Applied Energy 136 (2014) 881–893

Contents lists available at ScienceDirect

Applied Energy

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

Minimum-cost district heat production systems of different sizes under different environmental and social cost scenarios

Nguyen Le Truong *, Leif Gustavsson

Sustainable Built Environment Group, Department of Built Environment and Energy Technology, Linnaeus University, 35195 Växjö, Sweden

HIGHLIGHTS

- We analyzed options for district heat production systems (DHSs) under different scenarios.
- Environmental and social cost scenarios influent the design of minimum-cost DHSs.
- Composition and cost of district heat production is dependent on the scale of heat demand.
- Cogenerated district heat is cost- and fuel-efficient, except for small-scale DHSs.
- Primary energy use for district heat production varies with production scales and contexts.

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 8 July 2014
Accepted 23 July 2014
Available online 22 September 2014

Keywords:
Coproduction
District heat
Minimum cost
Environmental and social costs
Production scale

ABSTRACT

District heat systems can contribute to the achievement of social and environmental targets and energy security. District heat production systems (DHSs) vary in size depending on heat demand, which is influenced by several factors such as local climatic conditions and the sizes of the communities they serve. In this study, we analyzed options for minimum-cost DHSs of different sizes under different environmental and social cost scenarios. We calculated the production cost and primary energy use of district heat for minimum-cost options by considering a value of cogenerated electricity equivalent to the value of electricity produced in minimum-cost standalone condensing power plants. We varied the size of DHSs from 100 to 1800 GWh_{heat} per year to investigate how size influences the minimum-cost compositions of production units and district heat production costs. We determined that the optimal composition and cost of district heat production is dependent on the size of the system, the overall load factor of heat demand and the technologies considered for both DHSs and reference power plants. In general, cogenerated district heat is more energy-efficient than district heat from heat-only production and also more cost-efficient, except for small DHSs, for which cogenerated district heat is more costly than heat-only production. The cost and primary energy use of district heat production is dependent on environmental and social cost scenarios; however, this dependence is reduced if a DHS is cost-minimized and based on cogenerated units.

1. Introduction

Several potential pathways toward a sustainable energy system exist [1]. In any pathway, the use of locally available resources that are adapted to the local situation strengthens local energy security and may reduce environmental impacts. District heat is increasingly used in countries with a demand for space heating, such as the Nordic countries [1,2]. In Sweden, the use of district heat has increased so the current supply exceeds 10% of the total primary energy use and approximately 14% of the final energy use [3]. However, the average electricity-to-heat ratio of DHSs in Sweden is only 0.13 [4]. This indicates a vast potential for increasing the amount of coproduced electricity in combined heat and power (CHP) plants [5,6]. Use of high-efficiency cogeneration systems is also considered an important means of reducing primary energy use and improving the security of the energy supply [7].

Abbreviations: BIGCC, biomass-integrated gasification combined cycle; BIGGE, biomass-integrated gasification with gas engine; BST, biomass-based steam turbine; BORC, biomass-based organic Rankine cycle; CHP, combined heat and power; CST, coal-based steam turbine; CCS, carbon capture and storage; DHS, district heat production system; FGCC, fossil gas combined cycle; GEC, green electricity certificate; O&M, operation and maintenance; T&D, transmission and distribution.

* Corresponding author. Tel.: +46 470 767593; fax: +46 470 768540.
E-mail address: nguyen.truong@lnu.se (N.L. Truong).

http://dx.doi.org/10.1016/j.apenergy.2014.07.080
0306-2619/

DHSs vary in size, depending on the local climatic conditions and the sizes of the communities they serve. Of the 441 Swedish DHSs shown in 2013 [4], the majority of the systems (75%) are small, produce less than 100 GWh_{heat} per year and are based on heat-only boilers. However, approximately 95% of produced district heat is in systems that produce more than 100 GWh_{heat} per year. Of these, four systems have an annual district heat production greater than 2000 GWh_{heat} [4]. Large systems typically have plants in several locations [8,9].

Technologies change over time and need to adapt to different possible future environmental and social cost contexts. Normally, the service life of energy conversion systems falls between 20 and 30 years [10] and then need to be replaced or renovated. In connection with replacements or substantial renovations, the technical and economic performance of the systems can be improved, and the actually situation, and future trends of energy supply and demand could be considered. Therefore, studying the current status and future possibilities of existing energy systems could help to find suitable and flexible solutions.

District heating is a flexible platform for the application of energy-efficient conversion technologies and renewable energy resources, as shown in several research studies. For example, *Ecoheatcool* [11] showed a potential reduction in primary energy use of 5.5% and an annual emission reduction of 404 million tons of CO_2 by doubling the district heat sale in EU member states. A *Heat Roadmap Europe* study [12] indicated that increased market shares for district heating leads to reduced fossil fuel use, CO_2 emissions and production costs. Various energy sources can be mobilized for district heat production, such as local heat and fuel sources that may otherwise be lost or unused [13]. Danestig et al. [8] showed a high potential for cogeneration of heat and electricity in DHSs in Sweden and suggested that the cogeneration of electricity could be doubled [8]. Wetterlund and Söderström [14] and Difs et al. [15] demonstrated that the introduction of biomass gasification to produce biomotor fuels in DHSs has economic and CO_2 emission benefits due to the increased production of high-value coproducts. Additionally, Djuric Ilic et al. [16] showed that the coproduction of ethanol and biogas in DHS reduces CO_2 emissions and district heat production cost. However, these studies considered specific contexts of district heat production and were based on particular large-scale DHSs (above 10 [8,16] and 1.7 TWh_{heat}/year [14,15], respectively). Moreover, the competitiveness of the products from DHSs and standalone production was generally not considered in these studies.

There is potential for the co/polygeneration of different products in district heating systems [14,15,17,18]. The cogeneration of electricity in DHSs may be an economic choice for medium- to large-scale DHSs, especially if the value of cogenerated electricity is equivalent to the cost of producing electricity in standalone plants with corresponding technology [19,20]. Furthermore, emerging developments in CHP technologies, such as biomass-integrated gasification combined-cycle (BIGCC), biomass-integrated gasification with gas engine (BIGGE) and biomass-based organic Rankine cycle (BORC) systems, may improve the overall efficiency and performance of the technologies and increase their competitiveness for small-scale applications [21,22].

An energy system is typically designed and operated in a specific context. A cost-optimal DHS is typically composed of several production units [23]. In theory, each unit is based on different technologies with different conversion efficiencies. However, the selections of capacity and technology for a minimum-cost DHS is dependent on several factors, including specific investment and operation costs, heat demand, fuel prices and taxation. Additionally, specific investment and operation costs, as well as the conversion efficiency of each technology, are dependent on the size of the plants [22,24]. As a result, suitable technologies for and the overall production cost of district heat are dependent on the scale of district heat production. Taxation may also significantly influence the choice of technologies and the resulting production cost.

A tax on CO_2 emissions is the principal policy measure aimed at achieving targets of climate change mitigation [1]. Various countries have adopted strategies to reduce their dependency on fossil fuels and environmental impacts, including the promotion of renewable and low-carbon fuels and more efficient energy-conversion technologies. To achieve targets of energy and climate policies, a CO_2 tax system for fossil fuels and a tradable green electricity certificate (GEC) system for electricity production from renewable sources were introduced in Sweden [25,26]. These policy measures are aimed at increasing the cost of fossil fuel-based systems and the competitiveness of renewable-based systems. However, most of the current CO_2 taxation systems are based on the ready-to-pay capability of society and on the commitment levels of the country's CO_2 emission mitigation. This may not reflect the current costs caused by the emissions. Assessing damage costs due to CO_2 emissions may be an option for estimating the climate change costs of using fossil fuels. However, such damage cost assessments are highly uncertain and depend on the CO_2 concentration in the atmosphere [27–29].

In this study, we analyzed the options for various sizes of minimum-cost DHSs with electricity coproduction possibility under different environmental and social cost scenarios. We calculated the production costs and primary energy use of district heat for minimum-cost options, by considering the value of cogenerated electricity equivalent to electricity produced in minimum-cost standalone condensing power plants. We varied the sizes of DHSs from 100 to 1800 GWh_{heat}/year to investigate how the size influences the minimum-cost compositions of production units and district heat production costs.

2. Methods and assumptions

2.1. Study approach and heat load duration curve

We based our study on the measured district heat load in an existing DHS in Växjö, which is located in southern Sweden. The total and peak heat demands in 2011 were 610 GWh and 180 MW, respectively. Fig. 1 shows the 2011 heat load duration curve, in which the daily heat loads are arranged in descending order. We scaled the district heat load to a maximum of 1800 GWh_{heat} per year and a minimum of 100 GWh_{heat} per year to examine the influence of the size of the district heat demand on a cost-optimal DHS.

For each of five (100, 300, 610, 1200, and 1800) district heat loads, we designed a minimum-cost DHS that meet the district

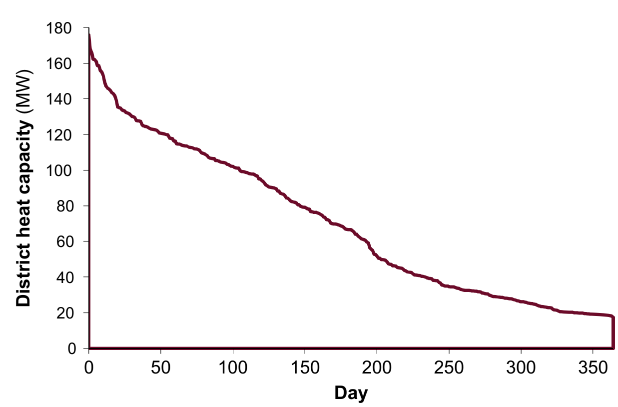

Fig. 1. Heat load duration curve of the existing DHS in Växjö in 2011.