Renewable and Sustainable Energy Reviews 67 (2017) 417–425

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Review of district heating and cooling systems for a sustainable future

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A R T I C L E I N F O

Article history:
Received 30 December 2015
Received in revised form
11 May 2016
Accepted 10 September 2016

Keywords:
District heating and cooling
District energy system
Thermal network
Energy resources
Renewable energy

A B S T R A C T

The present study explores the implementation of district heating and cooling systems across a broad set of case studies reported in the literature. Topics addressed include their history, system identification, energy sources, design considerations, environmental impact, economic feasibility, performance analysis and the role of energy policy. The history of district heating and cooling systems reveals how available technology has influenced the configuration of district energy systems as more efficient and cleaner methods of providing heating and cooling have arisen. This leads to system identification based on primary energy sources, including the deployment of more and more renewable energy streams. Advantages and disadvantages of each energy source are examined in detail. Policies created by government and international entities will have a major impact on the future of research and development in district energy systems. Incentives may become necessary for creating favorable conditions for the efficient construction and utilization of district heating and cooling. Outcomes of these policies influence design considerations underlying any district energy system and their contribution in sustainability. Studies on greenhouse gas emissions along with the economic impacts of district energy construction are part of the design process and optimization of district energy systems should include economic and environmental considerations and not solely thermal efficiency. District heating and cooling systems are often integrated with components such as absorption chillers, cogeneration and thermal energy storage. Performance analysis using exergy and energy analysis have revealed several sources of irreversibility in district heating systems with these elements. If understood properly, these can greatly enhance system operation. Awareness and accommodation of the many factors discussed in this paper can improve the soundness of any district heating or cooling installation.

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1. History

District energy systems have been around since the 14th century [1]. Since its inception district energy systems have utilized

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http://dx.doi.org/10.1016/j.rser.2016.09.061
1364-0321/Published by Elsevier Ltd.

Table 1
Production and energy sources for district energy [3].

	1st Generation	2nd Generation	3rd Generation	4th Generation
Peak Technology Period	1880–1930	1930–1980	1980–2020	2020–2050
Heat Production	Steam boilers	CHP and heat-only boilers	Large-scale CHP	Heat Recycling
Energy Source	Coal	Coal and oil	Biomass, waste and fossil fuels	Renewable sources

various energy sources including geothermal, fossil fuel, biomass and waste incineration [2]. The primary transport fluid for heat for district heating systems until the 1930s was steam; this system uses pipes in concrete ducts with steam traps and compensators, but steam at high temperatures generates large amounts of heat losses and poses a risk from steam explosions. These first systems were often used in apartment buildings to reduce the risk of boiler explosions. The second generation of district energy transport systems used pressurized hot water using water pipes in concrete, shell-and-tube heat exchangers and large valves. These systems showed inability to provide control for the heat demand but showed improvement in fuel savings. In the 1970s the third generation of district energy transport systems was developed; using pressurized water but at lower temperatures than the previous generation and often referred to as the "Scandinavian district heating technology" these systems featured prefabricated buried pipes, and compact substations and is the current system in use throughout the developed world [3]. Table 1 shows the common method of heat production and energy source associated with the technology period of the district energy system.

Coal is still used for district energy in China and recent exergetic and energetic efficiencies for those plants were calculated. In 2013, Lio et al. published an extensive analysis using the first law as well as the exergetic efficiency taking into account the chemical, thermomechanical, kinetic and potential exergy and concluded that the extraction ratio could be used as a design criteria [4]. Currently European countries are the leading users of district energy systems and have a number of countries who have made large strides to move toward sustainable district energy systems. Sweden began a transition from oil-based district heating systems to coal-based systems in 1973 due to the oil crisis [5]. Since then Sweden has increased the use of biomass to offset the current usage of fossil fuels consumed in district based heating [5]. As of 2014, 53% of the fuel mix in Sweden is biomass based [5]. Feasibility studies have been conducted on sustainable energy within district heating technologies and shown that further development is necessary to decrease losses, utilize synergies and enhance the efficiencies of low-temperature production. Renewable energy along with combined heat and power production is essential and making long term choices are important for the overall competitiveness of district heating systems [2,6,7,8].

2. System identification

Identification of district energy systems are used to identify a system and how it operates. Groupings are based on several factors:

- heat transport fluid
- thermal energy transported
- heat resource used

The heat transport fluid often refers to the systems use of low-pressure steam, hot water and hot air as the primary fluid to transport thermal energy. The thermal energy transported is usually categorized in three groupings: heating, cooling, and heating and cooling. Not only is the resources utilized by the facilities but this identification also takes into account any cogeneration or polygeneration done by a district energy system. The energy sources that can be used for district heating can include fossil fuels, nuclear power, waste heat, cogenerated heat, solar thermal energy, ground source heat pumps, and biomass. Renewable energy sources particularly geothermal and solar have been effectively used in district heating in Europe, Asia and in the Americas. Cogeneration plants, often referred to as combined heat and power plants (CHP) are also key identifications of district energy systems, this is because their simultaneous generation of electricity and usable heat [1]. New technologies have enabled cogeneration to be cost effective even in smaller scale sites and a well-designed system can increase energy efficiency to over 80% [9]. Cogeneration plants can be farther identified into topping cycles and bottoming cycles. These systems can also be revised by utility cogeneration, industrial cogeneration and desalination. Waste heat identifications are used for district heating systems that take advantage of excess heat often found in industrial facilities to provide heat to nearby towns and buildings. One of the key identifications used is the density based; this categorizes the facility based on the population and building density served by the district energy system [1]. It is important to classify district energy systems for better comparison and analysis based on the characteristics and sustainable aspects. Understanding how systems are identified present opportunities for improvements to existing systems.

3. Energy sources

District energy has used a number of energy sources since its beginning. Correspondingly, modern systems have been built to take advantage of heat from a variety of sources. Below in Fig. 1, the energy distribution for the United States is shown, while this is not representative of every country. The figure shows how the energy sources have changed over 9 years. It is noticeable that coal and oil have decreased while nuclear has remained constant and renewable and natural gas sources have increased in use.

From comparison of Figs. 1 and 2 there are some interesting trends, natural gas and renewable resource usage are becoming bigger shareholders of the United States energy market. Increasing trends to cleaner energy make it is clear that consideration of these goals is necessary for the continued success of district energy systems.

Table 2 summarizes the advantages and disadvantages associated with different energy sources that can be used for district heating and cooling systems. When designing systems to take advantage of available resources, careful consideration should be given to the availability of nearby energy sources as well as their impact on the environment.

Depending on a number of factors District Energy Plants would be able to provide:

- Low-temperature domestic hot water
- Heating of buildings
- Cooling using waste or excess heat
- Electricity

Each of these systems and their available options often is dependent on the local and national policies, as well as the considerations made during installation. Making informed planning