Applied Energy 130 (2014) 419–427

Contents lists available at ScienceDirect

Applied Energy

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

# Cost and primary energy efficiency of small-scale district heating systems

Nguyen Le Truong *, Leif Gustavsson

*Sustainable Built Environment Group, Linnaeus University, 35252 Växjö, Sweden*

## HIGHLIGHTS

- We analyzed minimum-cost options for small-scale DHSs under different contexts.
- District heat production cost increases with reduced DHS scales.
- Fewer technical options are suitable for small-scale DHSs.
- Systems with combined technologies are less sensitive to changes in fuel prices.

ARTICLE INFO

*Article history:*
Received 7 January 2014
Received in revised form 28 March 2014
Accepted 16 May 2014

*Keywords:*
Coproduction
District heating
Minimum cost
Environmental tax
Small scale

ABSTRACT

Efficient district heat production systems (DHSs) can contribute to achieving environmental targets and energy security for countries that have demands for space and water heating. The optimal options for a DHS vary with the environmental and social-political contexts and the scale of district heat production, which further depends on the size of the community served and the local climatic conditions. In this study, we design a small-scale, minimum-cost DHS that produces approximately 100 $GWh_{heat}$ per year and estimate the yearly production cost and primary energy use of this system. We consider conventional technologies, such as heat-only boilers, electric heat pumps and combined heat and power (CHP) units, as well as emerging technologies, such as biomass-based organic Rankine cycle (BORC) and solar water heating (SWH). We explore how different environmental and social-political situations influence the design of a minimum-cost DHS and consider both proven and potential technologies for small-scale applications. Our calculations are based on the real heat load duration curve for a town in southern Sweden. We find that the district heat production cost increases and that the potential for cogeneration decreases with smaller district heat production systems. Although the selection of technologies for a minimum-cost DHS depends on environmental and social-political contexts, fewer technical options are suitable for small-scale systems. Emerging technologies such as CHP-BORC and SWH improve the efficiency of primary energy use for heat production, but these technologies are more costly than conventional heat-only boilers. However, systems with combined technologies are less sensitive to fluctuations in fuel prices, specifically the SWH system, compared to technologies based on conventional fuels. Furthermore, increased market penetration of SWH will reduce the investment costs of such systems and, along with expected fuel price increases, SWH may be cost-efficient in DHSs.



## 1. Introduction

District heating is an important component of a sustainable energy supply system for cold weather climates, such as the Eastern Europe and the Nordic regions [1,2]. District heating systems have received attention under the context of energy security and climate change mitigation because these systems can use various primary energy sources to produce the same quality of products for district heat and electricity. Many countries have adopted

*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; EHP, electric heat pump; FGCC, fossil gas combined cycle; FOB, fuel oil boiler; GEC, green electricity certificate ; O&M, operation and maintenance; SWH, solar water heating; WCB, wood chip boiler; WPB, wood powder boiler.

* 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.2014.05.031
0306-2619/

favorable policies and consider district heating to be an important sector on the roadmap toward a more sustainable energy system [3–5].

Selecting technology and capacity for a district heat production unit in an optimal district heat production system is a dynamic issue. District heat production units are chosen based on the scale and variation of heat demand, the local availability and costs of energy sources, the investment cost of each technology, etc. District heating production systems (DHSs) with co/polygeneration of products other than heat provide primary energy as well as environmental and cost benefits [6,7]. These systems are also encouraged by the European Union to further the development of combined heat and power (CHP) production [8]. However, for small-scale district heating systems, co/polygenerated options may be more costly than heat-only production units that typically have lower specific investment costs [9,10].

In Sweden, district heat is commonly used and supplies up to approximately 32% of the total final energy use in the residential and service sectors [11]. DHSs vary in size depending on the scale of the community served and the local climatic conditions. However, small-scale DHSs that employ heat-only boilers are dominant in several district heat markets. Statistics from 2011 on existing Swedish DHSs showed that more than three-fourths of the Swedish DHSs had an annual district heat production of less than 100 $GWh_{heat}$ per year [12]. This small-scale district heat demand may limit the choice of technologies for a minimum-cost district heat production option.

Nevertheless, recent studies have shown the technical potential of using various bio-based technologies for small-scale CHP units, such as biomass integrated gasification with gas engine (BIGGE) and biomass-based organic Rankine cycle (BORC) [13–15]. These emerging technologies, which are normally in the range of less than one to several $MW_{elect}$, could possibly be used in small-scale DHSs. However, the cost efficiency of these technologies for heat production has not been analyzed in detail. In particular, co/polygeneration in small-scale DHSs may be financially feasible when exploring strategies to move toward an energy-efficient and sustainable society. Such strategies include the promotion of electricity production from renewable sources through the introduction of a green electricity certificate (GEC), as in Belgium, Poland, Sweden and the United Kingdom, or feed-in tariffs, as in Austria, Denmark, France, Germany and the Netherlands [16–20].

In Europe, conventional technologies for heating, such as an electric heat pump (EHP) and solar water heating (SWH), are receiving more attention [21–24]. In Sweden, 40% of detached houses use EHPs for heating purposes [25]. Additionally, EHPs are used for district heat production in Sweden in 30 out of 446 district heating systems [26], covering 8.7% of the total energy supply for district heating in 2011 [27]. With increased renewable-based electricity production, such as wind and biomass [28], heat production using EHPs can be a suitable option [21,24].

Solar thermal is considered an important future energy source for heating the European building stock, specifically by 2030 [29]. In Sweden, although the intensity of solar radiation varies strongly throughout the year, SWH systems have been installed and used in many households for space and water heating purposes [30]. Moreover, large-scale SWH has been integrated into district heat production systems [31,32] and proven to be efficient in reducing primary energy use from other sources [33]. In Sweden, large-scale SWH systems have been demonstrated in different communities, such as Kungälv (collector area of 10,000 $m^2$), Nykvarn (7500 $m^2$), and Falkenberg (5500 $m^2$) [34]. However, solar-based district heat production is a marginal contributor to Swedish district heat production [26]. With the trend of decreasing specific investment cost for solar energy [29] and the increasing price of conventional fuels for district heating production [28], solar energy may become cost-competitive in small-scale DHS.

The design and operation of a minimum-cost DHS also depend on the environmental and social-political contexts. To reduce the adverse effects of climate change, the damage from $CO_2$ emissions may be applied to fossil fuel users. According to Stern [35], this cost can be roughly estimated and further depends on the $CO_2$ concentration in the atmosphere. Furthermore, targets toward a sustainable society promote the development of renewable-based energy systems, including district heating [32,36]. For DHSs, these environmental and social-political contexts have been proven to strongly influence the design and operation of DHSs, but they have a lesser effect on district heat production costs for large-scale DHSs using co/polygeneration district heat production units [7,10,37,38]. However, in small-scale DHSs, these influences may be different due to limitations in the possibility of co/polygeneration systems [9,10].

In this study, we analyze minimum-cost options for a small-scale DHS under different environmental and social-political contexts. A minimum-cost DHS normally consists of different district heat production units to satisfy the varied district heat demand at the lowest district heat production cost. We use the existing heat load demand from a town in the south of Sweden as the basis for the calculations. We consider various technologies, including new developments, and evaluate the potential to integrate multiple units into the small-scale district heating system in a cost-efficient manner. We evaluate the contexts where various technologies can be feasible in a minimum-cost DHS.

## 2. Method and assumptions

### 2.1. Reference heat load duration curve and analyzed scenarios

Our study was based on the heat load profile of an existing district heating system in Ronneby, Sweden (Fig. 1). The existing DHS consists of various heat-only boilers of different fuel types and capacities, including two wood chip boilers incorporated with flue gas condensers at a total capacity of 18 MW, three identical wood pellet boilers at a total capacity of 9 MW and three oil boilers at a total capacity of 15 MW. Heat supply from this system reached 107 GWh per year at the peak heat load demand of 34 MW in 2011.

We examined the minimum-cost district heat production option under five difference scenarios, including (i) *No tax* scenario using the fuel price of 2011, (ii) *Swedish tax* scenario using the fuel price of 2011 plus energy, carbon and sulfur taxes in Sweden, (iii) *Social cost*-550 ppm scenario that imposes a social cost of carbon emissions equal to €21.6/t $CO_2$ ($30/t $CO_2$), (iv) *Social cost–BAU* scenario that imposes a social cost of carbon emission equal to €61.1/t $CO_2$ ($85/t $CO_2$) and (v) *Renewable-based* scenario that considers energy systems with different renewable energy resources without any tax.

Table 1 shows the fuel prices according to the different considered scenarios. In Sweden, fuel for electricity and heat production are taxed differently. The energy and $CO_2$ taxes are applied for heat production, but electricity production is exempted from taxation [25]. Moreover, the GEC system is used to provide incentives for renewable-based electricity production, including electricity from biomass-based CHP plants [25,39].

### 2.2. District heat production units and reference standalone power plants

We considered commercial/conventional district heat production units, including EHP and SWH, as well as semi-commercial