on collected data, heat demands, and system responds [32]. One example for the smart DH concept is shown in Fig. 6.

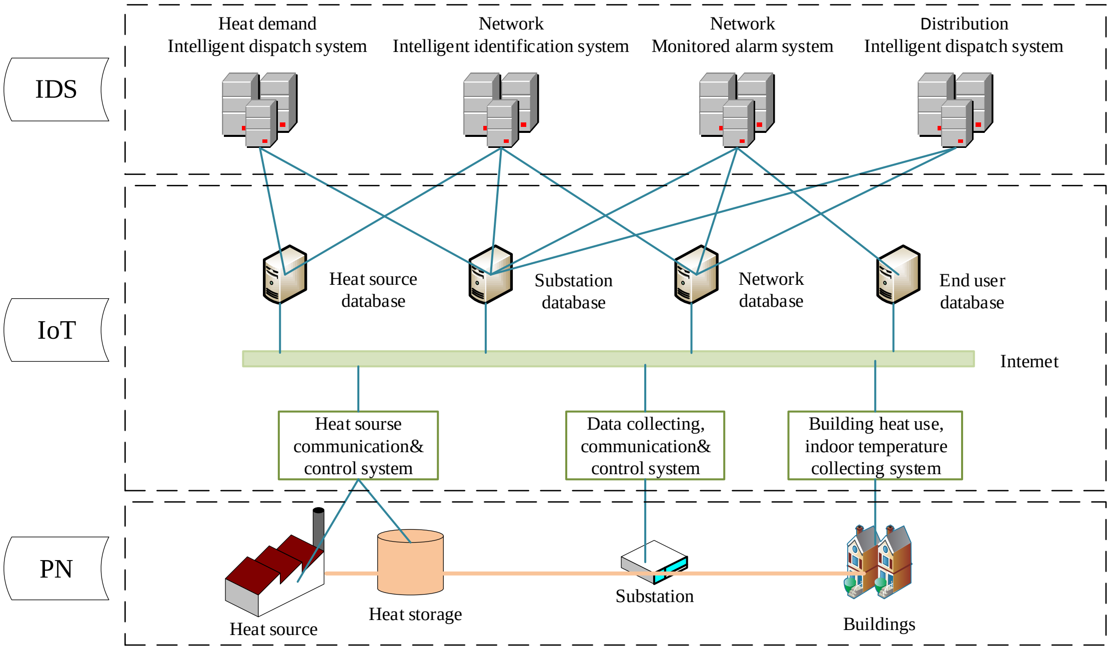

Fig. 6. Concept of smart DH system [33].

The final goal of the smart DH system is to become an essential part of the future smart and renewable energy system. In the future energy system, the focus is on the integration of the electricity, heating, cooling, and transport sectors, and on the use of flexibility in demands and various storages of different sectors. To enable this, the smart DH system must be able to coordinate with other sectors in the energy system [2, 34].

3. Facing challenges for the future district heating system

3.1. Heat losses through distribution network

Reducing heat losses in DH networks is one of the main challenges for the future DH system, because it will reduce the primary energy use and infrastructure investments. Heat loss in DH networks accounts for a relatively high share of heat supply [35], and it will become more significant for the future DH with decreased heat demand.

Real measurement data for heat losses for several DH systems are organized in Table 7. Except the three Swedish cases, all the cases are LTDH demonstration projects. From Table 7, it is obviously that the heat loss in DH networks should not be underestimated, even for the systems with the low temperature and newly upgraded networks. Ten of thirteen systems have a heat losses over 15%, and seven systems have a heat losess over 20%. For the system in Rotskär, the heat losses are up to 32%.

Table 7. Heat losses and detail information of several DH systems.

Location	Construction or upgrade year	Linear heat density MWh/(m·a)	Supply/Return temperature (°C)	Heat loss share (%)	Reference
Slough (UK)	2009~2010	0.319	52/32	28	[14]
Taastrup (Denmark)	2012	—	55/40	13~14	[14]
Lystrup (Denmark)	2008~2009	0.31	55/25	17	[36]
Samsø island (Denmark)	2005	—	—	20~24	[36]
Spjald (Denmark)	1998	0.57	65/32~39	26	[5]
Tarm (Denmark)	1995	0.66	65 /36	17	[5]

Location	Construction or upgrade year	Linear heat density MWh/(m·a)	Supply/Return temperature (°C)	Heat loss share (%)	Reference
Bramminge (Denmark)	—	—	68/-	20	[5]
Middelfart (Denmark)	—	0.72	68/44	19	[5]
Munich (Germany)	2006	1.43	55/30	3	[3]
Okotok (Canada)	2005~2007	0.7	40/35	5~13	[3]
Prästmarken (Sweden)	1995~2004	0.5	75/50	24	[37]
Munksundet (Sweden)	1997	0.84	70/40	22	[37]
Rotskär (Sweden)	2002	0.49	80/-	32	[37]

Some potential solutions to reduce the distribution heat loss are summarized in Table 8.

Table 8. Potential solutions to reduce the distribution heat loss.

Object	Solutions	Limitation	Project applications	Reference
Network	Install pipes inside buildings, to decrease the length of network and utilize heat loss for SH	Not welcomed by DH companies and customers	Peter Freuchenvej	[37]
Network	House-to-house connection, to decrease the length of service pipes	Not welcomed by DH companies and customers	Cederborg, Nordgren, Gudmundsson	[37]
Network	Three or four media pipes, to shut down one or two pipes in summer	—	Experiment in Nykøbing Falster	[37]
Network	Use booster pumps, to reduce the dimension of pipes	—	Widely used	[37, 38]
Network	Apply branched network with bypass units instead of looped network	Results in high return temperature	Widely used	[38]
Pipe	Improve the insulation of pipes	—	Widely used	[37]
Pipe	Pre-insulated twin pipes or triple pipes	—	Widely used	[1, 37, 39]
Pipe	Prevent over dimensioning of pipes	—	Widely used	[38]
Pipe	Use buffer tanks for DHW production, to reduce the dimension of pipes	Legionella problem with LTDH system	Widely used	[38]
DH system	Leakage detection to avoid hot water loss	—	Widely used	[40]
Substation	Fault detection to avoid any malfunction	—	Widely used	[1, 4, 7]

3.2. Decreased heat demands in the future district heating

The competitiveness of DH systems may be decreased when heat demands are expected to decrease in the future. One study, based on 83 DH systems in European cities shows that there is a lower risk for reduced competitiveness for large cities and inner city areas, however, the areas with low heat density will lose competitiveness in the future [41].

The experiences gained from different projects show that DH systems with low heat demand density require careful plan and design to achieve good economy. In some cases, innovative solutions have been applied and gained extra rewards. With those solutions, it is believed that DH may supply the areas with heat density of 10 kWh/(m^2·a), or linear heat density of 0.3 MWh/(m·a) [37]. Some potential measures to apply DH in low heat density areas are shown in Table 9.

Table 9. Potential measures to apply DH to low heat density areas.

Classification	Solutions	Limitation	Reference
Heat source	Use IWH, waste incineration and other cheap heat sources	—	[41]
System design	Optimized network layout with less pipeline length, to get higher linear heat density	—	[42]

Classification	Solutions	Limitation	Reference
System design	Low pressure and low temperature systems with direct connection of SH system	Hydraulic interaction between DH system and SH system	[1, 37]
System design	Reduce pipe dimensions by applying DHW tanks	Legionella problem with LTDH system	[37]
System design	Reduce pipe dimensions by applying booster pumps	—	[37]
System design	House-to-house connection to decrease the length of service pipes	Not welcomed by DH companies and customers	[37]
System design	Three or four media pipes, to shut down one or two pipes in summer	—	[37]
System design	Install pipes inside the buildings, to decrease the length of network and utilize heat loss for SH	Not welcomed by DH companies and customers	[37]
System design	Increase the degree of connection		[37]
Pipe	Improve the insulation of pipes		[37]
Pipe	Pre-insulated twin pipes or triple pipes		[37]
Pipe	Prevent over dimensioning of pipes		[38]
DH system	Leakage detection to avoid hot water loss		[40]
Substation	Fault detection to avoid any malfunction		[1, 4, 7]
Civil works	Reduce the ground cover		[37]
New loads	Supply household equipment previously supplied by electricity	Conflict with traditional practices	[37]

4. Conclusion

Transition to the 4th generation DH is a challenge issue. The process requires the upgrades of DH system and the collaboration with other energy systems. In addition, buildings may also need some refurbishment to coordinate the changes of those systems. The final goal of the transition is to make the future DH system more flexible, reliable, intelligent, and competitive, and become an essential part of the future smart and renewable energy system.

The upgrades of DH system involve the physical system as well as the virtual system. For the physical system, the transition will focus on lowering the system temperature levels, and integrating various heat sources and thermal storages. Two steps will be conducted to lower the temperature level. The first step is to achieve the temperature potentials of the current DH system by the means of eliminating system errors and improving system control. The second step is to further reduce the temperature levels through enhancing heat transfer performance of heat exchangers and improving system design. The renovation of buildings may also be conducted through those two steps when it is necessary. Various heat sources and different level TESs will be integrated into the future DH system. Transition to 4th generation DH should take into consideration all the consisting issues such as way of heat feed-in, type of heat sources and TESs, distribution heat losses, the design of DH system, and operation strategies. Finally, the decisions should be made depending on the local natural and economic conditions.

For the virtual system, transition to 4th generation DH will be based on the intelligent physical system, which is able to measure, transmit information, collect data, and control. In addition, IDS will become more powerful with advanced functions in the future DH system, such as the reliability assessment, accident analysis, accident alarm, operation evaluation, operation supervision, and operation optimization.

The large share of distribution heat loss and the decreasing heat demand are two challenges the future DH systems are going to face. The potential solutions involve innovating system design, upgrading physical and virtual system, integrating cheap heat sources, and introducing new heat loads.

The conclusion of this study is that even enjoying the developing trend of the 4th generation DH, transition to 4th generation DH should be conducted carefully and gradually. Comprehensive consideration must be took into, focus on the energy status, condition of existing systems, and the operation custom in different areas or countries. In addition, the technologies for the future system need further development, and the operation as well as management strategies should be innovated.

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