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

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ABSTRACT

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

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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.

Abbreviations

BCHP, biomass fuelled combined heat and power; CCP, coal condensing power; CHP, combined heat and power; CO₂, 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”.

Keywords

District heating; Biofuel; Energy cooperation; Transport sector

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 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.

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 (CO₂) 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[†] 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 Södeström (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 CO₂ charges have a negative influence on the profitability. Wetterlund and Södeström (2010) analysed the influences of different policy instruments on the

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

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.

1.1 Objective

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 million inhabitants and covers a total area of approximately 6,500 km². Since 1995, Stockholm has been committed to an ambitious climate policy. Some of the actions that have been taken during the last two decades are: expanding the DHS, increasing the use of public transportation, and increasing the renewable energy share in the region.

The PTS in Stockholm is well developed. During the last decade, the number of public buses has significantly increased. In 2010, the annual electricity demand for the subway and local railway was approximately 440 GWh and the electricity demand for commuter trains was approximately 160 GWh (SL, 2011). An increased use of public transport has been especially noticeable after the introduction of congestion charges in 2007. About 25 % of the total energy used in Stockholm is used in the TS, resulting in almost 40 % of the total greenhouse gases emissions in the region (Byman, 2009). The process of introducing "clean" vehicles and alternative fuels in TS started as early as 1994. By the end of 2010, the percentage of public buses that run on biofuel was about 37 % and the percentage of biofuel-propelled cars was about 7 %. While other biofuel is imported from other regions in Sweden, the ethanol used in Stockholm is mainly imported from Brazil, where it is produced from sugarcane. Poor biofuel

supply in the region has been recognised as a factor that could slow down a future sustainable development of the TS (Hjalmarsson et al., 2011).

Stockholm's DHS started as smaller DH networks that have gradually been expanded and interconnected. This was a result of a long-term municipal and regional strategy that has aimed to increase DH supply security and encourage investments in new CHP plants (Magnusson, 2011). Today the system consists of three networks that deliver more than 12 TWh heat annually (Table 1). The heat is produced in about 70 plants. Six of the plants are CHP plants with a total installed electricity capacity of about 600 MW and a yearly electricity production of approximately 2.5 TWh. Two CHP plants are fuelled by coal and oil while the other four are fuelled by biomass and waste (Dahlroth, 2009; Dotzauer, 2003).

3. Methodology

The methodology includes literary research, data collection, and optimisation of the DHS using an optimisation model framework called MODEST.

3.1 The model framework description

MODEST (Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions) is based on linear programming and was developed at Linköping University in Sweden. MODEST can be applied to different kinds of energy systems, and with different purposes. For example, it has been used to analyse how different changes in the building sector can affect a local DHS (Åberg and Henning, 2011), and to analyse the potentials of cooperation between industry and local DHSs (Difs and Trygg, 2009; Henning and Trygg, 2008).

The built-in aim of the optimisation is to minimize the annual system cost of supplying a certain load demand during the analysed period. Depending on the energy system analysed, different

types of load demands can be defined as: heat, steam, electricity or biofuel demand. The optimisation is performed by choosing the best operation at the right time from existing and potential new plants in the system. The system cost includes: new investments, operation and maintenance costs, fuel costs (including taxes and fees), revenues from by-products (negative cost), and lastly, the present value of all the capital costs. The plants in the model are described in terms of their: efficiencies, maximum capacity, power-to-heat ratio (if it is a CHP plant), maintenance periods and costs, technical lifespan, economic lifespan and investment cost (if it is a new plant). Inputs that also need to be defined are study period, time division, discount rate and the system's energy demands (Henning, 1999; Gebremedhin, 2003).

A model of the DHS in Stockholm was built considering the input data and assumptions presented in the following text.

3.2 Energy market scenarios

In order to perform sensitivity analyses of different EM conditions, two EMSs for Sweden for the year 2030 are applied (Table 2). Variations of the EM prices during the analysed period (2030 – 2040) are not considered in this study. Instead, the values of the prices for the year 2030 are used as input data during the entire period. The EMSs for Sweden are developed from two global EMSs using a tool called ENPAC (Energy Price and Carbon Balance tool). One of the global EMSs is based on the recent government policy commitments, known as “New Policies Scenario” (WEO-np), while the other one is based on the energy policies which would enable the 2 °C target (Pachauri and Reisinger, 2007) to be reached at a reasonable cost, known as “450 Scenario” (WEO-450). The global EMSs have been developed by the International Energy Agency (IEA, 2011). For a more thorough description of the ENPAC and the EMSs used, please see the first part of the study (Djuric Ilic et al., 2014b) and Axelsson et al. (2009; Axelsson and Harvey, 2010).

In this study it is assumed that the waste fuel will not be subject to any charges.

3.3 Stockholm's TS and DHS in 2030

According to Byman (2009), the number of vehicles in the region can be expected to increase by 35 % by the year 2030. The fuel economy ($\text{kWh}_{\text{fuel}}/100 \text{ km}$) would probably be improved and in the present study it is assumed that this improvement would be about 25 % compared to today's values. All assumptions regarding the road TS are presented in Table 3 and Table 4. The truck sector is not included in the study. It is assumed that the annual electricity demand would increase by 50 % for the subway and local railway and by 100 % for the commuter trains compared to the demand in 2010 (see section 2).

By the year 2030, Stockholm's DHS would probably change a lot. The fossil fuel-fired CHP plants would probably be phased out, as well as one of the BCHP plants, which today is almost 50 years old. Based on an expectation that the amount of household waste in the region would increase up to 5 TWh by the year 2030 (Byman, 2009), two new waste-fired CHP plants are planned to be introduced into the system by the year 2013. Technical and economic characteristics of those plants are shown in Table 5. One of the plants would produce about 90 GWh of biogas annually as a by-product (E.ON, 2011). The investments in those plants are not included in the study since they are already planned to be introduced in the system and as such they are included in all scenarios. However, even though new plants would be introduced in the system, the total heat capacity of the system would still be 650 MW lower than the present heat capacity. Thus, more new plants need to be built. In the present study, it is assumed that all those plants would be biomass fuelled plants.

Presently about 30 % of the biomass used in the DHS is transported by train or truck from the north of Sweden. The other part is imported from the Baltic countries by boat. The increased biomass use in the DHS would lead to an increased biomass import, probably over longer

distances. This may have an influence on global CO₂ emissions and on the biomass price. According to Börjesson and Gustavsson (1996), when the biomass is transported by boat, the CO₂ emissions are about two and four times lower than when it is transported by train or trucks, respectively. Furthermore, for distances longer than 200 km the cost is lowest when the biomass is transported by boat (Börjesson and Gustavsson, 1996). Because of this, in order to facilitate efficient transportation of the biomass, the new biomass fuelled plants should be built near shipping ports. Presently, there are only five suitable locations for building new biomass fuelled plants, thus limiting the number of plants that can be introduced into the system. This limitation was applied in the research.

A model of Stockholm's DHS was built according to data from Dahlroth (2009) and the changes mentioned above. As it was previously mentioned (see section 3.1), one of the results from the optimisation is the annual system cost of supplying the DH demand during the analysed period. In order to make the results comparable with the results from other similar studies, the results in this study are presented as DH production costs, which are calculated by dividing the annual system costs in the scenarios with the annual DH demand in the system. The period analysed is 10 years (2030 - 2040) and the capital costs in the model are based on a discount rate of 6 % and 10 %, depending on the scenario. Since the economic lifespans of the plants are longer than 10 years, the plants would still have some economic value after the analysed period and those values are included in the system cost (see section 3.1). The time division used in the study depict variations in DH demand. During the winter when the DH peaks and the DH demand variations are significant, the time division is at its finest. For each of the months from November to March, 12 time periods are modelled. For the remainder of the year, the months are divided into four periods (Henning, 1999). Based on DH production in 2007 and an assumed reduction of DH demand by 10 % by the year 2030 (Byman, 2009), the curves of the DH demands for the different parts of the system have been calculated and

adjusted to the time division. The operation and maintenance periods have also been included in the model. In order to avoid the differences in base productions in the networks, it is assumed that in the future all networks would be connected.

3.4 New investments

Five different types of plants have been considered to be introduced into the DHS (Table 6).

Two of the plants are ethanol production plants based on simultaneous saccharification and fermentation. In those plants, raw biogas is by-produced during the ethanol production. This raw biogas can be directly upgraded and sold as biofuel (the plant denoted as Ethanol 1 plant) or it can be directly used for CHP production (the plant denoted as Ethanol 2 plant). In the other two biofuel production plants, FTD and DME are produced through biomass gasification. The choices of the biofuel production plants are motivated and described technologically in the first part of the study (Djuric Ilic et al., 2014b). The fifth type of plant considered is a BCHP plant.

The investment costs have been adjusted to €2010 using the Chemical Engineering Plant Cost Index (CEPCI, 2010) and calculated from the data available in the referred studies using an overall scaling factor (R) of 0.7 (Remer and Chai, 1990), according to,

$$\frac{Cost_a}{Cost_b} = \left(\frac{Capacity_a}{Capacity_b} \right)^R,$$

where $Cost_a$ and $Cost_b$ represent the cost of the base polygeneration plant and the cost of the new plant. $Capacity_a$ and $Capacity_b$ are the capacity of the base plant and the new plant, respectively.

3.5 Descriptions of the chosen scenarios

A number of different scenarios have been analysed considering different EMSs and possible future developments of the TS. The sensitivity analyses of discount rate levels for the biofuel production plants have been performed as well. The assumptions regarding the development of the TS have been established using trend information and data collected during literature and field studies.

In all scenarios with large-scale biofuel production, three biofuel production plants were introduced into the DHS. In order to reach profitability, biofuel production plants which use biomass as feedstock need to have a large input capacity (Faaij, 2006). Thus, those three biofuel production plants have a biomass input capacity of 300 MW each. The types of the biofuel production plants were chosen based on the assumed TS development. In order to make the scenarios comparable to each other, the total heat capacity of the new plants is 600 MW in all scenarios. Based on this, the capacities of the CHP plants that need to be introduced into the DHS were calculated. Table 7 shows an overview of the new plants introduced into the DHS in the analysed scenarios.

According to Hjalmarsson et. al (2011), despite the fact that biogas import to the region does not always satisfy the local demand, the issue of increasing biogas use in Stockholm's TS is a subject that has gotten a lot of attention during the last few years. Thus, in the first group of scenarios ("biogas" scenarios) it is assumed that in the year 2030 all public local buses and all local taxis and mobility services will run on biogas. It is assumed that biogas used in private cars would increase as well. The plants chosen to be introduced into the DHS in this scenario are ethanol production plants in which the by-produced raw biogas (see section 3.4) is upgraded and sold to the TS (Ethanol 1 plant).

Another possible development of Stockholm's TS is a large increase in the number of PHEV (Hjalmarsson et. al, 2011). The second group of scenarios ("electricity" scenarios) represents a future in which all local public buses, taxis and mobility services are run on ethanol PHEVs. Hybrid electric cars would run on 50 % electricity and hybrid electric buses would run on 30 % electricity. The plants chosen to be introduced into the DHS are the ethanol production plants in which the by-produced raw biogas is directly used for CHP production (Ethanol 2 plant).

In the third group of scenarios ("diesel" scenarios) it is assumed that the diesel fuel used in the sector would increase rapidly due to a growing trend of switching from gasoline to diesel fuel over the last few years. FTD and DME are suggested as replacements for fossil diesel. In these scenarios, all local public busses run on DME, and taxis and mobility services run on FTD. Three biofuel production plants are introduced in the DHS: a DME plant, a FTD plant and an Ethanol 2 plant.

Due to the prerequisite that all biofuel and electricity used in the PTS are produced in the DHS, the biofuel and electricity used in the PTS are defined as demands. However, an allowance is made for the model to produce even more biofuel if the revenues from those biofuel would decrease the DH production costs. In all scenarios, the electricity demand for the subway, local railway and commuter train (corresponding to about 980 GWh; see sections 2 and 3.3) is also taken into account.

The reference scenarios are scenarios without large-scale biofuel production in the DHS; only 0.09 TWh biogas is produced in one of the waste fuelled plants. All new plants in the system are CHP plants with a total biomass input capacity of 810 MW.

In the rest of the paper the scenarios are denoted as follows:

- r-np (reference scenario in combination with EMS WEO-np);

- b-np, e-np, d-np (“biogas”, “electricity” and “diesel” scenarios in combination with EMS WEO-np);
- r-450 (reference scenario in combination with EMS WEO-450);
- b-450, e-450, d-450 (“biogas”, “electricity” and “diesel” scenarios in combination with EMS WEO-450).

4. Results and discussion

The estimated investment costs for the new plants differ significantly depending on the type and capacity of the plants. The lowest investment required is found in the reference scenarios (€654 million) where all new plants are CHP plants. The most capital intense investment is approximately two times higher and is found in “diesel” scenarios (€1355 million). The required investments in the “biogas” and in the “electricity” scenarios are €1210 million and €1089 million, respectively.

The biofuel and electricity demand in the PTS (Table 8) are calculated based on the assumed future developments of the TS (section 3.3), the future fuel economy (Table 4) and the situation in Stockholm’s TS in the year 2030 (Table 3). According to a prerequisite in this study, the DH producers would be obligated to produce all biofuel and electricity used in the PTS. Therefore, this biofuel and electricity (Table 8) are defined as demands in the model of the DHS. However, since the biofuel plants introduced in the model have higher capacities than is required for production of those demands, there is a surplus of biofuel and electricity produced in all scenarios (comparing the data from Table 8 and Figure 1). This surplus of biofuel can be sold to the public filling stations.

With large-scale biofuel production in the DHS, the total energy used in the system increases within the range from 25 % to 40 %, but at the same time the total energy produced is between

15 % and 28 % higher as well. The electricity produced is about 3.2 TWh annually in the reference scenarios, while in the other scenarios it varies within a range from 2.7 TWh to 3 TWh annually. The lowest electricity production is found in the “biogas” scenarios (b-np, b-450). In most of the scenarios with biofuel production, the biomass use is more than 40 % higher compared to the corresponding reference scenario. The share of biomass use of the total energy use is about 60 % in the reference scenarios, and about 70 % in the scenarios with the biofuel production, which leads to a higher sensitivity to the biomass price and biomass availability, and probably also to increased biomass import over longer distances. Furthermore, since biomass would probably become the subject of competition in the future, the increased biomass use in the DHS would lead to a decreased biomass use in some other energy system. This may result in an increase of the global CO₂ emissions. This has been discussed more in Djuric Ilic et al. (2014a).

The energy used and the energy produced are not significantly different in the two analysed EMSs. The only scenarios where a larger difference can be noticed are in the “diesel” scenarios. The reason for this is that in spite of the fact that a FTD production plant has the capacity to produce more than 1 TWh of FTD annually, only FTD demanded from the PTS is produced in scenario d-450. As a result, the biomass used in this scenario is about 15 % lower than the biomass used in scenario d-np.

The cooperation between the DH producers and the local TS would have a substantial influence on the fossil fuel used in the TS. Since there is a surplus of biofuel produced that can be sold to the public filling stations, the cooperation may promote a significant increase in biofuel use not only in the PTS but also for private cars. The highest biofuel production is in the “biogas” scenarios where 1.89 TWh biogas and 2.45 TWh ethanol are produced annually. The production surpluses of biogas and ethanol are enough to cover 9 % and 45 % of the total fuel demand for the local private cars. This would reduce the gasoline use in the TS by about

3.6 TWh annually. The production surplus of ethanol in the “electricity” scenarios covers 28 % of the total fuel demand for private cars. If it is assumed that this ethanol is used in PHEVs, the ethanol produced is enough to run 55 % of the private cars in the region. The ethanol produced in the “diesel” scenarios is enough to run 15 % of the private cars. In this scenario, in combination with EMS WEO-np, there is also a 1 TWh production surplus of FTD, which is enough to cover 20 % of the fuel demand of private cars.

4.1 Economic analysis of DH production costs

The introduction of biofuel production plants changes the economic characteristics of the DHS significantly. When DH production costs were estimated, revenues from electricity and biofuel sold were included as negative costs. The revenues vary within a wide range and are dependent on both the EMSs and the combination of by-products (Figures 2 and 3). The highest revenues from the biofuels and electricity produced would be achieved in the scenario b-450 when support for RES-T is included. In this scenario, the revenues would be about €844 million annually, which is an increase of 145 % compared to the revenues in the corresponding reference scenario r-450. With large-scale biofuel production in the DHS (b-np, e-np, d-np, b-450, e-450 and d-450), the revenues would increase within a range from 63 % to 181 % above the revenues in the reference scenarios (r-np and r-450) if RES-T support is included (Figure 2), and between 35 % and 130 % if RES-T support is not included (Figure 3).

In the scenarios b-np, b-450, e-np and e-450, the RES-T support guarantees between 36 % and 63 % higher revenues from the biofuels sold (comparing Figure 2 with Figure 3). When support for RES-T is included, the revenues from biofuel sales are higher than the revenues from electricity sales (e.g. in the scenarios b-np and b-450 about 70 % of the revenues would come from the sales of biofuels).

The sale of by-products has a substantial effect on the DH production cost. However, due to the capital intense investments, the higher revenues from the by-products do not necessarily imply profitability for DH producers. Figures 4 and 5 show how the DH production cost varies depending on the scenarios when the discount rate for the biofuel production plants is 6 % and 10 %, respectively. The largest profitability is achieved in scenarios b-np and b-450. In those scenarios, even if the supports for biofuel production are reduced or removed, and if the discount rate is 10 %, the cooperation between the DHS and the TS still results in profitability under the assumed EM conditions. With the support for RES-T included, and if the discount rate is low, the DH production cost in the scenarios b-np and b-450 is negative. This would make the DH production more competitive with other heating technologies, which consequently opens a possibility for an increased DH demand and a further expansion of the DHS. It proves to be less profitable to use the raw biogas that was by-produced during the ethanol production for CHP production (e-np and e-450), compared to upgrading and selling it as fuel for vehicles (b-np and b-450). This is in line with the conclusion drawn by Fahlén and Ahlgren (2009), who from an economic perspective, found that SNG produced in a DH plant should be sold as fuel for vehicles rather than used for CHP production. When investments are made in ethanol plants in which the by-produced raw biogas is used for CHP production (Ethanol 2 plants; e-np and e-450), compared to when investments are made in BCHP production, the DH production costs are still lower in all analysed scenarios, except in scenario e-450 when RES-T support is not included (Figure 4). Investments in FTD and DME productions (d-np and d-450) are competitive to investment in CHP production only with the support for RES-T included and if the discount rate for the biofuel production plants is low. Without the support for RES-T, the DH production costs are between 4 % and 16 % higher when the discount rate is 6 % (Figure 6) and between 62 % and 71 % higher when the discount rate is 10 % (Figure 5).

Compared to the EMS WEO-np, the EMS WEO-450 is characterised by higher energy prices on the Swedish EM (Table 2). This results in an increase of the revenues from the by-products in all scenarios where the EMS WEO-450 is considered, except in the scenario d-450 when the RES-T support is included (Figures 2 and 3). The reason for this is because in the scenario d-450 only 0.06 TWh of FTD is produced annually, while in the scenario d-np the annual FTD production is higher than 1 TWh (Figure 1; more explained in the beginning of section 4). Since the electricity use results in higher CO₂ emissions than gasoline and diesel use, the electricity and biomass prices are more sensitive to the CO₂ charges than the biofuel prices (see the description of ENPAC tool in the first part of this study; Djuric Ilic et al., 2014b). Because of this, the 2.4 higher CO₂ charges in the EMS WEO-450 (compared to the EMS WEO-np) results in approximately 25 % higher price ratios between electricity and biofuels in EMS WEO-450, compared to the corresponding price ratios in EMS WEO-np. As a consequence, the revenues from the by-products in the reference scenarios increase by 24 % (r-450 compared to r-np; Figures 2 and 3), while the increases of the revenues in the scenarios with the large-scale biofuel production (b-450, e-450 and d-450 compared to b-np, e-np and d-np; Figures 2 and 3) do not exceed 11 %. In the scenarios b-450, e-450 and d-450, the revenues from electricity increase within a range between 17 % and 25 %, while the revenues from biofuel sale are almost unchanged. Furthermore, with the introduction of large-scale biofuel production into the DHS, the biomass share of the total fuel used in DHS increases, which makes the system cost more sensitive to biomass prices. Since the biomass prices are about 20 % higher in the EMS WEO-450 scenario, the investment in biofuel production becomes even less attractive for the DH producers.

Due to the changed EM conditions, the DH production costs in all scenarios increase when the EMS WEO-450 is considered. The increase in the reference scenario is about 3 % (r-450 compared to r-np; Figure 4). In the scenarios with the large-scale biofuel production, the cost

increase varies within a range from 15 % to 68 %, when the discount rate for the biofuel production plants is 6 % (b-450, e-450 and d-450 compared to b-np, e-np and d-np; Figure 4); and within a range from 10 % to 31 %, when the discount rate is 10 % (b-450, e-450 and d-450 compared to b-np, e-np and d-np; Figure 5).

The results show that the profitability of introducing biofuel production into a DHS is highly dependent on the discount rate level and on the EMSs considered, above all, on the biomass and the biofuel prices. If the biofuel production is competing with CHP production, the price ratio between the electricity and the biofuel has an influence on the profitability as well. Those general conclusions are in line with findings from similar studies by Fahlén and Ahlgren (2009), Wetterlund and Söderström (2010) and Börjesson and Ahlgren (2010). However, it is not relevant to compare the results in more detail due to the different EM conditions, different technology cases and different local DHS conditions assumed in the present study and in the studies mentioned above.

The economic evaluations of the DH production are only valid for the DHS studied. In order to make a more comprehensive analysis and to have a possibility to reflect on the validity of the results for other DHSs, economic evaluations of the biofuel production were performed as well. The results from these evaluations are presented in the first part of this study (Djuric Ilic et al., 2014b). In this analysis it is assumed that the biofuel production plants would be built by a third actor and that the waste heat from the production would be sold to a local DHS. The revenues from electricity and the waste heat by-produced are included as negative costs, considering two different DHS price levels.

To make the results more reliable, more DHSs should be analysed and other technology cases for biofuel production should be considered. There is also a risk in making economic considerations based on the assumed EMSs, which include a large number of assumptions.

With the rapidly increasing awareness of the current unsustainable development of society (e.g. Millennium Ecosystem, 2005; IPCC, 2007; Rockström et al., 2009), it is likely that there will be more radical changes in the EM than has been seen so far. Suggested further work is therefore to backcast from a situation with a sustainable energy system within a sustainable society, and study what policy measures would be necessary to implement. Actors in the TS and DH sectors could then already start now to act strategically on to such plausible future policy measures.

5. Conclusion

In this study, cooperation between the TS and the DHS in the county of Stockholm has been suggested as a cost-effective strategy for increasing the share of renewable energy in the TS. The cooperation would be achieved by introducing large-scale biofuel production into the DHS. The choices of biofuel production plants introduced into the DHS were made with regards to three possible future developments in Stockholm's TS.

Although the introduction of large-scale biofuel production into the DHS would guarantee an increase in revenues from the sold by-products, due to the very capital intense investments required, this business strategy may still be less profitable for DH producers than further investments in CHP production. Which of these two business strategies would be most profitable is highly dependent on the biofuel production technology, on the discount rate level, and on the EM conditions. In the case of EM conditions, the profitability depends above all on the price ratio between electricity and biofuel, and on the price ratio between the biomass and biofuel.

Compared to the EMS WEO-np (which is based on the recent government policy commitments), the EMS WEO-450 (that according to the IEA would enable the 2 °C target to be reached at a reasonable cost) is shown to be less favourable for investment in biofuel

production when investment in CHP production is another alternative. The main reason is that the 2.4 times higher CO₂ charge suggested by the IEA in EMS WEO-450 leads to 25 % higher price ratio between electricity and biofuels, and consequently, to a higher ratio between the revenues from the electricity and biofuel produced.

Under the EM conditions assumed in this study, it is more profitable for DH producers to upgrade and sell the biogas as fuel for vehicles than to use it for the CHP production. Investment in ethanol and upgraded biogas production (the “biogas” scenarios; Table 7) instead of in the CHP production (the reference scenarios; Table 7) would guarantee more than two times higher revenues from the sold by-products. If RES-T support is considered, the revenues from the sold ethanol and upgraded biogas would be about €800, which is high enough to imply a negative DH production cost and to make the DH production more competitive to other heat production technologies. When investments are made in the Ethanol 2 plants, in which the raw biogas by-produced is directly used for CHP production (the “electricity” scenarios; Table 7), the revenues are about 55 % higher than the revenues in the reference scenarios with RES-T support is included. When RES-T support is not included, the revenues are 61 % and 74 % higher, depending on the EMS. In the scenarios where the FTD plant and DME plant are introduced into the DHS (the “diesel” scenarios; Table 7), the capital investments are most intense. As a result of this, and despite the fact that revenues from the by-products in those scenarios are higher than the revenues from the by-products in the reference scenarios, the investments in diesel production is shown to be not competitive when compared to investment in BCHP production if high RES-T support is not included or if the discount rate for the biofuel production plants is high (10 %). In all scenarios with large-scale biofuel production, and when RES-T support is included, the revenues from biofuel sales are higher than the revenues from electricity sales. Depending on the scenario analysed, the RES-T support guarantees between 36 % and 63 % higher revenues from the biofuels sold.

The introduction of large-scale biofuel production into the DHS would lead to an increased biomass share of the total energy used, which would make the system more sensitive to the biomass price and biomass availability. Compared to the reference scenario where the DH producers would invest in CHP production, the amount of biomass used in the scenarios with large-scale biofuel production would be between 3 TWh and 5.5 TWh higher. On the other hand, the cooperation between the DHS and the TS in the county of Stockholm would enable development of a local biofuel supply chain. This may facilitate the introduction of biofuel in the TS and reduce the dependency on imported fossil fuels in the region. Depending on the type of biofuel produced, the introduction of biofuel production plants with a total biomass capacity of 900 MW would lead to a reduction of fossil fuels used in the TS of between 2.4 TWh and 5 TWh annually. The highest reduction would be achieved if large-scale ethanol and biogas production would be introduced in the DHS. In this case, the whole PTS and more than 50 % of the private cars could be run on the biofuel and electricity locally produced.

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Figures

Figure 1. The total energy used (the negative part of the figure) and produced (the positive part of the figure) in the DHS.

Figure 2. Revenues from the sale of by-products when RES-T support is included.

Figure 3. Revenues from the sale of by-products when RES-T support is not included.

Figure 4. DH production costs for different EM conditions when the discount rate is 6 %.

Figure 5. DH production costs for different EM conditions when the discount rate is 10 %.

Table 1. Major DH networks in Stockholm.

Network	Heat production in the year 2005	Installed heat capacity	Installed electricity capacity
	(TWh)	(MW)	(MW)
South - Central	9.4	4000	493
Northwest	2.2	700	105
Southeast	0.5	300	20

Table 2. EMSs for the year 2030.

EMSs		WEO-np	WEO-450
Input data			
World market fossil fuel prices excluding CO ₂ charges (€/MWh)			
Crude oil		55	46
Natural gas		34	28
Coal		11	7
Energy policy instruments			
CO ₂ charge	(€/t)	30	72
RES-E support ^a	(€/MWh)	20	20
RES-E quota	(%)	20	20
RES-T support ^b , "diesel fuels"	(€/MWh)	26	26
RES-T support, "petrol fuels"	(€/MWh)	35	35
Output data			
Fossil fuel prices on Swedish EM including CO ₂ charges (€/MWh)			
Light fuel oil		74	75
Heavy fuel oil		56	61
Natural gas		46	49
Coal		23	35
Electricity market			
Build margin		CCP ^c	NGCC
Electricity price	(€/MWh)	67	86
Gate biofuel prices including RES-T support (€/MWh)			
Ethanol		122	124
FTD		104	105
DME		97	98
Biogas		138	141
Biomass market			
Marginal use of biomass		FTD ^d production	CCP
Low grade biomass	(€/MWh)	33	41
High grade biomass	(€/MWh)	47	57

^a Support for electricity produced from renewable energy sources.

^b Support for transportation fuel produced from renewable energy sources.

^c Coal condensing power.

^d Fischer-Tropsch diesel.

Table 3. Stockholm's TS in the year 2030.

	Passenger cars (excluding taxi and mobility service)	Taxi and mobility service	Buses
Number of vehicles (Byman, 2009)	1,026,840	5,160 ^a	5,123
Average annual distance travelled by vehicle (SIKA, 2011) (km/year)	12,500	30,000	57,000
Total annual distance (10 ⁶ km/year)	12,836	155	292

^a Assumed as 0.5 % of the number of passenger cars in the region.

Table 4. The future fuel economy (kWh/100 km), (Hjalmarsson et al., 2011; SIKA 2011).

	Cars	Buses
Ethanol	43	437
Biogas	42	457
FTD	40	447
DME	--	440
Electricity (PHEVs ^a)	22	110

^a Plug-in Hybrid Electric Vehicles

Table 5. Economic and technical characteristics of the new waste fuelled plants.

	Waste fuelled CHP plant (Hansson et al., 2007)	Waste fuel biogas/CHP plant (E.ON, 2011)
Efficiency		
Electricity	0.22	0.22
Biogas	-	0.12
Heat	0.69	0.59
Economic characteristics		
Base plant capacity (MW _{input})	136	91
Operating and maintenance costs (€/MWh _{input})	13.5	16
Operating time (h/year)	8000	8000
Economic lifespan (year)	25	25

Table 6. Economic and technical characteristics of the plants considered to be built.

		BCHP plant (Hansson et al., 2007)	Ethanol 1 plant (Barta et al., 2010)	Ethanol 2 plant (Barta et al., 2010)	FTD plant (Wetterlund, 2010)	DME plant (Wetterlund et al., 2011)
Efficiency						
Electricity		0.34	0.05	0.12	0.06	-
Biofuel 1		-	0.34	0.34	0.45	0.62
Biofuel 2 ^a		-	0.25	-	-	-
Heat		0.74	0.28	0.44	0.06	0.15
Economic characteristics						
Base plant capacity	(MW _{input})	200-300 ^b	300 ^c	300 ^c	300 ^b	300 ^d
Base investment cost	(€ million)	-	277	289	304	320
Spec. investment cost	(€/kW _{input})	807	-	-	-	1280
Fixed and variable operating and maintenance costs	(% of the total investment cost)	1.5	2.5	2.4	3.5	3.5
	(€/MWh _{input})	2.8	-	-	3.5	3.4
Operating time	(h/year)	8000	8000	8000	8000	8000
Economic lifespan	(year)	25	20	20	20	20

^a The biogas efficiency in the Ethanol 1 plant.

^b The biomass input.

^c The number includes not only the biomass input but also 4.57 MW molasses and 1.88 MW enzymes.

^d The number represent 284 MW biomass and 16 MW electricity used.

Table 7. The chosen scenarios - New plants introduced in the DHS.

	"reference" scenarios	"biogas" scenarios	"electricity" scenarios	"diesel" scenarios
Type	Base plant capacity (MW_{input})			
Ethanol 1	-	3×300	-	-
Ethanol 2	-	-	3×300	300
FTD	-	-	-	300
DME	-	-	-	300
CHP	4×203	2×235	275	2×274

Table 8. Biofuel and electricity used (TWh) in the local public buses, taxis and mobility services.

	“biogas” scenarios	“electricity” scenarios	“diesel” scenarios
Biogas	1.4	-	-
Ethanol	-	0.93	-
Electricity	0.98	1.09	0.98
FTD	-	-	0.06
DME	-	-	1.28