THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Large Heat Networks in District Heating Systems

– Energy System Modeling of Large-Scale Industrial Excess Heat Use

AKRAM (FAKHRI) SANDVALL

Department of Energy and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2014

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AKRAM (FAKHRI) SANDVALL

Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Abstract

District heating (DH) systems have experienced three generations since the 1880s. In chronological order, high temperature steam and pressurized hot water above and below 100 degrees have been used to carry heat over these three generations. The drive to increase energy efficiency and reduce investment costs of these systems have been the principal incentives for shifting from one generation to the other. The future development of DH systems towards the fourth generation will involve an attempt to recover heat from low-temperature sources (e.g. industrial excess heat (EH)), the use of renewable sources and the integration into smart energy systems.

In Sweden, DH currently supplies about 60% of the heat demand. For future DH developments, these systems need to be competitive compared to individual solutions (i.e. heat pumps and boilers) in supplying heat. They could also be incorporated in future sustainable energy systems by integrating renewables and establishing synergies with other energy sectors. There are currently some successful synergies between industry and DH systems but as one step towards the fourth generation of DH, industry-DH synergies could be further developed in order to recover still unused industrial EH.

Due to the diversity of Swedish DH systems in terms of local fuel use and heat demand, their choice of heat production technologies is affected. Thus, the environmental and economic impacts of DH systems-industry synergies that allow for industrial EH use in DH systems or the DH use in industrial processes have often been studied in a small geographical scale, limited to the boundaries of local DH systems. However, because it is often transported over relatively short distances, biomass as the main fuel used in DH systems has often turned into a regional market. With increasingly stringent targets for climate change mitigation, biomass use is likely becoming more attractive not only in the heat but also in the power and transport sectors. Since synergies between local DH systems and industry affect the regional market for biomass and, consequently, the power and transport sectors, a regional level combined with an inter-sectoral approach might provide a comprehensive way to identify the impacts of DH-industry synergies.

The aims of this thesis are, first, to develop a methodology for assessing an option for future DH development, i.e. a large heat network that would allow for long-distance industrial EH transmission for use in DH systems; and, second, to apply this methodology to assess energy systems, environmental and economic impacts of a large heat network between the cluster of chemical industries in Stenungsund and the DH systems of Gothenburg and Kungälv in West Sweden Region (Västra Götaland (VG)). The assessment has been carried out with the help of optimizing energy systems model MARKAL_WS, in which the DH systems in the VG Region are represented individually. In addition, options for transport biofuel production as competitors to regional biomass are included.

The thesis is based upon two papers. In the first paper, energy system and CO_2 emission impacts of the large heat network have been analyzed at a regional level. The results show that the heat network contributes to a reduction of biomass and fossil fuel use, and to a related reduction of CO_2 emissions, in the DH systems. This outcome opens opportunities for the earlier production of transport biofuels but implies decreased electricity generation from combined heat and power (CHP) plants in the Region. In the short-term, total CO_2 emissions increase, given an expanded systems view that effects on the DH systems, transport and European electricity system are accounted for, while in the mid-term they decrease.

In the second paper, the long-term system cost and marginal cost effects of the large heat network have been assessed. The results show that the heat network is profitable under most assumptions and that the profitability increases with biomass competition and the phase-out of fossil fuel use while it decreases with higher CO_2 charge, interest rates and the availability of other EH sources in the vicinity of the DH systems. The marginal cost of DH supply in the Gothenburg and Kungälv DH systems decreases during most seasons except for the cold seasons.

Keywords: Waste heat, MARKAL, Energy system modeling

List of papers

This thesis is based on the following appended papers:

Paper I: **Modeling of Environmental and Energy System Impacts of Large-Scale Excess Heat Utilization – a Regional Case Study**

Fakhri Sandvall A., Börjesson M., Ekvall T. & Ahlgren E.O., Accepted for publication in Energy (2014)

Paper II: **Economic Impacts of Large-Scale Utilisation of Excess Heat- Assessment through Regional Modelling**

Fakhri Sandvall A., Ahlgren E.O., Ekvall T., working paper (2014)

Akram (Fakhri) Sandvall is the main author of paper I and II. The following lists publications by the author not included in this thesis:

- Modeling Regional District Heating Systems – The Case of South-Western Sweden

  Fakhri A., Börjesson M., & Ahlgren E.O., *DHC13, the 13th International Symposium on District Heating and Cooling September 3rd to September 4th, 2012, Copenhagen, Denmark*

- Large-Scale Utilization of Excess Heat - Assessment through Regional Modeling

  Fakhri A., Ahlgren E.O, Ekvall T., *The 14th International Symposium on District Heating and Cooling, September 7th to September 9th, 2014, Stockholm, Sweden*

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1 Introduction

1.1 *Prospects for technological change - Past and future district heating developments*

District heating (DH) systems have experienced three generations since the 1880s. Until 1930, all DH systems established in Europe or USA were constructed based on the first generation systems in which high temperature steam in concrete ducts were distributed through heat networks. Due to large heat losses and harsh accidents from steam explosions, this generation was substituted by the second generation systems. Pressurized hot water (above 100 degrees) as the heat carrier was used in the second generation systems that emerged in the 1930s and dominated all new construction until the 1970s. The primary motivation for using these systems was to increase fuel efficiency and improve thermal comfort by utilizing CHPs. The third generation DH systems were initiated in the 1970s. Pressurized hot water, often below 100 degrees, remained the heat carrier medium for this generation. Energy-efficient heat networks and compact heat exchangers at end-users were typical components of these systems. The two oil crises motivated increasing energy efficiency through the use of CHPs and replacing oil by cheaper local fuels, e.g. coal, biomass and municipal solid waste [1].

These generations of systems are differentiated by distribution temperatures, the type of heat network components and construction methods. As a result, progress was made towards increasing energy efficiency and reducing the investment costs of these systems. In line with this trend, future fourth generation DH systems (projected 2020 - 2050) might involve lower heat carrier temperatures (i.e. 50 degrees), less grid losses and cheaper and easier construction design. These systems, moreover, may be able to recover heat from low-temperature sources (e.g. industrial excess heat (EH)), use renewable sources (e.g. solar and geothermal heat) and integrate smart energy systems (including smart electricity, gas, fluid and thermal grids) [1].

1.2 *DH systems and future challenges*

The basic idea of DH is increasing energy efficiency by utilizing local fuel or heat sources that would otherwise be wasted [2]. DH systems and their potential future improvements have been reviewed [3]. The European Commission (EC) encourages member states to identify the cost effective potential of delivering energy efficiency, mainly through the use of CHPs, efficient district heating and cooling and the recovery of industrial EH. Member states are required to analyze the costs and benefits of the alternatives that may exist. Accordingly, EC requires member states to take adequate measures to ensure their development if there is a cost-effective potential [4].

In Sweden, DH is the dominant form of heat supply and in 2011 accounted for 54 TWh (60%) of the total heat demand for space heating and hot tap water in buildings and industrial applications [2]. More energy-efficient buildings, competition and saturated markets as well as climate change were constitute external factors whereas the business strategies of DH companies were identified as internal factor causing stagnation (i.e. not growing or even starting to decline, short of phase-out) in Swedish DH systems [5]. In order to keep and also develop this market share, DH systems need to focus on customer demands; i.e. supplying affordable heat compared to alternative solutions including individual heat pumps and boilers [6]. These systems might also incorporate future sustainable energy systems by integrating renewables. Any future developments of DH systems might look to establishing synergies with other sectors [6], i.e. power, waste management, transport as well as industry and buildings, in order to increase energy efficiency and decrease primary energy use, in addition to the costs of heat supply and the environmental burden of energy systems.

In one study [7], different scenarios for opening market of DH systems by introducing third party access (TPA) were analyzed to solve the problem of imperfect competition rather than promoting the use of industrial EH. This study suggests that TPA can initially be introduced in large DH systems with extensive networks and number of production units to take advantage of the knowledge regarding the potential effects of TPA in smaller DH systems. This study concluded that a negotiated TPA might likely provide more efficient market designs, but uncertainties in terms of total system optimization exist.

Synergies between DH systems and other energy sectors have been frequently studied along different geographical and temporal scales (e.g. [8-11]). The environmental and economic impacts of industry-DH systems collaboration have often been studied in local DH systems cases (e.g. [12-14]). DH systems in Sweden, in particular show very different characteristics with regard to the choice of fuel and technology for DH production. Thus, assessments of EH utilization need to be based on specific cases in order to address real conditions and system differences.

Currently, because of high taxation of fossil fuels combined with a green electricity certificate system for renewable electricity generation, biomass contributes a large share of fuel use in Swedish DH systems both in heat-only boilers (HOB) and CHPs. Climate change mitigation policies promote biomass use not only in heat and power but also in transport biofuel production. Biomass is a renewable source of energy but is a limited resource and because it is often transported over short distances, a regional market for biomass is created. Interventions in the fuel supply of local DH systems in a region have direct impacts on these systems but due to the regional market of biomass, there are indirect impacts on other energy sectors of a region. Thus, the impacts of these interventions could be better assessed at a regional level.

Few studies have assessed the economic and environmental impacts of large heat networks, i.e. shared between several industries and DH systems. In these studies the geographical scale only included DH systems and industry. In this thesis, these impacts are assessed at a regional level in order to take the regional biomass market into account.

2 Aims of the thesis

In general, the aims of this thesis are as follows:

- Based on energy systems analysis, develop a methodology to assess of a single option for future DH developments.
- Apply the methodology developed to a real case that is vital to decision-makers

More specifically, a large heat network that allows long-distance EH transmission for use in DH systems is investigated as one option for future DH developments in Sweden. Such networks are often associated with high investment cost, financial and technical risks and lock-in effects. A comprehensive knowledge of the impacts on energy flows, CO_2 emissions, the technology and cost of DH production of building such networks is required for decision making. Thus, we aim at developing a methodology whereby this knowledge maybe generated and the methodology applied to a case in West Sweden.

2.1 Intended audience

The intended audience of this study includes researchers within energy systems analysis (modeling), experts and development planners of business associations (e.g. the DH and transport sectors), local and/or regional policy-makers and environmental NGOs.

2.2 Main limitations

Our assessment optimizes energy systems at the regional level without optimizing it for each DH system or DH supply plant. Thus, our results on energy systems impacts on industrial EH utilization do not reflect the real world if each of these systems were to optimize separately. Our assessment of environmental impacts of constructing a large heat network between industries and DH systems includes the use phase of the network, not its entire lifetime.

Furthermore, the results of our assessment are highly dependent on uncertain future fuel prices. The use of optimization models imposes limitation on the method applied which will be discussed in Section 3.3.

In this study, the temperatures and flows of forward hot water in DH systems are assumed to be equal to the demand for each season. Time resolution for heat demand in DH systems is seasonally based which means that the consequences of potential interactions between DH systems and intermittent power generation technologies are excluded from our assessment. In our energy systems assessment we include mature DH systems combined with a time perspective reaching 2050. Thus, our model is conservative in terms of systems innovation as described in Section 1.1.

3 Methodology

This study applies an inter-sectoral approach, in which environmental, energy system and economic impacts of a large heat network allowing for long-distance EH transmission for the use in DH systems are assessed with a mid- to long-term perspective at the regional level. Our inter-sectoral approach takes the interactions between DH systems, power and transport sectors into account. Our time perspective accounts for uncertainties in future energy markets and the lifetime of heat networks. The assessment is carried out by selecting a case, developing and applying a computer-based energy system model, designing future development scenarios and forming a Reference Group.

3.1 Regional approach

In energy system analysis, the choice of geographical scope (boundaries) can to a large extent affect the results and conclusion drawn. Thus, the choice of geographical scope for an energy system analysis is crucial. With a system thinking approach, any intervention in an energy system affects its surroundings. An intervention that appears to be an improvement given a narrowly defined boundary may not be seen as an improvement given the extended boundaries [15]. An improvement in an energy system may lead to failures in its surrounding system. In this case, by extending the geographical scope of an energy system analysis in order to include all interactions with other energy systems, the totality of intervention may be captured. However, such broadening of the scope adds to the complexity of the system analysis, making it difficult to interpret results. Furthermore, the more the geographical scope of analysis is extended, the more the data need to be aggregated.

Since in Swedish DH systems, unrefined biomass including forest residues and energy crops contributes a large share of fuel use, any intervention in DH systems can affect this major source of energy. Unlike fossil fuels, because it is a bulky fuel, mainly transported by trucks over short distances (in the order of 50 km [16]), unrefined biomass have a regional market. Due to its regional market, biomass is a renewable but limited source of energy. Biomass use in the heat, power and transport sectors is strongly motivated by favourable climate policies. Thus, a change in biomass use in a local DH system can affect the marginal cost of biomass and, consequently, its competitiveness in power and transport sectors in the region.

The regional approach to our energy system analysis takes the regional market of biomass into account. A region including several local DH systems that share a biomass market and interact with industry, waste management systems, power and transport sectors provides all desirable characteristics required for our energy system analysis.

3.2 Case

Case studies can be used to ask "how" and "why" questions. Such case studies can also help reveal patterns in relation to larger phenomena [17]. Studies on industrial EH use in Swedish DH systems to a large extent are based on the choice of specific cases. First, DH systems differ in terms of their size (i.e. heat supply capacity) and characteristics (i.e. fuel use and heat supply technology). Second, collaboration between industry and DH companies varies depending on these cases. In some cases, there is two-way collaboration between industry and DH systems, i.e. industrial EH utilization in DH systems and DH use in industrial processes. In other cases, due to technical limitations of industrial processes, these types of collaboration only occur in one-way, i.e. industrial EH use in DH systems.

Our case of industry-DH company collaboration is based on the current strong interest in large-scale EH from a cluster of chemical industries for use in two local DH systems (i.e. one-way collaboration) located in West Sweden. The cluster and DH systems are described in Sections 4.1 and 4.3.

3.3 Optimization models in energy system assessments

Bottom-up optimization models of energy systems have been widely used to study future energy systems developments and the environmental impacts of climate policies during the past 30 years. By describing current and future technological options both in technical and economic terms, these models represent energy sectors in detail. Often the objective function of these models minimizes the total cost of the energy system studied (e.g. to meet future energy demand) under a number of constraints. MARKAL (acronym for MARKet ALlocation) [18], is an example of these energy system models, in this study. MARKAL is strictly an energy-sector model that interacts with the rest of the nation's economy through the exogenous specifications of useful energy demands [18]. In MARKAL, energy markets are computed using the partial equilibrium method, i.e. the suppliers produce exactly the quantities demanded by the customers and the price and quantities of the different fuels are established for each time period. Moreover, all investment decisions for each period are made with the complete knowledge of future events, often referred to as "perfect foresight" [19].

The optimization models have limitations, such as the difficulty of specifying the objective function, an unrealistic linearity [20] and shortsightedness. The first limitation is deciding on an objective function including values and preferences. The conflicting goals of different groups (stakeholders) need to be identified and balanced against each other through techniques available for extracting information (e.g. interviews)[20]. The second limitation, linear programming, is introduced to simplify complex optimization problems. This assumption requires the objective function and all constraints to be linear which is invalid in reality [20]. Mixed integer programming (MIP) is used as a technique for solving non-linear optimization problems, in which some of the investments can be made at discrete levels to take the economies of scale into account [19]. The third limitation, shortsightedness, occurs because investments at any given period are optimal across the horizon of the model [19], thus the investments made at the end of the model horizon exclude fixed and variable O&M costs of the investments until their end-life. Consequently, these investments may not reflect the optimal solution and the model results at the end of the model horizon should be cautiously interpreted.

3.4 Scenario analysis

A scenario paradigm was presented for future studies for which the main purpose is constructing several future scenarios and the paths to reach them without predicting those futures [21]. Scenario studies are classified into three major categories based on the following principal questions. what will happen? what can happen? and how can a specific target be reached? [22] These questions are referred to predictive, explorative and anticipative scenarios.

Predictive scenarios make use of the forecasting approach, continuing historic trends. Such scenarios are useful for short-term analysis and for mid-term business-as-usual scenarios. Long-term perspectives increase the uncertainties surrounding energy markets, the risk of overestimating or underestimating the potential of new technological growth, in addition to radical changes in energy systems [23].

Explorative scenarios demonstrate a variety of equally reasonable developments, widening the approaches of potential future changes. These scenarios may include radical technological innovation and extensive changes in social and economic structures. The difficulties of choosing relevant scenarios and the uncertainties of estimating the costs and characteristics of new technologies might be improved by defining the criteria for selecting scenarios and for documenting the assumptions related to each scenario [23].

In contrast to predictive scenarios, anticipative scenario studies that respond to the third question, is implemented by setting high-level, long-term targets that are unreachable given current development trends. Backcasting is one example of this type of scenario which aims at finding new paths and options to achieve the development target [22]. Backcasting has been identified as an alternative scenario to resolve the uncertainties of investing decisions, e.g. technology and fuel prices until the end of the life-cycle investment options. However, an inconvenience associated with anticipative scenarios is the risk of favoring certain technologies and socio-technical systems in selecting desirable future [23].

In this study, explorative scenarios are designed to assess energy systems and the economic and environmental impacts of large heat networks. These scenarios are described in Section4.4.

3.5 Reference group

The main idea of energy systems modeling is gaining knowledge rather than predicting the future. Such learning may occur through collaboration between researchers and stakeholders. The significance of such collaborative ventures is that they start at the early stage of the modeling process, i.e. the collection of the main input data and assumptions and the choice of scenarios, and continue until the final stage, i.e. the evaluation of model results. As a consequence, the outcomes of the modeling may facilitate decision-making [22, 24, 25].

Moreover, parameters that might hinder the DH-industry synergies included an unwillingness to take risks, imperfect information, asymmetric information, a lack of credibility and trust and an opposition to change [14]. The involvement of universities through applying energy system optimization models of DH systems and industries was shown to facilitate the collaboration, resolving the imperfect information parameter [14]. Establishing a reference group from the early stage of modeling also helps build trust between DH companies and industries.

In this study a Reference Group is established with the title of "Collaboration on industrial EH utilization in West Sweden". The procedure for our collaboration is described in Section 4.5.

4 Scope and methods of the papers appended

This section presents the scope and methods of the appended papers, a description of the case studied, techno-economic aspects of bio-refineries as competitors to DH systems in biomass use, cluster of chemical industries delivering large-scale EH to DH systems, scenarios designed and, finally, a Reference Group.

Paper I applies a regional and mid-term perspective for assessing the energy systems and environmental impacts of large-scale industrial EH use in DH systems through a large heat network. The West Sweden Region (VG) is selected as our case. A heat connection between the cluster of chemical industries in Stenungsund and DH systems in Gothenburg and Kungälv is investigated to assess the impacts on energy flows and DH production technologies at the regional level, as well as CO_2 emissions with a European electricity system perspective. Two climate policy scenarios and five sensitivity cases have been designed to make these assessments. The climate policies represent two extreme climate scenarios (i.e. ambitious vs. collapse of climate policy scenarios, see Section 4.4). As a result, all climate scenarios are located somewhere between these extremes. The sensitivity cases assess the robustness of the results given the main scenario assumptions vary. These cases include the future DH demand, the level of EH available from the industrial cluster, the technology and the supply of fuel for marginal electricity generation, and the learning rate of bio-refinery for transport biofuel production. The assessment is carried out by the MARKAL_WS model developed and applied in [26, 27]. MARKAL_WS (West Sweden) is an energy systems optimization model in which the energy system of the VG Region is represented. Technical and economic aspects of 37 DH systems and bio-refineries for transport biofuel production within VG are represented in the model. The assessment of the large heat network also include a local level addressing only the direct impacts on the DH systems connected, i.e. the DH systems of Stenungsund, Kungälv, Gothenburg plus Partille and Mölndal. The main question of the investigation is:

- How would the energy systems and CO_2 emissions be affected by a large heat network between DH systems and industry?

Paper II applies a regional and long-term perspective to assess the economic impacts of the large heat network between the chemical industries in Stenungsund and DH systems of Gothenburg and Kungälv in the VG Region. Two climate policy scenarios (i.e. the ambitious and New Policy scenarios, see Section 4.4) and seven sensitivity analyses are designed through cooperation with the Reference Group (see Section 4.5). All costs associated with constructing heat extraction capacity within the chemical industries and a long pipeline between the industries and DH systems of Gothenburg and Kungälv are represented in detail in the MARKAL_WS model. The main questions of the investigation are:

- How would the system cost of DH supply be affected on a regional level by the construction of a large heat network allowing for long-distance transmission of EH?
- How is the marginal cost of DH supply affected by such a large heat network?

4.1 DH systems in West Sweden

The case selected in this study, the VG Region (Figure 1), is the second largest county in West Sweden with a total population of 1,623,400 (17% of Sweden’s population) in 2014 [28]. The region is divided into 49 municipalities of which 37 municipalities have established local DH systems [29]. Biofuels (including unrefined biomass, energy crops and biogas), peat and municipal solid waste accounted for 56% of the fuel use in the VG DH systems in 2011[29] (Figure 2).

Gothenburg with a population of 536,800 inhabitants [28] is the largest city in the VG. The first investigation of DH in 1946 led to continued development of the Gothenburg DH system, reaching its current status of 1200 km [30] of DH network supplying about 4 TWh heat [31], corresponding to 52% of the total DH demand in the VG in 2011 (Figure 3). After Gothenburg, Borås with a heat demand of about 560 GWh (8% of VG’s total heat demand) is the second largest DH system [29]. The other 36 local DH systems are small compared to the Gothenurg DH system (Figure 3). The large difference between DH systems (in terms of the amount of heat supply) illustrates that a large share of the impacts occurs in the Gothenburg DH system.

Figure 1- Geographical location of the Västra Götaland, Stenungsund, Gothenburg and Kungälv.

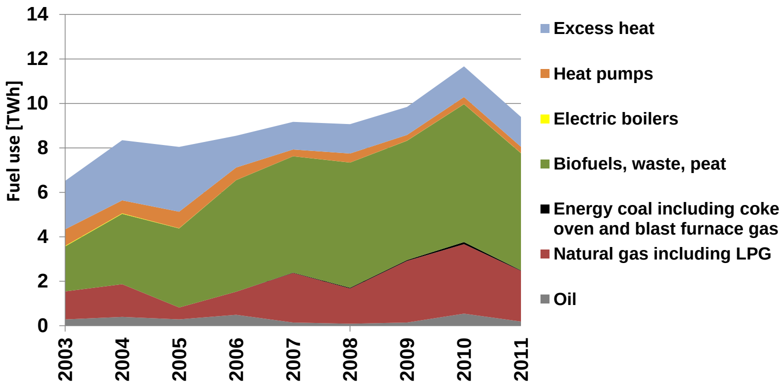

Figure 2- Fuel use in DH systems of the VG of Sweden, 2003-2011 (based on [29]).

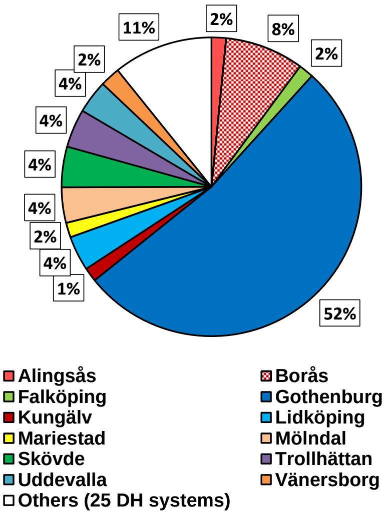

Figure 3- Share of heat demand in DH systems in the VG of total 7000TWh in 2010 (based on [29]) .

4.2 Bio-refinery (as a competitor to DH systems in biomass use)

Several studies have investigated the process of bio-refinery for transport biofuel (synthetic natural gas (SNG)) production from the thermal gasification of biomass and forest residues, e.g. [11, 32, 33]. The integration of these bio-refineries into local DH systems has also been assessed [34, 35]. However, the technology is not commercially available globally and its technical and economic aspects are subject to high uncertainty.

In the VG Region, based on an agreement in 2012 [36], two bio-refinery plants for SNG production were planned to be constructed. During the first phase, one of these plants was built in Gothenburg with a capacity of 20MW SNG production (Table 1). From 2014, the plant has been in operation as a demonstration project and SNG is distributed throughout the existing natural gas grid in the Region. After an evaluation of the first plant, a second plant will be built a capacity of 100MW SNG production by 2016. At optimal production, these plants are capable of delivering 1 TWh SNG corresponding to the fuel required for 100,000 cars. These plants also deliver their EH to the Gothenburg DH system [37].

Since the 20 MW plant is the first relatively large-scale SNG production plant in the world, investment costs of other capacities are scaled up using a general relationship:

$$\frac{C}{C_{base}} = \left(\frac{S.\eta}{S_{base}.\eta_{base}}\right)^{R}.(1-LR)$$

where C,S and η represent the investment cost, capacity and efficiency of the new plant, C_{base}, S_{base} *and* η_{base} represent the known investment cost, capacity and efficiency of the base plant, here 20MW SNG production (see Table 1). R is the scale-up factor, here equal to 2/3, and LR is the cost reduction by learning, here equal to 10%.

In the model, the Gothenburg 20 MW SNG production plant is assumed to be operated as of 2015 (for this plant, investment costs are treated as sunk cost). From 2020 on, the model may choose to invest in new SNG production plants (100, 150 and 200 MW) if such a measure developed were to reduce 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 option is a bio-refinery connected to a DH system producing SNG and heat with biomass and electricity as external inputs to the plant (Bio-refinery SNG 1, 2 and 3 in Table 1) whereas the second option is a stand-alone bio-refinery where SNG is the only output and biomass the only input (Bio-refinery SNG 4, 5 and 6 Table 1). In the latter option, the electricity required for the process is generated from the heat produced in the process.

In the model, the bio-refineries are available 8,000 hours annually. Fixed cost for all plants is assumed to be the same and equal to monthly salary payments for 22 employees (6 people of 3 shifts each, plus management and administration staff of 4 people) with an average salary of about €3,900 per month. The cost of Raps Metyl Ester (RME) and catalyst required for the SNG production processes is assumed at to be variable cost, i.e. equal to 15% of biomass cost [38].

Table 1- Assumptions of bio-refinery SNG technologies as potential investment options in the model.

	Capacity	**Efficiency**	**Investment cost**				**Fixed O&M cost**	**Variable O&M cost**
Technology	**(MW biofuel/MW heat)**	**(%)**	**(MEUR/MW biofuel)**				**(MEUR/year)**	**(EUR/MWh fuel)**
			2012	**2020**	**2025**	**2030**		
Biorefinery SNG (base plant)*	20/3	70	7.8				2.3	3
Biorefinery SNG 1	100/15	70		4.1	3.7	3.3	2.3	3
Biorefinery SNG 2	150/22.5	70		4	3.2	2.9	2.3	3
Biorefinery SNG 3	200/30	70		3	2.9	2.6	2.3	3
	Capacity (MW biofuel/MW biomass)							
Biorefinery SNG 4	100/150	67		4.1	3.7	3.3	2.3	3
Biorefinery SNG 5	150/225	67		4	3.2	2.9	2.3	3
Biorefinery SNG 6	200/300	67		3	2.9	2.6	2.3	3

4.3 Cluster of chemical industries in Stenungsund

A cluster of chemical industries is located near Stenungsund, a community in the VG Region with population of about 25,000 people [28], approximately 50 km North of Gothenburg. It occupies six production sites operated by five companies [39], i.e. AGA, AkzoNobel, Borealis, Perstorp and INEOS. Current electricity and fuel use within the cluster are about 1.8 TWh and 4.9 TWh annually, respectively, a large part in the products leaving the plants (see [40] for the description of their fuel use and products). Most plants operate continuously over the entire year [39]. A total site analysis of the cluster, investigations of increased energy integration and the potential for common utility systems and cogeneration on-site were carried out in [40], concluding that approximately 150 MW of burning fuel might theoretically be avoided by means of well-managed heat recovery within the cluster. For the current situation a maximum heat extraction capacity of 230 MW for use in DH might be achieved if no heat were recovered within the cluster, whereas through constructing a total utility network site and implementing energy efficiency measures, only 110 MW heat (less than half of the current potential) might be extracted for DH use [39].

When industry makes other large investments in their facilities for totally different purposes, such actions may be interpreted by a DH company as a form of guarantee indicating that there is less risk of shutting down in a near future [12]. The chemical industries in the cluster have been cooperating over the past 20 years. For the next 20 years, their vision of “Sustainable Chemistry 2030” will complete the transition to renewable feed stocks, and their products will contribute towards sustainable development future and their plastics will be recycled. The aim of the industrial cluster is to further the clean the environment and economic prosperity of the Region [41]. The implementation of these plans would likely decrease the risk of DH supply uncertainty.

4.4 Climate policy scenarios

Explorative scenarios that broaden the scope for potential future climate policies address uncertainties with regard to climate policy decisions and, consequently, energy markets. The 450 ppm scenario in the World Energy Outlook (WEO) International Energy Agency (IEA) is in line with the goal of limiting the increase of global temperature to 2 degrees by introducing a cap on concentration of greenhouse gases. This scenario represents a rigid climate policy scenario and has been identified as relevant when the environmental sustainability of future energy systems was assessed, referred to as BASE. This scenario induces an increasing price (tax) on CO_2 emissions, resulting in decreasing fossil fuel prices while raising the price of renewable fuels in energy markets.

The other end of the climate policy scenarios, the competition between national competitiveness and climate change concerns creates a race to the bottom when it comes to climate policies, referred to as collapse (POLCOL). The emission trading system (ETS) of the European Union (EU), a market-based climate policy, has induced higher energy prices on industry. Business and industry in the EU are lobbying hard to reduce energy prices which are much higher than energy in Asia and the US. An EU energy summit took place on May 2013. Before the meeting it was suggested that the ETS would not be reformed (in order to keep prices down) and fracking would be promoted to increase the supply of cheap gas [42].

For the purpose of this study, a third climate policy scenario is identified as relevant. The New Policies scenario in IEA WEO (NEWPOL) is less ambitious but takes broad policy commitments and plans that have been announced by countries into account. This scenario includes national pledges to reduce greenhouse gas emissions and plans to phase out fossil fuel subsidies, even though the measures to implement these commitments have yet to be identified or announced. This scenario investigates a future consistent with current climate change mitigation concerns.

4.5 Collaboration on industrial EH utilization in West Sweden

Our energy system modeling has been implemented in close collaboration with academic colleagues; i.e. the researchers at the Heat & Power Division, Chalmers that addressed the cost of heat extraction within the cluster, the Swedish Environmental Research Institutes (IVL) that assessed sustainability aspects and national environmental policies affecting the decision to build the large heat network and the Sweden's Technical Research Institute (SP) that designed market models making the necessary heat investments possible, in addition to various stakeholders; i.e. the energy utility companies that might come to own a future large heat network and the chemical industries in Stenungsund. This collaboration was organized into two groups: (1) a Research Group including only the researchers, (2) a Working Group composed of all the stakeholders and researchers. The Research Group met continuously during the modeling process to discuss input data assumptions and scenario choices and to evaluate results. Each individual researcher planned several meetings with experts at the energy utility companies and industries to generate ideas for the Research Group meetings. Finally, the decisions made by the Research Group and research outcomes were communicated to all stakeholders in the regular Working Group meetings to receive feedback and generate new ideas.

The sustainability of the large heat network between the chemical industries and energy utility companies has been our main research focus. Since sustainability is a broad concept with a large number of environmental, economic and social aspects, any sustainability assessment can only cover a selection of aspects. This selection of aspects and indicators is vital since it may substantially affect the conclusions of the assessment (see [43]). Three workshops were held to collect the principal aspects of sustainability relevant to the construction of the large heat network; an internal workshop involving three researchers and two external workshops with stakeholders, involving members of the Working Group for the modeling process, as well as representatives of the Government and NGO's. Based on the workshops, the environmental (e.g. climate change and primary energy use) and economic (e.g. long-term profitability and competitiveness) aspects of sustainability were prioritized as particularly important. The first, environmental aspects, is addressed in Paper I and the second is assessed in Paper II.

5 Main findings

This section presents the main findings of the papers appended with regard to energy systems (including energy flows and technologies), as well as environmental impacts (CO_2 emissions) and economic impacts (the total cost and marginal cost of DH production) impacts of a large heat network between the cluster of chemical industries in Stenungsund and the DH systems in Gothenburg and Kungälv in the VG Region. First, from a mid-term perspective, the impacts on energy flows and technologies at the regional and local levels and the impacts on CO_2 emissions at the local and European electricity systems levels were assessed. Second, from a long-term perspective, the optimum size and timing of investments in the large heat network were investigated. Moreover, the impacts on the total cost and marginal cost of DH production were assessed at regional and local levels, respectively.

5.1 Energy flows

The introduction of the large heat network between the industrial cluster and the Gothenburg/Kungälv DH systems increases EH use in the VG DH systems by 832 TWh/year given up to 125 MW heat were to be extracted from the cluster. The EH replaces fuel use during DH production because it is a cheap source of energy compared to the other fuels except for municipal solid waste. The fuels replaced differ depending on scenario assumptions and time perspective. With the rigid climate policy scenario, the EH replaces unrefined biomass (forest residues and energy crops) in short-term but in the mid-term, it replaces NG. However, with the collapse of future climate policies, the EH replaces unrefined biomass, NG and coal in the short-term but in the mid-term, it only replaces coal. The replaced fuels are those that would have been dominating the regional district heating systems if the large heat network would not have been constructed under the respective climate policy and time perspective.

In the short term, after the introduction of the heat network, biomass use shifts from heat to SNG production. Simultaneously, EH delivered through the pipeline is insufficient to compensate for the reduced availability of biomass in the DH systems. Consequently, the use of electricity for heat pumps and NG increases during DH production to meet the VG heat demand.

5.2 Energy technologies

As a consequence of the increased use of EH in the Region’s DH systems, as energy flow changes, some DH production technologies lose their profitability whereas others become more competitive. In the VG region with a rigid climate policy scenario, EH utilization decreases the profitability of biomass and NG CHPs in the mid-term, decreasing the electricity generation in the Region. This less profitability of biomass CHPs decreases the marginal cost of regional unrefined biomass, which in turn opens opportunities for earlier production of transport biofuels in the Region. In contrast, the profitability of investments in NG HOB plants rather than in NG CHPs increases to meet the peak heat demand in DH systems. In the long-term, the EH utilization replaces heat pumps, resulting in less electricity use in the Region.

In the mid-term if coal CCS (carbon capture and storage) technology is the marginal electricity generation in the European electricity system, instead the profitability of NG HOBs decrease leading to no change in electricity generation in the Region.

Because lower heat demand decreases the demand for and price of regional unrefined biomass, lower heat demand in the Region favors transport biofuel production in the Region. Simultaneously, the EH utilization in DH systems decreases the profitability of biomass CHPs. These changes in DH production decrease the marginal cost of regional biomass, increasing the profitability of bio-refineries.

5.3 CO_2 emissions

The changes in energy flows and technologies in the VG Region affect CO_2 emissions at the local level whereas these effects also depend on the geographical scope and time perspective applied. The changes in energy flows (i.e. reduction of fossil fuel use in future climate policy scenarios) decrease CO_2 emissions in the DH systems. This result is valid only if the direct impacts on the DH systems connected, i.e. the DH systems of Stenungsund, Kungälv, Göteborg plus Partille and Mölndal (*the local level*) are assessed.

However, the changes in energy technology (i.e. the lower DH production in biomass CHPs) increase CO_2 emissions with European electricity system scope in the short-term given climate policies are rigid. This increase is due to the lower electricity generation in biomass CHPs that is substituted by greater marginal electricity generation in NGCC (combined cycle) power plants.

In a rigid climate policy scenario, if we keep the geographical scope of the European electricity system but extend the time perspective to the mid-term, the changes in energy technology (i.e. the lower DH production in NG CHPs and greater transport biofuel production in bio-refineries), decrease CO_2 emissions. This reduction is due to lower electricity generation in NG CHPs and greater biofuel production in bio-refineries that are substituted by additional marginal electricity generation in higher electrically efficient NGCC power plants (with efficiency of 57%) and diesel in the transport sector, respectively.

5.4 Optimum timing and capacity of the large heat network investments

This assessment takes into account all costs associated with the construction of such heat networks, including investments in heat extraction capacity within the cluster of chemical industries and the pipelines between Stenungsund, Kungälv and Gothenburg (SKG) and between Stenungsund and Kungälv (SK). The optimization of energy systems in the VG Region including DH systems, bio-refineries and investment options for the large heat network, illustrates that the closing down of the refineries in Gothenburg opens opportunities for investments only in the large heat network between Stenungsund, Kungälv and

Gothenburg. Despite the fact that the SK pipeline, compared to the SKG pipeline, is cheaper, the investment in the heat network between Stenungsund and Kungälv is not cost-effective because the heat demand in Kungälv is smaller than that of Gothenburg, and there already exists a heat connection between Gothenburg and Kungälv.

The energy systems optimization in the VG Region illustrates that investment timing is scenario dependent. The less ambitious climate policy scenario, NEWPOL, is in favor of earlier investments in the heat network compared to the rigid climate scenario. This delay in investments in the rigid climate scenario is attributable to the subsidy allocated for renewable electricity generation as well as high electricity prices, resulting in a high profitability of biomass CHPs.

When the investment in the large heat network is profitable, the SKG pipeline is always constructed at the highest capacity level of 150 MW. However, the cost-effectiveness of investments on the heat extraction capacity level depends on future climate scenarios. In the rigid climate policy scenario, the highest capacity of 150 MW becomes profitable, whereas in the less ambitious climate policy, NEWPOL, the capacity of 140MW remains profitable.

The energy system optimization model does not invest in the large heat network if the refineries in Gothenburg continue to supply their EH to the base load of the Gothenburg DH system in the long-term. Similarly, in the ambitious climate policy scenario, the model does not build the heat network if the competitor to DH systems in biomass (i.e. bio-refineries) is ignored. These effects are attributed to an abundance of EH and low cost unrefined biomass in the Region, respectively. See Figure 4 for the summary of the sensitivity analyses on investments in heat extraction capacity within industries in 450PPM and NEWPOL.

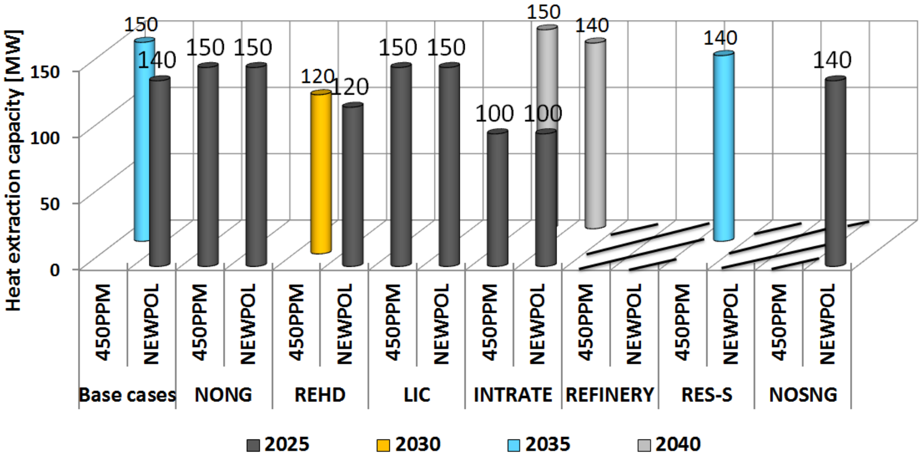

Figure 4- Sensitivity analyses on investments in heat extraction capacity within industries in 450PPM and NEWPOL.

Given local politicians decide to phase out fossil fuels in the Region in the mid-term (2030), or given the cost of constructing the SKG pipeline is reduced by half, the investments in the large heat network become profitable at the maximum capacity (150 MW) and the earliest possible time (in 2025). However, in case the heat demand in the VG Region is reduced or in the event that renewable electricity generation is encouraged by allocating subsidies until 2050, a relatively lower capacity of heat extraction becomes profitable.

5.5 Total Cost

In the rigid climate policy scenario, the construction of the large heat network is profitable because it allows for over 1 TWh/year EH utilization, replacing NG and electricity use in the DH systems associated with CO_2 charges. These changes slightly decrease the cost of DH systems for heat production but the majority of cost reduction occurs due to lower CO_2 charges in DH production.

In the NEWPOL scenario, the construction of the large heat network becomes even more profitable because a large share of NG would be replaced by the EH utilization in DH systems which in turn both the cost of DH production and CO_2 charges decrease significantly.

The sensitivity analysis illustrates that the large heat network is profitable even if the heat demand were to decrease in the Region or if the cluster were to require higher interest rates and a shorter payback time for investments in heat extract capacities. These investments are also profitable if national subsidies for promoting renewable electricity generation are combined with high CO_2 charges over the long-term.

5.6 Marginal cost

The marginal cost of heat supply in the DH systems connected to the large heat network (the Gothenburg and Kungälv DH systems) is significantly reduced except for the cold seasons (Figure 5). The reason is that, in the Gothenburg DH system, the EH utilization leads to peak load capacity investments in NG HOBs rather than in NG CHPs. In the Kungälv DH system, the heat supply from NG HOB increases during peak load since the total system cost is optimized at the regional as opposed to the local level. At the regional level, compared to the Kungälv DH system, the EH utilization is more profitable in the Gothenburg system during all seasons, especially during the peak load (i.e. cold seasons). At the local level the DH systems of Gothenburg and Kungälv also compete for EH utilization. Since the heat demand in the DH system of Gothenburg is about 34 times larger than that of the Kungälv DH system, an average of 87% and 13% of the EH is supplied to Gothenburg and Kungälv, respectively.

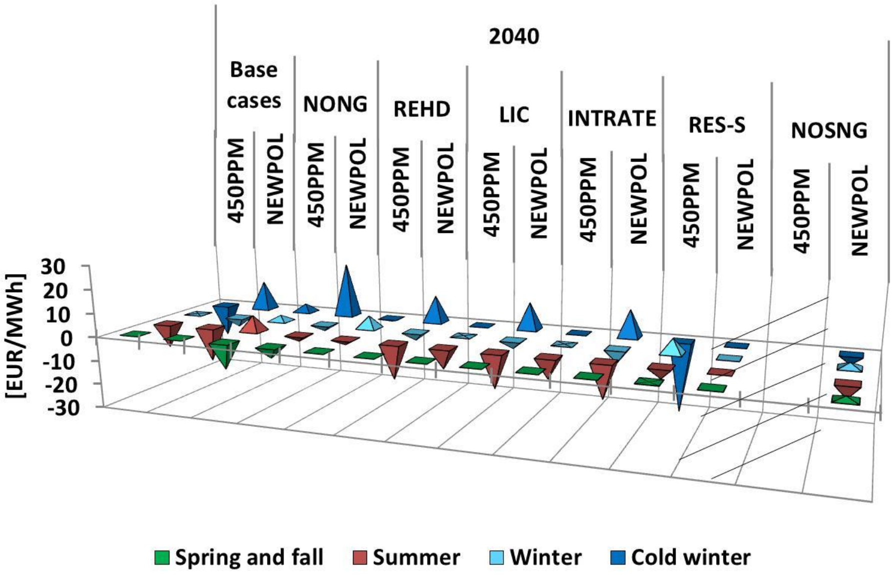

Figure 5- Consequences for marginal cost of DH supply ([EUR/MWh]) in Gothenburg of the EH utilization in 2040.

6 Concluding discussion

The main conclusion of this study is that a large heat network in the VG Region of Sweden between the cluster of chemical industries in Stenungsund and the DH systems of Kungälv and Gothenburg would increase EH use of about 1 TWh/year while decrease biomass, fossil fuel and electricity use in the DH systems. The increased use of EH is likely to weaken the competitiveness of biomass and NG CHPs in the mid-term and heat pumps in the long-term. These changes would decrease electricity generation while opening up opportunities for earlier transport biofuel production in the Region. The investments in the large heat network are likely to lead to a reduction in the total long-term system cost in the VG Region, if the competition for regional biomass is taken into account and if other sources of EH in the vicinity of the DH systems do not supply heat.

These results highlight the importance of the methodology developed to carry out an energy system, economic and environmental assessment of the large heat network. First, the regional level assessment illustrates that the use of EH in the DH systems of Gothenburg and Kungälv changes biomass flows in the Region. It is shown that local and regional results may differ significantly with regard to biomass use. Because of the existence of a regional market for biomass, some changes occur outside the connected DH systems (i.e. biomass use in the transport sector), which cannot be captured at the local level. This finding implies that energy system decision-making may be better supported given the interactions of energy carriers between the energy system and its surroundings are taken into account, as well as the importance of assessing local changes at a wider geographical scale.

Second, the regional and inter-sectoral approach, which includes the transport biofuel production option as an alternative to regional biomass demand, shows that the investment in the heat network is cost-effective under various conditions. However, making this investment with a regional single-sector perspective, a narrower systems approach that would include only the stationary energy sector represented by the DH systems in the Region, becomes uncertain.

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

At the local level, since it would replace fossil fuels, the EH utilization in these local DH systems would decrease local CO_2 emissions. However, if the interactions between DH systems and the power and transport sectors are taken into account, the CO_2 emissions would increase in the short-term while decreasing in the mid-term with a European electricity system perspective. Our results might overestimate the reduction in CO_2 emissions because they do not account for any increase in emissions from the cluster. Such increases may occur if the price of the EH is sufficiently high to reduce the profitability of energy-efficiency measures within the industrial cluster.

In general, in the cases of one-way cooperation between an EH source industry and a DH system (only utilization of industrial EH in the DH systems), the EH would replace more expensive energy sources and DH production technologies in the DH system. Due to the large diversity of Swedish DH systems in terms of locally available resources, the DH technologies replaced differ between DH systems. In many DH systems, EH replaces CHP plants resulting in reduced electricity generation within the DH systems which in turn results in an increased generation from marginal electricity technologies elsewhere.

Long-distance transmission of excess heat in a heat network requires large investments. Such investments can become profitable if the excess heat were to replace DH supply that to a large extent is based on fossil fuel. These investments are less likely to become profitable if other major sources of excess heat are more closely located and if there is an abundance of low cost biomass available in the Region. Whereas higher future fossil fuel prices (that are associated with lower CO_2 charges) are likely to increase the profitability of the investments, higher interest rates would reduce such profitability.

7 Future research

In this study the environmental and economic impacts of large-scale industrial EH for direct use in the distribution networks of DH systems have been assessed. The potential for the utilizing the short- or long-term heat storage capacities within DH systems or industries leads to greater EH use in DH systems. For future study, the short- or long-term heat storage capacities might be included in the MARKAL_WS model to assess the energy system, environmental and economic impacts of different types of heat storage capacities in the VG Region.

Compared to the industrial cluster EH, there are other larger or smaller industrial EH sources in the VG Region. These industries are located close to small communities with minor DH systems in terms of heat supply technologies and short heat distribution networks. A research question might be: could heat connections between several DH systems offer opportunities to capture the industrial EH potential for DH purposes within the VG Region? The environmental and economic impacts of large DH systems can be assessed at the regional level to answer this question.

This study addressed the energy system impacts of large-scale EH use in the DH systems of Gothenburg and Kungälv at the regional level. The MARKAL_WS model illustrated the consequences of EH utilization on energy flows in the DH systems of the VG Region. A research question might be: how would the national and/or international market for substituted energy sources be affected by EH use in DH systems?

If EH use in DH systems were to replace NG in HOB and CHP plants or the electricity in heat pumps, energy system models of larger geographical scope would be required to assess the indirect effects of this NG or electricity reduction outside of the VG Region. However, if EH use in DH systems were to replace unrefined biomass in HOB and CHP plants, the indirect effects might be easily assessed given a regional market for the biomass whereas these effects are more complex given an international market where the biomass can be used in different energy sectors.

The level of EH available from the industrial cluster in Stenungsund is subject to uncertainty. Higher energy prices promote additional energy efficiency measures, whereas the utilization of additional EH in DH systems is likely to lead to a reduced motivation to implement these measures. There are also investment costs associated with implementing energy efficiency measures and constructing heat extraction capacities for DH systems within the cluster, in addition to building the long-distance pipeline for EH utilisation in the DH systems. The optimized level of EH availability for DH systems should be assessed. A capacity-cost model has been developed by researchers at the Heat and Power Division of Chalmers to investigate heat extraction capacity levels and corresponding costs within the cluster. The optimised level of EH availability for the DH systems can be identified by linking the MARKAL_WS model and the capacity-cost model.

The results of this study are currently used as input to other studies at the Swedish Environmental Research Institutes (IVL) to assess national environmental policies affecting a decision to build the large heat network as well as at the Sweden’s Technical Research Institute (SP) to design market models to make the necessary heat investments possible. We acknowledge that the energy systems modeling applied in this study is not sufficient to make an environmental assessment of a large heat network. Life cycle assessment (LCA) is a broad environmental assessment tool but it does not take economic and social aspects into account. LCA also results in a static model. Thus, a combination of tools (i.e. energy systems modeling and LCA) might provide a so called “a multi-criteria” decision analysis.

Three workshops were held to collect the main aspects of sustainability relevant to the construction of the large heat network. Based on the workshops, some of these aspects were prioritized to be assessed in this study in addition to other aspects that may be addressed in order to broaden the sustainability assessment.

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