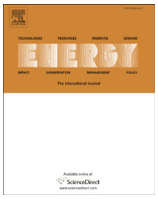
Energy 68 (2014) 1–11

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Review

4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems

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ARTICLE INFO

Article history:
Received 24 January 2014
Accepted 23 February 2014
Available online 31 March 2014

Keywords:
4GDH
District heating
Smart thermal grids
Smart energy systems
Sustainable energy systems
Renewable energy systems

ABSTRACT

This paper defines the concept of *4th Generation District Heating* (4GDH) including the relations to *District Cooling* and the concepts of *smart energy* and *smart thermal grids*. The motive is to identify the future challenges of reaching a future renewable non-fossil heat supply as part of the implementation of overall sustainable energy systems. The basic assumption is that district heating and cooling has an important role to play in future sustainable energy systems – including 100 percent renewable energy systems – but the present generation of district heating and cooling technologies will have to be developed further into a new generation in order to play such a role. Unlike the first three generations, the development of 4GDH involves meeting the challenge of more energy efficient buildings as well as being an integrated part of the operation of smart energy systems, i.e. integrated smart electricity, gas and thermal grids.

1. Introduction

The design of future sustainable energy systems including 100 percent renewable systems is described in a number of recent reports and studies including [1–6]. Such systems are typically based on a combination of fluctuating renewable energy sources (RES) such as wind, geothermal and solar power together with residual resources such as waste and biomass on which we may expect increasing pressure due to environmental impact and future alternative demands for food and material. For example, biomass resources in Europe are small compared to the European energy balance [7]. In order to ease the pressure on biomass resources and investments in renewable energy, feasible solutions to future sustainable energy systems must involve a substantial focus on energy conservation and energy efficiency measures.

District heating infrastructures have an important role to play in the task of increasing energy efficiency and thus making these scarce resources meet future demands. District heating comprises a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants or a number of distributed heat producing units. This approach allows any available source of heat to be used. The inclusion of district heating in future sustainable cities allows for the wide use of combined heat and power (CHP) together with the utilisation of heat from waste-to-energy and various industrial surplus heat sources as well as the inclusion of geothermal and solar thermal heat [8–14]. In the future, such industrial processes may involve various processes of converting solid biomass fractions into bio(syn)gas and/or different sorts of liquid biofuels for transportation fuel purposes, among others [15,16].

Future district heating infrastructures should, however, not be designed for the present energy system but for the future system. One of the future challenges will be to integrate district heating with the electricity sector as well as the transport sector [17]. In the following, such a future system will be referred to as a *smart energy system*, i.e. an energy system in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each

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http://dx.doi.org/10.1016/j.energy.2014.02.089
0360-5442/

individual sector as well as for the overall energy system [18]. A transition from the current fossil fuel- and nuclear-based energy systems into future sustainable energy systems requires large-scale integration of an increasing level of intermittent renewable energy. This also entails a rethinking and a redesign of the energy system. In smart energy systems, the focus is on the integration of the electricity, heating, cooling, and transport sectors, and on using the flexibility in demands and various short-term and longer-term storage across the different sectors. To enable this, the smart energy system must coordinate between a number of smart grid infrastructures for the different sectors in the energy system, which includes electricity grids, district heating and cooling grids, gas grids and different fuel infrastructures.

A number of recent studies [19–30], including Heat Roadmap Europe [19,27], come to the conclusion that district heating plays an important role in the implementation of future sustainable energy systems. However, the same reports also emphasise that the present district heating system must undergo a radical change into low-temperature district heating networks interacting with low-energy buildings as well as becoming an integrated part of smart energy systems.

The development of future district heating systems and technologies involves energy savings and conservation measures as an important part of the technology [31]. The design and perspective of low-energy buildings have been analysed and described in many recent papers [32,33], including concepts like energy efficient buildings [34], zero emission buildings and plus energy houses [35,36]. However, such papers mostly deal with future buildings and not the existing building stock which, due to the long lifetime of buildings, is expected to constitute the major part of the heat demand for many decades to come. Some papers address the reduction of heat demands in existing buildings and conclude that such an effort involves a significant investment cost [37]. The share of currently existing buildings in the building stock is expected to remain high for many years. No study has been found which identifies how to completely eliminate the heat demand in existing buildings within a reasonable time frame. In the European Commission's strategy [38] for a competitive, sustainable and secure "Energy 2020", the need for "*high efficiency cogeneration, district heating and cooling*" is highlighted (p. 8). The paper launches projects to promote, among others, "*smart electricity grids*" along with "*smart heating and cooling grids*" (p. 16). In recent state-of-the-art papers [39–41] and discussions [42], the specific requirements of future grids have been discussed and such future district heating technologies have in some cases been named 4th Generation District Heating Technologies and Systems (4GDH). The purpose of this paper is to define the concept of *4th Generation District Heating* and thereby contribute to the understanding of the need for research and development of this future infrastructure and related technologies.

2. The first three generations of district heating and cooling

The first generation of district heating systems used steam as the heat carrier. These systems were first introduced in USA in the 1880s. Almost all district heating systems established until 1930 used this technology, both in USA and Europe. Typical components were steam pipes in concrete ducts, steam traps, and compensators. Today, such systems using steam can be considered an outdated technology, since high steam temperatures generate substantial heat losses and severe accidents from steam explosions have even killed pedestrians. The condensate return pipes have often corroded, giving less condensate returns and lower energy efficiency. Steam is still used as the main heat carrier in the old New York (Manhattan) and Paris systems, while replacement programmes have been successful in Salzburg, Hamburg, and Munich. In Copenhagen, a replacement programme is almost completed. The primary motivation in society for the introduction of these systems was to replace individual boilers in apartment buildings to reduce the risk of boiler explosions and to raise comfort. The main part of heat was delivered by steam condensation in radiators at the consumers. One of the main challenges for the authorities with regard to providing suitable planning and market regulation was to deal with the problem arising from competing supplies in the same streets and urban areas [43].

The second generation of systems used pressurised hot water as the heat carrier, with supply temperatures mostly over 100 °C. These systems emerged in the 1930s and dominated all new systems until the 1970s. Typical components were water pipes in concrete ducts, large tube-and-shell heat exchangers, and material-intensive, large, and heavy valves. The large Soviet-based district heating systems used this technology, but the quality was poor and lacked any heat demand control. Outside the former USSR, the quality was better and remains of this technology can still be found as the older parts of the current water-based district heating systems. The societal reasons behind using this technology as well as the institutional framework and regulation used for the implementation varies slightly between countries and cultures, however in general, the primary motivation was to achieve fuel savings and better comfort by utilising CHP. If governmental policies and planning initiatives were introduced, the purpose was to achieve and coordinate a suitable expansion of CHP in urban areas.

The third generation of systems was introduced in the 1970s and took a major share of all extensions in the 1980s and beyond. Pressurised water is still the heat carrier, but the supply temperatures are often below 100 °C. This third generation is sometimes referred to as "Scandinavian district heating technology", since many district heating component manufacturers are Scandinavian. Typical components are prefabricated, pre-insulated pipes directly buried into the ground, compact substations using plate stainless steel heat exchangers, and material lean components. This technology is used for all replacements in Central and Eastern Europe and the former USSR. All extensions and all new systems in China, Korea, Europe, USA and Canada use this third generation technology. Again, the societal reasons and institutional framework and regulation vary between the different countries and cultures, however in general, the primary motivation is security of supply in relation to the two oil crises leading to a focus on energy efficiency related to CHP and replacing oil with various local and/or cheaper fuels such as coal, biomass and waste. Moreover, solar and geothermal heat has been used as a supplement in a few places.

The trend throughout these three generations has been towards lower distribution temperatures, material lean components, and prefabrication leading to reduced manpower requirements at construction sites. Following these identified directions, a future fourth generation of district heating technology should comprise lower distribution temperatures, assembly-oriented components, and more flexible pipe materials. Moreover, an important framework condition for the need for further development of district heating infrastructures and technologies is the change in primary motivation in various societies, namely to transform into a future sustainable energy system as mentioned in the introduction. This entails an institutional framework in which infrastructural planning is used to identify and implement where to have district heating and where not to have district heating 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.

Similar technology generations can be defined for district cooling systems. The first generation was the pipeline refrigeration systems introduced in the late 19th century. They consisted of centralised condensers and decentralised evaporators with the refrigerant as the distribution fluid [44]. They appeared in both North American and European cities. The second generation became the district cooling systems introduced in the 1960s based on large mechanical chillers and cold water as distribution fluid. Some first systems of this second generation were installed in Hartford, La Défense area outside Paris, and Hamburg. The third technology generation constitutes a more diversified cold supply based on absorption chillers, mechanical chillers with or without heat recovery, natural cooling from lakes, excess cold streams, and cold storages. The distribution fluid is still cold water. Many of these third generation installations were established in the 1990s, when CFC refrigerants were banned according to the Montreal protocol. A future fourth generation of district cooling systems can be defined as new smart district cooling systems more interactive with the electricity, district heating, and gas grids. However, the definition of this district cooling generation technology is outside the scope of this paper.

3. The future 4th generation of district heating

Recent studies have investigated the feasibility of district heating in terms of implementing a sustainable energy system based on renewable energy and including substantial reductions in the space heating demand [25,45,46]. The studies conclude that the role of district heating is significant, but that 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. Renewable energy, together with energy conservation and CHP production, is an essential factor in the climate change response in Europe as well as in many other regions [46–49].

The competitiveness of district heating derives from a combination of the conditions for heat supply and heat distribution. One important condition for heat distribution is that the heat demands must be concentrated in order to minimise distribution costs and heat losses [44]. Low heat densities in sparse areas lead to relatively higher distribution costs and losses [50,51]. Of fundamental importance when making strategic longer-term choices is the fact that the major Central European cities are dense enough to handle a major reduction in the customer heat demands without losing the overall competitiveness of district heating [39].

In order to be able to fulfil its role in future sustainable energy systems, district heating will have to meet the following challenges which will be elaborated in the following:

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

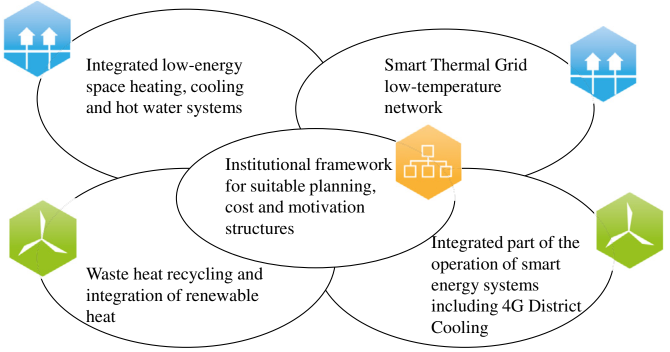

Fig. 1. Illustration of the concept of 4th Generation District Heating including smart thermal grids.

3.1. *Ability to supply low-temperature district heating for space heating and hot water*

In most countries, buildings account for a substantial part of the energy supply. Therefore, the development of sustainable buildings plays an important role in the transformation of national energy systems into future sustainable energy supplies aiming at reductions in fossil fuel use and CO_2 emissions. The 4th Generation District Heating and cooling technology implies coordinating the performance of the buildings and the district heating system in order to improve the energy efficiency of the total system and it may include the following integrated building design features:

3.1.1. *Synergies of combining energy conservation with expansion of district heating*

It is possible to reduce the total energy use for space heating of new buildings to a level equivalent to the energy use for domestic hot water heating. Consequently, a better balance is obtained between the energy needed during summer and winter. In this way, the total energy use, being at a relatively constant low level, can be delivered by heat recycling or RES at a lower cost [52]. The reduction of heating demands of existing buildings may be exploited by the district heating system in the following two ways:

- First, the capacity of the district heating grid and production units allows more buildings to be connected to the same grid.
- Next, the insulation of existing buildings means comfort is achieved by lower supply temperatures. This will also reduce grid losses and will increase the recycling of heat and the efficiencies of the production units.

The cooling demands can similarly be reduced by insulating the existing buildings and new low-energy buildings, thus enabling the same system benefits. The Heat Roadmap Europe study illustrates how a least-cost energy efficiency solution can be reached for Europe, if energy conservation is combined with an expansion of district heating and cooling [19].

3.1.2. *Low-temperature space heating system*

The change in temperature demand may be further improved by introducing heating systems that can use supply temperatures of 40 °C and cool down the district heating water to near room temperature (20–22 °C). Floor heating or wall heating with an average water temperature just a few degrees higher than room temperature is a possibility. Oversized water heating panels with a proper flow control system to cool the water to a low temperature may alternatively be used.

3.1.3. Low-temperature domestic hot water (DHW) supply system

Further, by using substations without storage of DHW at the end-user and pipes with only a small volume between the heat exchanger and the taps, the hot water volume is so small that the potential problem with legionella bacteria is minimised [53]. Therefore, it may be possible to use 40–50 °C supply temperature of DHW. In this way, the temperature level of the district heating supply to the buildings can be as low as 45–55 °C. In large buildings, local DHW heat exchangers are used to ensure a very small volume of DHW supply pipes. Heat supply for space heating and the DHW heat exchangers are provided by a circulation pipe in the building.

3.1.4. Intelligent control of the heating of buildings and peak shaving

The optimal operation of the buildings and the district heating system may be obtained by use of intelligent control of the heating system of buildings. The intelligent control makes use of weather forecasts to calculate the need for heating in each room and this information is used to control the operation of the heating system. This is especially relevant for floor heating installations, where a weather forecast based control of the floor temperature can improve the indoor environment. Moreover, the efficiency of the heating system improves, as the thermal capacity of the concrete deck may be allowed to discharge before the occurrence of excess solar gain. The 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. Alternatively, an intelligent control system based on 24-h weather forecasts may be used to calculate the required need for space heating and to feed the individual rooms with the predicted energy for heating.

The focus here is on groups of new buildings, but the new district heating concept can also be used in existing buildings and existing district heating systems. By making use of the new types of low-temperature substations in existing buildings, a low-temperature district heating system may be implemented generally and widely in cities. To realise the new 4th Generation District Heating concept, the network can be developed to be more energy efficient based on the use of integrated building design features.

3.2. Ability to distribute heat in networks with low grid losses

Smart thermal grids are defined 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 or cooling production units including individual contributions from the connected buildings [54]. The focus is on lowering costs and heat grid losses by improving the components and creating synergy by decreasing the buildings' heat or cooling demands. This paves the way for better utilisation of low-temperature renewable heat and increases the efficiency of CHP and large-scale heat pumps [55], also by integrating heat storage. The following elements are of relevance to district heating smart thermal grids:

3.2.1. Low-temperature network

Future grids may use low-temperature heat distribution networks with normal distribution temperatures of 50 °C (supply pipe) and 20 °C (return pipe) as annual averages. This will cut the current 3rd generation distribution temperature difference between average water temperature and ground by a factor 2.

3.2.2. Smaller pipe dimensions

By reducing the peak flow rate in the distribution network, the pipe dimensions can be reduced. This can make it possible to use twin pipes with a factor 2 lower heat loss coefficient than two single pipes. By use of low temperature and small pipes, it is possible to reduce distribution heat losses compared to existing systems by a factor 4. The use of small pipes increases the pressure requirement but this may be solved by the use of local pumps in the network or buildings.

3.2.3. District heating pipes with improved insulation

By use of twin pipes with the supply pipe in the centre and the return pipe located at the isotherm equal to the return temperature, the heat loss can be reduced and the heat exchange between supply and return pipes eliminated. Insulation materials may be improved by adding opacifiers to reduce the heat transfer caused by thermal radiation.

3.2.4. Supply and return pipes in a loop layout to establish circulation of supply pipe during summer

In the summer, the flow rate may be so low that the heat loss of the supply pipe may cool the water to a temperature that is too low for the heating of DHW in the buildings at the end of the supply pipes. In order to avoid bypass to the return line, a layout of the supply pipes in a loop back to the heating plant or to main parts of the grid makes it possible to circulate sufficient warm water in the supply line to heat DHW in the summer. If the return pipe is also connected in a loop with the flow direction as the supply pipe, the differential pressure between supply and return pipes may even out at all places in the grid.

3.2.5. Intelligent control and metering of the network performance

Decentralised intelligent metering in order 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. Wireless gathering of heat meter readings over short time intervals makes this possible. This may also include metering the sale of surplus heat from e.g. solar thermal from the individual building to the grid as well as motivate to better cooling at the consumers.

To realise the vision of a district heating system based only on heat from renewable sources in a cost efficient way, a number of options are to be investigated with a special focus on the distribution benefits of having low supply and return temperatures. Additional benefits include a reduced risk of scalding at water leakages, less thermal expansion of steel pipes leading to less risk of low cycle fatigue, less risk of boiling in the distribution pipes, and the possibility to use pipe materials other than steel.

Table 1 gives an overview of the challenges and their development over the generations within distribution and demand.

3.3. Ability to utilise renewable heat and recycled heat from low-temperature sources

As mentioned, an important part of *smart thermal grids* is to pave the way for better utilisation of renewable heat and recycled low-temperature heat, and increase the efficiency of CHP and large-scale heat pumps, together with the use of thermal storage. This includes the following aspects:

3.3.1. Heat from CHP and waste incineration

The heat from waste incineration is very useful for district heating systems as it is supplied all year round. However, priority should be given to recycling and therefore the heat resource from waste is limited and should be used in an optimal way. Looked upon from the perspective of the optimum overall sustainable energy

Table 1

	1st Generation	2nd Generation	3rd Generation	4th Generation
Label	Steam	In situ	Prefabricated	4GDH
Period of best available technology	1880–1930	1930–1980	1980–2020	2020–2050
	Distribution and demand			
Heat carrier	Steam	Pressurised hot water mostly over 100 °C	Pressurised hot water often below 100 °C	Low-temperature water 30–70 °C
Pipes	In situ insulated steel pipes	In situ insulated steel pipes	Pre-insulated steel pipes	Pre-insulated flexible (possible twin) pipes
Circulation systems	Steam pressure	Central pumps	Central pumps	Central and decentralised pumps
Substations heat exchanger	No	Tube-and-shell heat exchangers	Without or with plate heat exchangers	Probably mostly with plate heat exchangers Introduction of flat-stations (decentralised supply of hot water in new buildings)
Buildings	Apartment and service sector buildings in the city	Apartment and service sector buildings 200–300 kWh/m^2	Apartment and service sector buildings (and some single-family houses) 100–200 kWh/m^2	New buildings: <25 kWh/m^2 Existing buildings: 50–150 kWh/m^2
Metering	Condensate meters in order to measure the amount of steam used.	Initially only flow meters in substations, later replaced by heat meters. Annual or monthly readings. Sometimes use of allocation meters on radiators for internal distribution of heat costs.	Heat meters and sometimes additional metering of flow in order to compensate for high return temperatures. Wireless readings introduced for more frequent readings.	As earlier but continuous reading used for continuous commissioning of customer heating system.
Radiators	High-temperature radiators (+90 °C) using steam or water.	High-temperature radiator (90 °C) using district heating water directly or indirectly.	Medium-temperature radiators (70 °C) using district heating water directly or indirectly. Floor heating.	Floor heating. Low-temperature radiators (50 °C). Indirect system.
Hot water	Hot water tanks heated directly with steam or from a secondary water circuit.	DHW tank heated to 60 °C. Circulation at 55 °C when needed.	Heat exchanger heating DHW to 50 °C. Domestic hot tank heated to 60 °C. Circulation at 55 °C when needed.	Very efficient local heat exchanger heating DHW to 50–40 °C. In district heating systems with supply temperature of 30 °C, a heat exchanger preheats DHW and a heat pump with buffer tank and heat exchanger increases DHW temperature to 40 °C by cooling down the return temperature.

solution, the best outcome will be to produce as much electricity as possible. However, a substantial proportion will still emerge as heat which again may be increased by including condensation of the combustion flue gases when low-temperature district heating renders this useful. In order to make use of all the heat production from waste incineration, it is necessary to have a sufficiently large district heating network coupled to the incineration plant. This may be accomplished by establishing a main distribution network for district heating.

3.3.2. Waste heat from processes in industry and commercial buildings

With a low-temperature district heating network with supply and return of about 50/20 °C, there is much higher potential for usable waste heat from industrial processes and from cooling processes in commercial buildings (e.g. supermarkets). Even though the waste heat may be available all year round, it is not controlled from the heat demand in the district heating system and it is also a local input. Therefore, a district heating system that makes use of local waste heat from processes in commercial buildings is a much more complex type of district heating system that requires detailed dynamic performance investigation and planning. It does, however, also enable a central thermal storage facility which is both low cost and can integrate such sources.

3.3.3. Geothermal heating plants

In most areas of Europe, usable hot water is available in the ground. The temperature level and the availability of water-filled porous layers govern the extent of useful geothermal heat but a much lower district heating supply temperature makes it much easier to construct geothermal plants for use in district heating systems. In many cases, the utilisation of geothermal heat will imply the use of absorption heat pumps which may again 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.

3.3.4. *Central or local solar heating plants with seasonal storage*

Solar heating systems may be used to supplement the heat supply to the district heating system. Ground-based large solar heating plants may be placed in areas slightly outside the cities and coupled to the main distribution lines of the district heating system. Due to a seasonal mismatch of solar availability and the use of heat in buildings for space heating, seasonal storage may have to be established to raise the fraction of solar heat delivered to the district heating system. Large long-term storage may also be useful for coupling other heat sources to the network. Smaller local solar heating systems with short-term storage may be used to maintain the necessary temperature in the outer part of the network.

3.3.5. *Additional supply benefits with low-temperature distribution*

Lower supply and return temperatures in the distribution networks will also bring additional benefits for the supply part in the whole supply chain. Examples of these benefits are higher power-to-heat ratios in steam CHP plants, higher heat recovery from flue gas condensation, higher coefficients of performance in heat pumps, higher utilisation of geothermal and industrial heat sources with low 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.

3.4. *Ability to be an integrated part of smart energy systems*

The large-scale integration of RES into existing energy systems must meet the challenge of coordinating fluctuating and intermittent renewable energy production with the rest of the energy system. Meeting this challenge is essential, especially with regard to electricity production, since electricity systems depend on an exact balance between demand and supply at any time. Given the nature of photovoltaic (PV), wind, wave, and tidal power, little can be gained by regulating the renewable source itself. Large hydropower producers are an exception, since such units are typically well suited for electricity balancing. However, in general, the possibilities of achieving a suitable integration are to be found in the surrounding supply system—that is, in power and CHP stations. The regulation in supply may be facilitated by flexible demands—for example, heat pumps, consumers' demands, and electric boilers. Moreover, the integration can be helped by different energy storage technologies. However, these insights are not new; they were discovered a century ago in national power systems dominated by intermittent renewable power sources [56].

The discipline of analysing large-scale integration of renewable energy into existing systems must address the challenge of redesigning the systems based on the characteristics of the fluctuating renewable sources. The systems must be designed in such a way that they are able to cope with the fluctuating and intermittent nature of RES, especially with regard to the electricity supply. Such a redesign of future electricity supply systems has recently been defined as a smart grid, i.e. a smart electricity grid.

However, it is essential to emphasise that the development of smart electricity grids to facilitate the large-scale integration of renewable energy should be considered only one part of the step towards future renewable non-fossil energy systems [57]. Optimal long-term energy systems are those in which such measures are combined with energy conservation and system efficiency improvements. In that respect, future developments in district heating systems will play an essential role in the operation of smart energy systems [58], i.e. when smart electricity grids as well as smart thermal and smart gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system [59].

The utilisation of biomass poses large challenges in renewable energy systems while buildings account for a substantial part of the energy supply even in 100 percent renewable energy systems. District heating systems are important in limiting the dependence on biomass and create cost effective solutions. They are especially important in renewable energy systems with large amounts of fluctuating sources as it enables fuel efficient and low-cost energy systems with thermal heat storages. They can increase the efficiency with the use of CHP production, while reducing the biomass demand by enabling the use of other renewable resources such as large-scale solar thermal, large heat pumps, geothermal heat, industrial surplus heat, and waste incineration. Where the energy density in the building stock is not high enough for district heating to be economical, ground source heat pumps should be used for individual heating systems [60].

The key elements in such development and interaction have been examined in a number of research papers [57,61–67] of which the coherent conclusions have been described in Ref. [68] as listed below. The percentages refer to the Danish energy system with a high share of CHP. While the principal point is the same, the percentages may differ for other countries and systems. However, as already described, it will be essential to implement energy efficiency measures such as CHP in most future sustainable energy systems.

3.4.1. *Active regulation of CHP plants by use of thermal heat storage*

CHP stations should be operated in such a way that they produce less when the renewable electricity production input is high and more when the input is low. When including heat storage capacity, such measures are likely to integrate fluctuating renewable electricity up to 20–25 percent of the demand without sacrificing fuel efficiency in the overall system. After this point, system efficiency will decrease as heat production from CHP units is replaced by thermal or electric boilers.

3.4.2. *Integration of large-scale heat pumps in CHP systems*

Heat pumps, and possibly additional heat storage capacity, should be added to CHP stations and operated in such a way that further RES can be efficiently integrated [69]. Such measures will allow for the integration of up to 40 percent of fluctuating RES into the electricity supply without affecting the overall system efficiency.

In general, compared to the measures mentioned above, it is not beneficial to include electricity storage capacity in the preceding steps. Such a storage capacity is both inefficient and expensive compared to the benefits that may be achieved. Moreover, the nature of fluctuating RES dictates the need for high capacities of both conversion units and storage in combination with a low number of full load hours. Thus, the electricity storage technologies call for high investments in combination with low utilisation. If such technologies are to be competitive, they should provide further benefits, such as saving power station capacity and/or securing grid stability. Moreover, apart from heat pumps, it is not feasible to cater for flexible consumer demands in the regulation. The use of such measures raises the same problems as for electricity storage technologies. The nature of fluctuating RES calls for large quantities of energy and long time spans, to such an extent that matching supply with a realistic flexible consumer demand becomes impossible.

3.4.3. Involving integrated CHP plants in securing grid stabilisation tasks

Along with raising the share of fluctuating renewable electricity production, it becomes essential to involve flexible technologies, such as CHP, heat pumps, and the electrification of transport (batteries and electrolysers), in grid stabilisation tasks—in other words, to secure and maintain voltage and frequency in the electricity supply. Such an involvement becomes increasingly important along with the acceleration of the share of RES. The first attempts to achieve this have already been implemented on the NordPool market in Scandinavia, in which small CHP plants are active not only on the spot market but also on the regulating power market, and even on the automatic primary reserve market. The latter is where CHP combustion engines are used to balance electricity supply for time periods less than 30 s. In practice, the CHP units are bet into the spot market and operated on a minus 10 percent of maximum capacity in combination with being operated at the primary reserve market on a plus/minus 10 percent service. Such an involvement has been furthered by combining the CHP units with electric boilers (also being operated on the automatic primary reserve market) and furthermore in the future also in combination with heat pumps.

Table 2 gives an overview of the challenges and their development over the generations within production and system integration.

3.5. Ability to ensure suitable planning, cost and motivation structures

The implementation of 4th Generation District Heating systems is an integrated part of the transformation into sustainable energy systems. The technological change from nuclear and fossil fuel-based energy systems to renewable energy systems involves an economic redistribution, as investments in large power stations are replaced by investments in energy conservation and distributed CHP plants. Furthermore, fossil fuel extraction (e.g. coal mining) is replaced by harvesting biomass resources and investing in wind turbines and solar thermal power.

Typically, the existing energy supply system is characterised by single-purpose companies, i.e. enterprises which have production and/or sale of energy services as their only purpose. They are often segmented into heat, electricity or natural gas supply systems. Investments are capital intensive; they have a very long technical lifetime of often 20–40 years and are almost 100 percent asset specific. Asset specificity means that the assets, such as district heating systems, supply stations, and power grids, can only be used for their present purposes. The organisations linked to the existing technologies are consolidated from an economic as well as a political point of view.

The existing consumers' system is characterised by many multi-purpose organisations, which refers to the fact that households and private or public firms have other main purposes than investing in renewable energy system technologies. Such organisations often lack capital for investing in renewable energy system technologies, including energy conservation activities, and have no common organisation of activities related to these technologies.

Unlike nuclear and fossil fuel technologies based on large power stations, renewable energy system technologies will typically benefit from a wide distribution throughout their geographical areas of consumption [70]. The technological solutions differ from one place to another and sometimes new, not well-proven technologies must be implemented. The maintenance of such new technologies is dependent on ownership and organisation. Along with the implementation of new technologies, new types of organisations are therefore likely to develop.

Investments must be made by multi-purpose organisations. Thus, electricity savings must be implemented by private households and industries with only a limited awareness of consumption, and with main objectives quite unrelated to simply producing or consuming heat or electricity. This has to be compared with the former situation in which investments in supply technologies were carried out by single-purpose organisations, such as utility companies, with energy production as their primary objective.

The technologies must be implemented by many mutually independent organisations. Again, this has to be compared with the former situation of a limited number of companies. The financial capital of these new organisations will often be scarce compared with the financial capital of the existing supply companies. The political capital of these new organisations will also be relatively scarce compared with that of the existing companies.

Table 2

	1st Generation	2nd Generation	3rd Generation	4th Generation
Label	Steam	In situ	Prefabricated	4GDH
Period of best available technology	1880–1930	1930–1980	1980–2020	2020–2050
	Production and system integration			
Heat production	Coal steam boilers and some CHP plants	Coal and oil based CHP and some heat-only boilers	Large-scale CHP, distributed CHP, biomass and waste, or fossil fuel boilers	Low-temperature heat recycling and renewable sources
Integration with electricity supply	CHP as heat source	CHP as heat source	CHP as heat source, and some large electric boilers and heat pumps in countries with temporary electricity surpluses. Some very few CHP plants on spot market as exception	CHP systems integrated with heat pumps and operated on regulating and reserve power markets as well as spot markets

All in all, this technological change can often be seen as a change from undifferentiated solutions implemented by a few single-purpose organisations to differentiated solutions implemented by many multi-purpose organisations. Therefore, the change to renewable energy systems is to be regarded as a radical technological change. The important point is that this entails substantial changes in existing organisations and institutions and their knowledge base; and such a change will challenge these organisations [71]. Moreover, it will influence the general perception of choice in society.

Since the use of institutional framework and regulation with regard to district heating varies between the different countries and cultures, there will be different solutions on the concrete level which fit better into some societies than others. However, some of the principle challenges are the same and so are by definition the primary motivation in society, namely to transform into a future sustainable energy system. Three principle challenges are highlighted here: The first is to decide where to have district heating and where not to have it; the second is to decide to which extent heat should be produced versus the implementation of energy conservation; the third is how to motivate a suitable integration of fluctuating RES including the integration with other parts of the overall energy system.

3.5.1. Integrated strategic infrastructure planning procedures

The planning process needs to enable a transition to 4GDH in existing supply systems as well as for new neighbourhoods. 4GDH planning is a change from the 3GDH heat and power sector planning to integrated resource planning and energy system planning.

It needs 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. This requires improved communication systems where the proponents for energy conservation and intermittent renewable energy systems are given analytical power and a voice in their communication with the existing supply companies. Coordination between implementing lower temperatures and planning for energy conservation is necessary, which entails planning procedures that facilitate this.

3.5.2. GIS, system based planning, design tools and methodologies

The identification of optimal plans for the levels of heat saving versus heat production and which technologies to apply (district heating versus various individual solutions) can only be carried out on the basis of a combination of, on the one hand, detailed data on the location of heat demands and, on the other hand, knowledge on the future system of which district heating should be a part [72,73]. This calls for the development of tools with geographical information system (GIS) and advanced energy system analysis tools of coherent systems.

3.5.3. Tariffs and cost principles based on long-term marginal costs

Tariff policies of the present 3GDH tariff system are characterised by being dominated by the short-term marginal costs of the existing supply systems. In a 4GDH 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.

3.5.4. Create a balance in implementation power between supply and demand

It is important that the organisers of different components in a smart energy system have the same access to finance and pay the same interest on their loans. Here, this entails that long-term loans

Table 3

	1st Generation	2nd Generation	3rd Generation	4th Generation
Label	Steam	In situ	Prefabricated	4GDH
Period of best available technology	1880–1930	1930–1980	1980–2020	2020–2050
	Planning and implementation			
Primary motivation in society (why to have DH)	Comfort and reduced risk	Fuel savings and reduced costs	Security of supply	Transformation to a sustainable energy system
Infrastructure planning (where to have DH)	Governing competing district heating infrastructures	Developing and expanding DH suitable for cost efficient use of CHP	Identifying and implementing suitable DH infrastructures in fossil based energy systems	Identifying and implementing suitable DH infrastructures in fossil free energy systems
Cost principles for investments (DH supply versus savings in demand)	Minimising the per unit supply costs. Few concerns regarding savings because space is more important.	Minimising the per unit supply costs. Few concerns regarding savings because CHP is cheap and plenty.	Dilemma between short- and long-term marginal costs with short-term marginal costs winning based on existing investments (sunk costs)	Dilemma between short- and long-term marginal costs with a need to integrate better long-term marginal costs (future investments). Incl. DSM costs
Motivation in operation (how to best operate given supply/demand system)	Consumers have to condensate steam. Further cooling is of minor concern.	Motivation of consumers' cooling is of less importance.	Motivation of consumers' cooling gradually becomes important. Expansion of CHP and use of biomass and waste are important.	Motivation of consumers' cooling is essential. Motivation of the integration of fluctuating RES is essential.

should be made accessible to all participants in a smart energy system, in order to facilitate a long-term change to these systems.

It is crucial that different participants in a smart energy system are given similar access to consultancy services. Consumers are in general much less organised than supply companies. This imbalance should be compensated in a smart energy system development process by ensuring that the demand side is organised so energy conservation takes place as buildings are renovated.

New education curricula may enable university candidates as well as craftsmen to learn how to handle the development and coordination of components in a smart energy system. They can also experience how to work interdisciplinary, i.e. with regard to combining technical components in the right way in an energy system, and regarding the combination of policies and technological systems.

Table 3 gives an overview of the challenges and their development over the generations within planning and implementation.

4. Summary and definitions

The purpose of this paper has been to define the concept of *4th Generation District Heating* (4GDH) including the concept of *smart thermal grids*. The paper has described the historical development of district heating systems in terms of three generations and afterwards identified the future challenges for the district heating technology of reaching a future renewable non-fossil heating and cooling supply as part of the implementation of overall sustainable energy systems.

On such a basis, the paper has defined the concept of *smart thermal grids* 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. The concept of *smart thermal grids* can be regarded as being parallel to *smart electricity grids*. Both concepts focus on the integration and efficient use of potential future RES as well as the operation of a grid structure allowing for distributed generation which may involve interaction with consumers.

However, the two concepts differ slightly in the sense that *smart thermal grids* face their major challenge in the utilisation of low-temperature heat sources and the interaction with low-energy buildings, while *smart electricity grids* face their major challenge in the integration of fluctuating and intermittent renewable electricity production. It should also be emphasised that the two concepts complement each other and both of them are to be regarded as necessary for the implementation of sustainable energy systems.

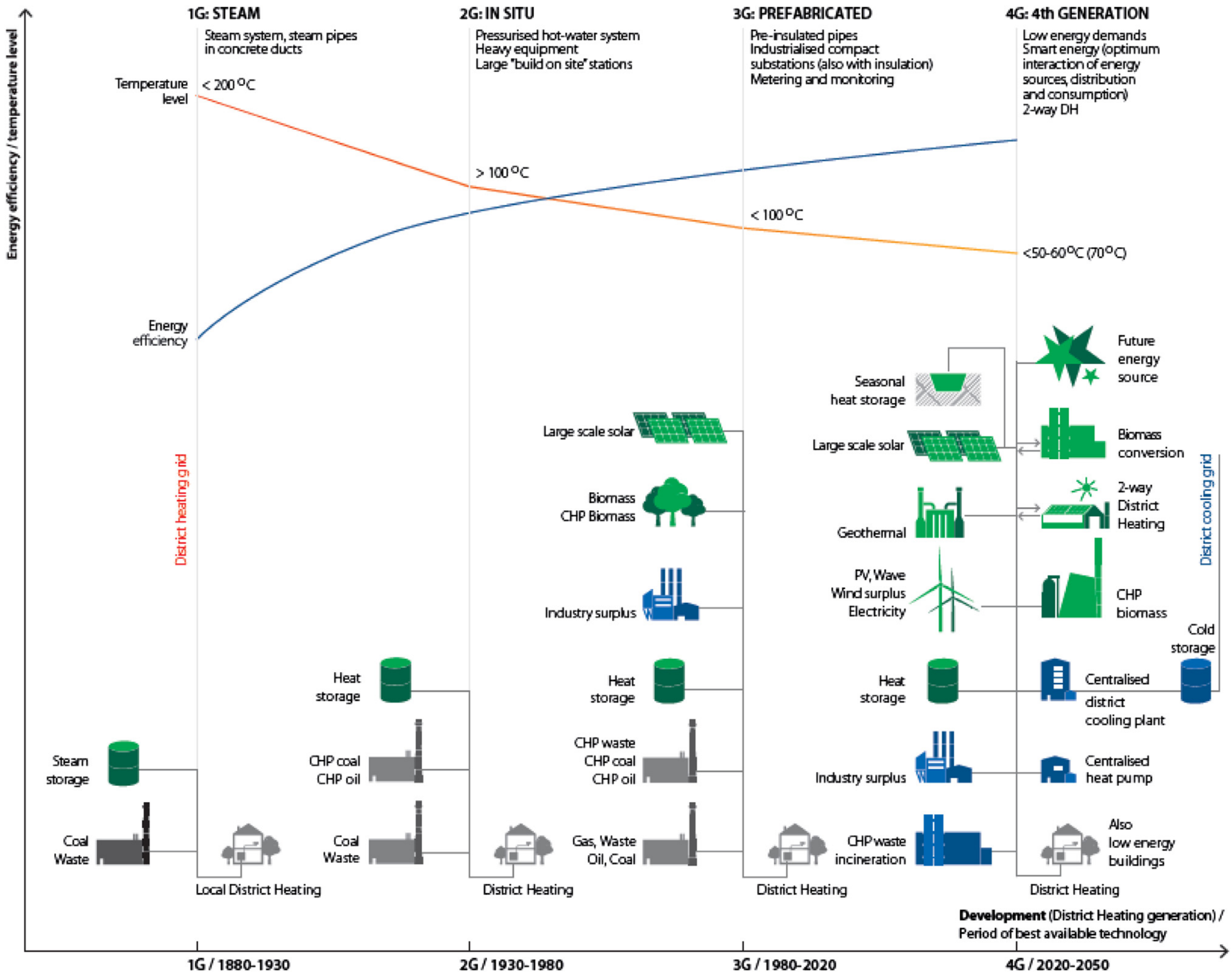

Fig. 2. Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations.

The 4th Generation District Heating (4GDH) system is consequently defined as a coherent technological and institutional concept, which by means of *smart thermal grids* assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. The concept involves the development of an institutional and organisational framework to facilitate suitable cost and motivation structures.

Identical definition is used in Ref. [18].

A comparison between the four generations of district heating technologies is shown in Fig. 2. The diagram, as well as the previous tables, is illustrating the typical applied technologies of each generation and the period of best available technology. Note that e.g. technologies from the fourth generation can be seen during third generation typically by realised pilot projects.

Acknowledgement

The work presented in this paper is a result of the research activities of the Strategic Research Centre for 4th Generation District Heating (4DH), which has received funding from the Danish Council for Strategic Research. We especially wish to thank all our colleagues within the 4DH centre for helpful comments and fruitful discussions.

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