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System profitability of excess heat utilisation – A case-based modelling analysis

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ABSTRACT

The use of EH (excess heat) in DH (district heating) may contribute to increased sustainability through reduced use of primary energy. In Sweden, while biomass has become the most important DH fuel during the last decades, there is a significant amount of industrial EH that could be utilised in the DH systems if it could be shown to be an economically viable alternative. This study addresses the long-term system profitability of a large heat network between a cluster of chemical industries and two DH systems that enables an increased use of EH. An assessment is carried out by scenario and sensitivity analyses and by applying the optimising energy systems model MARKAL_WS, in which the DH systems of the Västra Götaland region of Sweden are represented individually. The results show heat network profitability under most assumptions, and that the profitability increases with biomass competition, phase-out of natural gas use and higher CO_2 charges, whereas it decreases with the availability of other EH sources in the base load of the DH systems.

1. Introduction

DH (District heating) systems represent a structural and organizational energy efficiency measure since they enable low temperature EH (excess heat) recovery from thermal power plants, waste incineration, and industrial processes [1]. The recovered heat (together with heat from other sources) is distributed through a heat network to supply residential and commercial buildings and industries with space heating and hot tap water. This heat recovery system could increase the utilisation of EH in the European Union (EU27) member states by four times compared to current average levels (9%) [2]. The European Commission proposes strategies to cut 80–95% of annual greenhouse gas emissions by 2050 compared to 1990 levels in the Energy Roadmap 2050 report [3]. The utilisation of EH in DH systems would also effectively decrease the cost of these CO_2 emission reductions in the EU energy system [4].

In Sweden, DH systems had in 2010 a market share of nearly 60% (66.5 TWh) of the total heat supply to the residential and service sectors [5]. While biomass (including forest residues and energy crops), municipal solid waste and peat combustion contributed a large share (63% or 42 TWh), industrial EH had a relatively small share of less than 7% (4.5 TWh) of the heat supply [6]. The high share of biomass is due to favourable policies, including an energy tax and a CO_2 emission tax on fossil fuels as well as a tradable certificate system for renewable electricity generation [6]. As a result, biomass is used both in HOB (heat-only boilers) and, increasingly, in CHP (combined heat and power) plants.

Biomass is a limited resource, which can be utilized not only in DH systems for heat and electricity generation but also in biorefineries to produce transport biofuels. In Sweden, there is now a strong interest in transport biofuel production [7,8], which is likely to lead to stronger competition for biomass and consequently higher biomass prices. Therefore, incentives for substitution of biomass with other heat sources or technologies are anticipated to grow.

Various studies have shown environmental benefits of industrial EH utilisation in DH systems [9], [10]. In a recent study, a total of 21 TWh/year of unused industrial EH was identified that could possibly be utilized in Swedish DH systems, of which 2 TWh/year can be utilized directly (i.e. available at suitable temperatures, meaning that additional heating is not required) [11]. Capturing the available potential of EH depends on the willingness of industries and DH companies to collaborate. Such collaborations concern

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mainly ownership costs (e.g. how to share construction costs of heat exchangers and heat networks) and ownership benefits (e.g. how to share the expected revenues). Parameters affecting such collaborations have been analysed in several studies. Techno-economic parameters were analysed and classified as obstacles or facilitators of the collaboration; structure, length of contract, and cultural distance (rather than geographical distance) were identified to be crucial in initiating the cooperation [12]. Parameters that could hinder the collaborations included unwillingness to take risks, imperfect information, asymmetric information, credibility and trust, opposition to change [13]; high interest rate and short payback time for investments within industries [11], policy instruments, and international energy prices [1]. In contrast, involvement of universities through the application of energy system optimization models of DH systems and industries was shown to facilitate the collaboration, resolving the imperfect information parameter [13].

A few studies have addressed economic aspects of industry-DH utility collaborations and assessed the potential economic benefits. In one of these it was concluded that EH sources close to large cities in combination with fossil fuel taxes, and CO_2 emission taxes may justify the high investment cost of heat distribution networks in DH systems, and increase the competiveness of DH systems compared to individual heat supply solutions [2]. Large heat networks, shared between different stakeholders, including several DH systems and industries, have also been identified to be an attractive solution for increased utilisation of industrial EH [14–16].

Ignoring the infrastructure cost, in a study including three DH systems and three industries it was shown under different scenario conditions that most of the stakeholders would benefit from a large heat network and the total system net benefit was also large in the mid-term [16]. In a study addressing short and mid-term environmental and energy system impacts of a large-scale DH utilisation of industrial EH, it was concluded that the EH utilisation would reduce the use of primary energy resources as well as reduce CO_2 emissions [17].

In a recent study, including only the cost of extraction of EH within a cluster of industries, the economic feasibility of potential industrial EH supply to DH systems was analysed. It was shown that the EH delivery could be profitable for a wide range of heat extraction capacities [18].

In these studies, the major part of the investment cost for EH utilisation, the cost of the construction of the large, sometimes long-distance, heat pipelines connecting the EH source (industries) with the sink (larger DH systems) were totally or partly ignored. Since the construction of large heat networks, including both the pipelines and necessary heat extraction investment capacities within industries, is associated with large investment costs and lock-in effects, it is important to obtain comprehensive knowledge on the economic consequences of such heat networks. Thus, by including pipeline and heat extraction investment costs, we aim at assessing whether the construction of a large heat network allowing for long-distance transmission of EH is profitable from a societal point of view.

DH systems, particularly in Sweden, show very different characteristics with regards to the choice of fuels and technologies for DH production. Therefore, only by including the local characteristics the required level of detail can be obtained [19]. The assessments of EH utilisation often were based on specific cases in order to address real conditions and system differences (e.g. Refs. [9,14–16,20,21]). Furthermore, in a study identifying European sites suitable for future heat synergy collaborations between industries and DH systems, landscape aspects, site-specific factors and contextual circumstances were emphasized as critical parameters to capture the full potential of unutilised industrial EH [22]. Based on these arguments we chose to focus on a case, which is presented below.

Biomass accounts for a large share of the energy supply to the DH systems in Sweden. Changes in the biomass demand due to the construction of an industrial EH network will thus likely have an impact on biomass markets. However, the DH systems biomass supply is characterised mostly by a local-regional rather than national scale and, thus, a regional approach is selected.

In line with the current strong interest in transport biofuel production [8] a future demand for biomass from the transport-sector is included in the study, which below is referred to as an inter-sectoral approach.

Due to the long technical lifetimes of major infrastructure investments, a long-term focus is applied.

2. Case

In the VG (Västra Götaland) region in western Sweden there is now strong interest in constructing a large heat network between a cluster of chemical industries (located in Stenungsund) and the Kungälv/Gothenburg DH systems to utilise the large amount of industrial EH available at the chemical industries in the DH systems. Therefore, this industrial EH collaboration was selected as our case. In VG, Gothenburg is the main town in the region with about 530,000 residents. The Mölndal DH system (a part of the southern Gothenburg urban area) is connected to the Gothenburg DH system by a 1.1 km transmission pipeline with the capacity of 10 MW. Stenungsund is a small town with a population of about 25,000 people located about 50 km north of Gothenburg. Currently, the chemical industries are supplying the Stenungsund DH system with heat; however, their EH capacity is considerably larger than the demand in Stenungsund (see Ref. [18]). Between Gothenburg and Stenungsund is also the small town of Kungälv with a DH system currently supplied by a biomass CHP. Kungälv was recently connected to the Gothenburg DH system through a transmission pipeline with a capacity of 19 MW.

In 2011, the total heat supply in the Gothenburg DH system amounted to 4 TWh [23]. Excess heat from municipal solid waste CHP and two oil refineries (currently supplying 23% of total heat load), natural gas CHP and HOB, biomass CHP and HOB, bio oil HOB, and large-scale heat pumps contributed to supply the heat to the system. The system met the demands of 90% of the apartment buildings, about 12,000 smaller residential houses, plus numerous industries, offices, business and public buildings [24] in the town itself and in Partille, a municipality within the same urban area.

3. Method

The method applied, which includes two major steps, is based on energy system modelling, scenario analysis and data of the selected case. The first step aims to find the key parameters that would substantially affect the profitability of the heat network. Fig. 1 schematically shows the method applied in the first step. We assume two options: either that an investment in the SK (Stenungsund – Kungälv) and/or SKG (Stenungsund – Kungälv – Gothenburg) pipelines will not be made ("no connection"), or that the operation of the SK and/or SKG pipelines will be possible from 2025 if investments in these pipelines are profitable ("connection"). We design two main policy scenarios (see Section 3.2) and six sensitivity cases (see Section 3.2). Then, we apply an energy system model to generate future developments of the DH sector for each scenario/sensitivity case for the "no connection" and "connection" options, respectively. Next, we assess the difference, in terms of heat supply technologies, total system costs and total CO_2 charges,

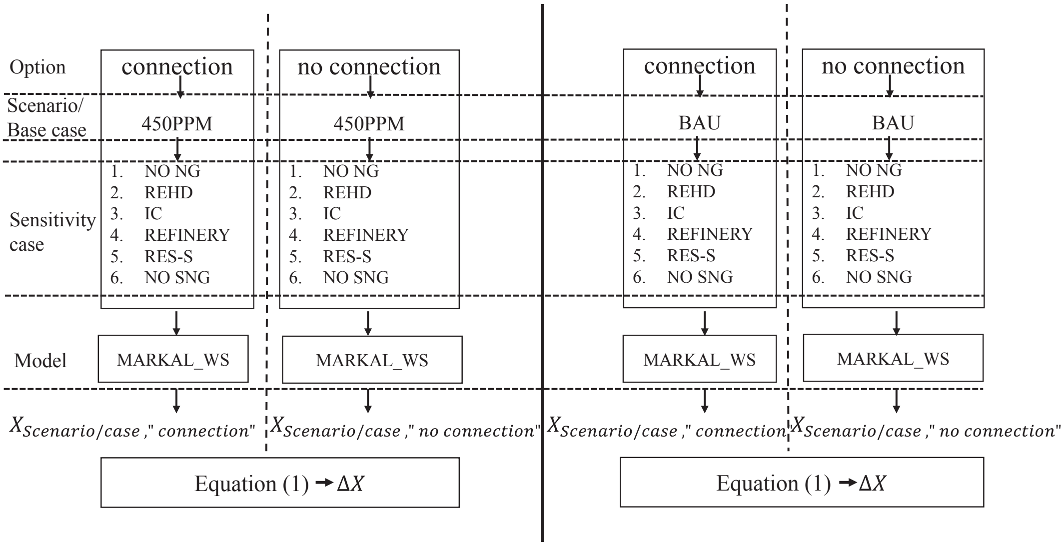

Fig. 1. Method applied in the first step. See Section 3.1 for the model description and Section 3.2 for the description of scenarios and sensitivity cases. Abbreviations: NO NG, no natural gas; REHD, reduced heat demand; IC, investment cost; RES-S, renewable energy sources support; NO SNG, no synthetics natural gas.

between "connection" and "no connection" for each of the scenarios/sensitivity cases as:

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

where X represents DH production or total system cost. Thus, 'ΔX' represents the impacts of the large heat network construction on DH production technologies, total system costs and total CO_2 charges. Furthermore, the system profitability of the heat network is calculated as negative of the sum of the 'Δtotal system costs' and 'Δtotal CO_2 charges'.

The second step aims to deepen the knowledge about the key parameters that affect the system profitability of the heat network by taking into account the results of the scenario and sensitivity analyses of the first step. In other words, the results of the first step create a foundation for the deeper analysis of the heat network system profitability. We apply a systematic sensitivity analysis where we design a matrix of sensitivity cases. The axes of the matrix consist of incremental change of parameters that were found (in the first step) to be critical for the system profitability of the heat network. Then, each element of the matrix represents various combinations of sensitivity cases. For each of these, the heat network system profitability is presented in a ranking order. Moreover, in order to develop a basis for comparison between the sensitivity cases in terms of the system profitability of the heat network, in the second step, the investments in the pipelines (i.e. in the "connection" option) will only be allowed in 2025.

Our assessment of the heat network impact represents a broader systems approach taking both the stationary energy sector and the transport sector into account where the two sectors are allowed to compete for the regionally available biomass resources. In this way, the assumption of a regional biomass market and the profitability of the investment in the new infrastructure become linked. With the assumption that the DH sector seeks to minimize the total cost of heat production through the choice of cost-effective technologies and resources, a dynamic cost-optimizing energy system model can be used for estimating the system response to an intervention (e.g. construction of a large heat network between industries and DH systems). To make a regional assessment possible, we need the model to represent the technical and economic aspects of both the individual DH systems in the VG region and the heat network that allows for long-distance transmission of EH between the cluster and the Gothenburg/Kungälv DH systems. The model is described in Section 3.1.

Our study is part of a larger project including two other studies, addressing the cost of heat extraction within the cluster of chemical industries and market models that could make the necessary heat investments possible. Where required, information is shared between the three studies. There is also a strong stakeholder involvement in the project.

3.1. Model

We choose a computer-based model for our energy system assessment. The modelling approach enables evaluation and comparison of economic, environmental and technical aspects of studied systems quantitatively under different conditions and scenarios. MARKAL [25], a well-established cost-optimizing bottom-up model generator, comprises the properties required for this assessment. In MARKAL, an objective function minimizes the total system cost within a large number of constraints, generally through LP (linear programming). In this study we apply, adapt and further develop, the MARKAL_West_Sweden (MARKAL_WS) model application. This model, which represents the energy system of the VG region, was originally developed and applied in earlier studies [17,26,27].

The current version of MARKAL_WS has a time horizon from 2010 to 2050, which is divided into nine model periods (i.e. the length of each time period is 5 years). It is comprised of 37 DH systems with different system characteristics, such as demand levels, installed capacities and energy technology options. Each DH system is described in great detail in regard to available technologies and investment options for DH generation. In addition to HOBs and heat pumps, the model representation also includes CHP technologies and two bio-refineries with transport biofuel (SNG (synthetic natural gas)) as their main output (Table 1). Other parts of the energy system, such as fuel extraction and end-use technologies, are described in a less detailed way in the model.

Including perfect foresight and demand inelasticity the objective function of the model is the cost minimization of DH

Table 1
Cost[a] and performance data for DH production technologies, based on [27] and references therein.

Technology	Conversion efficiency[b]		Specific investment cost[c]	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[d]
	Heat [%]		**[kEUR/kW heat]**	**[% of inv. cost/year]**	**[EUR/MWh fuel]**
Heat plants					
Gas HOB	90		0.05–0.1	2.5	0.7
Biomass HOB	110		0.34–0.56	1.5	2.0
Oil HOB	90		0.09–0.17	2.5	0.7
Heat pump	300 (COP)		0.70	0.5	0.7
	SNG [%]			**[MEUR/year]**	**[EUR/MWh biomass]**
Bio-refinery plants					
SNG[e]	67–70			2.3	3

ST CHP, Steam turbine combined heat and power; HOB, heat-only boiler.

[a] In this paper, a currency exchange rate of 9 SEK = 1 EUR is used.

[b] Efficiencies are based on lower heating value.

[c] 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).

[d] Including income from waste disposal fee, estimated at 22 EUR/MWh_{waste}.

[e] Two SNG plants are included in the modelled Gothenburg DH system. Their capacities are 100/150 [SNG_{out}/biomass $_{in}$] and 20/3/30 [SNG_{out}/$heat_{out}$/$biomass_{in}$]. Both of these plants are part of the GoBiGas project [19] but until today (2015) only the smaller of these has been constructed. The investments in both these plants are in the model assumed as sunk costs. The operation hours of the larger of these is assumed to be equal to 8000 h/yr, independent on DH, in the both "connection" and "no connection" options. The operation hours of the smaller plant is calculated endogenously in the model, included in the DH supply optimisation in the VG region. Fixed/variable O&M costs are based on [51].

production in the VG region over 40 years. Credits for selling electricity and transport biofuels at exogenously assumed prices are taken into account. In the model, the total cost of the energy system is optimized with regard to an individual demand for DH in each DH system. The duration curve of DH is defined by four seasons, and day and night. The four seasons are: summer (5 months), winter (2 months), cold winter (1 month) and spring/autumn (4 months). We assume that the DH demand is inelastic, independent of price fluctuations.

For the purpose of this study, model development and updates were required for the SK and SKG pipelines and also with regards to the extraction of EH-CCIS (EH from the Cluster of Chemical Industries in Stenungsund). Investments in the pipelines and in the EH-CCIS extraction can only be made at discrete capacity levels and, thus, these investment options change the linear LP model (i.e. technologies can be built at any capacity level, disregarding economies of scale) into a MIP (mixed-integer programming) model.

3.2. Model scenarios and sensitivity cases

Two main policy scenarios are simulated as our base cases based on the IEA (International Energy Agency) WEO (World Energy Outlook) [28]. One scenario with ambitious climate targets in line with a 2-degree maximum global warming is referred to as the 450 ppm scenario, hereafter "450PPM". The other scenario, referred to as New Policies scenario (hereafter "BAU" (business-as-usual)), is less ambitious but takes account of broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse gas emissions and plans to phase out fossil fuel subsidies, even if the measures to implement these commitments have yet to be identified or announced. Energy policies and prices are then implemented accordingly for each scenario in our study (Sections 4.1 and 4.2). Fossil fuel prices utilised in the 450PPM and BAU scenarios are based on the 450 ppm and New Policies scenarios of the IEA WEO [28] (Table 2) and are thus consistent with the respective climate policies.

In both main scenarios a model discount rate of 5% is used for all kinds of investments. There is no scientific agreement on which social discount rate to use but recent studies on investments in DH systems (e.g. Refs. [26,29]) have used a discount rate of 5–6% reflecting a societal rather than business perspective.

In the base cases, the heat demand is assumed to be constant from 2010 to 2050 representing a future where possible expansions of the DH grids equal heat demand reductions due to building energy efficiency measures. Furthermore, we assume that by 2025 the oil refineries in Gothenburg will no longer deliver EH to the Gothenburg DH system, strongly reducing the amount of locally available EH. However, despite choosing this option for the base case, we do not regard this as more likely than the alternative and, therefore, as a sensitivity case, the continued EH delivery from local refineries, as shown below in (4), is assumed.

In the first step of our assessment six 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. Except for these parameters, the sensitivity cases apply the same conditions as in the 450PPM and BAU scenarios.

(1) The NO NG sensitivity case reflects a local political ambition, which asks for phasing out of the NG use in the region until 2030 [30].
(2) REHD (The Reduced Heat Demand) sensitivity case represents a decreasing DH demand, linearly decreasing by 10% between 2010 and 2030 followed by an extra 10% reduction between 2030 and 2050 [31], in line with a recent study [32] showing that a high application of energy conservation measures and heat pumps in the buildings would lead to a 20% decrease in total DH demand from 2007 to 2025.
(3) The IC (Investment Cost) sensitivity case delineates a much lower investment cost of the SK and SKG pipelines for different capacities based on a report from the Swedish District Heating Association [33] (Table 3).
(4) The REFINERY sensitivity case, represents a longer lifetime for the refineries in Gothenburg in which these refineries are available and supply EH to the city's DH system until 2050.

Table 2
Summary of main assumptions and input data for the 450PPM and BAU scenarios.

		450PPM	BAU
Policy tools		**2010/2020/2030/2040/2050**	**2010/2020/2030/2040/2050**
CO$_2$ charge	EUR/tonne	16.9/25.2/68.4/110/153	16.9/14.4/23.8/33.5/43
Renewable electricity subsidy	EUR/MWh	20/20/0/0/0	20/20/0/0/0
Energy prices/costs[a]			
Natural gas	EUR/MWh	28.7/28.3/25.1/22/18.5	28.7/29.2/30.2/32/33
Fuel oil, light	EUR/MWh	64.2/64.7/61.8/58/54.9	64.2/66.2/70/75/80
Fuel oil, heavy	EUR/MWh	41.6/42/39.8/37.2/34.6	41.6/43.1/46/50/53.5
Wood chips/forest residues	EUR/MWh	SC/SC/SC/40.5/55	SC
Energy forest (willow)	EUR/MWh	20/20/20/40.5/55	20
Wood pellets	EUR/MWh	35/44/50/59/78	35/41/45/50/53
Excess heat	EUR/MWh	0.56	0.56
Electricity			
Winter cold (1 month)	EUR/MWh	70/97/113/119/119	70/87/96/101/106
Winter (2 months)	EUR/MWh	64/89/103/109/109	64/80/88/93/97
Spring and fall (4 months)	EUR/MWh	50/70/81/86/86	50/63/69/73/76
Summer (5 months)	EUR/MWh	36/49/58/61/61	36/44/49/52/54
Biofuel/SNG	EUR/MWh	53/73/80/87/94	53/71.3/76.5/83/88.9
Others		**2010/2020/2030/2050**	**2010/2020/2030/2050**
Land available for energy forest	Ha	1000/18950/36900/36900	1000/18950/36900/36900
Refineries in Gothenburg		No excess heat delivery by 2025	No excess heat delivery by 2025
Natural gas import		Allowed until 2050	Allowed until 2050
Heat demand		Constant (at 2010 level)	Constant (at 2010 level)

SC, Supply curve (see Fig. 2).
For the parameter values, which are not constant over the whole model time period, values for different time steps between 2010 and 2050 are given (separated with/).
[a] Energy prices are representing payments by DH plants and are based on output from the ENPAC model [35] (only biofuel/SNG price is payment at filling stations). CO$_2$ charges are not included in the fossil fuel prices. For excess heat, the value represents an assumed minimum compensation for excess heat providers over and above the technical costs of bringing the heat to the DH system – it does not represent a market price.

TTable 3
Cost and input data assumptions for the EH-CCIS utilisation in the Kungälv/Gothenburg DH systems in the 450PPM and BAU scenarios and the IC sensitivity case.

		450PPM & BAU	IC
		Investment [44]/Variable O&M Cost [45] [EUR/m]/[EUR/MWh heat]	Investment [44]/Variable O&M Cost [45] [EUR/m]/[EUR/MWh heat]
SKG pipeline (55 km)	Cap $\leq$ 50 MW	1800/0.25	1100/0.25
	50 < Cap $\leq$ 100 MW	2200/0.12	1200/0.12
	100 < Cap $\leq$ 150 MW	2600/0.08	1300/0.08
SK pipeline (35 km)	Cap $\leq$ 50 MW	1800/0.16	1100/0.16
		Investment cost (80/50 hot water) [47] [MEUR]	Investment cost (80/50 hot water) [47] [MEUR]
EH-CCIS extraction	Cap $\leq$ 20 MW	4.4	4.4
	20 < Cap $\leq$ 40 MW	6.7	6.7
	40 < Cap $\leq$ 60 MW	12.8	12.8
	60 < Cap $\leq$ 80 MW	20.6	20.6
	80 < Cap $\leq$ 100 MW	26.7	26.7
	100 < Cap $\leq$ 120 MW	37.8	37.8
	120 < Cap $\leq$ 140 MW	51.1	51.1
	140 < Cap $\leq$ 150 MW	61.1	61.1

Abbreviations: Cap, capacity; IC, investment cost.

(5) The RES-S (Renewable Energy Sources Support) sensitivity case, only applied to the 450PPM scenario, reflects concerns about the sufficiency of CO$_2$ emissions reduction policies to foster renewable energy sources (see Ref. [34]). In this sensitivity case, renewable power generation is encouraged through the allocation of a constant renewable electricity generation subsidy, equal to the 2010 subsidy, until the end of the studied time horizon, 2050.

(6) The NO SNG sensitivity case represents a single-sector perspective, with no transport biofuel production option and thus no alternative regional biomass demand. This approach represents a narrower systems approach, which includes only the stationary energy sector represented by the DH systems in the region.

In the second step, i.e. the systematic sensitivity analysis as described in Section 3, the sensitivity case LO FUEL, reflecting a development with generally lower international fuel and electricity prices where all fuel and electricity prices decrease by 50% independent of climate policies, is assessed.

4. Input data assumptions

4.1. Energy markets

Three types of biomass resources are represented in the model: wood chips from forest residues (tops, branches and stumps) and energy forests (willow plantations),[1] and wood pellets. Forest

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[1] The authors acknowledge that the energy content of wood chips from forest residues and energy crops varies due to their moisture content. However, in this study, for simplification purposes, they are treated in the same way.

residues and energy forests are assumed to be supplied locally until 2030. From that year in the 450PPM scenario it is assumed that an international biomass market has developed as a consequence of strongly increasing biomass demand due to stringent climate targets while in the BAU scenario, the local supply is assumed until 2050. The wood pellets market is assumed to be international with unrestricted availability due to import possibilities. Wood pellets prices are related to the wood chips price and calculated by a method presented in the ENPAC (Energy Price and Carbon Balance Scenarios) tool [35], using data consistent with our policy scenarios (Table 2).

Supply curves, representing the regional potential (in VG) and production cost of forest residues [36,37] are included in the model. The supply curves are modelled as stepwise variations in the production (e.g. Fig. 2). Energy forest yields are assumed as 28 ha/GWh [38] and, in the model, its price equals the production costs, 20 EUR/MWh [39]. The land currently used for energy forest cultivation in VG is assumed as 900 ha based on [40]. In the model, the future potential area for energy forest cultivation is allowed to increase and in 2030 it reaches 36,900 ha, equal to the lay-land available in VG [41].

Since the electricity system is international rather than regional, electricity prices are treated exogenously (i.e. as input data to the model). The ENPAC tool [35] generates yearly average electricity prices for each of the scenarios. Seasonal electricity prices are then calculated by assuming that the relative seasonal electricity price deviations from the annual average are equal to the 2010 relative deviations (Table 2).

It is assumed that SNG can be sold as transport fuel at a price equal to 80% of the filling station diesel price. This lower SNG price is in accordance with the historic difference between diesel and gas prices, and reflects the higher cost of gas vehicles compared to diesel vehicles. Two levels of SNG distribution costs are included in the model representing distribution through the available NG grid in VG (28 EUR/MWh) and by trucks (39 EUR/MWh). The lower cost distribution supply is limited in the model and is assumed to increase linearly from 0.43 TWh in 2010 to reach 1.73 TWh in 2030, see also [27]. In accordance with the scenario dependent diesel price, also the SNG price differs between the scenarios (Table 2).

4.2. Energy policies

A simplified energy policy situation is simulated consisting of only a CO_2 emissions charge and a subsidy for renewable electricity generation. Since international and national energy policies regulate the regional energy policies, these are in the model defined in an exogenous way (i.e. as input data). They are included in all model scenarios and cases. The CO_2 charge is assumed to increase linearly during the studied period in the main scenarios, which is in line with the 450 ppm and New Policies scenarios of the IEA WEO [28] (Table 2).

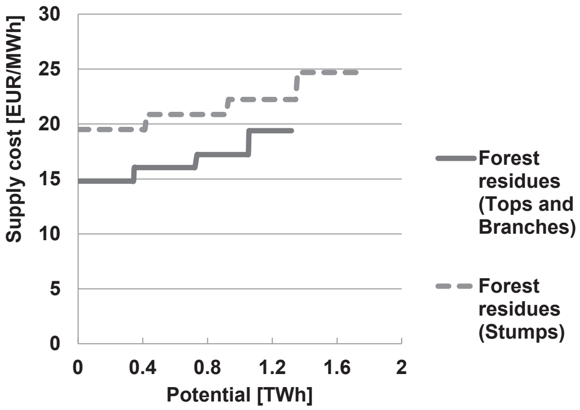

Fig. 2. Assumptions of wood chips/forest residues supply curves (2010–2020) [36,37].

The subsidy for renewable electricity in 2010 is equal to the historic TGC (tradable green certificate system) costs (20 EUR/MWh) [42], but is assumed to be phased out in a linear fashion from 20 EUR/MWh to zero between 2020 and 2030. After 2030 until 2050, this subsidy is assumed to be zero. This phase-out of the renewable electricity subsidy is in line with the idea of it being a temporary support with increasing CO_2 charges between 2030 and 2050 supporting renewables instead (e.g. Ref. [43]) (Table 2).

4.3. Large heat network

The investment in the SK and SKG pipelines is modelled at three discrete capacity levels. The investment costs are based on [44] and the pipelines operation and maintenance costs are estimated based on [45] for each heat delivery level (Table 3). A technical lifetime of 30 years is assumed for both the investments in the SK and SKG pipelines and in the EH-CCIS extraction.

The circulation pumps required to circulate the hot water in the pipeline produce heat energy by friction in the pipes. This friction 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 [5]. For the SKG and SK pipelines the total pumping power, required to circulate the water, is different. While the power demand for the SKG pipeline is estimated to be 9.2%, 8% and 8% of the heat delivery at 50 MW, 100 MW and 150 MW capacities, respectively, it is only 5% of the heat delivery at the 50 MW capacity for the SK pipeline [46].

Data for the investment cost of the EH-CCIS extraction was obtained from Ref. [47] as a non-linear function of capacity for hot water supply and return temperatures of 80 and 50°, respectively. In the model, this cost curve is modelled as stepwise variations of the capacity levels (i.e. eight discrete capacity levels) so as to better represent the non-linear function (Table 3).

5. Results

Fig. 3 shows the model results of the “no connection” option for the two scenarios. The development in 450PPM and BAU is similar until 2040, with large shares of biomass and NG CHPs, while only in 450PPM heat pumps have a dominant role towards the end of the studied time period.

In the study, the closing down of the oil refineries in Gothenburg was assumed and this opens opportunities for investments in the large heat network in 2025. The model chooses to invest in industrial excess heat extraction of 150 MW combined with investment of 150 MW in the SKG pipeline capacity in both the 450PPM and the BAU scenarios. These investments enable over 1 TWh/year of EH-CCIS utilisation in the Gothenburg and Kungälv DH systems. On average only 12% of the EH-CCIS is supplied to the Kungälv DH system, equal to the entire heat demand in Kungälv from 2025. The rest of the EH-CCIS (i.e. 88%) is supplied to the Gothenburg DH system. The model results show that it is not cost-effective to construct the SK pipeline. The reason is that the heat demand in Kungälv is considerably smaller than in Gothenburg. The EH-CCIS supply to the DH systems would to a larger extent replace both biomass, NG CHPs and heat pumps in 450PPM whereas in BAU it substitutes a larger share of NG CHPs and heat pumps (Fig. 4).

5.1. Profitability of the heat network

Investments in the EH-CCIS extraction and the SKG pipeline are done when the sum of Δ system cost and Δ CO_2 charges in the VG

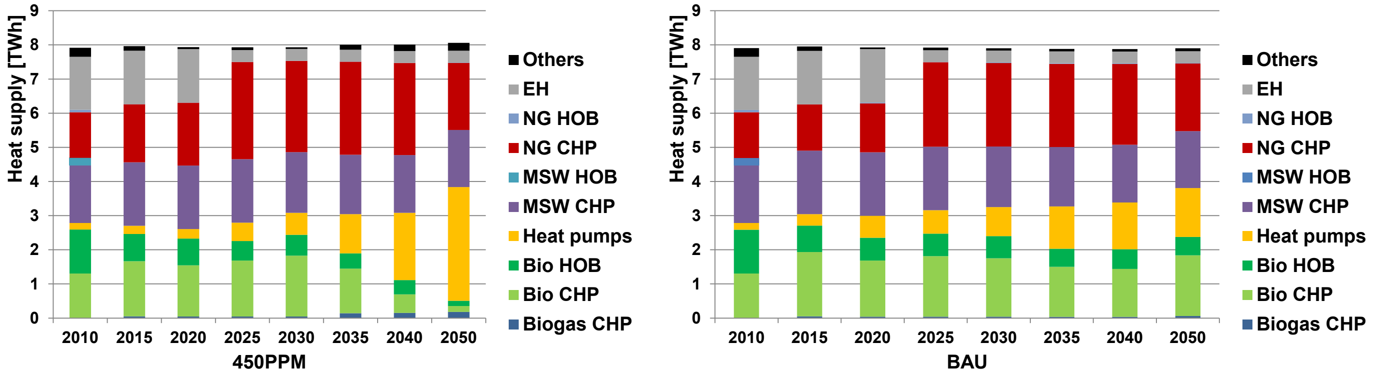

Fig. 3. Heat supply in the VG region in the "no connection" option of 450PPM (left) and BAU (right).

region is negative. The system profitability of the investments is shown with the black dots in Fig. 5. For the base cases, with EH-CCIS utilisation in the VG region, the system cost of the DH supply increases by 100 MEUR in the 450PPM scenario and by 13 MEUR in the BAU scenario (blue bars in Fig. 5). In 450PPM, the sum of CO_2 charges decreases by 190 MEUR but only half of this in BAU (red bars in Fig. 5). This reduction in CO_2 emissions charges is due to less use of NG in the DH supply, particularly in the 450PPM scenario.

It should be noted that the presented aggregation of the CO_2 charges indicates cost for the DH sector but since we have not specified which form the CO_2 charges take, taxes or tradable permits, we cannot conclude if they also correspond to revenues for the government. In other words, the results indicate that the pipeline is profitable for the system studied but not necessarily for the entire country if they (i.e. the red bars in Fig. 5) mean lost tax revenues. On the other hand, the society as a whole benefits from the reduced CO_2 emissions.

5.1.1. *Key parameters of the heat network system profitability*

Our sensitivity analyses (presented in Fig. 5) illustrate that only in the REFINERY case of the BAU scenario is the construction of a large heat network not cost-effective. In this case, the relative abundance of EH in the base load of the Gothenburg DH system reduces the need for other sources of DH. The REFINERY case highlights that in the base case the assumed closing down of the oil refineries in Gothenburg plays a key role in motivating investments in the large heat network between the Stenungsund's industries and the Kungälv and Gothenburg DH systems. In the IC (Investment Cost) case, the system profitability of the heat network substantially increases due to the reduced investment cost of the SKG pipeline that decreases the system cost. In the NO NG case considerable cost savings occur as a consequence of the connection due to the reduced need for heat pump investments and resulting reduced electricity demand.

Furthermore, if the large heat network investments are cost-effective, the model chooses the highest capacity level of the SKG pipeline, 150 MW, in all cases. However, the system profitability of the large heat network investments is case dependent with regards to the investment timing and the optimised heat extraction capacity. In REHD (Reduced Heat Demand), RES-S and NO SNG of BAU, the heat extraction capacity is reduced by 10 MW but still occurs in 2025. Since the model can only choose between three pipeline capacity levels while it can choose between eight heat extraction

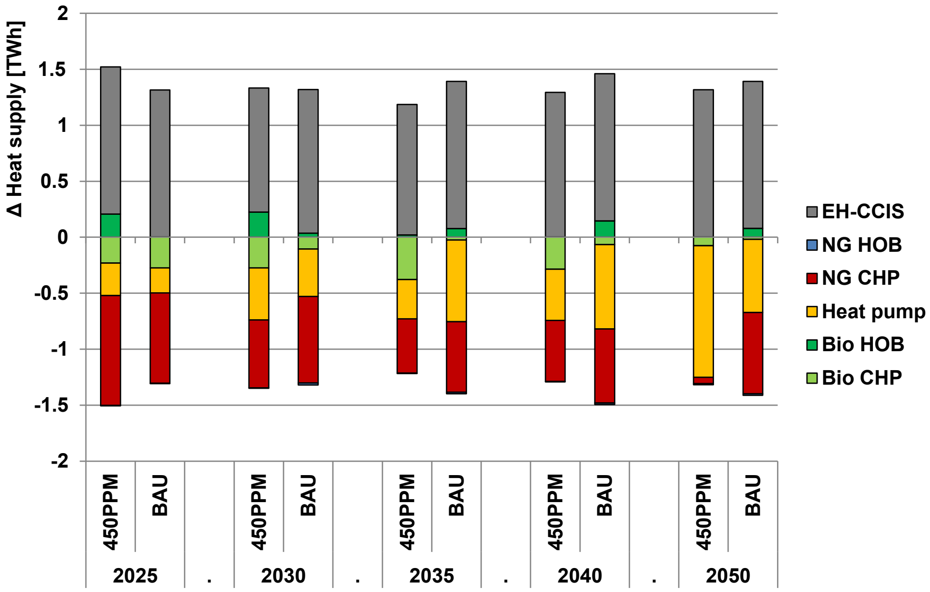

Fig. 4. Consequences for the DH supply in the entire Västra Götaland region of the EH-CCIS utilisation (CHP, combined heat and power; HOB, heat only boiler; NG, Natural gas; Bio, biomass; EH-CCIS, excess heat of the cluster of chemical industries in Stenungsund).

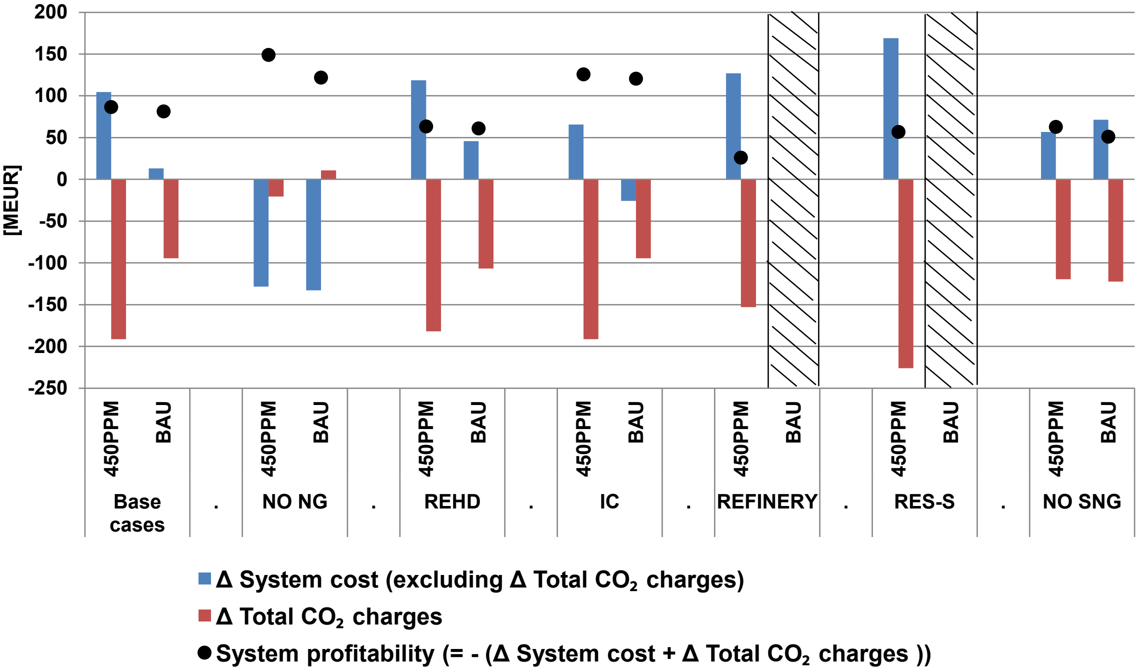

Fig. 5. Consequences for system cost and system profitability in Västra Götaland of the EH-CCIS utilisation. The two hatched areas in the figure indicate entirely different issues. While for $BAU_{REFINERY}$ the hatched area indicates that the heat extraction and pipeline investment is not profitable and, therefore, no pipeline is built by the model in the 'connection' option, the hatched area in BAU $_{RES-S}$ indicate that the sensitivity analysis was deemed not applicable as described in Section 3.2.

capacity levels, the non-identical optimum capacity levels of 150 MW pipeline combined with 140 MW heat extraction are achieved. In NO SNG of 450PPM the heat extraction capacity is 150 MW but it is delayed by 10 years due to less competition for the low-cost regional biomass.

As described in Section 3, based on these initial sensitivity results, first the most important parameters for further analysis are selected then a systematic sensitivity analysis is carried out. The REFINERY, IC, NO NG and NO SNG sensitivity cases were selected and complemented by the LO FUEL sensitivity case as already mentioned (see Section 3.2). In the systematic sensitivity analysis the X and Y axes of the matrix represent incremental changes to REFINERY and IC. The base case, LO FUEL, NO NG and NO SNG cases and the four combinations of these are chosen as the elements of the matrix. For each of these, the heat network system profitability is presented in a ranking order in Fig. 6.

5.1.2. *Systematic sensitivity analysis of the heat network system profitability*

The results of our systematic sensitivity analysis, shown in Fig. 6, illustrates that the system profitability of the heat network strongly decreases if the DH systems are the only users of unrefined biomass in the region (i.e. the NO SNG case). The lack of a competitor for biomass use in the region leads to unprofitability of the heat network if the investment cost increases or the EH capacities of existing refineries remains (Fig. 6).

The profitability of the heat network is highly dependent on future energy markets. Low fuel and electricity prices (i.e. the LO FUEL case), elimination of NG use (i.e. the NO NG) and any combinations of these two cases increase the profitability of the investments in the heat network even in cases where the remaining EH capacity of the refineries is high. Therefore, decision makers at energy companies and chemical industries need to be aware of local political decisions on NG use and also on changes in the European electricity market as a result of, for example, renewable electricity developments.

6. Discussion and conclusions

The district heat supply optimisation in the entire VG region including investment options for the use of EH from the Stenungsund chemical cluster in nearby DH systems leads to new investments in a large heat network in most of the combinations of scenarios and cases analysed. The investments include heat extraction capacity within the chemical cluster and the heat pipeline between Stenungsund and Kungälv/Gothenburg at the capacity of 150 MW (the highest available in the study) in most but not all of the tested cases.

The large heat network investments depend on the scenario assumptions and on the energy system perspective applied. The results illustrate that the economic viability of the heat network depends on future CO_2 emissions charges, fuel and electricity prices and biomass markets. The future availability of other excess heat sources in or near the DH system is also important for the economic viability of the heat network, since such heat sources compete with heat from the Stenungsund cluster in the base load segment of the DH system.

Competition over the available unrefined biomass (in the model represented both by an inter-sectoral perspective by including regional transport biofuel production in both scenarios and by an assumed development of an international biomass market in the 450PPM scenario) is important for the economic benefits of the heat network. Climate policies aiming at reducing the environmental burden of energy systems as well as policies aiming at increasing the share of local fuel use in the national energy systems are more likely to lead to future competition for this biomass. Our results show that when transport biofuel production is included in the regional heat supply optimisation, the profitability of investments in the heat network increases. However, when the heat

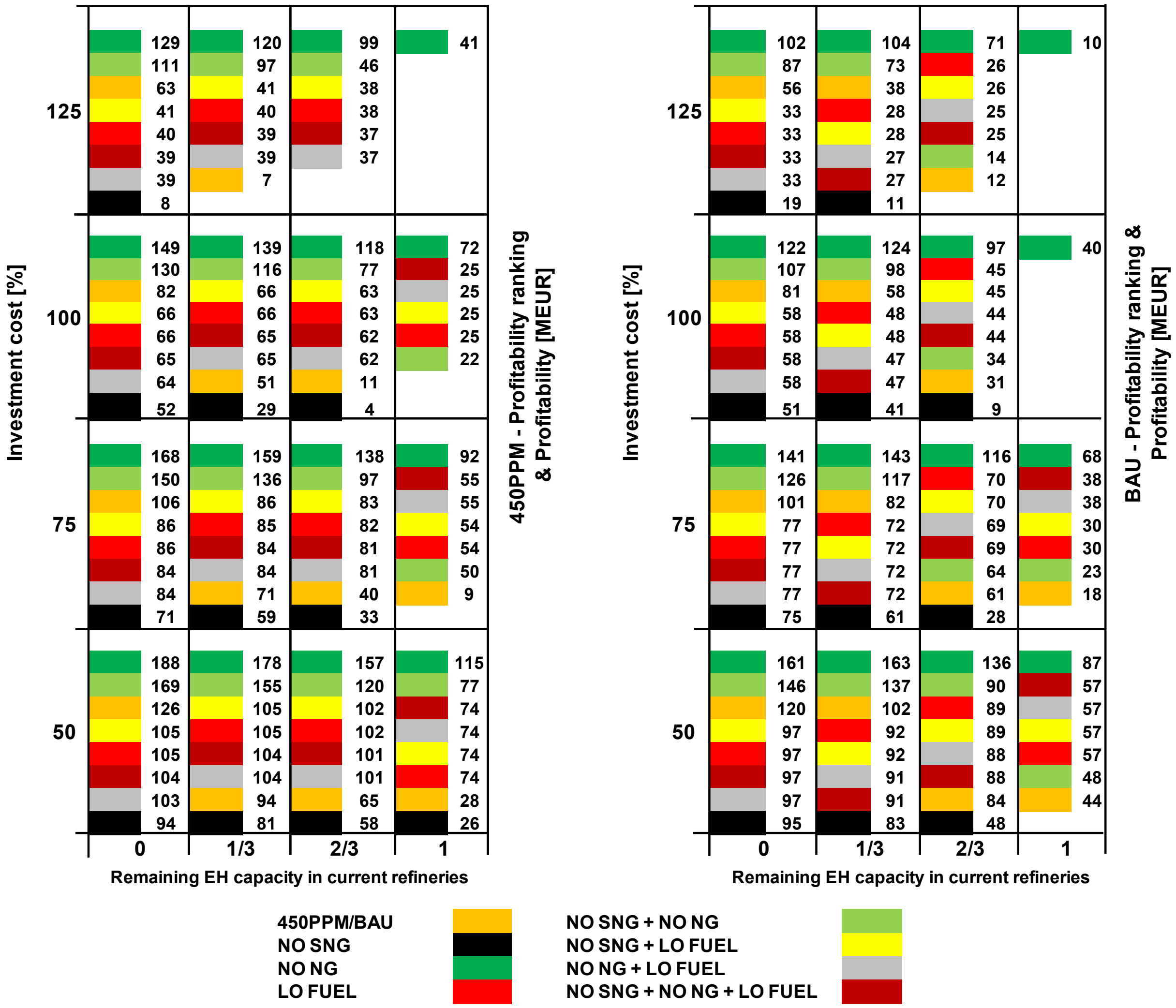

Fig. 6. Systematic sensitivity analyses of the 450PPM (left) and BAU (right) scenarios (The X-axis represents various shares of the total EH capacity of oil refineries in Gothenburg and the Y-axis represents deviations of investment costs of the SKG pipeline from the ones assumed in the base case). The system profitability is calculated and presented only if the model is actually investing in the SKG pipeline.

supply optimisation ignores the alternative use of the regionally available biomass, the heat network investments are unprofitable when both the EH capacity of refineries and the cost of investments are high. Thus, stakeholders need to be aware of other investments that would compete for the regional biomass.

A ban on the use of NG in the DH system starting in 2030 contributes to the profitability of the heat network and in this case, the investment in the large heat network is profitable even for the combination of a high investment cost of the heat network and full EH delivery of refineries. Therefore, the local political ambition to phase out NG use in the region is consistent with large-scale EH use and industrial EH heat recovery.

Variation of interest rates were not directly analysed, however, their impacts were illustrated by including various investment cost levels in our systematic sensitivity analysis. Low interest rates reduce the capital cost of the investments, generally increasing the competitiveness of the large heat network. While lower interest rates for these investments are not in line with excess heat providers' pay-off time for energy efficiency measures, they can be motivated by the fact that the technical lifetime of DH networks often reaches 50 years and face relatively low market risks.

The utilisation of over 1 TWh/year of excess heat increases the competitiveness of the industries of the chemical cluster compared to similar industries not having access to an EH infrastructure. This extra revenue for the EH delivering companies combines with reduction of costs of EH cooling, and also with avoided costs of CO_2 allowances since EH supply to DH system is qualified for free allocation of CO_2 allowances according to the EU-ETS post 2012 [48].

The chemical cluster currently uses fossil fuels as its energy source. Thus, the utilisation of the EH originating from use of fossil fuels in the DH systems can be argued to increase CO_2 emissions in the heat sector. However, actually the system consequences of EH use in DH systems on CO_2 emissions depends on what other sources and technologies were already supplying the DH system [17,49]. Our study results illustrate that the EH would replace a large amount of NG use in the DH systems, decreasing local CO_2 emissions. In addition, the EH would replace biomass use in the DH systems. Future competition between power, heat and transport sectors for biomass use would likely make long distance biomass transport an economically viable option. Consequently, the unused biomass in the region could substitute fossil fuels in DH systems outside the region or in other energy sectors (e.g. transport sector), resulting in global CO_2 emission reduction.

The profitability of EH supplying industries may change with time and decreased or discontinued EH deliveries would result in a loss of heat supply to the DH systems. In this way, EH collaborations imply increased supply uncertainty. These risk issues were not covered in this study. However, the literature presents actions which can be interpreted by a DH company as a kind of guarantee indicating reduced supply risk. First, when EH supplying industries are willing to take a large share of the common pipeline investments; and second, when industries make other large investment in their facilities for totally different purposes [12]. In our case, the Stenungsund chemical cluster has expressed plans for large investments aiming at developing sustainable chemistry by 2030 [50]. These plans, independent of the excess heat extraction, could be interpreted at least as an expression of an ambition to stay in business for an extended time period, thereby decreasing the risk of DH supply disruptions.

The MARKAL model applied in this study becomes short-sighted at the end of the time horizon (i.e. 2040–2050) since running costs are not taken into account beyond the model time horizon. Therefore, we acknowledge that the model results towards the end of the studied time horizon should not be taken at face value (e.g. the large investments in heat pumps during the last model years). One way to overcome this problem is by extending the model time horizon by 10 years in order to capture systems changes beyond the studied time perspective.

The presented study is using a specific EH resource in the region of Västra Götaland as its selected case. The same method can be applied to other EH heat resources and regions but the outcomes of the study are likely case dependent. However, in order to test the robustness of the results, we developed and applied a two-step sensitivity method to test our results under a wide range of changing parameters and conditions. This may also be regarded as a test of the generalizability, since the wide range of conditions may also represent other, while not all, DH systems.

To conclude, long-distance transmission of excess heat in a heat network requires large investments. Such investments are likely to be profitable if the excess heat replaces DH that is primarily supplied by costly primary energy sources. The investments are less likely to be profitable from a systems perspective if other sources of excess heat contribute to a large share of the DH base load and if there is an abundance of locally available low cost biomass.

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References

[1] Persson U, Werner S. District heating in sequential energy supply. Appl Energy 2012;95(0):123–31.

[2] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88(3):568–76.

[3] Energy Roadmap 2050. European Commission. 2011. http://ec.europa.eu/energy/energy2020/roadmap/index_en.htm (accessed 09.05.14).

[4] Connolly D, Lund H, Mathiesen BV, et al. Heat roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89.

[5] Frederiksen S, Werner S. District heating and cooling. 1st ed. Lund: Studentlitteratur AB; 2013.

[6] SEA. Energy in Sweden 2011. Eskilstuna: Swedish Energy Agency; 2011.

[7] GoBiGas, GöteborgEnergi, http://gobigas.goteborgenergi.se/En/About_us, (accessed 09.05.14).

[8] Burman Å, Brändström L. GoBiGas Estapp1. Gothenburg: Göteborgs stad; 2012. p. 43.

[9] Holmgren K. Role of a district-heating network as a user of waste-heat supply from various sources – the case of Göteborg. Appl Energy 2006;83(12):1351–67.

[10] Ajah AN, Patil AC, Herder PM, Grievink J. Integrated conceptual design of a robust and reliable waste-heat district heating system. Appl Therm Eng 2007;27(7):1158–64.

[11] Broberg S, Backlund S, Karlsson M, Thollander P. Industrial excess heat deliveries to Swedish district heating networks: drop it like it's hot. Energy Policy 2012;51:332–9.

[12] Grönkvist S, Sandberg P. Driving forces and obstacles with regard to cooperation between municipal energy companies and process industries in Sweden. Energy Policy 2006;34(13):1508–19.

[13] Thollander P, Svensson IL, Trygg L. Analyzing variables for district heating collaborations between energy utilities and industries. Energy 2010;35(9):3649–56.

[14] Gebremedhin A, Moshfegh B. Modelling and optimization of district heating and industrial energy system – an approach to a locally deregulated heat market. Int J Energy Res 2004;28(5):411–22.

[15] Klugman S, Karlsson M, Moshfegh B. Modeling an industrial energy system: perspectives on regional heat cooperation. Int J Energy Res 2008;32(9):793–807.

[16] Karlsson M, Gebremedhin A, Klugman S, Henning D, Moshfegh B. Regional energy system optimization - potential for a regional heat market. Appl Energy 2009;86(4):441–51.

[17] Sandvall AF, Börjesson M, Ekvall T, Ahlgren EO. Modelling environmental and energy system impacts of large-scale excess heat utilisation – a regional case study. Energy 2015;79(0):68–79.

[18] Morandin M, Hackl R, Harvey S. Economic feasibility of district heating delivery from industrial excess heat: a case study of a Swedish petrochemical cluster. Energy 2014;65:209–20.

[19] Knutsson D, Sahlin J, Werner S, Ekvall T, Ahlgren EO. HEATSPOT – A simulation tool for national district heating analyses. Energy 2006;31(2–3):278–93.

[20] Difs K, Trygg L. Pricing district heating by marginal cost. Energy Policy 2009;37(2):606–16.

[21] Klugman S, Karlsson M, Moshfegh B. A Swedish integrated pulp and paper mill-energy optimisation and local heat cooperation. Energy Policy 2009;37(7):2514–24.

[22] Persson U, Möller B, Werner S. Heat roadmap Europe: identifying strategic heat synergy regions. Energy Policy 2014;74:663–81.

[23] Dalman BG. Obstacles and opportunities for a regional DH system, in Bussiness Region Göteborg Workshop. Gothenbug: Göteborg Energi; 2012.

[24] GöteborgEnergi. District heating in Göteborg (Fjärrvärmen i Göteborg)..

[25] Loulou R, Goldstein G, Noble K. The MARKAL Family of Models. Energy Technology Systems Analysis Programme (ETSAP) October 2004.

[26] Börjesson M, Ahlgren EO. Biomass gasification in cost-optimized district heating systems-a regional modelling analysis. Energy Policy 2010;38(1):168–80.

[27] Börjesson M, Ahlgren EO. Cost-effective biogas utilisation – A modelling assessment of gas infrastructural options in a regional energy system. Energy 2012;48(1):212–26.

[28] World Energy Outlook 2013. Paris: IEA (International Energy Agency); 2013.

[29] Liljeblad A, Jansson M, Nohlgren I. Regional district heating cooperations, drivers and success factors [Regionala Fjärrvärmesamarbeten, Drivkrafter och Framgångsfaktorer]. Sweden: Fjärrsyn: Energiforsk AB; 2015. p. 102.

[30] Strategic climate program for Gothenburg (Klimat- strategiskt program för Göteborg). November, 2013, Göteborg Stad Grafiska gruppen samt Dragster Kommuniktion AB: Göteborg Stad.

[31] Svernlöv A. Deparment manager cooling. Gothenburg: Göteborg Energi AB; 2014. personal communication.

[32] Göransson A, Johnsson J, Sköldberg H, Stridsman D, Unger T, Westholm E. District heating in future- demand [Fjärrvärme i framtiden – behovet]. Stockholm: Svensk Fjärrvärme AB; 2009. in 2009:21.

[33] SDHA. Kulvertkostnadskatalog (The district heating pipe cost catalog). Stockholm: The Swedish District Heating Association; 2007.

[34] Lehmann P, Gawel E. Why should support schemes for renewable electricity complement the EU emissions trading scheme? Energy Policy 2013;52:597–607.

[35] Axelsson E, Pettersson K. Energy price and carbon balances scenarios tool (ENPAC) – a summary of recent updates. Göteborg: Chalmers University of Technology; 2014. https://publications.lib.chalmers.se/publication/194812-energyprice-and-carbon-balances-scenarios-tool-enpac-a-summary-of-recent-updates.

[36] Athanassiadis D, Melin Y, Lundström A, Nordfjell T. Marginal costs for harvesting branches and stumps of regeneration fellings in Sweden [Marginalkostnader för skörd av grot och stubbar från föryngringsavverkningar i Sverige]. Swedish University of Agricultural Sciences; 2009.

[37] Athanassiadis D. Swedish University of Agricultural Sciences. Umeå: Personal communication; 2012.

[38] Rosenqvist H. Production costs for energy crops [Produktionskostnader för åkermarksenergi]36. Billeberga: SOU; 2007.

[39] SOU. Bio energy from agriculture – a growing resource [Bioenergi från jordbruket- en växande resurs]36. Stokholm: The Swedish Government Official Reports: Ministry of Agriculture; 2007.

[40] Johansson T. Biobränslen i Västra Götaland- en förstudie [Biomass in Västra Götaland- a prestudy]26. Vänersborg: The County Administration of Västra Götaland; 2001.

[41] Broberg A. Potential for biogas production in Västra Götaland [Potential för Biogasproduktion i Västra Götaland]. Vänersborg: Hushållningssällskapet; 2009.

[42] SOU, Restructuring of the energy system – final report from the Energy Commission, [Omställning av energisystemet, slutbetänkande av energikommissionen], 1995, Swedish governmental energy commission; Stockholm, 139, 1996, Norstedt; Stockholm.

[43] Unger T, Ahlgren EO. Impacts of a common green certificate market on electricity and CO2-emission markets in the Nordic countries. Energy Policy 2005;33(16):2152–63.

[44] A. Svernlöv, Göteborg energi, 2014, personal communication; Gothenburg

[45] Reidhav C, Werner S. Profitability of sparse district heating. Appl Energy 2008;85(9):867–77.

[46] J. Ahlgren, Göteborg energi, 2014, personal communication; Gothenburg

[47] Eriksson L, Morandin M, Harvey S. Targeting capital cost of excess heat collection systems in a complex industrial site for district heating applications. Energy 2015;91:465–78.

[48] Guidance document n 6 on the harmonized free allocation methodology for the EU-ETS post 2012-cross-bounday heat flows. 2011, European Commission.

[49] Ivner J, Broberg Viklund S. Effect of the use of industrial excess heat in district heating on greenhouse gas emissions: A systems perspective. Resour Conserv Recycl 2015;100:81–7.

[50] Sustainable chemistry 2030. Stenungsund chemical cluster, http://www.kemiforetagenistenungsund.se/pdf/foldereng.pdf (accessed 15.05.14).

[51] Thunman H. Chalmers University of Technology, Energy Technology Division. Gothenburg: Personal communication; 2012.