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Modelling environmental and energy system impacts of large-scale excess heat utilisation – A regional case study

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A B S T R A C T

EH (excess heat) is an important, but yet partially unused, source for DH (district heating). This study analyses energy system and CO_2 emission impacts at a regional scale of integration of EH from a large chemical cluster and local DH systems. The assessment is carried out with the optimising energy systems model MARKAL_WS, in which the DH systems in the Västra Götaland region of Sweden are represented individually. In addition, options for transport biofuel production are included. The results show that the connection contributes to a reduction of biomass and fossil fuel use, and to a related reduction of CO_2 emissions, in the DH systems. This opens opportunities for earlier production of transport biofuels but instead electricity generation from combined heat and power plants in the region decreases. In the short term, total CO_2 emissions increase if an expanded systems view is applied in which effects on the DH systems, transport system and European electricity system are accounted for, while in the mid-term they decrease. The study is based on a case and due to the diversity of Swedish DH systems in terms of use of fuels and local available resources, a generalisation of the results is not straightforward.

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1. Introduction

DH (district heating) is a way to supply residential and commercial buildings, and industrial users with heat for space heating, hot water and process heat, through a heat distribution network. The network is often fed with heat from heat plants using locally available fuel or heat sources that would otherwise be wasted. Generally, heat plants are located close to the heat market in order to minimise capital investments in the distribution network [1]. Thus, most DH systems have a limited geographical extension and are located within a municipality.

Countries with a cold climate and large heating demand are the main users of DH for space heating and water heating purposes. The largest relative diffusion of DH is seen in the Scandinavian countries, Northern and Eastern Europe, Russia and China [1]. In Sweden, DH was introduced in the late 1940s and a continuous expansion then followed. This resulted in significant CO_2 reductions and other environmental benefits. Currently, DH is the dominant form of heating in central areas of more than 240 of the 290 municipalities, and accounted for over 50 TWh (60% [1]) of supplied heat in Sweden in 2011 [2]. As a result of the oil crises in the 1970's and a high oil taxation combined with governmental subsidies for domestic fuels such as peat and biomass, oil has almost been phased out in the Swedish DH sector [3]. The introduction of a national TGC (tradable green certificate) system in 2003 encourages investment in biomass-based CHP (combined heat-and-power) plants [4]. Consequently, biomass accounts for the major share[1] of the fuel use in Swedish DH systems and is used both in HOB (heat-only boilers) and, increasingly, in CHP plants. Further, EH (excess heat) from industries (defined as heat which cannot be utilised directly in industrial process [6]) and municipal solid waste incineration constitutes a large amount of the base load heat in many DH systems, but it has been estimated that in Sweden there is still 2 TWh/year of unused primary EH which can be directly utilised for DH [7]. Analyses of utilisation of industrial EH in local DH systems indicate that this can result in reduced total system cost and CO_2 emissions, and increased utilisation of locally available energy resources [8,9]. A study on eight co-operations

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[1] Biomass, peat and municipal waste together accounted for 71% of energy supplied to DH in Sweden in 2011 [5] SEA. Energy in Sweden- Facts and Figures 2012. Eskilstuna: Swedish Energy Agency; 2013.

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between DH utilities and industries in Sweden concluded that the main benefits of the EH use are reduced primary energy use, total system cost, and environmental burdens [6]. A multi-actor viewpoint in utilising residual EH for a sustainable DH system was analysed, concluding that the involvement of various stakeholders and the promotion of their participation already from the early phases of the project design plays a crucial role for the successfulness of the project [10]. In all of these studies, the economic, environmental and social aspects of EH use are assessed only in local DH systems.

Currently, there is a growing interest in integration of local DH systems into larger, regional systems (for the purpose of this study, local DH systems are defined as DH systems with grids only covering a single town/city while regional DH systems are DH systems with grids connecting several towns/cities). One incentive for such developments is the possibility to transmit heat from distant EH sources. The integration is also driven by the advantages of scale. As fuel and electricity prices increase, DH production from larger CHP plants with higher electric efficiency becomes more cost-effective, while the heat demand in a local DH system is limited. These drivers for DH systems integration encourage the construction of transmission pipelines between local DH systems and between DH systems and industries. However, such decisions are associated with large investment costs and lock-in effects. Thus, it is important to obtain comprehensive knowledge on the consequences of such integration for the energy system and the environment.

The literature on modelling of regional energy systems is not extensive. Examples include modelling studies on strategies, measures and interventions [11] and waste management strategies [12], both in the Basilicata region of Italy, on greenhouse-gas mitigation from waste-to-energy [13] and from the replacement of electricity and fossil fuel use for heating with biomass [14], both at the regional scale in Sweden, on the economic performance of biomass gasification utilities and cost-effective biogas utilisation in the Västra Götaland region [15,16] of Sweden, and finally, on the optimum level of interaction between energy system components in the Yazd district of Iran [17].

Regional integration of DH systems and industries has rarely been studied. The few examples include modelling studies in a mid-term perspective on the economic potential and environmental impact of heat connections of industrial plants and local DH systems in Sweden forming a small regional heat market [18–20]. In this paper, we assess energy system impacts, in regard to DH technology choices, energy flows and CO_2 emissions, of utilisation of large amounts of EH in DH systems through regional integration of large-scale heat sources and sinks.

Large scale EH utilisation will have a strong impact on the systems directly connected by the pipeline but due to the regional scale of biomass markets in Sweden, there will likely also be indirect regional DH system consequences that should be taken into account. Thus, impacts should be assessed in a wider regional perspective. Our analysis will apply a time horizon up to 2030, and we will consider long-term marginal electricity generation for CO_2 emission calculations since changes in the local and regional electricity generation can affect investment decisions elsewhere in the electricity system.

Due to the strong diversity and importance of local conditions both with regards to Swedish DH systems [21] and with regards to industrial EH sources (character and location), studies on EH utilisation have to be based on a detailed local representation in order to well reproduce real conditions. Therefore, we need to select one particular case for the purpose of this paper. Currently, there is a strong stakeholder interest focussing on the possibility of utilising EH from a large industrial cluster in DH systems in the VG (Västra Götaland) region of Sweden. Hence, we have chosen this as our case, which consists of the cluster of chemical industries in Stenungsund, the DH systems of Kungälv, Göteborg, Partille and Mölndal, and heat integration through a 50 km heat transmission pipeline.

The VG region has a population of 1.6 million [22] and is located in the south-west of Sweden. Currently, there are local DH systems in 37 of the 49 municipalities in VG [23]. These 37 DH systems differ widely with regards to scale, heat production technologies and fuels used. In Göteborg, the largest town in VG, with about 530,000 residents [22], the DH system supplies heat to 90% of the apartment buildings and to about 12,000 smaller residential houses plus numerous industries, offices, and business and public buildings [24] in the town itself and in Partille, which is part of the same urban area. In 2011, the total heat production in the Göteborg DH system amounted to 4 TWh. Municipal waste, natural gas, industrial EH, and renewables (including biomass) contributed to the heat production [25]. The Mölndal DH system (a part of southern Göteborg urban area) is connected to the Göteborg DH system by a 1.1 km transmission pipeline with the capacity of 10 MW.

50 km to the north of Göteborg lies the small town of Stenungsund (population only about 25,000 [22]) next to the cluster of chemical industries where a large amount of EH (in the order of 100–200 MW) is available. The cluster includes the AGA, AkzoNobel, Borealis, Perstorp and INEOS companies. Between Göteborg and Stenungsund is also the small town of Kungälv located. Kungälv has a DH system, currently primarily based on a biomass CHP, that was recently connected to the Göteborg DH system through a 4 km transmission pipeline with a capacity of 19 MW [26]. See Fig. 1 for a map of the VG region.

2. Method

The method applied is based on a case study, scenario analysis and energy system modelling. This section presents the model, our main input data and our most important assumptions.

We design two main scenarios and five sensitivity cases. For each of these, we assume two options: either that the SKG (Stenungsund – Kungälv – Göteborg) pipeline will not be built ("no connection"), or that the SKG pipeline is constructed and will be in operation from 2020 ("connection"). Then, we apply an energy system model to generate future developments of the DH sector for each scenario for the "no connection" and "connection" options respectively. Next, we assess the difference, in terms of energy use and CO_2 emissions, between "connection" and "no connection" for each of the scenarios as:

$$\Delta X = X_{\text{Scenario/case, "connection"}} - X_{\text{Scenario/case, "no connection"}} \quad (1)$$

Thus, 'ΔX' presents the "connection" impacts on the energy use and CO_2 emissions.

Our assessment of the pipeline impact addresses two different systems levels: (1) the "regional level" and (2) the "local level". The first represents an *energy market level*; a broader systems approach taking all DH systems in the VG region into account for the estimation of impacts on the regional biomass market. It also accounts for impacts on marginal emissions of the European electricity system from changes in electricity generation and use in the regional system. The second is a level addressing only the direct impacts on the connected DH systems (DH systems directly affected by the EH supply), i.e. the DH systems of Stenungsund, Kungälv, Göteborg plus Partille and Mölndal. Finally, we compare the regional and local level impacts and reflect on the importance of the choice of system boundary in this particular research.

Fig. 1. The geographical locations of Göteborg & Partille, Mölndal, Kungälv and Stenungsund are marked in the Västra Götaland region of Sweden.

With the assumption that the DH sector seeks to minimise the total cost of heat production through the choice of cost-effective technologies and resources, a dynamic cost-optimising energy system model can be used for estimating the system response to an intervention. To make both a regional and a local assessment possible, we need the model to represent the relevant technical, economic and environmental aspects of each individual DH system in the VG region.

2.1. Model

The assessment is carried out assisted by the MARKAL_West Sweden (MARKAL_WS) model (developed and applied in Refs. [15,16]). MARKAL_WS is based on the well-established, cost-optimising bottom-up model MARKAL (MARKet ALLocation) model [27] and describes 37 municipal DH systems in the VG region. Each DH system is described individually with currently available DH production capacity as well as with potential future investment options. Through MILP (mixed-integer linear programming) (see also Section 2.6), the model finds the least cost-combination of fuels and technologies that meet the exogenously defined DH demands of each represented DH system. In addition to HOBs, the model representation also includes CHP technologies and bio-refineries with biofuels for transport as main output. Markets for electricity and transport biofuels are defined with exogenously assumed prices to which these products can be sold. The objective function of the model, which is minimised in the optimisation, thus represents the cost of DH generation of the region when credits for sold electricity and transport biofuels are taken into account. Fig. 2 gives an overview of a local DH system and its interaction with power and transport systems in the model. The MARKAL_WS has a time-horizon reaching from 2005 to 2030 divided into six time steps, each representing 5 years.

2.2. Model scenarios and sensitivity cases

Due to uncertainties with regards to future climate policies, which play a crucial role in energy market developments, two main climate policy scenarios are simulated. In the reference scenario, referred to as “BASE”, political climate targets are ambitious and energy policies are implemented accordingly. In contrast, the alternative scenario, “POLCOL” (policy collapse), simulates a future where a focus on national competitiveness creates a race to the bottom when it comes to climate policies.

Besides the BASE and POLCOL scenarios, five sensitivity cases are used to assess the robustness of the model outcomes with regards to parameter values for which future levels are uncertain and of particular relevance for the present study: future DH demand, level of EH available from the industrial cluster, technology and fuel for marginal electricity generation, and learning rate of bio-refinery for transport biofuel production. In addition to these factors, the sensitivity cases apply the same conditions as the reference scenario BASE. Table 1 summarises the scenarios and their input assumptions.

In the BASE scenario, the DH demand is assumed to be constant from 2010 to 2030 representing a future where possible expansions of the DH grids equal heat demand reductions due to building energy efficiency measures in line with e.g. the Energy Performance of Buildings Directive [28]. One of the sensitivity cases, REHD (Reduced Heat Demand), represents a decreasing DH demand, linear decrease by 25% from 2010 to 2030, in line with a recent study [29] showing that a high application of energy conservation measures and heat pumps in the building sector would lead to a 20% decrease in total DH demand from 2007 to 2025.

In the BASE scenario, we assume that 125 MW of EH from the chemical cluster in Stenungsund can be delivered at constant load [30] to the SKG pipeline. We assume that the “connection” does not affect the energy use and emissions at the chemical

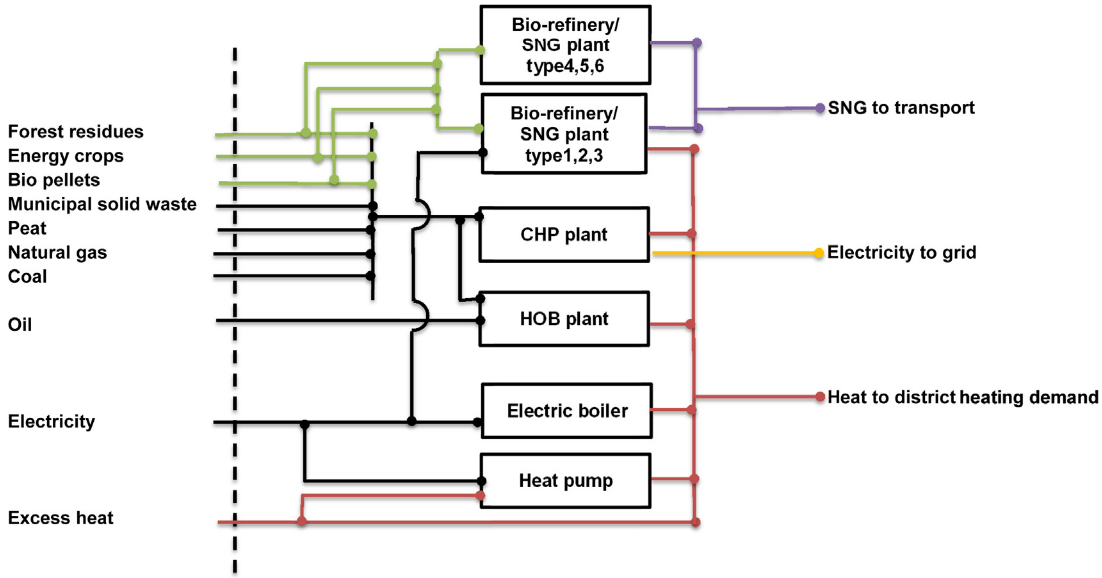

Fig. 2. Schematic model representation of a local DH system and its interaction with power and transport systems (Abbreviations: synthetic natural gas (SNG), combined heat and power (CHP), heat-only boiler (HOB)).

cluster. However, the level of EH availability from the chemical cluster in Stenungsund is subject to uncertainties. Higher energy prices promote more energy efficiency measures, while utilisation of more EH in DH systems is more likely to lead to less motivation to implement energy efficiency measures. There are also investments associated with utilisation of EH both at the cluster (mainly in heat exchangers) and in the heat pipeline. The optimised level of EH availability for DH systems is yet to be assessed but rather than optimising the investments we apply alternative EH capacity levels of 225 and 75 MW, the "225 MW" and "75 MW" sensitivity cases.

In the BASE scenario, it is assumed that marginal electricity is generated in NGCC (natural gas combined cycle) plants (see also Section 2.5). Due to the large European coal resources, application of CCS (carbon capture and storage) technology may be an option for CO_2 emission reductions. However, strong local oppositions and uncertain natural gas prices increase the future uncertainty around CCS and decrease the likeliness for CCS to become widely commercial before 2025 (e.g. Ref. [31]). Hence, in our CCS sensitivity case, coal condensing power plants + CCS with electric efficiency of 40% and CO_2 capture efficiency of 90% [32] are applied from 2025 for the calculation of European marginal electricity generation (affecting electricity prices and CO_2 emissions). Between 2010 and 2025, like the Base scenario, NGCC plants take this role.

In the BASE scenario, an exogenously provided learning curve of new bio-refineries for transport biofuel production (see also Section 2.6) is included leading to investment cost decreases of 10% in 2025 followed by a further 10% in 2030. Since, high uncertainties are associated with the bio-refinery developments by 2030, in our fast bio-refinery development (FAST SNG) sensitivity case, the investment cost of bio-refineries decreases similarly to the BASE case, but with the rate of 20%.

2.3. Energy markets

The studied system is a price-taker on the international fossil fuel markets and fossil fuel prices are exogenous inputs to the model. The BASE scenario fossil fuel prices are based on the "450 ppm scenario" of the IEA's (International Energy Agency) World Energy Outlook 2011 [33] while the POLCOL scenario prices are based on the IEAs "Current policies scenario" [33] (Table 1).

It is assumed that SNG (synthetic natural gas) can be sold as transport fuel at a price equal to 80% of the diesel price at filling station (i.e. including distribution costs for diesel) (Table 1). The lower price for SNG is in accordance with the historic difference between diesel and gas prices, and compensates for the higher cost of gas vehicles compared to diesel vehicles. Two levels of SNG distribution cost are included in the model representing distribution through the existing NG grid in VG (lower cost) and the construction of a new gas grid in the region (higher cost), see also Ref. [16].

Three types of biomass resources are represented in the model: residues from forestry (tops, branches and stumps), energy forest from cultivation on agricultural land, and bio-pellets. Markets for forest residues and energy forests are assumed to have a local/regional character while the bio-pellets market is assumed to be international in line with the current biomass for energy use in the region. Forest residue supply curves, defining the production cost and potential in VG, are included in the model [34,35]. We model the supply curves as stepwise variations in the production (Fig. 3). Energy forest (willow) yields are assumed to 28 ha/GWh [36] and, in the model, its price is based on production costs [37] (see Table 1). In 2001, the land use for energy forest cultivation in VG was 900 ha [38]. In the model, this area can increase and in 2030 reach 36,900 ha, which is equal to the lay-land available in VG [39]. Market prices on bio-pellets are based on current prices and trends [40] and the availability is assumed to be unrestricted due to import possibilities (see Table 1).

Since the electricity system is international rather than regional, the electricity prices are treated exogenously. In our BASE scenario, we use electricity prices for each model season and year based on outputs from the energy system model ELIN [31]. In ELIN, 27 national electricity systems in the European Union plus Norway and Switzerland have been modelled, and electricity scenarios that are consistent with our BASE scenario have been produced (Table 1).

In the POLCOL scenario, electricity prices are assumed to be based on coal condensing power plants with different efficiencies for each model season and year, according to Table 2.

Table 1
Assumptions of model parameter values regarding policy tools and energy prices/costs for the BASE and POLCOL scenarios.

	BASE	POLCOL
Policy tools		
CO_2 tax (EUR/ton CO_2)	17/53	17/0
Green electricity subsidy (EUR/MWh)	20	20/0
Biofuel/SNG subsidy (EUR/MWh)	48	48/0
Excess heat delivery (MW)	125	
District heat demand	Constant	
Marginal electricity	Long-term (NG, η 57%)	Long-term (Coal, η 47%)
Land available for energy forest (Willow) (Ha)	1000/36,900	1000
Energy prices/costs (i)		
Natural gas (EUR/MWh)	18.5/24	18.5/31
Coal (EUR/MWh)	Not allowed	10/11.5
Fuel oil, light (EUR/MWh)	43/52	43/69
Fuel oil, heavy (EUR/MWh)	37/46	37/64
Wood chips/forest residuals (EUR/MWh)	Supply curves	
Wood pellets (EUR/MWh)	35/42	35
Energy forest (Willow) (EUR/MWh)	20	
Excess heat (EUR/MWh)	0.56	
Biofuel/SNG (EUR/MWh)	53/67	53/71
Electricity Winter (EUR/MWh)	54/65	54/37
Electricity Spring/Autumn (EUR/MWh)	47/62	47/33
Electricity Summer (EUR/MWh)	42/62	42/33

For those parameter values which are not constant for the whole model time period, values for time steps 2010 and 2030 are given (separated with/). Since some parameter values and descriptions are similar in the scenarios, they are given only for the "Base" scenario.
(i) Energy prices are the payments by DH plants, only Biofuel/SNG price is payment at filling stations. CO_2 tax has not been included in fossil fuel prices. For municipal waste, the negative price is due to a waste disposal fee. For excess heat, the value represents an assumed minimum compensation for excess heat providers over and above technical costs of bringing the heat to the DH system – it does not represent a market price.

2.4. Climate policies

The study applies a stylised policy situation and only includes representations of the policy tools which are of largest significance for the studied system. This includes a CO_2 tax, a green electricity subsidy, and a transport biofuel subsidy.

Climate policies such as the TGC (tradable green certificate) and ETS (emission trading systems) have a national and international scope, respectively. Since the scale of the VG region energy system is sub-national, these policies have similar effects as subsidies for renewable energy and emission taxes: "green" electricity is associated with extra revenue and emissions are associated with a cost. Thus, we can model the effects of a broad range of climate policy instruments as subsidies promoting "green" electricity and biofuel/SNG production and CO_2 taxes. These are exogenously given in the model. Subsidies for renewable electricity and biofuels are based on historic TGC system costs levels [41] and current tax exemptions on biofuels [42], respectively (see Table 1).

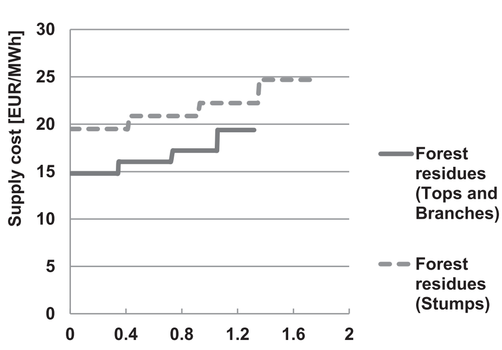

Fig. 3. Wood chips/forest residues supply curves in model (2010–2020) [34,35].

Table 2
Electrical efficiency of coal condensing plants (%).

	2005–2020	2025–2030
Winter	35	40
Spring/Autumn	40	45
Summer	45	45

In the BASE scenario, the climate polices are either constant (green electricity subsidy, transport biofuel subsidy) or increase (CO_2 tax) during the studied period as a reflection of continuously high climate ambitions. In POLCOL, climate policies are assumed to gradually collapse. As a result, environmental taxes and subsidies decrease linearly from 2010 to reach zero value in 2030 (see Table 1).

2.5. Net CO_2 emissions

When estimating the environmental impacts of a change in a DH system, the handling of the marginal effects on the electricity markets is of large significance. The DH system might be both a user (e.g., in heat pumps) and a producer (in CHP) of electricity. In previous studies, it was shown that marginal electricity production can be described as a mix of electricity and heat supply technologies [43,44]. A change in the local generation or use of electricity can affect both the utilisation of existing production capacity and future generation capacity itself. The latter effect is the most important in the long-term perspective [44], which is relevant in a strategic sustainability assessment. For this reason, our assessment uses information on marginal effects on the production capacity (referred to as long-term or built margin). Short-term (few years) and long-term (decades) evolutions in marginal electricity of current use and future generation of electricity were identified in a study concluding that for the long term, adequate scenarios for the development of electricity systems need to be modelled [45].

With the European electricity system perspective, we calculate the net CO_2 emissions based on the long-term (built) margin. In the BASE scenario, we identify this, based on output from the ELIN model [31], to be powered from NGCC plants with electrical efficiency of 57% for all model seasons and years from 2010 to 2030 (see Table 1). In POLCOL, marginal emissions of electricity are assumed to be based on coal condensing power plants with different efficiencies for each model season and year, according to Table 2.

Most new vehicles are diesel-fuelled and thus when net CO_2 emissions are calculated for the system, we assume that between 2020 and 2030 SNG replaces diesel. Due to the lower efficiency of gas vehicles compared to diesel vehicles [46], the CO_2 abatement of SNG is linked to 80% of the emission factor of diesel (i.e. 0.8 * 259 ton CO_2/MWh).

The net total CO_2 emissions are calculated as the sum of CO_2 emissions from the DH systems, transport system, and the long-term marginal electricity generation.

2.6. Technology assumptions

Technology data of the current version of the MARKAL_WS model is to large extent based on earlier versions of the model [15,16]. For cost and performance data for HOBs and CHPs are

Table 3
Main model input assumptions regarding DH technologies (based on Ref. [15] and references therein).

Technology	Conversion efficiency (i)		Specific investment cost (ii)	Fixed O&M cost	Variable O&M cost
Combined heat and power plants	Electricity [%]	Total [%]	[kEUR/kW electricity]	[% of inv. Cost/year]	[EUR/MWh fuel]
Gas CC CHP	45–49	90	0.8–1.2	1	2.5
Gas Engine CHP	38	86	0.75		4.3
Biomass ST CHP	25–34	110	2.3–7.2	1.5	2.7
Waste ST CHP	22	91	5.9–8.2	3	−12 (iii)
Coal ST CHP	25–34	89	2.2–6.8	1.5	2.7
Heat plants	Heat [%]		[kEUR/kW heat]	[% of inv. cost/year]	[EUR/MWh fuel]
Gas HOB	90		0.05–0.1	2.5	0.7
Biomass HOB	110		0.34–0.56	1.5	2.0
Coal HOB	89		0.31–0.52	1.5	2.0
Oil HOB	90		0.09–0.17	2.5	0.7
Waste HOB	91		1.0–1.1	3	−16
Heat pump	300 (COP)		0.70	0.5	0.7

ST CHP, Steam turbine combined heat and power; HOB, heat-only boiler.
(i) Efficiencies are based on lower heating value.
(ii) Plant properties are size dependent; larger plants are linked to lower specific investment costs and, for CHP plants, higher electricity output. In the model, typical plant sizes and thus plant properties are assumed to be dependent on the size of the DH system (DH supply per year).
(iii) Including income from waste disposal fee, estimated at 22 EUR/MWh_{waste}.

presented in Table 3. For the purpose of this study, additional model development and updates were required with regards to the heat pipeline and the model representation of transport biofuel production.

The SKG pipeline is assumed to be in operation in model year 2020. Due to the long length of the pipeline, circulation pumps will be required to pump both the forward and the return water. The electricity required for pumping depends on the flow and on the pipeline's diameter and length, and is calculated to be approx. 7% [47]. Due to friction in the pipes heat will be produced. This heat can be considered as a form of added electric heating and, thus, no temperature drop occurs in the flow direction in the transmission pipelines [1].

The model also includes investment options for potential new bio-refineries for production of SNG assumed to be used as transport fuel. The SNG option is included in the model since there is in Sweden a strong focus and development efforts on such bio-refineries. For instance, a bio-refinery SNG production plant with the capacity of 20 MW (the first phase of a larger plant) was recently (spring 2014) taken into operation in Göteborg [48]. The SNG from this plant will be distributed through the existing natural gas grid in the region. Even so, there is as yet little experience from commercial application of the technology globally and its thermo-economic specifications are subject to high uncertainties [49]. For this study, data of different plant configurations and sizes have been developed based on the data for the Göteborg plant (see Table 4).

In the model, the Göteborg 20 MW SNG production plant is assumed to be up and running from 2015 (for this plant, investment costs are treated as sunk cost). From 2020, the model can choose to invest in new SNG production plants (100, 150 and 200 MW) if this reduces the net total system cost. To capture the strong economies of scale characteristic of SNG production, the technology is only available at discrete capacity levels (i.e. MILP). The model has two options for each capacity level. The first is a bio-refinery connected to a DH system producing SNG and heat with biomass and electricity as external input to the plant (Bio-refinery SNG 1, 2 and 3 in Table 4) while the second option is a stand-alone bio-refinery where SNG is the only product and biomass the only input (Bio-refinery SNG 4, 5 and 6 in Table 4). In the latter option, the electricity required for the process is generated from the heat produced in the process.

3. Results

3.1. Regional perspective

Even without the SKG pipeline, the DH production in VG will change over time both in terms of DH production technology and fuel use under the two climate policy scenarios (Fig. 4). Comparing

Table 4
Assumptions of bio refinery SNG technologies as potential investment options in the model.

Technology	Capacity (MW biofuel/MW heat)	Efficiency (%)	Investment cost (MEUR/MW biofuel)				Fixed O&M cost (MEUR/year)	Variable O&M cost (EUR/MWh biomass)
			2012	2020	2025	2030		
Bio-refinery SNG (base plant)[a]	20/3	70	7.8				2.3	3
Bio-refinery SNG 1	100/15	70		4.1	3.7	3.3	2.3	3
Bio-refinery SNG 2	150/22.5	70		4	3.2	2.9	2.3	3
Bio-refinery SNG 3	200/30	70		3	2.9	2.6	2.3	3
Technology	Capacity (MW biofuel)	Efficiency (%)	Investment cost (MEUR/MW biofuel)				Fixed O&M cost (MEUR/year)	Variable O&M cost (EUR/MWh biomass)
			2012	2020	2025	2030		
Bio-refinery SNG 4	100	67		4.1	3.7	3.3	2.3	3
Bio-refinery SNG 5	150	67		4	3.2	2.9	2.3	3
Bio-refinery SNG 6	200	67		3	2.9	2.6	2.3	3

[a] Bio-refinery SNG (base plant) is based on Ref. [48]. Capacity, efficiency, investment cost, and fixed and variable O&M cost are calculated based on Ref. [51].

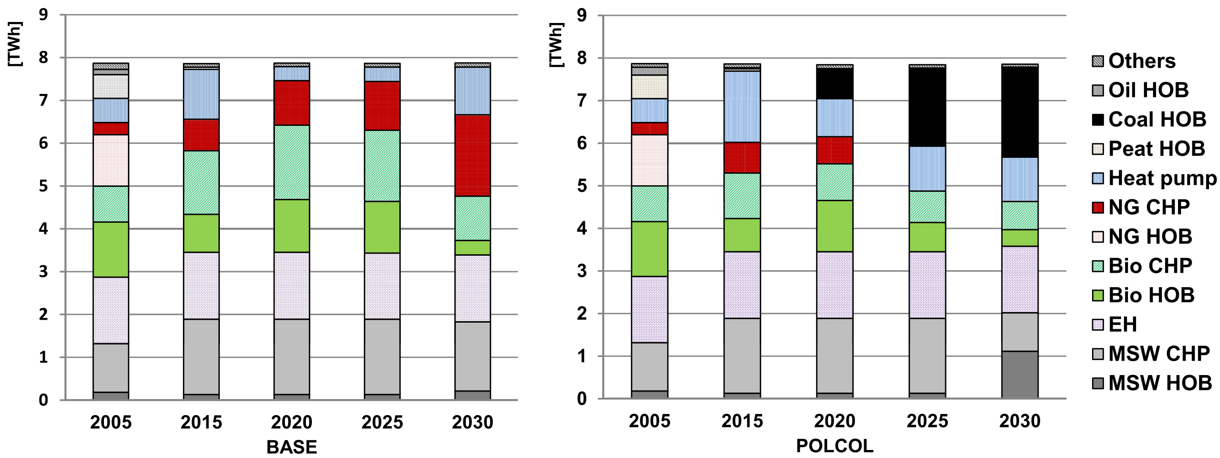

Fig. 4. Production of DH in the VG region in the BASE (left) and the POLCOL (right) scenarios without the SKG pipeline. Abbreviations: Municipal solid waste (MSW), heat only boiler (HOB), combined heat and power (CHP), excess heat (EH), natural gas (NG).

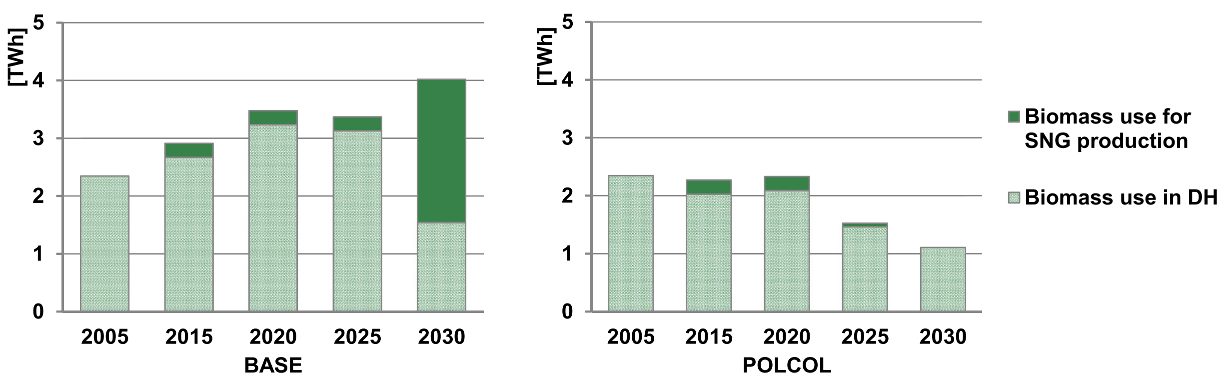

Fig. 5. Biomass use in VG in the BASE (left) and the POLCOL (right) scenarios without the SKG pipeline.

the BASE and POLCOL scenarios, in particular, biomass use develops differently under the studied time horizon (Fig. 5).

3.1.1. Energy flow impacts

The introduction of the SKG pipeline affects the results in significant ways. In the BASE scenario, the "connection" increases EH use by 832 GWh in the year 2030, i.e. 76% of the available EH from the chemical cluster is utilised, considerably decreasing fuel use in the DH systems in the VG region (Fig. 6). The type of fuel replaced by EH differs with time. While in 2020, EH mainly replaces forest residues, NG is mainly replaced in 2030. This is a reflection of the fuel mix for the "no connection" option of the BASE scenario, in which biomass has a large share in 2020 and NG in 2030 (see Fig. 4). The reduction in fuel use is larger than the EH increase due to conversion losses and the fact that the fuels in the DH system are used not only for DH production, but also for electricity generation.

In model year 2025, not only EH but also the use of electricity and NG increase in the DH systems. This is because the reduction of biomass use in the DH systems reduces the marginal cost of biomass (Fig. 3). As a result, a new bio-refinery SNG production (Type 6, see Fig. 2 and Table 4 for technical and economic specifications) is built one model time step earlier (Fig. 7). In this time step, the "connection" shifts the biomass use from heat to SNG production. At the same time, the EH delivered through the pipeline is insufficient to compensate for the reduced availability of

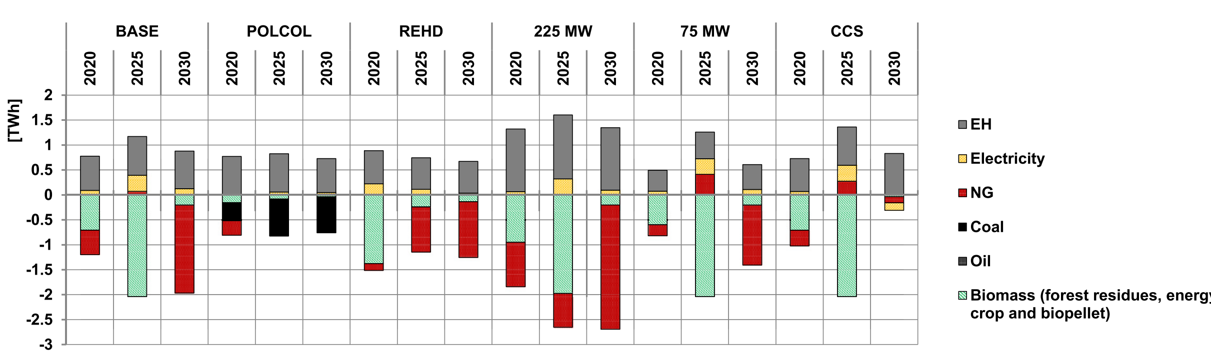

Fig. 6. Differences in fuel and electricity utilised in the DH systems in VG due to the "connection".

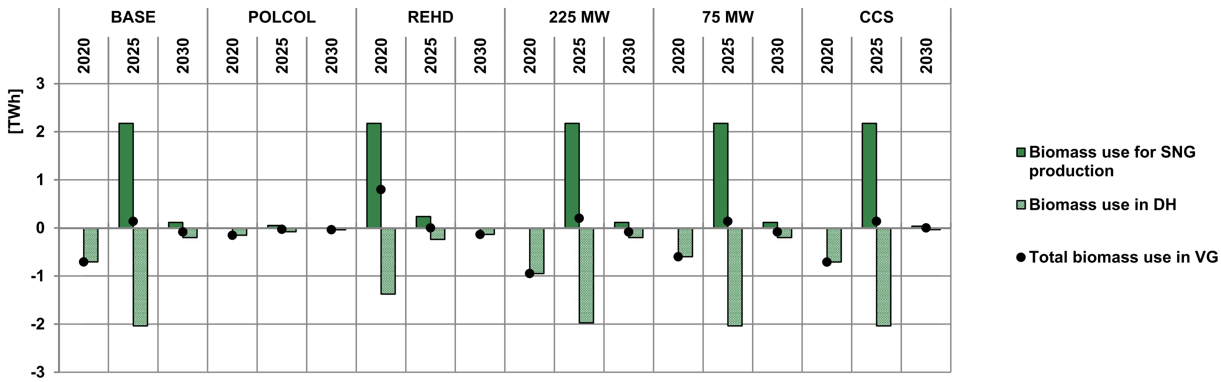

Fig. 7. Difference in biomass use in DH and SNG production in VG due to the "connection".

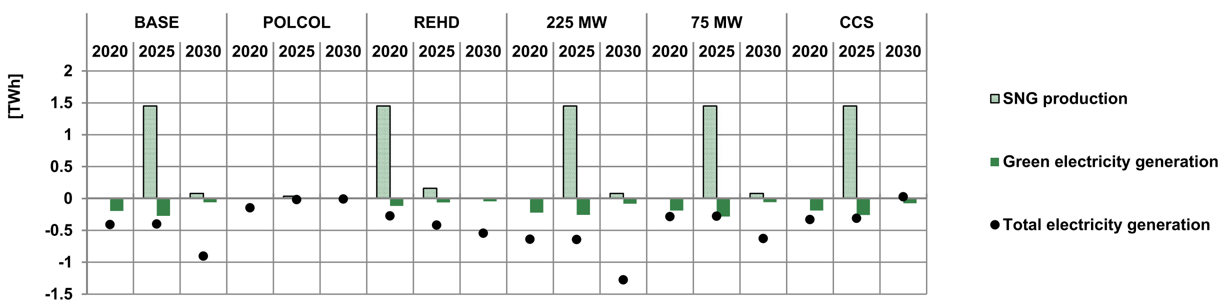

Fig. 8. Difference in SNG and electricity production in VG due to the "connection".

biomass in the DH systems. Consequently, the use of electricity for heat pumps and NG increases in the DH production to meet the heat demand in VG (Fig. 6).

In the POLCOL scenario EH replaces coal, NG and biomass in time step 2020 and only coal in time step 2030. This is also consistent with the fuel mix in the absence of the SKG pipeline (see Fig. 4). A comparison of the POLCOL and BASE results thus shows that future policy instruments affect the type of substituted fuels over time.

3.1.2. Technology change

Utilisation of the EH in the region's DH systems change the competiveness of DH production technologies. Due to interactions between DH system, power and transport sectors, changes in DH production technologies affect electricity generation and transport biofuel production. The low running cost of EH decreases the competitiveness of CHPs in heat production. As a result, as shown in Fig. 8, electricity generation in both NG CHPs and biomass CHPs decreases in VG.

There is a large increase in the production of SNG when an investment in a new bio-refinery is made (Fig. 8). The model chooses a stand-alone bio-refinery (Type 6, see Fig. 2 and Table 4) in order to allow maximum annual utilisation time, unrestricted by the heat demand variations of the DH systems.

In the POLCOL scenario, however, the subsidy for SNG disappears with time and no investment is made in SNG production. The "connection" does not change this since it hardly affects the demand for and price of biomass (Fig. 8).

3.1.3. CO_2 emissions impacts

From time step 2020, the CO_2 emissions from the DH systems decrease (Fig. 9), because the EH in part substitutes fossil fuels in

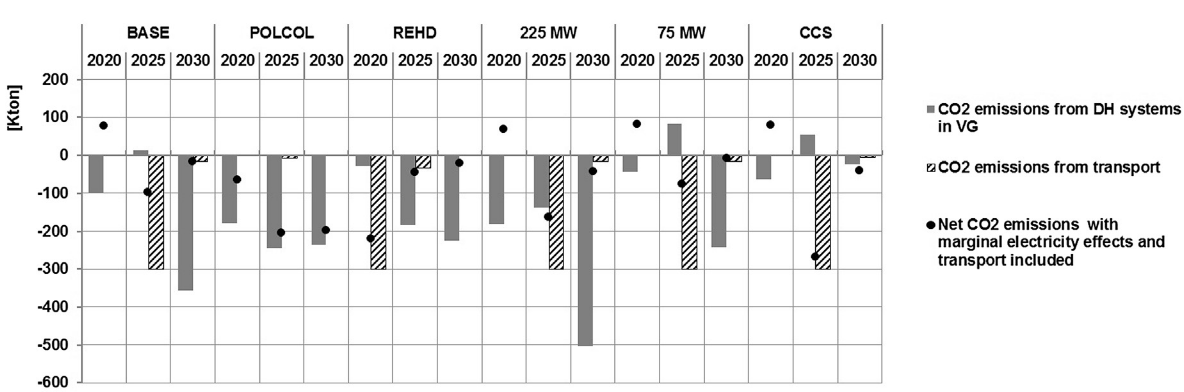

Fig. 9. Difference in CO_2 emissions due to the "connection".

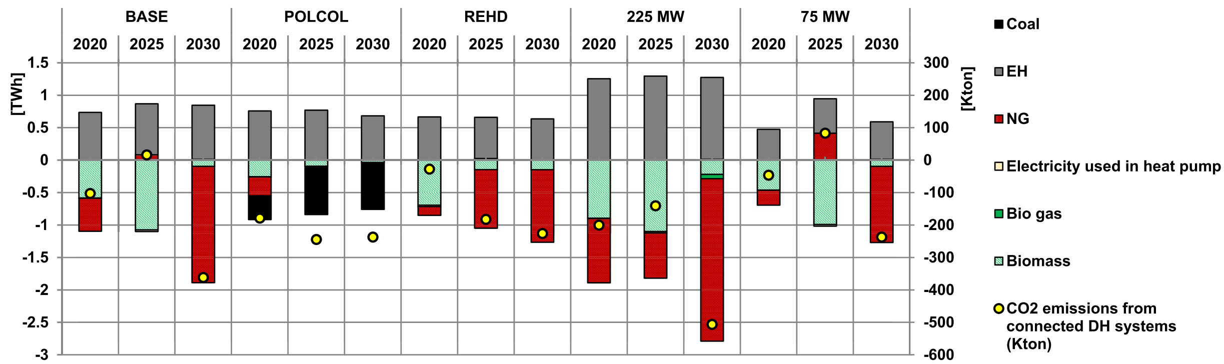

Fig. 10. Difference in fuel and electricity use and CO_2 emissions at *the local level* (Göteborg, Mölndal, Kungälv, Partille and Stenungsund DH systems only) due to the "connection".

the DH systems. A further reduction in emissions occurs in the transport system since SNG from the new bio-refinery starts replacing diesel in transport one time step earlier with the "connection" (Figs. 8 and 9).

As illustrated in Fig. 2, the DH systems and electricity system are already strongly connected. The reduction in electricity generation in NG and biomass CHPs in the DH systems is assumed to be compensated through construction of new generation capacity (the long-term marginal electricity generation assumption/built margin) somewhere in the European electricity system. Despite the high electric efficiency (57%) of the long-term NGCC-based marginal electricity generation in the BASE scenario (see Section 2.5) net CO_2 emission increase when marginal electricity substitutes electricity from biomass CHPs while CO_2 emissions decrease when the marginal electricity substitutes electricity from existing NG CHPs in the VG region due to their lower efficiency compared to new NGCC plants.

The net total CO_2 emissions (sum of CO_2 emissions from the DH systems, transport system, and the long-term marginal electricity generation), presented in Fig. 9, shows that the net CO_2 emissions may increase in the short-term, while decrease in the mid-term.

3.1.4. Sensitivity analysis on energy flow and technology change

Our sensitivity cases with variations on the BASE scenario show that the difference in fuel use in time step 2025 is sensitive to the amount of EH delivery (see the 225 MW and 75 MW cases in Fig. 6). While the NG use decreases in the 225 MW case, it increases in the 75 MW case. The difference in fuel use in year 2030 is sensitive to the marginal electricity generation technology. In the CCS case, EH replaces a small amount of the NG use in HOBs and thus the total electricity generation in CHPs in the region remains unchanged. Moreover, the advent of the new bio-refinery depends on the heat demand in VG. While for the BASE scenario the model invests in the bio-refinery in year 2025, the investment is cost-effective already in year 2020 if the heat demand is lower (REHD case). The reason is that as the heat demand decreases in VG, biomass utilisation in DH production decreases more in comparison with the BASE scenario. This affects the marginal cost of biomass and makes the bio-refinery profitable one time step earlier.

The sensitivity analysis on fast development of bio-refineries for SNG production (the FAST SNG case) illustrates that the EH delivery is insufficient to decrease the marginal cost of biomass in the region to the amount needed to shift biomass use from the DH systems to transport biofuel production and, thus, the FAST SNG case results in no change compared to BASE.

3.2. Local perspective

3.2.1. Energy flow impacts

Figs. 10 and 11 present results of the assessment at the local level addressing only the direct impacts on the connected DH systems, i.e. the DH systems of Stenungsund, Kungälv, Göteborg plus Partille and Mölndal (*the local level*). In similarity to the regional level assessment, the "connection" increases EH use at the local level, by 832 GWh in year 2030, and decreases fuel use. Replaced fuels include biomass and NG in the BASE scenario (see Figs. 6 and 10). The amount of replaced biomass is smaller than at the regional level in model year 2025 and the total biomass use in DH and SNG production is also smaller in this model year (see Figs. 7 and 11). This is because the new bio-refinery plant is independent of the DH systems. Thus, this plant can be built somewhere close to the NG grid but not necessarily within Göteborg, Mölndal, Kungälv and Stenungsund DH systems. When the impacts of the "connection" at the local level are assessed, the regional biomass which is utilised in the new SNG production plant is neglected.

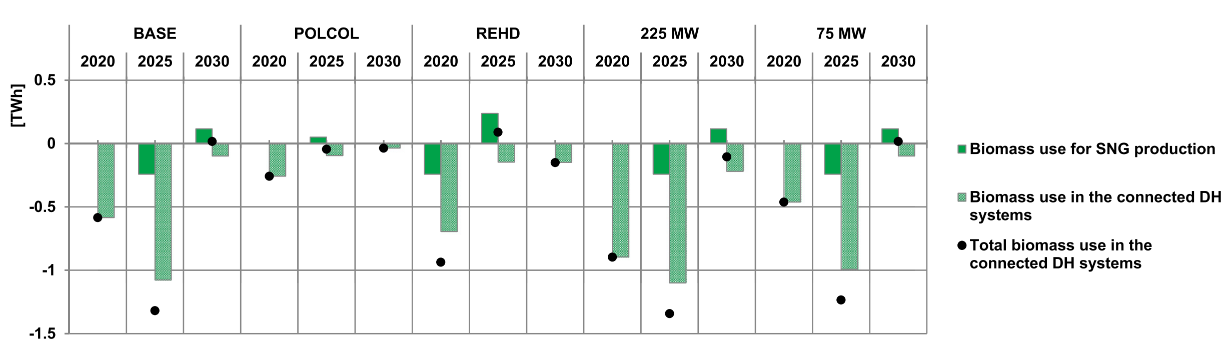

Fig. 11. Difference in biomass use for SNG and DH production at *the local level* (Göteborg, Mölndal, Kungälv, Partille and Stenungsund DH systems only) due to the "connection".

3.2.2. CO_2 emissions impacts

The connection decreases CO_2 emissions at *the local level* for both scenarios and all sensitivity cases (see Fig. 10) except in a few time periods. A comparison of changes of CO_2 emissions at the local and regional levels shows that they differ in all time steps (see Figs. 9 and 10). This is because in the presentation of emissions at *the local level*, emissions from marginal electricity production and transport systems are not included.

4. Discussion

The heat connection of local DH systems with the chemical cluster leads to increased utilisation of industrial EH and thus reduced demand for primary energy sources in the entire VG region. Which energy sources are being displaced by EH depends on the scenario. In BASE, EH displaces mainly biomass and natural gas while in POLCOL, where the climate policy collapses, EH displaces coal since coal is introduced in the VG DH systems when environmental taxes and subsidies decline.

In our model, the “connection” reduces electricity generation at CHPs in the region. This could be foreseen due to the decreased heat demand when a large share of the base load is covered by EH decreasing the CHP operating time, which in turn reduces electricity output. As a contrast, in the previous study of a regional DH system in Sweden [18], the connection to the industries increased the utilisation of the CHP plants. This was because heat from CHP production could be used as process heat in the industry. In our case, the heat produced in the DH systems does not meet the requirements for process heat used in the chemical cluster processes, and a two-way cooperation between the DH systems and the cluster is thus unrealistic. This illustrates that the results are highly dependent on local conditions.

The only similar study in the literature [18] focused on the impacts of a heat market on individual DH systems and industries, and a small region including three DH systems and three industries. That resembles the local level of our study. However, besides the local view, we addressed also the larger VG area, and its 37 DH systems. This provides the opportunity for analysing resource use, more specifically biomass use, at a regional scale. As a bulky fuel, biomass (including forest residues and energy crops), is mainly transported by trucks over short distances (in the order of 50 km [50]), creating a regional biomass market. A change in biomass use in a local DH system can affect the marginal cost of biomass and consequently its competitiveness in the region. It is shown that local and regional results can differ significantly in regards to biomass use. Due to the existence of a regional market for biomass, some changes occur outside the connected DH systems, which cannot be captured with a local perspective. This implies that energy system decision-making can be better supported if interactions of energy carriers between the energy system and its surroundings are taken into account, and also that it is of importance to assess local changes at a wider geographical scale.

In the model the “connection” makes bio refinery SNG production a cost-effective option one time step earlier. The uncertainties with regards to future costs and efficiencies of SNG production plants are large because there is little real experience from such production. However, the connection of DH systems can be expected to make future investments in SNG production easier if it contributes to reduction of the marginal cost of biomass resources.

Since the model has perfect foresight, it can foresee the SNG investment in the region before it happens. As the result, it cancels investments in biomass CHP and biomass HOB in the DH systems in VG. Real decision-makers do not have perfect foresight. Hence, we cannot conclude that these effects are likely to occur in reality.

Our results indicate that the “connection” reduces the net CO_2 emissions most of the time in all calculated cases. The reduction is mainly because of the reduced use of fossil fuel in the DH systems and the transport system. However, under some circumstances the net CO_2 emissions increase with the “connection”. This is because the CO_2 emissions in the electricity system increase when less electricity is generated in biomass CHP plants in the connected DH systems. The fluctuating model results indicate that, although the “connection” is likely to reduce net greenhouse gas emissions, the uncertainty of the real net effect is great. It can be noted that the reduction in CO_2 emissions is more significant in the POLCOL scenario. The increased use of EH results in a greater environmental benefit in the absence of climate policy instruments since then coal is likely to be reintroduced into the DH systems. Our results might also exaggerate the reduction in CO_2 emissions because they do not account for any increase in emissions from the chemical cluster. Such increases can occur if the price of the excess heat is sufficiently high to make less energy-efficiency measures profitable at the chemical cluster.

In our study, the dynamic energy system modelling has shed light on both the short-term and mid-term regional system impacts of a heat connection between a large chemical cluster and three DH systems. This represents an advantage of this study since energy systems are dynamic by nature and the response to any intervention in the systems can differ over time.

There is ongoing research addressing ways of substituting fossil fuel with biomass in the chemical cluster in Stenungsund. The cluster has plans of utilising renewable energy and thus the cluster is a potential competitor for biomass in the region. However, due to the chosen system boundary, this was excluded in our assessment.

The presented assessment is based on specified regional conditions (of the VG region) and on the use of a specific, today only partly utilised, EH resource. The same method can be applied to other regions and EH resources, but the outcomes of the study are likely case dependent. In cases of one-way cooperations between an EH source industry and a DH system (utilisation of industrial EH in the DH systems only), the EH replaces more expensive energy sources and DH production technologies in the DH system. Due to large diversity of Swedish DH systems in terms of use of fuel and locally available resources, the replaced DH technologies differ between DH systems. In many DH systems EH replaces CHP plants. This results in reduced, electricity generation within the DH systems which in turn results in increased generation from marginal electricity technologies elsewhere. This is a general result but the amount of electricity generation reduction depends on local conditions as the type of CHP (NG or biomass based), the size and conversion efficiencies of the CHP, electricity prices and availability of heat pumps within the DH system. As already mentioned, due to the current regional biomass market in Sweden, and the strong dependence of Swedish DH systems on biomass, the regional biomass supply curve is also an important factor. This in turn points to the importance of the system level at which the assessment is done; if it is at the local or regional level.

5. Conclusions

The main conclusion of our assessment is that in the studied case, the regional integration of DH systems and industries through a DH pipeline between Stenungsund and Kungälv/Göteborg, DH pipeline between Stenungsund and Kungälv/Göteborg would change the use of energy sources in the energy systems of the region. In the VG DH systems, the increased EH use would lead to reduced biomass and fossil fuel use. The type of substituted fuel varies over time and depends on the future development of policy instruments and other circumstances. The excess heat use would further reduce the environmental burden of the energy system.

Since regional low-cost biomass availability is constrained, reduced biomass demand from the DH systems provides an opportunity for other biomass competitors to access this resource at a lower cost. In this study, the available but unused biomass in the DH systems is to a large extent utilised in bio-refinery with SNG production for transport.

In the reality, in the region, investments in biomass CHP and biomass HOB compete with investments in SNG. The investment that is made first will affect the profitability of later investments. If the stakeholders are not aware of investment plans of other stakeholders, there is a risk of overinvestments, resulting in a demand for and price of biomass that is too high for any of the investments to be profitable. We can deduce a recommendation to stakeholders that consider an investment in biomass CHP, biomass HOB or SNG production. Our results highlight the need for these stakeholders to obtain information on other investment plans before making the investment decision.

The reduced use of fossil fuel in the DH systems leads to reduced CO_2 emissions. Increased use of biomass for SNG production will also reduce CO_2 emissions if the SNG displaces fossil fuel in the transport sector. On the other hand, an increased use of EH is likely to reduce the electricity generation from biomass at CHP plants. If the European electricity generation from fossil fuel increases as a result, the electricity system will emit more CO_2. The net effect of these changes is likely to be a reduction in net CO_2 emissions, but the uncertainty is great.

Thus, we found that a DH pipeline between Stenungsund and Kungälv/Göteborg is likely to reduce the use of primary energy resources as well as CO_2 emissions. There is a large diversity among Swedish DH systems and, therefore, it is not straightforward to draw any more general conclusions from our case. However, in most larger DH systems there is a certain amount of fossil fuels still being used, and there is potential competition for regional biomass resources in the southern part of the country. Thus, it is likely that studies under the same scenario assumptions would get to similar conclusions where there are large-scale heat sources and sinks which can be linked.

Acknowledgements

The presented study is part of a larger study in which the sustainability of various future district heating options are assessed using a combination of energy systems assessment and modelling and LCA methodology. The study is financed by FORMAS and E.ON.

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