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Review

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

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A B S T R A C T

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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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.