Journal of Cleaner Production 69 (2014) 188–198

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Integration of biofuel production into district heating – Part II: an evaluation of the district heating production costs using Stockholm as a case study

Danica Djuric Ilic [a,*], Erik Dotzauer [b], Louise Trygg [a], Göran Broman [c]

[a] Division of Energy Systems, Department of Management and Engineering, Linköping University, SE-581 83 Linköping, Sweden
[b] School of Sustainable Development of Society and Technology, Mälardalen University, SE-72123 Västerås, Sweden
[c] Department of Strategic Sustainable Development, School of Engineering, Blekinge Institute of Technology, Karlskrona, Sweden

A R T I C L E I N F O

Article history:
Received 26 April 2013
Received in revised form
10 January 2014
Accepted 12 January 2014
Available online 27 January 2014

Keywords:
District heating
Biofuel
Energy cooperation
Transport sector

A B S T R A C T

Biofuel production through polygeneration with heat as one of the by-products implies a possibility for cooperation between transport and district heating sectors by introducing large-scale biofuel production into district heating systems. The cooperation may have effects on both the biofuel production costs and the district heating production costs. This paper is the second part of the study that investigates those effects. The biofuel production costs evaluation, considering heat and electricity as by-products, was performed in the first part of the study. In this second part of the study, an evaluation of how such cooperation would influence the district heating production costs using Stockholm's district heating system as a case study was performed. The plants introduced in the district heating system were chosen depending on the future development of the transport sector. In order to perform sensitivity analyses of different energy market conditions, two energy market scenarios were applied.

Despite the higher revenues from the sale of by-products, due to the capital intense investments required, the introduction of large-scale biofuel production into the district heating system does not guarantee economic benefits. Profitability is highly dependent on the types of biofuel production plants and energy market scenarios. The results show that large-scale biogas and ethanol production may lead to a significant reduction in the district heating production costs in both energy market scenarios, especially if support for transportation fuel produced from renewable energy sources is included. If the total biomass capacity of the biofuel production plants introduced into the district heating system is 900 MW, the district heating production costs would be negative and the whole public transport sector and more than 50% of the private cars in the region could be run on the ethanol and biogas produced. The profitability is shown to be lower if the raw biogas that is by-produced in the biofuel production plants is used for combined and power production instead of being sold as transportation fuel; however, this strategy may still result in profitability if the support for transportation fuel produced from renewable energy sources is included. Investments in Fischer–Tropsch diesel and dimethyl ether production are competitive to the investments in combined and power production only if high support for transportation fuel produced from renewable energy sources is included.

1. Introduction

District heating (DH) is well developed in Sweden and is a strong competitor with other heating options, such as private boilers and heat pumps. From a system's perspective, the benefits of DH include the possibility of combining heat and power (CHP) production (which implies high fuel efficiency), and a possibility to increase the renewable electricity share in the power system (Andersen and Lund, 2007; Amiri et al., 2009; Gebremedhin, 2012). One large boiler rather than many small private boilers, also makes better emission control possible and facilitates energy recovery

Abbreviations: BCHP, biomass fuelled combined heat and power; CCP, coal condensing power; CHP, combined heat and power; CO_2, carbon dioxide; DH, district heating; DHS, district heating system; DME, dimethyl ether; EM, energy market; EMS, energy market scenario; ENPAC, energy price and carbon balance tool; FTD, Fischer–Tropsch diesel; IEA, international energy agency; MODEST, model for optimisation of dynamic energy systems with time-dependent components and boundary conditions; NGCC, natural gas combined cycle; PHEV, plug-in hybrid electric vehicle; RES-E, electricity produced from renewable energy sources; RES-T, transportation fuel produced from renewable energy sources; SNG, synthetic natural gas for use as transport fuel; TS, transport sector; PTS, public transport sector; WEO-np, "new policies scenario"; WEO-450, "450 scenario".

* Corresponding author. Tel.: +46 13 281114; fax: +46 13 281788.
E-mail addresses: danica.djuric.ilic@liu.se, noblicaa@gmail.com (D. Djuric Ilic).

0959-6526/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2014.01.042

through waste incineration. However, in a future sustainable society, the marginal electricity production will no longer be linked to greenhouse gas emissions, so the benefits of DH would then be less obvious. Together with an expected reduced demand for heating, DH producers will face new challenges and need to develop new business strategies (Magnusson, 2012). There might be new roles for DH in a sustainable society and, not least, DH could play a key role in transforming society towards sustainability.

1.1. Background

Cooperation between DH producers and industry has been of great interest over the last decade. The most common forms of cooperation are: the utilisation of industrial waste heat in DH systems (DHSs), production of industrial process steam in local DHSs, and the utilisation of DH in other industrial processes. Several previous studies have shown that conversion to DH for industrial processes is often a cost-effective, energy-efficient measure that also results in a reduction of global carbon dioxide (CO_2) emissions (Difs et al., 2009; Karlsson and Wolf, 2008; Trygg et al., 2006).

There are many techno-economic factors that can trigger energy cooperation between a DHS and some other energy system. Two of the factors are: new internal conditions – the need to replace old DH production plants; and new external conditions – new technologies or policy measures come in to play (Grönkvist and Sandberg, 2006). Thus, development of biofuel[1] production through polygeneration with heat as one of the by-products implies a possibility for cooperation between the transport and DH sectors by introducing large-scale biofuel production into DHSs.

In a number of previous studies, economic benefits of introducing biofuel production into Swedish DHSs were analysed. Wetterlund and Söderström (2010), Difs et al. (2010), Fahlén and Ahlgren (2009) and Börjesson and Ahlgren (2010), evaluated the economic effects on the DH production when different biomass gasification applications (including biofuel production) were integrated with DH production. Wetterlund and Söderström (2010) and Difs et al. (2010) analysed the economic effects when synthetic natural gas (SNG; for use as transport fuel) production through gasification was integrated with DH production in Linköping's DHS. They compared this investment option with investment in biomass fuelled CHP (BCHP) plants. Difs et al. (2010) performed sensitivity analyses of the different energy market (EM) conditions and came to the conclusion that higher oil prices make the investments in SNG production more profitable, while higher CO_2 charges have a negative influence on the profitability. Wetterlund and Söderström (2010) analysed the influences of different policy instruments on the profitability and concluded that in order to make the investments in SNG biorefinery plants attractive for DH producers, biofuel subsidy levels in the range of 24–42 EUR/MWh are required. This result is in line with the results from the study done by Börjesson and Ahlgren (2010), who introduced dimethyl ether (DME) and SNG productions through gasification into 15 local DHSs in the southwestern region of Sweden. They found that biofuel subsidy levels of 30–40 €/MWh are needed to make investments in DME and SNG productions more profitable than investments in conventional energy technologies for DH production. Fahlén and Ahlgren (2009) studied the integration of SNG and DME production through gasification with an existing natural gas combined cycle (NGCC) CHP plant in Gothenburg's DHS, while Djuric Ilic et al. (2012) analysed the integration of ethanol and biogas production through simultaneous saccharification and fermentation with Stockholm's DHS. In both of these studies the investments in biofuel production were compared with reference scenarios that did not include any new investments. In the case described by Fahlén and Ahlgren (2009), four future EM scenarios (EMSs) with interdependent parameters were applied, while Djuric Ilic et al. (2012) applied EM prices for the year 2010 and performed sensitivity analyses of the biomass, electricity and biofuel prices. Because different technology cases and different EMSs were used, these two studies resulted in different conclusions. The introduction of the ethanol and biogas production into Stockholm's DHS was shown to be profitable. The profitability of introducing SNG and DME production into Gothenburg's DHS under the assumed EMSs was shown to be dependent on the price ratio between biomass and fossil fuels, the existing DHS's production mix, and the level of policy instruments for biofuels and renewable electricity; several of the previous mentioned studies showed the same results.

1.2. Objective of the study

In this paper it is suggested that cooperation between the transport sector (TS) and the DH sector, by introducing large-scale biofuel production into a DHS would be a good strategy for DH producers from an economic point of view. The paper aims to evaluate how the economic characteristics of the DHS and energy use/by-produced in the DHS would be changed if DH producers were to invest in biofuel production instead of CHP production in the future. When the DH production costs are evaluated, the revenues from electricity and biofuel by-produced are included as negative costs. Another aim of the paper is to investigate how this cooperation would affect the biofuel percentage of the total fuel used in the TS.

Due to its developed public TS (PTS) and DHS, the county of Stockholm was chosen as a case study.

Since the cooperation would include financial risks for both partners (TS and DH sector), some agreements are required in order to secure a regular supply to biofuel users (TS) and to guarantee a possibility to sell by-produced biofuel for biofuel producers (DH sector). Thus, prerequisites for the cooperation are as follows:

1. The final biofuel price at filling stations is not higher than the price of the fossil fuel replaced. The prices are not compared per litre, instead the fuel economies for different fuels (kWh/100 km) are considered.
2. All biofuel and electricity used in the local PTS (subway, local railway, commuter train, local buses, local taxi and mobility service) are produced in the DHS.
3. All biofuel produced in the DHS is used in the local TS.

This paper is the second part of a two-part study which evaluates the possible economic effects of introducing biofuel production into DHSs. The analysis of the effects on biofuel production costs when a third actor invests in biofuel production (and sells the waste heat from the production to a local DHS) has been conducted in the first part of the study (Djuric Ilic et al., 2014b).

Four different biofuel production plants were chosen to be introduced into Stockholm's DHS. Despite a number of research and development projects, the commercialisation of the biofuel production technologies suggested to be used is still far off (this is discussed more in the first part of the study; Djuric Ilic et al., 2014b). Thus, the period analysed in this study is between 2030 and 2040. Sensitivity analyses of two different future EM conditions were performed.

2. Case study

Stockholm is the largest city in Scandinavia. Including its surrounding communities, the metropolitan area has almost two

[1] In this study the term biofuel is used to denote renewable transportation fuel.