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District heating and cooling optimization and enhancement – Towards integration of renewables, storage and smart grid

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ABSTRACT

District heating and cooling (DHC) systems are attracting increased interest for their low carbon potential. However, most DHC systems are not operating at the expected performance level. Optimization and Enhancement of DHC networks to reduce (a) fossil fuel consumption, CO_2 emission, and heat losses across the network, while (b) increasing return on investment, form key challenges faced by decision makers in the fast developing energy landscape. While the academic literature is abundant of research based on field experiments, simulations, optimization strategies and algorithms etc., there is a lack of a comprehensive review that addresses the multi-faceted dimensions of the optimization and enhancement of DHC systems with a view to promote integration of smart grids, energy storage and increased share of renewable energy. The paper focuses on four areas: energy generation, energy distribution, heat substations, and terminal users, identifying state-of-the-art methods and solutions, while paving the way for future research.

1. Introduction

Globally, buildings account for 40% of total energy used and contribute towards 30% of the total CO_2 emissions [1,2]. Buildings are the largest consumer of energy in the European Union, accounting for up to 40% of the total energy consumption and approximately 36% of the greenhouse gas emissions [3]. Buildings' share of CO_2 emissions is higher in some countries; e.g., the sector represents 50% of the total of 570Mt CO_2 emissions in the UK in 2013 [4]. Energy is used in buildings for heating and cooling, hot water, lighting and appliances, and the majority of this energy come from the burning of fossil fuel, which amounted to 81.23% of global energy consumption in 2011 [5]. Associated GHG emissions from the burning of fossil fuels have been attributed as the extremely likely cause of anthropogenic climate change [6]. According to the International Energy Agency (IEA) [7], global greenhouse gas emissions are rapidly increasing and it will be difficult to limit the long-term rise in global average temperature to 2 °C below pre-industrial levels. Addressing the issue of global climate change and reversing the trend of rising energy consumption is essential to reduce the impact of climate change to a 2 °C rise in global average temperature [7]. The building sector, therefore, plays a significant role in mitigating the impacts of climate change – first, through reducing the demand; i.e. energy conservation, and second, by maximizing the use of renewable energy – both aimed at reducing GHG emissions [8]. This has increased the need for new energy substitutes and conversion methods to meet an increasing energy demand and pave the way to cost-effective heating and cooling solutions. District Heating and Cooling (DHC), with its potential to integrate local renewable energy generation and industry or municipal surplus energy, is attracting increased interest from local authorities and developers.

District Heating (DH) is a system that delivers hot water or steam derived from a central plant to buildings via extensive underground pipe network. DH has gone through three generations [9] and [10]. The first commercial DH network emerged in the 1880s and dominated the market until the 1930s: High temperature steam was applied as the heat carrier causing serious heat loss and steam explosions, thus leading to pressing demands for network improvements. Pressurized hot water with a temperature over 100 °C was used to phase out steam in the second generation (until the 1970s). A scarcity of heat control and poor overall quality of DH led to the third and present generation. The biggest evolution of the third generation is reflected in lower supply temperatures, less than 100 °C, with improved energy-efficiency and cost saving. While deployment policies tend to be country specific, the driving incentives are motivated by performance and economic considerations [9]. DH enjoys high popularity in northern European countries. For instance, Sweden has installed a length of 30,000 km DH system which supplied over 61% heating capacity of the country by 2011, as illustrated in Fig. 1. The successful implementation of

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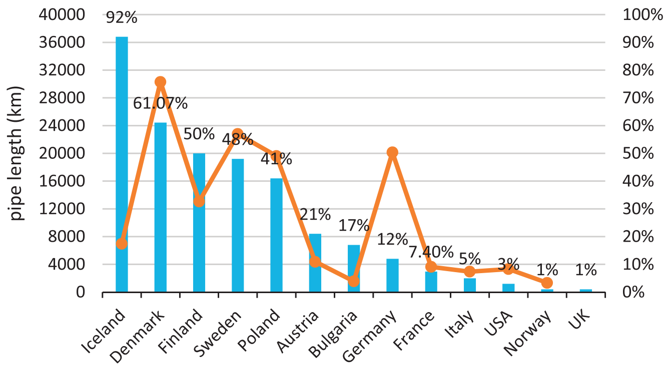


Fig. 1. District heating proportion and pipe length in 2011 [16].

Combined Heat and Power (CHP) is the main driving factor for extensive use of DH in the Danish energy network, 52% of electricity met by CHP [11,12]. This situation is similar in the United states that have experienced a growing interest across cities in the deployment of DHC as a result of advances in CHP technology [13]. Nevertheless, the development of DH is extremely disparate. In Iceland the share of DH was as high as 92% given its abundance in geothermal energy, while Norway and UK lagged far behind with a share of 1%. Cheap fuel and electricity prices and the focus on short term investments are the major barriers for DH deployment in Europe [14]. Research indicates that DH will remarkably contribute to the European Energy Roadmap 2050 of 80% CO_2 emission reduction [15].

Conversely, District Cooling (DC) delivers chilled water from a central plant to buildings via pipe network. The essential difference between DC and DH is the temperature of the distribution medium. Fluid temperature for DC is normally under 10 °C. The development of DC can also be characterized by three generations [9]. The first DC system originated from the 19th century and was used at Denver's Colorado Automatic Refrigerator Company in 1889. Refrigerant was used as the distribution medium at that time. Large DC systems were in operation in New York in the 1930s [17]. It first spread to Europe in the 1960s in countries such as Germany, Italy, Sweden and Finland [17], where the second generation DC developed. Cold water was then applied as the delivery medium. The third generation was based on various cold supply technologies, including absorption chillers, mechanical chillers, natural cooling from lakes, excess cold waste and cold storage, which became popular in the 1990s [9]. However, the development of DC is much slower than that of DH and much less DC systems have been installed to date. The main reason is that temperature drop for supply and return temperatures in DH network is larger than DC network, which means the pipe size for DC is much bigger for the same effect transmission, leading to a more expensive investment in DC network [18]. The major users of DC are densely populated areas such as schools, hospitals, offices and airports. The distribution pipe length of different countries in 2011 is illustrated in Fig. 2. In spite of their finite population and colder climate, Nordic countries were leading the market share of DC in Europe, with Sweden accounting for 30% of DC in EU27. Meanwhile, Finland also displayed a constant growth [19]. Given the prospect of global warming, it is expected that cooling demand will increase in the future. The efficiency of DC may be 5–10 times higher than traditional power driven air-conditioning by making use of resources that otherwise would be wasted or difficult to use [20]. This indicates a necessity for the development of DC in Europe, where almost all individual cooling systems rely on electricity [21].

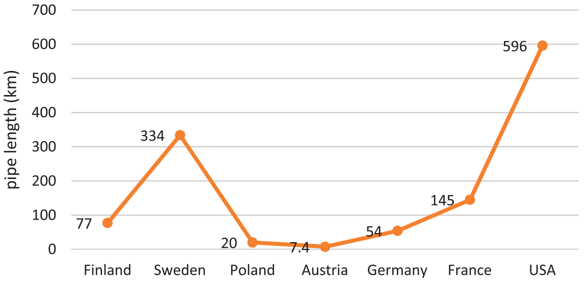


Fig. 2. District cooling pipe length in 2011 [16].

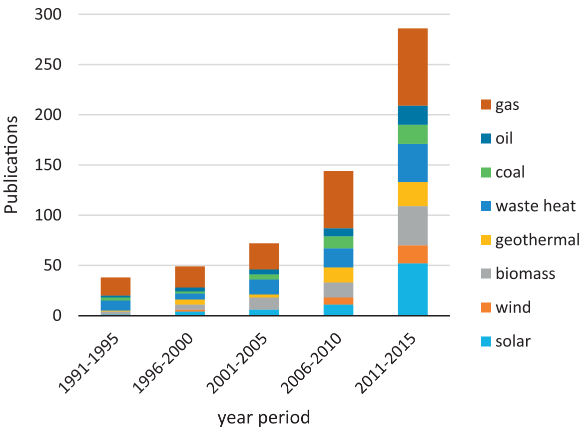


Fig. 3. Publication related to district heating optimization from 1991 to 2015.

Although DHC has attracted increased attention in recent years reflected by higher adoption rates, there are still problems to overcome to trigger large-scale acceptance. These problems relate to (a) huge investment for the construction and deployment of DHC, (b) inefficient operation of the generation units and (c) poor delivery quality of the network [22]. Researchers proposed a wealth of approaches to optimize DHC systems with a view of improving their competitiveness in the future energy market. The Scopus scientific search engine is applied here to study recent publications related to DHC optimization. Data obtained are based on the search key words ‘district heating’ or ‘district cooling’ and ‘optimization’ included in article title, abstract and key words. Fig. 3 illustrates the number of publications about DHC optimization from 1991 to 2015.

An increasing number of optimization studies based on DH and DC have been examined in recent years, but there is still a lack of a comprehensive review which addresses the multi-faceted dimensions of the optimization and enhancement of DHC systems with a view to promote integration of smart grids, energy storage and increased share of renewables. The present study focuses on four areas: energy generation, energy distribution, heat substations, and terminal users, identifying state-of-the-art methods and solutions, while paving the way for future research. This paper is organised as follows: The first section describes the evolution of DH and DC networks and their current utilization in various countries. Following this introduction, future trends for the development of DHC are discussed. Next, DHC optimization is discussed focussing ranging from algorithm development to field-based experimentations. Section 4 reviews and discusses DHC optimization from an energy generation perspective factoring in a wide range of generation technologies, including Combined Cooling, Heating and Power (CCHP) and Thermal Energy Storage (TES). This is followed by a discussion of DHC optimization from an energy distribution perspective through network configuration (including pipe dimension, insulation, and layout) and the trend towards low energy heating and cooling networks. Chapter 6 elaborates on heat substation optimization focussing on heat exchangers’ efficiency while Section 7 addresses enhancements from terminal users reflected in low energy buildings, variable pricing schemes and improving public awareness. Section 8 provides directions for future research paving the way to the concept of smart thermal grid. The last section provides conclusion remarks.

2. Future trends for district heating and cooling

Lund et al. [9] have defined future smart thermal grids (STGs) as "a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants as well as from a number of distributed heating and cooling producing units including individual contributions from the connected buildings". Future STGs will be more intelligent, involving automatic metering, control and configurable equipment, integrating with electricity and gas grids [9].

Traditional fossil fuels are the dominant energy sources for existing DHC systems. However, Combustion of fossil fuels has brought about severe issues such as environment pollution, price rise and health problems. Consequently, an enhancement of present systems is a prerequisite for more cost-effective and efficient DHC to deliver a clean and sustainable energy system without overexploiting natural resources. DHC has been proved to be capable of working together with various sustainable energy sources, including solar, wind, biomass, geothermal and industry waste heat [23–28] and [29]. A high penetration of renewable and waste energy greatly diminishes the dependence on fossil fuel.

Moreover, heat losses in current DHC systems are sizeable, ranging between 7.6% and 27.8% [30] in DH networks. A slight change in the temperature of the distribution medium can effectively enhance the performance of the whole system. Several publications have identified the possibility of low temperature DH [31,32] which can (a) improve the efficiency of the generation units by reducing recycling times, and (b) lower heat loss of the distribution system by narrowing down temperature differential. A supply of 50 °C and return of 20 °C will be sufficient to meet the demand for space and water heating [9]. Furthermore, this would facilitate the utilization of renewable energy such as solar, geothermal, and waste industrial heat as more low-grade energy is used. Intelligent monitoring and management of DHC is another interesting trend. This enables energy producers to adjust heat production according to dynamic weather variation and consumers requirements.

Future DHC systems have the potential to deliver sustainable, reliable, affordable and intelligent energy to customers. These smart systems are characterized by the following capabilities:

1) Integration with a variety of renewable energy solutions, industry excess heat or cold and combined cooling heating and power to maximize the utilization of local energy sources for future sustainable energy strategy and GHG mitigation target;
2) Adoption of a lower temperature for heating or a higher temperature for cooling to both improve the efficiency of the generation units and transportation network so as to maximize economic and environmental benefits;
3) Working together with thermal energy storage systems for peak-shaving and addressing effectively the fluctuation of renewable energy to reduce investment cost and to improve network stability;
4) Interacting between customers and energy companies to ensure that allocated energy can satisfy energy demand while not causing any waste to further improve the DHC system efficiency;
5) Relying on intelligent energy management technology that allows users to visualize and control energy consumption and air quality from smart interfaces (including phones).

3. Characterising optimization of district heating and cooling systems

By effectively utilizing DHC systems, heating and cooling can be achieved with lower emission and reduced exploitation of fossil fuel resources. Optimization is the most effective way to improve the performance of DHC networks [33]. Several studies have been carried out using optimization algorithms (as shown in Table 1), simulations, experiments, and other methods (as shown in Table 2) to optimize DHC networks.

The objectives of the above methodologies and algorithms are focused on reducing investment costs, operation costs, CO_2 emission and payback periods. The decisive factors for improvement of the network can be categorized into four interrelated categories: (a) energy generation, (b) energy distribution, (c) heat substations, and (d) terminal users. In order to effectively optimize the DHC network, a comprehensive and critical understanding of each sub-process is necessary as elaborated in the following sections.

4. Energy generation enhancement potential

In DHC networks, heat and cold are usually generated from central plants using large generation units with higher efficiency and more advanced air pollution control methods. Despite the fact that DHC is able to work together with a variety of energy sources, the efficiency and output of generation units are variable. An over-generation or under-generation may result in energy waste or consumers' complaints, respectively. It is vital to ensure optimal management of the generation units to guarantee that the energy hub provides sufficient energy to terminal users at its optimal efficiency, economy and minimum emission.

4.1. Integration with sustainable energy

DHC networks are able to use highly flexible energy mix. This facilitates the deployment of energy and carbon reduction plans with a view of gradually decarbonizing heat and cool production. Meanwhile, providing heating and cooling from energy centres is easier and cheaper compared with installing renewable energy conversion facilities in individual buildings [56]. Renewable energy such as biomass, geothermal and solar thermal can generate heat directly and are widely applied for DH. When they are used for cooling, an adsorption or absorption cooling driver – chiller is adopted to convert heat, in the form of steam, hot water or exhaust gas into cooling power. More detailed technologies concerning thermal activated cooling are introduced in [57]. This greatly reduces electricity consumption as primary energy is used more efficiently [58]. Renewable electricity such as solar PV, wind power and hydropower can also be used for DHC by equipping electric boilers and compression chillers in generation plants to convert renewable electricity into heat and cold. Natural cooling from deep sea, lakes and rivers is another interesting option for DC given their relatively stable temperature, as evidenced by their successfully use in Sweden [59], Canada [60] and China [61]. Most of the DHC networks are established in urban cities with high population densities, making it difficult to rely on renewable energy [58]. Therefore, it is important to make good utilization of local available low grade energy, an additional energy source to ease the pressure on environment and fossil fuels. The principle for using low valued energy such as waste incineration and industry waste heat for heating and cooling is similar to biomass and geothermal. For more information about converting waste to energy, readers can refer to [62] and [63].

Using renewable energy and waste energy for DHC is an effective way to reduce GHG emission as no extra pollutant is generated during the process of operation. Meanwhile, there is nil or little capital investment for fuels during the running process. In addition to that, it also increases energy security as less primary energy is imported from other countries. However, the technology for the utilization of some renewable sources such as solar and wind is not as mature as fossil fuel and is not yet competitive in the market. The cost for DHC is relatively expensive when compared with fossil fuels because of the high investment in installation and materials procurement. As a result, innovative techniques should be developed to reduce the costs for the investment on infrastructure construction and to make the utilization of renewable energy more affordable and competitive in the energy

Table 1
Publications related to DHC optimization and related algorithms.

Authors	Network Type	Optimization Method	Optimization targets and scenarios
Söderman 2007 [18]	DC	mixed-integer linear programme modelling	Optimization from cooling plants location and capacity, cold medium storage location and capacity, distribution layout, operation strategy to minimize the overall cost
Burer et al. 2003 [34]	CCHP	multi-objective evolutionary algorithm	Optimizing energy output of multi-generation units to achieve minimal CO_2 emission at a given investment or to achieve minimal cost at a given CO_2 emission
Chow et al. 2004 [35]	DC	genetic algorithm	A proper mix of consumption buildings to achieve a shorter payback period
Sakawa and Matsui 2013 [36]	DHC	Interactive fuzzy satisficing method	Optimal control of generation units and thermal storage to minimize running cost and primary energy amount
Feng and Long 2008 [37]	DC	Single parent genetic algorithm	Optimal piping layout to reduce annual equivalent cost of piping network
Keçebaş et al. 2014 [38]	DH	Artificial neural network	Evaluation of energy input, losses, output, efficiency and economic optimization to provide information for the optimal design and operation of the system
Khir and Haouari 2015 [39]	DC	Mixed-integer programming model	Optimal chiller capacity, storage tank capacity, pipe size and layout, quantity of cold water produced and stored to minimize investment and operation costs
Fang and Lahdelma 2015 [40]	DH	genetic algorithm	Optimal power generation from different generation plants to minimize cost in fuels and pumping cost
Haikarainen et al. 2014 [41]	DH	mixed-integer linear programme	Further development of the network at different network distribution and operation scenarios to achieve the lowest annual cost while satisfy heat demand
Omu et al. 2013 [42]	CHP	mixed-integer linear programme	Optimal design of generation unit size and location, distribution network structure to minimize annual cost and CO_2 emission
Byun et al. 2015 [43]	DH	Heat supply control algorithm	Simultaneously regulating the secondary supply water temperature and flow rate to minimize heat loss of a district heating network while satisfying heat demand
Jiang et al. 2014 [24]	DHC	Group search optimizer	Optimal number of generation units and operation strategy to optimize the running cost
Ameri and Besharati 2016 [44]	CCHP	mixed integer linear programming	The optimal size and operation of several different generation units, including gas turbines, boilers, chillers, PV units, to minimize capital and operational costs in DHC networks
Lozano et al. 2010 [45]	CCHP	mixed integer linear programming	An installation of thermal energy storage to reduce annual operation cost

Table 2
Publications related to DHC optimization based on simulation, experiments and other approaches.

Authors	Network	Methods	Targets
Ortiga et al. 2013 [46]	CCHP	Scenario analysis	Maximum utilization of fossil fuel and renewable resources in the energy supply system to reduce energy consumption and CO_2 emission
Kuosa et al. 2013 [10]	DH	Model based on Excel/Visual basic environment	A ring distribution topology to reduce operation cost
Keçebaş et al. 2011 [47]	DH	Life-cycle cost analysis	Different fuel, pipe size and insulation thickness to analyse energy saving and payback period of a district heating system
Kayfeci 2014 [48]	DH	Life-cycle cost analysis	Different insulation materials with variable diameter to investigate energy saving and payback period
Dodoo 2010 [49]	CHP	Software ENSYST	Building renovation to reduce primary energy consumption in DH
Yan et al. 2013 [50]	DH	Hydraulic model	Pump power saved by using a distributed variable speed pump to replace conventional central circulating pump
Calise et al. 2015 [51]	CHP	SoftwareTRNSYS	Different operation control strategies to analyse fuel consumption of the network
Udomsri 2012 [52]	CCHP	Software TRNSYS	Installation of higher efficiency pumps and reduction of dry cooler's return temperature to increase electrical COP
Li et al. 2015 [53]	CHP	Software Ebsilon	Simultaneously considering heat source, piping system and heat users to optimize heat loss, pressure drop, pump power consumption and supply temperature
Pirouti et al. 2013 [54]	DH	Software PSS SINCAL	Different operation strategy to minimize the annual total energy consumption of the system, including pump electric energy consumption and pipeline energy loss
Sun 2014 [55]	DH	Experiments	A new heat exchanger to improve distribution network and generation unit efficiency

market. It is essential to better balance the infrastructure investments, operation costs and production interest in the life cycle of the holistic DHC network. When payback periods and GHG emissions are taken into consideration as important factors for choosing generation units in a DHC system, an integration of renewable and non-renewable energy generation units is the optimal approach for the production of heat and cold.

4.2. Combined cooling heating and power

DHC is making substantial progress towards environmental target not only due to the reason that it is an extremely flexible technology which can incorporate with any renewable energy and waste energy, but also because it is capable of working together with CCHP units, which is also known as trigeneration. CCHP is an extension of CHP, which has been proved to be more environmentally friendly and cost effective when compared with conventional power generation process by further utilizing excess heat. The efficiency of a typical steam turbine is 20–38% for power generation, but it exceeds 90% when heat and power are generated simultaneously [64,65]. Linking heat and electricity in a district level can eliminate CO_2 emission by 81–90%, raise energy efficiency by 53–55%, and reduce peak load electricity by 73–79% [66]. CCHP is a combination of CHP and thermally activated chillers that extract waste heat from CHP for cold generation [57,67]. Using waste heat for cooling can both reduce electricity demand and further enhance overall efficiency of the traditional CHP [52].

A typical CCHP system is illustrated in Fig. 4. It consists of a combustor, turbine, generator, heat exchanger and a chiller. Water absorbs heat derived from fuel combustion in the combustor to produce high temperature steam, which is used to drive the steam

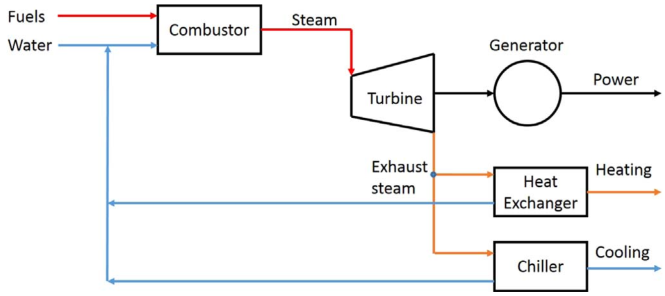


Fig. 4. Schematic diagram of a typical CCHP system.

turbine and the mechanical work is converted into electricity by the generator. During winter, the heat of exhaust steam from the turbine is transferred to water through the heat exchanger for heating. During summer, the heat is used to drive the chiller to generate cold water for cooling. Kong et al. [68] claimed that 33% primary energy could be conserved to generate the same amount of energy flow when compared with traditional independent generation system.

Although the share of renewable energy is growing, fossil fuels are still the dominant energy for technical restrictions [69]. The penetration of CCHP offers an optimal exploitation of natural resource, which can even out the disadvantages of uncertainty and intermittence of renewable energy, strengthening system reliability and stability.

4.3. Intelligent meters for heat demand prediction to control heat generation

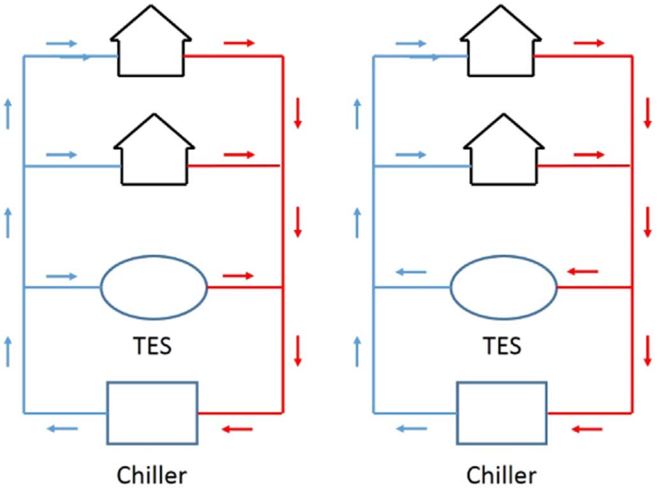
It is essential to guarantee that the amount of energy produced is able to satisfy heat demand while not causing waste for over-generation, especially in a complex network where there are multiple heat generation plants. When intelligent meters are not available, energy producers tend to supply more heat or cold than demanded to ensure customers obtain sufficient energy. Over-generation causes less temperature differentials between supply and return, which implies less condensed steam from the boilers, resulting in lower efficiencies of the generation units [70]. Intelligent control of the generation units helps the heat producers to manage heat production effectively. Smart meters working together with weather forecasts is a good solution to predict energy consumption of each building which can be applied to control heat and cold generation in the energy centre. Such an energy generation system can achieve the target of supplying heat and cold with less fuel, less emission and higher efficiency. This will be further discussed in Section 7.3 from the consumers' perspective.

4.4. Thermal energy storage

There are two challenges for renewable resources utilization. The first challenge is focused on the intermittent feature of energy generated from solar and wind energy. The second challenge is related to dynamic characteristics. It is impossible for such kind of renewable energy fuels to work individually to support all the heat or cold load of a community without the help of other technologies. Thermal Energy Storage (TES), which can store heat or cold, has been used to level off the constraint of short-term variation and to provide a continuity of energy supply [71]. The development of TES is a promising technology to aggrandize resources utilization and conservation from a variety of fuel sources. Approximately 1.4 million GWh could be saved and 400 million tonnes of GHG could be reduced annually by the application of TES in Europe [72]. There are three types of TES technology: sensible thermal energy storage, latent thermal energy storage and thermo-chemical energy storage. Sensible TES and latent TES are more common [73]. Latent thermal energy refers to energy that is released or stored during the process of phase change. Phase change materials (PCMs) are used for latent TES. Sensible thermal energy relies on specific heat of storage medium, which is related to the amount of energy variation during the process of temperature alteration. Table 3 displays some frequently used materials for sensible TES. Water is the most widely used TES medium due to its cheap price and favourable thermal properties [74].

Table 3
Thermal capacities at 20 °C of some frequently used sensible TES materials [75,76].

material	Density (kg/m^3)	Specific heat (J/(kg K))	Volumetric thermal capacity (MJ/(m^3 K))
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Concrete	2000	880	1.76
Mineral oil	1700	1300	2.21
Glass	2710	837	2.27
Iron	7900	452	3.57
Steel	7840	465	3.68
Water	988	4182	4.17



(a) Off-peak load (b) Peak load

Fig. 5. A simplified thermal energy storage for cooling.

TES not only buffers the fluctuation of renewable energy sources and ensures the security of energy supply, it also significantly levels out peak load in DHC system as energy produced during off-peak hours can be used for peak hours. Fig. 5 provides a simplified flow diagram of TES used in DC network at peak hours and off-peak hours. Although this energy only covers a small amount of total energy demand, it leads to a large investment in production units. Meanwhile, It provides an extra advantage of reducing operation cost as all generation units work continuously at their optimal conditions [45]. The advantages of TES in DHC are concluded as:

- Peak-shaving.
- Providing time-varying management.
- Relieving renewable energy intermittence.
- Increasing overall efficiency.
- Reducing generation units size.
- Lowering operation cost.
- Realization of smart thermal grids.

Except for the aforementioned advantages, TES has an additional superiority when compared with other storage systems, particularly with batteries. It is more economical because of the cost, lifetime, stable capacity and cycle efficiency [77]. The investment cost for

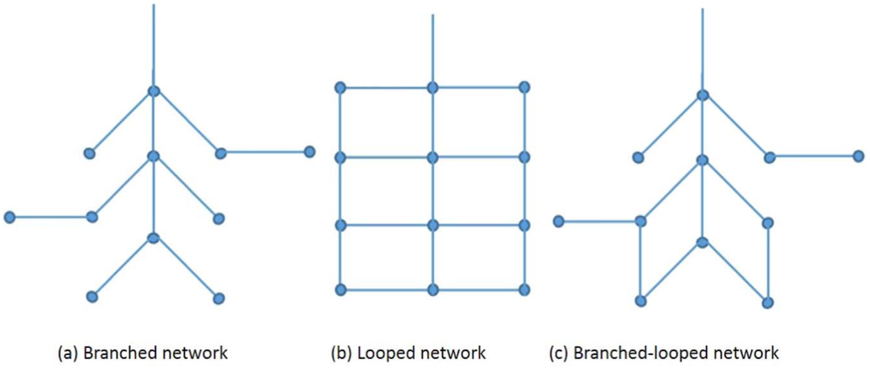


Fig. 6. Three types of distribution network.

electricity storage electricity is 170 €/kW while the price for thermal energy is 0.5–3 €/kW [65].

5. Optimization from energy distribution perspective

Distribution network optimization is also regarded as a key factor to eliminate excessive consumption of fuels and to ultimately decrease CO_2 emission. A distribution network is typically comprised of a buried piping system for water circulation together with one or multiple pumps. Pumps are usually selected to meet the maximum pressure difference for the most remote users to provide sufficient pressure for circulation [54]. The optimal design of the distribution system involves but not limit to network layout, pipe insulation, operation control. Optimization of the distribution system will result in a more sustainable and efficient transmission network.

5.1. Pipe layout

The expected performance of DHC system cannot be achieved without an efficient pipeline system [44]. Pipe layout is generally arranged in three forms, namely branched, looped, and branched-looped network, as shown in Fig. 6. Branched network is simple and unreliable. Looped network increases reliability of the system at the expense of a higher investment. Branched-looped network is a combination of both. The topology of a pipeline directly affects the construction cost, heat loss and pressure differential of the pipeline. The capital cost for the distribution network accounts for 60% of the total cost on infrastructure construction investment [39]. Heat losses in piping networks for DH are 10–30% of the heat supply while the data for DC surpass 10% during peak cooling season [78,79]. Those data may be even higher in sparse districts [80]. Because of the substantial investment cost and distribution loss, a structural optimization of the topology of the distribution network is crucial for successful implementation of DHC system.

Here we review typical techniques for handling the optimization of pipe layout. Sustainable development advocates that consumption should be close to the site of generation to minimize the length of the distribution line, which is critical to pressure drop, heat loss and investment cost. In terms of solution approaches, it is feasible to evaluate the optimal configuration of the piping network using mixed-integer programming models, genetic algorithm, and probabilistic search heuristic [39,81–83] and [84]. Alternative distribution schemes are assessed thoroughly before construction to understand the distribution system configuration and to further minimize the installation expenditure and operation cost.

5.2. Underground depth and soil conductivity

Heat loss in the distribution network is attributed to the thermal conductivity of the insulation and thermal conductivity of soil. The influence of soil is not as obvious as the insulation. Thermal conductivity of soil varies between 0.5 W/(m K) and 2.5 W/(m K) subjecting to the composition, structure and moisture content [85]. Higher thermal conductivity results in bigger heat loss. Due to the high thermal inertia of soil, underground temperature variations decrease with the increase of depth. The depth of DHC pipe is around 0.6–1.2 m, where the soil temperature is relatively stable.

5.3. Pipe insulation and size

Heat loss of the distribution network plays a significant role in the network cost-effectiveness. Pipe size and insulation materials have a remarkable effect on the thermal performance of the piping system. An increased insulation thickness leads to a better thermal performance of the pipe but it also has a cost implication. Table 4 describes thermal conductivities and price values of different insulation materials. Polyurethane foam is the most widely used insulation material with a thermal conductivity ranging from 23 mW/(m K) to 27 mW/(m K) for different pipe companies and production technologies [86]. Adopting gases such as carbon dioxide or cyclopentane with a lower conductivity in the pore system and smaller pore sizes to reduce molecule collision offers a good solution to improve the thermal performance of the insulation [86]. Hybrid insulation as shown in Fig. 7(b), with higher performance material closer to the centre of the cylinder, is a paramount method to both control heat loss and insulation cost. The effect of hybrid insulation using vacuum insulation panel can decrease heat loss by 15–20% when compared with insulated with pure polyurethane [87].

The selection of proper pipe size is another crucial task in the design process. Pipe size should be considered together with insulation thickness and pump power consumption to achieve the shortest payback time. Optimal design of pipe cross sectional area in accordance with the maximum flow rate and maximum pressure drop can be obtained through size-searching algorithm and life cycle assessment so as to ensure the minimal cost of piping network for purchase, installation and operation [88].

Table 4
Thermal conductivities and price values of insulation materials (adapted from [48]).

Insulation materials	Conductivity (mW/(m K))	Price ($\$/m^3$)
Foam board	0.027	193
XPS	0.031	224
Rockwool	0.040	95
EPS	0.028	155
Fiberglass	0.033	350

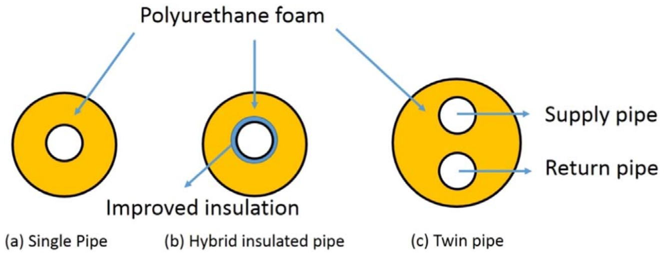


Fig. 7. Description of the concept of insulated pipes.

5.4. Twin pipe or double pipe

A twin pipe as shown in Fig. 7(c), with supply and return pipe under the same carrier has a better thermal insulation than one single pipe with concurrent higher economy for its smaller pipe size [89]. An asymmetrical insulation of twin pipes can reduce total heat loss by 3.2%, with a reduction of 4–8% heat loss in the supply pipe without causing increased investment in the pipes [90].

5.5. Pump and operation control strategy

Pumps in a DHC system should be able to overcome the flow resistance of the piping network, including pressure losses through heat exchangers, chillers and auxiliary devices. The operation of the pumps directly influences the supply strategies of the distribution network and the pump power consumption. Up to 70% pump power can be saved by using distributed variable speed pumps to replace conventional central circulating pumps [50]. It has been proved that variable flow – variable temperature can achieve the lowest energy consumption when compared with variable flow – constant temperature, constant flow – variable temperature and constant flow – constant temperature [54].

5.6. Low energy DHC

The potential of recovering abundant excess heat and waste incineration is far less utilized as would be expected [91]. Such discrepancy can be attributed to the high supply temperature of today's DH network. The supply temperature of current heating system is over 80 °C. This high temperature causes a higher operation cost. As the development of low energy building and better performance heat exchanger, less energy will be required in future (These will be discussed later). The next generation DH system calls for a supply temperature of 50–55 °C and a return temperature of 20–25 °C [9] and [92], which will reduce the temperature gap. It is also regarded as one of the most important approaches to reduce heat loss of the distribution network [93]. A reduction in supply temperature will also result in a higher efficiency for the boilers [94]. The same is true for DC with higher supply temperature. Higher supply temperatures in DC network increase COP (coefficient of performance) of the absorption chillers [95] and [96].

A lower temperature for DH and a higher temperature for DC have several advantages: (1) lower heat loss in distribution network; (2) easier to meet heat load from geothermal and waste heat; (3) enhancing the efficiency of solar thermal collector and heat pump; (4) promoting waste heat and cold recovery from industrial processes; (5) higher energy output from biomass/ waste incineration plant; (6) increased efficiency of CHP [90]; (7) increased performance of thermal energy storage system [90].

6. Optimization from heat substation

Heat substation is a heat transfer interface between the distribution network and the building pipe circuits, usually including the following parts: heat exchanger, energy meter and control valve, as shown in Fig. 8(a). In most European countries, energy consumptions in DHC system are billed according to energy meters measuring temperature differences of supply and return in the substations. The performances of the heat substations affect not only the energy capacities delivered to buildings, but also the prices that customers pay for heating and cooling. However, most of the substations are not working in the appropriate way. Gadd and Werner [97] unveiled that around 75% of the analysed substations existed certain kind of faults in a case study of 140 substations.

6.1. Increasing the performance of heat exchanger

Yamankaradeniz [98] used advanced exergy analysis to study a geothermal district heating system, and pointed out that heat exchanger has the highest priority when focusing on system components to improve network performance. Heat exchangers in the heat substations lead to substantial heat loss due to the temperature gaps between the primary and secondary networks. Improving the efficiency of the heat exchanger can directly enlarge heat transmission capacity and allow more customers to be connected to the system. It can also affect the temperature of the circulation medium and influence the efficiency of energy generation units. The biggest challenge for future low energy DHC network is how to improve the efficiency of the heat exchanger so as to extract more heat or cold from the primary line with the purpose of generating greater environmental and financial benefits.

A higher performance heat exchanger can absorb more energy from the distribution medium, namely more energy transfer per unit volume, which directly impacts on the effectiveness of the network heat transfer capacity. Sun et al. [55] and [99] studied a new ejector heat exchanger which could limit the primary heating network return water temperature to 30 °C, reduce steam extracted from steam turbine by 41.4% and recover more heat without altering water circulation flow rate. Increasing ΔT by 10 °C contributed to a reduction of ~55% pump power consumption depending on the heat production method and contributed to a total of 0.1–14% fuel-source saving [70]. The development of building entrance AHP (absorption heat pump) makes it possible to cool the temperature of the primary side even lower than the secondary side. Heat capacity increases to 1.3 ~ 1.8 times without extra investment in heat production units and heat delivery network [22]. The increased investment in application of AHP can be compensated from the heat network as it provides the same amount of heat with 20% investment reduction on the heat network [22]. The advancement of technology results in a compact size of AHP which can be installed in each independent building [63]. Heat exchanger with an insulated water storage tank attached to the primary side allows a smaller pipe size in the distribution network [92]. The small dimensioned pipe leads to lower investment cost in the construction stage and reduces heat loss during the operation. Meanwhile, the control of the heat exchanger is another key factor to improve the performance of the heat substation. By adjusting the pump rotation speeds to achieve lower flow rates in the heat exchanger can cool the return temperature by 5 °C on yearly average [100].

6.2. Installation of by-pass

To ensure the thermal comfort of the consumers and guarantee that heat can be supplied to them promptly, an installation of by-pass between the supply and return pipes is necessary, as shown in Fig. 8(b). The valve in the by-pass is a thermostat valve with a temperature control system, which allows a tiny amount of hot water running through under a pre-set temperature. The temperature is usually set between 35 °C and 40 °C [101]. The by-pass will inevitable result in a certain amount of heat loss by decreasing the temperature difference, but it is necessary for preventing freezing and reducing waiting time for

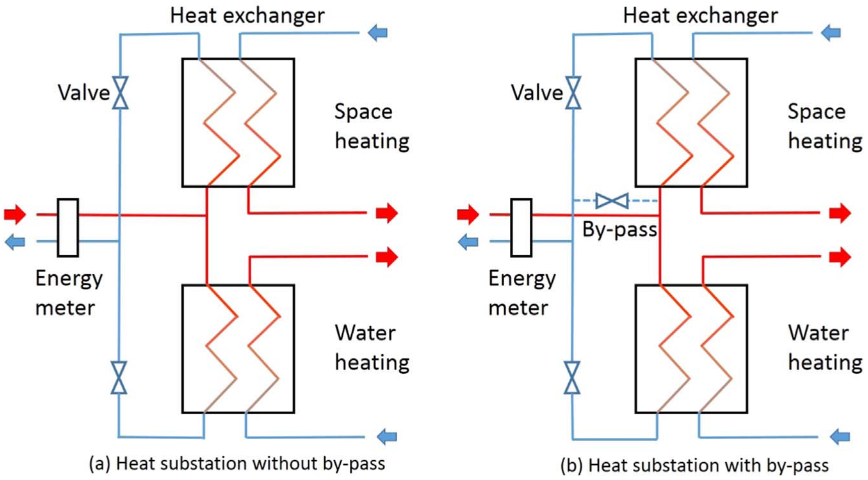


Fig. 8. simplified substation.

heating up the heat exchanger [93]. Brand [102] proposed an innovative method of redirecting the by-pass water to bathroom with the purpose of both improving thermal comfort and reducing heat loss.

7. Enhancements from terminal users perspective

Residential houses, hospitals, schools and commercial buildings are common terminal users of DHC systems. Several issues with regard to building energy conservation, energy price and residents awareness of energy saving directly or indirectly affect energy consumption and thereby the efficiency of the entire DHC system. Optimization from the heat users will result in less energy consumption, which facilitates the advancement of future 100% renewable DHC and low energy DHC network.

7.1. Future low energy building

Future low energy building should be able to provide thermal comfort to occupants at a lower energy consumption with less GHG emission. Better energy performance building with a lower demand for energy promotes the evolution of future DHC system. The most widespread technology to bring down thermal loss is to improve the insulation of envelopes. A better insulation aiming at reducing heat dissipation, which intrinsically features envelope thermal inertial, is an efficient method to minimize energy demand for heating and cooling. Polymeric (plastic) foams and inorganic wools are the most widely used insulation materials in Europe [103]. The share of different insulation materials in European market in 2010 is shown in Fig. 9.

Using chemicals embedded into windows, envelopes and floors to store or release heat during the process of solidification/fusion can also improve the thermal inertial of buildings to meet thermal comfort and energy conversion purposes [105]. Those chemicals are Phase Change Materials. Under passive heating and cooling conditions, a melting temperature ranging between 17°C and 25°C is able to offer a comfortable living condition in most countries at any climatic condition [106]. Salt hydrates as PCMs are seldom used for passive heating as their highly corrosive to building construction materials if used without capsules and high cost with capsules [106]. Organic PCMs which overcome the above disadvantages are deployed for building thermal regulation. Table 5 lists some organic PCMs that are suitable for passive heating and cooling in buildings.

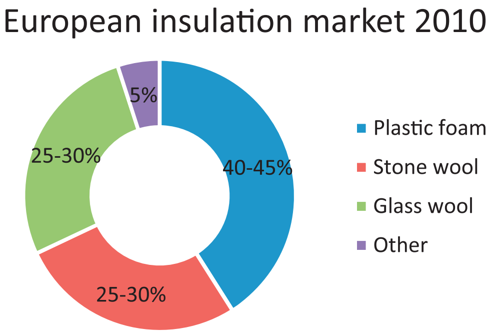


Fig. 9. European insulation market in 2010 [104].

Buildings require adequate fresh air to replace indoor air pollutants in order to provide occupant comfort and to maintain a healthy environment. An increased air infiltration has a negative effect on thermal comfort. It is not economic to sacrifice thermal comfort for air quality. Heat recovery from buildings is an effective way to alleviate heating and cooling requirements while guaranteeing enough fresh air and thermal comfort. Research showed that 80–90% ventilation losses can be recovered [107]. Using heat exchangers or heat pumps to retain energy in exhaust air as heat source or heat sink is an effective way to pre-heat or pre-cool incoming fresh air, thereby diminishing energy demand for heating and cooling [108]. A typical heat recovery scheme is shown in Fig. 10.

7.2. Energy-efficient renovation of existing buildings

Owning to the long life time of buildings, around 70–80% of existing poor performance building stocks will be still in service by the year of 2050 [109]. Building renovation has the potential to save up to 68% heating load of the building [110]. Another study by Tommerup [107] pointed out that heating-related energy for buildings has the potential to be saved by 80% in Denmark after renovation.

The trend for renovation of existing buildings is to improve the thermal performance of existing buildings, including better insulation of walls and ceilings, energy efficient windows and doors and ventilation heat recovery while maintaining a healthy and comfortable indoor climate. Better insulation of envelops is a vital option for implementing the transition into future low-energy green building. By increasing insulation thickness and replacing energy-cost windows with energy-efficient ones, less heat or cold is transferred through from indoor to outdoor, resulting in less energy consumption of the buildings. Dodoo et al. [49] studied a multi-story building by using energy-saving doors and windows, 39% space heating saved after retrofit.

7.3. Effective building energy management system

Building Energy Management system (BEMSs) aiming at optimizing energy utilization by simultaneously guaranteeing air quality and

Table 5
organic PCMs suitable for passive heating and cooling (adapted from [106]).

Material	Melting point (°C)	Heat of fusion (J/cm^3)	Freezing point (°C)	Heat of freezing (J/cm^3)
Methyl Stearate-Cetyl stearate eutectic blend (90.6–9.4 mol%)	22.2	180	21.8	175
Thermotop 20 (Butyl stearate blend)	21.5	126	18.5	125
CA-LA eutectic blend (73–27 mol%)	18.2	120	16.6	119
CA-MA eutectic blend	21.7	168	21.4	165
CA-PA eutectic blend	21.8	171	22.1	173
CA-TD (62–38 wt%)	19.1	153	13.3	148
LA-TD (46.4–53.6 wt%)	24.4	163	24.4	146
CA-MA (55 wt%)/ expanded perlite	20.7	85	21.7	88
CA-LA (20 wt%)/ expanded vermiculite	19.1	27	17.1	31
CA-LA (40%)/expanded vermiculite	19.1	61	19.2	58
EPT (57 wt%)/ diatomite	19.6	111	18.8	101

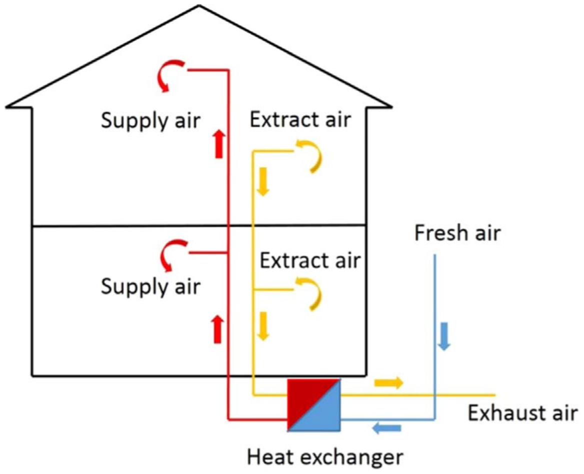


Fig. 10. Building heat recovery.

thermal comfort are attracting increased attention through the application of smart meters. Previously, heat meters were read manually which entails a big amount of man-hour and they have been only utilized for billing. Smart meters can read and send data to BEMS through a virtual network for further analysis. The system is linked to a cloud environment where rich data sources are stored for intelligent management and measurement of building performance. Alternatively, they are able to identify whether energy usages are at their anticipated level at an early stage [111].

Fig. 11 shows a BEMS based on heating and cooling. Smart meters and smart appliances are included in the system. Smart meters collect real-time information about room temperature, humidity, air quality, occupancy together with weather conditions. The gathered data are transferred to BEMS for processing and then the system dispatches heat and cold according to predicted heat and cold consumption, which is based on historical data. Meanwhile, it simultaneously sends instructions to energy providers about the amount of energy that should be generated in the next few hours. The application of smart appliances in the network enables the system to automatically adjust individual consumption according to energy demand and energy price. For example, during peak periods it turns off electrical appliances such as dishwasher and washing machines, and during off-peak periods it turns on these devices to take advantage of price difference to save money. The realization of BEMS provides a more efficient, reliable and affordable energy network. The most important factor for BEMS is digital processing and communication compared with traditional control systems, which enable quick response and efficient energy management. In future, these systems will be more intelligent. Users can even monitor and control from smart interfaces such as smart phones by installing a BEMS App. Electricity and gas consumption should also be incorporated into this system for a comprehensive understanding of building energy consumption.

7.4. A better pricing system

Heating and cooling prices are challenges for sustainable development of DHC system, which should be transparent, fair and competitive. Traditional DHC pricing in some countries is billed according to heated areas regardless of the amount of heat or cold consumed, leading to issues: the properties lose interest in improving building insulation and the residents lose interest in using energy effectively. A good pricing system should not only ensure that energy transmitted to households is the amount of energy required, it should also be a financial driver to speed the development pace of future green buildings and an enlarged share of sustainable energy. A real-time

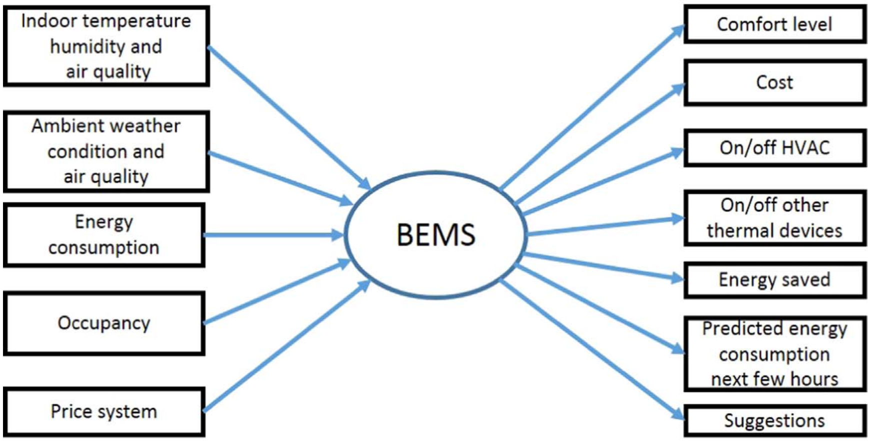


Fig. 11. Configuration of BEMS focusing on heating and cooling.

Table 6
Migration through Retrofit of existing DHC grids to the low energy DHC smart grid concept.

Migration through Retrofit of existing DHC grids to the low energy DHC smart grid concept	
Existing State-of-the-Art	Proposed progress beyond State-of-the-art
The trend throughout the three generations of DH systems has been towards lower distribution temperatures, material lean components, and prefabrication leading to reduced manpower requirements at construction sites [9]. Various advantages in the use of low-temperature DH have been shown (increased efficiency in heat distribution, and the exploitation low temperature renewable energy sources such as geothermal sources, and solar energy and of waste heat from industry). District heating technologies must be further developed to decrease grid losses, exploit synergies, and thereby increase the efficiencies of low-temperature production units in the system.	STG will promote a migration through retrofitting of present district heating into low-temperature networks interacting with low-energy buildings. STG is based on a future generation of district thermal technology that involve lower distribution temperatures, assembly-oriented components. Lower supply and return temperatures will bring additional benefits, including higher electrical distribution efficiency, higher power-to-heat ratios in CHP plants, higher heat recovery from flue gas condensation, higher coefficients of performance in heat pumps, higher utilization of geothermal and industrial heat sources with temperatures, higher conversion efficiencies in central solar collector fields, and higher capacities in thermal energy storages if they can be charged to a temperature above the ordinary supply temperature. Also, STG will solve the endemic grid thermal losses problem through optimization with a focus on: heat generation units, heat distribution, heat substation and heat users.
Existing DHC is a standalone system that does not involve any interaction with other grids. Most of the existing DHC are oversized resulting in a large amount of energy waste.	STG is a new generation of DHC system which involves more interaction with electricity, district heating, and gas grids within a given community/district, while factoring in existing individual gas boiler heating and power driven air-conditioning systems through the proposed concept of smart DHC. STG will promote heat production based on real-time demand to efficiently match supply, while promoting peak shaving strategies and efficient storage of excess energy.

Table 7
Retrofit existing buildings to become DHC smart grids ready.

Retrofit existing buildings to become DHC smart grid ready	
Existing State-of-the-Art	Proposed progress beyond State-of-the-art
Conversion of individual buildings, including natural gas areas, to DHC should be informed by a socio-economic assessment of the retrofitted overall system efficiency and its environmental impact. Hourly balances of heat and power demand and the use of conversion and storage facilities are essential to maximize the efficient use of renewables and end-use efficiency measures.	STG design will first develop a geo-clustered, building typology aware, heating and cooling technology catalogue, publicly available. This catalogue will serve as a base for the design technology packages associated with a design and simulation environment, and a dedicated toolbox. STG technological packages rely on state of the art technologies enabling demonstration of replicability on representative pilots
Most of the existed heating appliances in Europe are gas-fuelled, with a market share over 45%, while the share of heating oil appliances is just under 20% [115]. A wide range of renewable and energy-efficient technologies are already available to replace the two thirds of the heat market which today are covered by fossil fuels.	STG technological packages moves beyond the state of the art in two significant directions. Firstly, the cutting edge and market ready heating technologies such as GAHP (gas absorption heat pump) and microCHP will be utilized to further reduce domestic heating from gas network. Secondly, as the market and legislation moves towards a systemic approach, STG technological packages will deliver the tools necessary to select and size the technologies for the customer needs both within and outside the DHC network.
Existing generations of heating and cooling systems do not fully exploit demand management solutions nor try to optimize local generation systems. Peak load for space heating during a day may be reduced by use of higher thermal capacity of the building and by using space heating systems with a peak shaving control system. This may be realised in a simple way by use of a maximum flow controller, an intelligent scheduler or control system based on weather forecasts.	STG will rely on state of the art internet enabled heating and cooling appliances to gather additional local and network wide intelligence. Domestic control system will be able to communicate with the DHC control to enable the smart exchange of heat and control of energy use. This will be achieved by inferring at residence level parameters such as available thermal storage, potential building inertia storage, predicted heat (and electricity in the case of microCHP) demand and supply.

pricing mechanisms established on smart metering in electricity systems has proved to be efficient in demand management, and be able to improve economic benefit and promote transparency [112]. If smart meters are installed in the DHC network, a real-time pricing mechanism should also be a good solution to DHC network [112].

7.5. Improving public awareness of energy conservation

Consumer behaviours such as opening the window and control of the thermostat are substantially responsible for the energy consumption of buildings. In particular, residents activities result in 50% higher heating demand and 60% higher heating power than the expected values that are computed from the standard energy demand of energy-efficient buildings [92]. It is important to encourage people to turn off radiators when natural ventilation can provide thermal comfort to occupants. Further on, for the reason of personal control, occupants in naturally ventilated buildings are able to bear a higher room temperature than those that stay in air-conditioned buildings [108]. In the near future, with the popularization of BEMS in smart phones, customers can share their energy saving obtained from BEMS in social networks, which can both make them feel proud and stimulate their social connections to save more energy.

8. Research directions towards smart thermal grids

The concept of DHC smart grids has never been tested so far but successful examples of low-temperature DH systems have been demonstrated in Lystrup, Denmark [113] and in Slough, UK [114]. It is important to further develop, optimize, design and test the concept of DHC smart grids with a view to transform existing buildings to smart DHC ready buildings, i.e. buildings that can both withdraw and supply heat to the grid, favouring decentralised production. Decentralised production will allow low overall capital cost, a better matching between production and demand, decreased maintenance, reducing impact of system failure, and reducing oversizing. The following challenges form avenues for future research as elaborated in the Tables 6–10:

- How to convert/extend existing DHC grids to the low energy DHC smart grid concept with typical supply/return temperatures of 50/20 °C (Table 6)?
- How to supply low energy DHC smart grid for space heating and

Table 8
Technologies to recycle heat from low-temperature sources and integrate renewable heat sources.

Technologies to recycle heat from low-temperature sources and integrate renewable heat sources	
Existing State-of-the-Art	Proposed progress beyond State-of-the-art
Geothermal heat exploitation as a renewable energy source implies the use of absorption heat pumps that may be operated in an efficient way together with steam production from e.g. waste CHP plants. Another option is to use compressor heat pumps in which case integration with the electricity supply becomes essential.	STG will promote the large-scale integration of RES into existing energy systems and will therefore address the challenge of coordinating fluctuating and intermittent renewable energy production with the rest of the DHC system. STG will also fully exploit the integration of RES in CHP stations. The regulation in supply may be facilitated by flexible demand, for example, heat pumps, consumers' demands, and electric boilers. Moreover, the integration can be helped by energy storage technologies (water tank & building inertia).
The energy source for DHC systems are fossil fuels or other energy sources, and mixed systems combining two or more energy sources, like natural gas, wood waste, municipal solid waste and industrial waste heat, can be feasible economically. Heat suppliers can also include heat from CHP, waste-to-energy, biomass and geothermal energy plants, as well as industrial excess heat. hybrid systems combining renewable or alternative energy technologies like solar collectors, heat pumps, polygeneration, seasonal heat storage and biomass systems are being used as the energy source [116].	As a minimum baseline, STG will devise appropriate use of DHC energy sources to achieve the Europe 2020 target of (a) reducing greenhouse gases emissions by 20% with respect to 1990, (b) renewable energy sources by 20%, (c) reducing the share of primary energy by 20% with respect to 2008. As such, STG will promote the wide use of CHP together with the utilization of heat from various industrial surplus heat sources and the inclusion of heat from renewables. The proposed DHC retrofitting will be scalable to accommodate various technology evolutions, including processes of converting various forms of biomass into bio(syn)gas and/or different types of liquid biofuels for transportation fuel purposes, among others [117] and [118]
Allowing entities to be connected to a thermal network to generate thermal energy will promote greater use of renewable energy (e.g., solar thermal, geothermal, biomass), by establishing a market for excess thermal energy.	STG will deliver methods and tools to assess the potential advantages of different forms of renewable energy in the context of integrated thermal networks, so that a holistic (socio-economic and environmental) comparison of the different sources of energy can be performed and the most advantageous options determined for thermal networks and applications.

Table 9
Surplus heat use in the smart thermal grid.

Surplus heat use in the smart thermal grid	
Existing State-of-the-Art	Proposed progress beyond State-of-the-art
Many domestic heating systems are installed with extra capacity either due to fixed power outputs of available products or mismatches between demand types. This can lead to sub-optimal operation when run in isolation. Decentralised intelligent metering to get a close link between the power and the energy used by the buildings may be used for the continuous commissioning and the payments.	STG will fully exploit the innovation potential of a smart grid in terms of maximizing installed asset utilization in the most cost effective way. STG will exploit metering informed by weather forecast to estimate thermal demand for the next few hours so that DHC companies can rely on those readings to distribute energy effectively, thus helping shift peak load as well. Thermal trading can enable the efficient use of over capacity to serve the district and provide further incentives to homeowners or asset owners to operate the systems most efficiently. This will lead to novel business models on the district level.
Thermal load shifting in thermal networks is rarely implemented, mainly because the absence of suitable smart meters and the lack of motivation [119].	STG will propose a district thermal management approach, aggregating the end-user production/consumption needs. Advanced control techniques for storing heat in the network will be explored and assessed by simultaneously varying supply temperature and pressure drop in the pilots.
The academic and industrial literature is pointing at the advantages of low supply temperature in DH networks. There is an urgent need to develop technologies to recycle heat from low-temperature sources (extra solar heat from individual solar panel install in buildings)	STG will fully utilise the advantages of lower supply and return temperatures in distribution networks by fully exploiting the potential of decentralised production proposed. The surplus heat from individual buildings will be incorporated into the grid.

cooling and domestic hot water (DHW) to existing buildings, energy-renovated existing buildings and new low-energy buildings (Table 7)?

- How to recycle heat from low-temperature sources and integrate renewable heat sources such as solar (Table 8)?
- How to connect the surplus heat to the STGs in the most efficient way (Table 9)?
- How to ensure suitable planning, cost structures in relation to the operation as well as to strategic investments related to the transformation of existing buildings to smart DHC ready buildings (Table 10)?

9. Conclusion

This paper firstly reviewed the development of DH and DC systems, future trend for DHC, and then it emphasises on the optimization of the DHC through four main processes: generation, distribution, transformation and consumption. Subsequently, research directions towards STG are proposed. Conclusions can be summarized as follows:

1. Integration of sustainable energy, CCHP and TES are the major solutions to alleviate fossil fuel depletion, reduce GHG emission and enhance system stability and efficiency.
2. Optimal design of the heating and cooling networks (piping network), including pipe layout, pipe insulation, underground depth, supply temperature, and an optimal operation of pumps to ensure the efficiency of the distribution network.
3. Improving the performance of the heat exchanger and an installation of by-pass can enhance the effectiveness of the heat substation and reduce response time to guarantee efficiency and comfort.
4. Less energy demanding buildings, BEMS, a stimulating price and strengthening public awareness of energy saving are the key approaches to reduce energy consumption in building and to facilitate the development of future low energy DHC.
5. STGs will involve more interaction among DHC, individual heating and cooling system, electricity and gas. Communication between production and demand is important to ensure efficient utilization of energy.

Table 10
Planning, cost and motivation structures for the transformation of existing buildings to smart DHC ready buildings.

Planning, cost and motivation structures for the transformation of existing buildings to smart DHC ready buildings	
Existing State-of-the-Art	Proposed progress beyond State-of-the-art
The DHC planning process needs to enable a transition into STGs in existing and future supply systems. There is a need to facilitate a planning procedure where the energy supply side is synchronised with the energy conservation side in such a way that the increasing proportion of intermittent renewable energy systems is integrated in an economical way in the total energy system. Coordination between implementing lower temperatures and planning for energy conservation is necessary, which involves planning requirements.	STG will promote the development of a DHC planning framework in which infrastructural planning is used to identify and implement where to have DHC and where not to have DHC as well as cost principles and incentives in operation with the aim of achieving an optimal balance between investments in savings versus production and an optimal integration of fluctuating renewable energy in the overall energy system.
The identification of optimal plans for the levels of heat/cold saving versus heat/cold production and which technologies to apply can only be carried out on the basis of a combination, on the one hand, of detailed data on the location of energy demands and, on the other hand, of knowledge on the future system of which DHC should be a part.	STG proposes to develop a geo-clustered, building typology aware, heating and cooling technology catalogue, publicly available. This catalogue will serve as a base for the STG planning.
Tariff policies of the present DHC tariff system are characterized by being dominated by the short-term marginal costs of the existing supply systems. In a smart district heating and cooling system, a synchronisation of supply system and demand system, and the technological change to renewable energy supply systems, require price signals (via the tariffs) that support this synchronisation. Basically, this means a change to a tariff policy where the long-term costs of future renewable energy systems will be the tariff base.	STG system will lead to measures that incentivise investment in retrofitting or deploying new DHC systems. STG will deliver methods and tools that support the demand side so energy conservation takes place as buildings and districts are being energy retrofitted/renovated.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.01.061.

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