THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Future District Heating Interactions – Modelling Impacts of Industrial Excess Heat Utilisation and Energy Efficient Buildings

AKRAM (FAKHRI) SANDVALL

Department of Space, Earth and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2018

Future District Heating Interactions – Modelling Impacts of Industrial Excess Heat Utilisation and Energy Efficient Buildings

AKRAM (FAKHRI) SANDVALL

ISBN 978-91-7597-707-2

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr. 4388
ISSN 0346-718X

Department of Space, Earth and Environment

Division of Energy Technology

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Printed in Sweden

Chalmers Reproservice

Gothenburg 2018

To Magnus

Future District Heating Interactions – Modelling Impacts of Industrial Excess Heat Utilisation and Energy Efficient Buildings

AKRAM (FAKHRI) SANDVALL
Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY

Abstract

International goals for climate change mitigation plus energy security targets could be met cost-effectively by interactions between different parts of energy systems. The fourth generation of the district heating systems concept was developed as an attempt to accelerate district heating (DH) systems' interactions with other energy systems. This thesis investigates future interactions of district heating (DH) systems with industries and buildings. This is investigated by developing a methodology and applying it to real cases.

Taking a long-term and system-wide perspective, the investigation includes carbon (CO_2) and techno-economic impacts of increased energy efficiency in industries and buildings on the DH systems. Real case studies are selected to capture the local conditions of DH systems. Climate policy scenarios are designed as the starting point for the investigations and systematic sensitivity analyses are designed to test the robustness of the case study results. The tool applied is dynamic energy systems optimisation modelling. A regional MARKAL model is applied for DH-industry interactions, whereas a local TIMES model is applied for DH-building interactions. The heating sector and parts of the electricity, transport, industry and building sectors are represented in the optimisation models.

The results show that, through a large heat network allowing for long transmission of industrial excess heat (EH) to DH systems, the DH-industry interaction requires major investment. Such investment is likely to be profitable if the EH replaces DH (which is primarily supplied by costly primary energy sources). From a systems perspective, the investment is less likely to be profitable if other EH sources contribute a large share of the DH base load and if there is an abundance of locally available, low-cost biomass. If built, heat networks help reduce biomass and fossil fuel use and provide a related reduction in CO_2 emissions in DH systems. This outcome implies decreased electricity generation from combined heat and power (CHP) plants, in the region studied.

In low-energy building (LEB) areas, DH-building interactions (using a heat connection which allows heat to be supplied from a nearby urban area DH system to an LEB area) are cost-effective relative to local (on-site) DH and individual heat supply options. However, changes in energy flows (and CO_2 emissions resulting from the nearby urban area DH systems) depend on assumptions about future climate policies, marginal electricity generation and alternative use of biomass, as well as the scale of the urban area DH system.

Keywords: waste heat, excess heat, low-energy buildings, passive houses, fourth generation district heating, MARKAL, TIMES, dynamic energy system modelling, urban planning.

List of publications

This thesis is based on the following appended papers:

Paper I: **System Profitability of Excess Heat Utilisation – A Case-based Modeling Analysis**

Sandvall A.F., Ahlgren E.O., Ekvall T., *Energy* 97 (2016): 424-434.

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

Sandvall A.F., Börjesson M., Ekvall T. & Ahlgren E.O., *Energy* 79 (2015): 68-79.

Paper III: **Cost-efficiency of Urban Heating Strategies – Modelling Scale Effects of Low-energy Building Heat Supply**

Sandvall A.F., Ahlgren E.O., Ekvall T., *Energy Strategy Reviews* 18 (2017): 212-223.

Paper IV: **Low-energy Buildings Heat Supply – Modelling of Energy Systems and Carbon Emissions Impacts**

Sandvall A.F., Ahlgren E.O., Ekvall T., *Energy Policy* 111 (2017): 371-382.

Akram (Fakhri) Sandvall is the main author of Papers I, II, III and IV and contributed writing, modelling and calculations, Martin (Börjesson) Hagberg contributed discussions and editing in Paper II. Professor Erik Ahlgren, the main academic supervisor, contributed discussions and editing of all four papers. Tomas Ekvall, contributed discussions and editing in the four papers. The following is a list of publications by the author, not included in this thesis:

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

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

- Large-Scale Utilisation of Excess Heat - Assessment through Regional Modelling

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

- Economically Optimal Heat Supply to Low-energy Building Areas.

  Sandvall A.F., Ahlgren E.O, Ekvall T., *15th International Symposium on District Heating and Cooling, 4th-7th September, 2016, Seoul, Republic of Korea (South Korea).*

Table of Contents

List of abbreviations

BAU	Business-as-usual
CC	Combined cycle
CCIS	Cluster of Chemical Industries in Stenungsund
CCS	Carbon capture and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
DH	District heating
EH	Excess heat
ENPAC	Energy price and carbon balance scenarios (a tool)
EOH	End of the horizon
ETS	Emission trading systems
HOB	Heat-only boiler
HP	Heat pump
IEA	International Energy Agency
LP	Linear programming
LEB	Low-energy buildings
MARKAL	Market Allocation (an energy system model)
MIP	Mixed integer programming
MSW	Municipal solid waste
NG	Natural gas

ppm	Parts per million
PV	Photo voltaic
SK	Stenungsund-Kungälv
SKG	Stenungsund-Kungälv-Göteborg
SNG	Synthetic natural gas
TGC	Tradable green certificate
TIMES	The Integrated MARKAL -EFOM System (an energy system model)
TPP	Thermal power plant
UH	Urban heating
VG	Västra Götaland (region in West Sweden)
WEO	World Energy Outlook
WGT	Wind+gas turbine
WS	West Sweden

Definitions

Local DH: DH systems with heat networks covering a single town/city.

Regional DH: Regional DH systems with heat networks connecting several towns/cities.

Plot ratio: The ratio between the heated area and the associated land area.

Linear heat density: The ratio between annual heat quantity sold to customers and the trench length.

Low-temperature district heating: Forward/return temperatures of 50/25 ℃ rather than the current 80/40 ℃.

Large heat network: In DH-industry interactions, the heat connection between industry and multiple DH systems, as opposed to DH-building interactions when it means the heat connection between an LEB area and its nearby urban area DH system.

On-site: Small local DH system within an LEB area.

Individual: Individual devices in each LEB for providing heat.

1 Introduction

District heating (DH) systems continue to increase their vital role in supplying renewable heat and enabling integration of different parts of the energy system, thereby increasing overall energy efficiency [1]. However, DH systems face some challenges. Firstly, the potential of DH for climate change mitigation needs to be recognised. Secondly, in line with increasing efforts to integrate renewable energy sources into energy systems, DH systems will need to evolve continually and use non-fossil heat sources. Thirdly, with increasing energy efficiency in energy systems, DH technology will also need to be adapted to lower heat demand in future buildings [2, 3].

The fourth-generation district heating system is a concept developed to describe how the efficiency of DH supply and distribution could be increased, how heat (from heat sources that would otherwise be wasted) could be recovered, how renewable energy forms could be integrated into energy systems and how DH technology could be harmonised with lower future heat demands. These are achieved by means of lower supply and return temperatures in DH distribution networks, compared to the current third-generation DH systems [4].

Figure 1 illustrates potential interactions of DH systems with other parts of energy systems where they interact with: 1) power systems, through CHP plants, heat pumps and electric boilers, 2) transport systems, through bio-refineries, 3) waste management systems, through waste incineration plants, 4) industries, by providing heat and using industrial excess heat (EH) and 5) buildings, by providing heat.

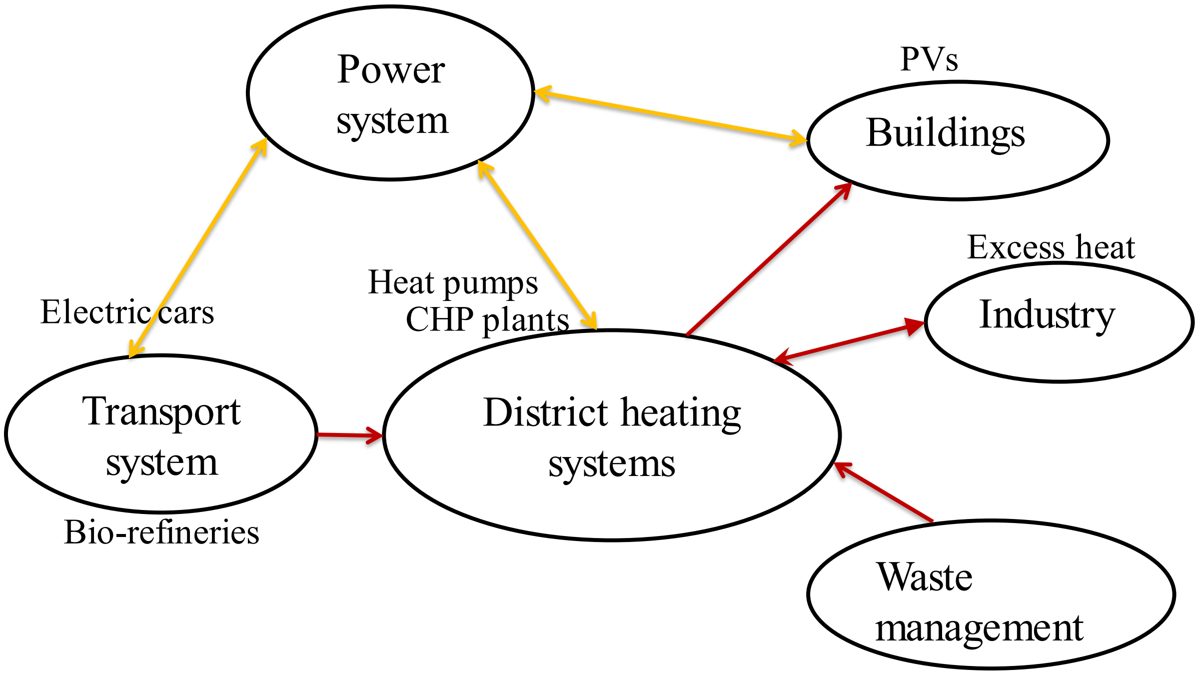

Figure 1. District heating (DH) system interactions. Abbreviations: photovoltaic (PV), combined heat and power (CHP).

Opportunities for heat recovery by DH systems could increase through interaction between industries and DH systems, based on industrial EH use in DH systems. Consequently, the use of EH may reduce primary energy use and the system costs of DH systems, whilst making it possible to achieve climate and resource efficiency targets. The likely reduction in the cost of DH systems could open up opportunities for DH systems to interact with low-energy buildings (LEBs), in areas where all buildings have been constructed with very low-level heat demands. Based on the interaction of DH systems with the industry and building sectors, achieving various goals for increasing energy efficiency and mitigating climate change could therefore be made easier. These interactions with industrial and building systems (representing different aspects of DH systems, i.e. supply and demand) are associated with major investment costs and lock-in effects. Any benefits of these interactions therefore need to be addressed in a medium to long-term perspective.

In Sweden, biomass accounts for a large share of fuel use in DH systems, in heat-only boilers (HOBs) as well as CHPs. Climate change mitigation policies promote biomass use for heat and power and the production of transport biofuel. Biomass is a renewable energy source, but is not an unlimited resource. Currently, it is often traded locally. This creates local markets for biomass, which are generally associated with low prices. However, in the future, stringent climate change policies are likely to bring about competition for biomass. This would likely increase demand and thus also prices, creating an international biomass market. Interventions in the fuel supply or heat demand of local DH systems (due to DH-industries and interactions in DH-buildings) impact DH systems directly but, due to local or international biomass markets, there are indirect impacts in other energy sectors which may use biomass, such as power and transport.

DH systems also interact with the electricity system through CHP plans, large heat pumps and electric boilers. Interventions in the fuel supply or heat demand of local DH systems (due to DH-industries and DH-buildings) interactions directly impact DH systems but, due to DH-electricity sector interactions, there are indirect impacts on the electricity system. Changes in local electricity generation can affect investment decisions elsewhere in the electricity system, (the built margin in the electricity system [5]) and, consequently, global carbon emissions.

The complexity of the DH systems' interactions and the fact that energy systems are dynamic, (they evolve over time) requires the application of computerised dynamic energy systems modelling. This modelling approach aids the representation of energy systems interactions, illumination of core dynamics and uncertainties, handling complexity [6] and exploration of possible future paths for energy systems under different scenarios.

Interactions between DH systems and other energy sectors have been studied along different geographical and temporal scales (see [7-10]). While the techno-economic and carbon emission impacts of DH-industry interactions have often involved case studies of local DH systems (see [8, 11, 12]), the same impacts for DH-building interactions have been assessed by studying a single building ([13, 14]), on a local scale (see [10, 15, 16]) and on a national scale (see [17]). None of these studies applied a dynamic energy system modelling in a medium to long-term perspective.

In this thesis, potential future DH systems' interactions with industries and buildings are studied by using a system-wide perspective. This aims to capture the indirect impacts of DH systems' interactions on energy flows and global carbon emissions. In addition, due to the dynamics of DH systems and longevity of DH infrastructure, the study applies dynamic energy systems modelling in a long-term perspective.

1.1 *Aim and scope*

As mentioned in Section 1, DH interactions with industry and building systems could play an important role in increasing energy efficiency and reducing the environmental burden. The overall aim of this thesis and appended papers is to assess the long-term, techno-economic and carbon emission impacts of these DH systems' interactions. The assessment has been implemented using a system-wide perspective, incorporating the impact of surrounding systems; the biomass market and electricity generation system. The assessment has been carried out for DH systems, industries and buildings in Sweden. More specifically, this thesis will address the following key questions:

- Does DH-industry interaction through a large heat network contribute to system profitability as well as carbon emissions reduction? How does the choice of system perspective affect the outcomes?
- Is DH-building interaction through a large heat network associated with lower costs and carbon emissions compared to other heat supply options to LEB areas? How does the choice of system perspective affect the outcomes?
- How can the DH interactions with industry and buildings be modelled to give a good representation of local and case-specific characteristics and, specifically, what are the opportunities and challenges of integer/mixed integer programming (MIP) optimisation of energy systems modelling at the local level?

The questions raised above are addressed through dynamic energy systems modelling covering the heat system and parts of the industry, building, electricity and transport systems. The applied models take the form of MIP optimisation models. The results of the models that are presented (for two totally different future climate policy scenarios) do not aim to predict the future but rather to fill the knowledge gap by exploring the dynamics of the DH-industry and DH-building interactions and by educating stakeholders and the general public. They may also serve as a basis for decision and policymakers.

1.2 *Overview of appended papers*

In line with the key questions, as presented in Section 1.1, the thesis is divided into three themes: 1) system perspective and parameters affecting system costs and carbon emission impact of the interaction between DH and industries, as covered in **papers I** and **II**; 2) system perspective and scale effects affecting system costs and carbon emissions impact of interaction between DH and energy efficient buildings in LEB areas, as covered in **papers III** and **IV**; 3) the opportunities and challenges of MIP optimisation energy systems modelling at local (municipal) level. This is covered to some extent in all four papers and dealt with more specifically in **Paper IV.**

The following is a brief description of each paper:

Paper I investigates whether the construction of a large heat network allowing for long-distance transmission of industrial EH for utilisation in DH systems is profitable from a societal point of view. The study includes two major steps. The first aims to find the key parameters which would substantially affect the profitability of the heat network. The second aims to deepen the knowledge of key parameters affecting the system profitability of the heat network. A regional MARKAL model, MARKAL_WS (West Sweden), is applied in this paper.

Paper II investigates energy system impacts (in regard to DH technology choices, energy flows and CO_2 emissions) of utilising large amounts of EH in DH systems at two different system levels: a "regional level" and a "local level". The first is a broader systems approach, taking all DH systems in a region into account to estimate their impact on the regional biomass market. It also accounts for the impact of changes in electricity generation and use in the regional system on marginal emissions by the cross-border electricity system. The second is a level addressing only the impact on DH systems directly affected by the EH supply. MARKAL_WS is applied in this paper.

Paper III compares the system cost of three heat supply options to LEB areas, to identify the cost-effectiveness threshold of the various options. Moreover, it investigates the cost components of the system cost of each heat supply option in the long-term. With system boundaries widened to include both an LEB area and its assumed nearby urban area DH system, the three heat supply options include: an individual, an on-site and a large heat network. The study takes the scale impacts of LEB areas and DH systems into account. A local TIMES model, TIMES_UH (Urban Heating) is developed and applied in this study.

Paper IV aims to identify energy system and CO_2 emission impacts of the three stated heat supply options in an LEB area. The system boundaries are expanded to include the LEB area and its assumed nearby urban DH system. The scale impacts of the urban DH system are taken into account. The impacts of heat supply options are investigated not only on the local energy systems but (due to the alternative use of biomass and international electricity markets) they are also assessed on a global scale. The TIMES_UH is applied in this study.

Table 1 also presents an overview of the papers, in terms of their goals and scopes.

Table 1- Goals and scopes of the four papers in this thesis.

	Title	Aim	Spatial scope	Temporal scope	Model focus	Approach	Outputs
Paper I	System profitability of excess heat utilisation - A case-based modelling analysis.	Assess profitability (from a societal point of view) of constructing a large heat network, allowing for long-distance transmission of EH for utilisation in DH systems.	Västra Götaland (VG) region of Sweden.	2010- 2050	37 municipal DH systems, one cluster of chemical industries and two bio-refineries in the VG region.	Bottom-up dynamic energy system modelling, cost-optimising, regional MARKAL model, MIP, scenario analysis, systematic sensitivity analysis, reference group.	Profitability of long-distance transmission of EH, key parameters of the heat network system profitability
Paper II	Modelling environmental and energy system impacts of large-scale excess heat utilisation - A regional case study	Assess energy system impact and CO_2 emissions of utilisation of large amounts of EH in DH systems.	VG region of Sweden & cross border electricity system.	2005-2030	37 municipal DH systems, one cluster of chemical industries and bio-refineries in the VG region - interaction with power and transport systems.	Bottom-up dynamic energy system modelling, cost-optimising, MARKAL model, MIP, scenario analysis.	Impacts on the energy flows and CO_2 emissions at local and regional level.
Paper III	Cost-efficiency of urban heating strategies – Modelling scale effects of low-energy building heat supply	Systematically assess the system scale economy of three heat supply options to LEB areas, determine the approximate cost-effectiveness thresholds of the various options.	LEB area and its assumed nearby urban DH system	2014-2052	Three real LEB areas and three real DH systems in Sweden.	Literature review, creation of hypothetical cases, dynamic energy system modelling, TIMES model, MIP, policy scenarios and systematic analysis.	Threshold analysis.
Paper IV	Low-energy buildings heat supply– Modelling of energy systems and carbon emissions impacts	Compare energy system impact and CO_2 emissions of the three heat supply options to LEB areas, across a broad range of conditions.	LEB area and its assumed nearby urban DH system, cross border electricity system and international biomass market.	2014-2052	One real LEB area and three real DH systems in Sweden.	Creation of hypothetical cases, dynamic energy system modelling, TIMES model, MIP, policy scenarios and sensitivity analysis.	Impact on energy flows and local and global CO_2 emissions.

1.3 Outline

This thesis is organised as follows:

Chapter 2 is a literature review focusing on studies of DH systems' interactions with industry and the building sector. It places special emphasis on the used bottom-up optimization models and studies that involve the regional and local MARKAL and TIMES models. Chapter 3 summarises the methodology used in the four papers. Chapter 4 discusses the method and data used. Chapter 5 presents and discusses the results of the appended papers. Chapter 6 presents the main findings. Chapter 7 outlines some ideas for future study.

2 Overview of related research

This thesis concerns DH systems' interactions with industries and buildings, focusing on: their impacts on societal system costs; DH systems and their linked energy systems; global CO_2 emissions. These impacts are primarily assessed in the literature dealing with energy systems models.

This chapter is divided into three sections. The first and second sections cover research into the techno-economic and carbon emission impacts of DH-industry and DH-buildings interactions respectively, applying an optimisation energy system model. The third section covers widely-used optimisation models in energy system assessments and explains how they were applied on a local/regional level.

2.1 DH-industry interaction

Cost-optimisation energy systems models have been applied to study the environmental and economic impacts of industrial EH use in local/ municipal DH systems. Holmgren [8] and Weinberger et al. [18] each applied the MODEST model in the Gothenburg and Hofors DH system and concluded that industrial EH use results in reduced overall system costs and global CO_2 emissions. Jönsson and Algehed [19] applied the reMIND model in an average Scandinavian Kraft pulp mill and concluded that the mill's EH use in a DH system led to a reduction in both system costs and global CO_2 emissions.

Only a few studies have fully addressed the economic aspects of DH-industry interaction, including the infrastructure cost for industrial EH extraction and transmission, for the potential economic benefits assessments. One of them concluded that EH sources close to large cities in combination with fossil fuel and CO_2 emission taxes may justify the high investment cost of heat distribution networks in DH systems [20]. Large heat networks, shared between different stakeholders (including multiple DH systems and industries) have also been identified as an attractive solution for increased DH-industry interaction [21-23]. The MODEST model was applied in a mid-term perspective, to assess the economic potential and environmental impact of a large heat network in Sweden forming a small regional heat market [21-23]. Ignoring the infrastructure cost, Karlsson et al. [23] included three DH systems and three industries located in a small region and showed that, in various scenarios, most of the stakeholders would benefit from a large heat network and that the total system net benefit was large in the mid-term. Morandin et al. [24] applied the Pinch Analysis tool, including only the cost of extraction of EH within a cluster of industries, to analyse the economic feasibility of potential industrial EH supply to DH systems. It was shown that EH delivery could be profitable for a wide range of heat extraction capacities.

In these studies, the major part of the investment cost of EH utilisation, plus the cost of constructing large (and sometimes long-distance) heat pipelines connecting the EH source (industries) with the sink (larger DH systems) was partly or entirely ignored. Since the construction of large heat networks (including the pipelines and necessary heat extraction investment capacity within industries) is associated with major investment costs and lock-in effects, it is important to obtain comprehensive knowledge on the economic consequences of such heat networks.

From the energy systems, carbon emissions and system cost point of view, EH utilisation will strongly impact the DH systems directly connected by the large heat network. However, due to DH-electricity system and DH-regional biomass market interactions (in Swedish cases), it will likely impose indirect regional DH system consequences. Previous studies did not entirely include the dynamics of the DH system, electricity system and biomass market (in other words, their development over the time horizon studied).

2.2 DH-building interaction

In countries with mature DH systems meeting a large share of the heat demand, there are three distinctly different options for providing LEB area heating. A *large heat network* is one; heat is produced in a nearby urban area DH system and transmitted to the LEB area by a pipeline. A second option is constructing a standalone local DH system within the LEB area – an *on-site* option. The third option is installing a heat production device in each building – an *individual* option.

Optimisation energy systems modelling was used to assess the energy system and carbon emission impacts (in energy-efficient building areas) of one of the above heat supply options [10, 16, 25]. These studies applied the MODEST model and presented the consequences (in terms of changes in fuel use, electricity generation and use and impact on global CO_2 emissions) of energy savings in DH-connected, multi-family buildings for current DH systems. Lidberg et al. [10] modelled the DH system of Borlänge and concluded that biofuel and oil use in HOBs and electricity input to heat pumps decreased, but that electricity generation from CHP plants would increase or decrease depending on the selected energy saving measures in the buildings. Åberg and Henning [16] and Åberg et al. [25] modelled two DH systems, Linköping and Uppsala respectively, using different DH production unit composition and different fuel use. They concluded that although electricity generation in CHPs decreases, primary energy use or global CO_2 emissions did not increase in the Uppsala DH system. In the Linköping DH system, not only did electricity generation in CHP decrease, but so did global CO_2 emissions and the use of fossil fuels. These model results indicate that the system impacts of DH-building interaction depend on local conditions. Åberg later [26] applied the FMS (fixed model structure) tool to draw general conclusions on the sensitivity of Swedish DH systems to heat demand reduction in DH-connected buildings and concluded that the local conditions were critical.

Other optimisation energy system modelling studies in the field focus neither on energy efficient building areas nor on the techno-economic and carbon emissions impact of each of the three heat supply options. Some of these studies included a single building [27], while others included an entire country [28, 29]. In Danish conditions, Möller and Lund [29] applied the national EnergyPLAN model to assess the economic potential of DH expansion into areas supplied with individual natural gas boilers, in a future energy system using higher shares of renewables. In a cost-effective solution, boilers were replaced with individual heat pumps in rural and remote areas. Karlsson et al. [28] applied the TIMES-DTU model and showed that (from the entire energy system perspective) DH expansion from a nearby city to a group of single-family buildings with an existing local DH network was cost-effective. Milan et al. [27] developed a linear programming cost-minimisation model to investigate optimal capacity of individual devices in an energy-efficient building, to achieve a 100% renewable energy supply.

In the previous studies, LEB heating assessments were limited to a single building or were carried out in an aggregated way for an entire country. None of the previous studies on energy systems, CO_2 emissions and system cost impacts of LEB heating optimised and compared all three heat supply options in LEB areas. The applied energy system optimisation models in the existing literature partially or totally ignored the dynamics of energy systems, in which the heat and electricity systems could develop with time during the studied time horizon and interact with each other and with the buildings.

2.3 Dynamic energy system optimisation models

Two well-known dynamic bottom-up energy system optimisation models will be briefly described. Then, since modelling of DH interactions with industry and buildings needs to take local conditions into account, a review of the application of these two models at local/regional level is provided.

In this thesis, MARKAL (acronym for MARKet ALlocation) [30] and TIMES (The Integrated MARKAL [31]-EFOM System [32]) are two examples of bottom-up energy system models. Bottom-up optimisation energy systems models have been widely used to study future energy system paths and the environmental impacts of climate policies over the past 30 years. By describing current and future technological options in both technical and economic terms, these models provide a detailed representation of energy sectors. Normally, the objective function of these models minimises the total cost of the energy system being studied so that it meets future energy demand, subject to certain constraints. These are rigidly energy-sector models which interact with the rest of the nation's economy through the exogenous specifications of useful energy demands [30]. In MARKAL and TIMES, energy markets are computed using the partial equilibrium method. In other words, the suppliers produce exactly the quantities demanded by their customers, maximising the total surplus (defined as the sum of all suppliers' and consumers' surpluses). This equilibrium feature is present at all the energy system phases: primary and secondary energy forms and energy services. Moreover, the model makes all investment decisions based on complete knowledge of future events within the model time horizon. This is often referred to as "perfect foresight" [33].

The MARKAL and TIMES models have been used to analyse the evolution of energy systems over several decades, often on a national/global level but rarely on a local/regional level (one or more municipalities). In these models, the objective function and total system cost was normally minimised using linear programming (LP), which assumes all constraints to be linear. This assumption reduces the complexity of the national/global models. However, it creates unrealistic investments (for example in new capacities in the local/regional models). The lumpy investment feature of the MARKAL and TIMES models (which limits new investments to discrete capacity levels) turns the LP model into an MIP one, allowing economies of scale to be taken into account. This is of great importance since some conversion technologies are not built at any capacity levels and because the specific costs of the technologies decrease and conversion efficiencies increase as capacity increases. The MIP feature also allows investments in an infrastructure (which may or may not take place) to be investigated [34].

Regional/local MARKAL or TIMES models have been applied in a few studies. Comodi et al. [35] (see Table 2) applied a local TIMES model and discussed its pros and cons in regard to the small scale of the energy system that was modelled. The local model allowed for more realistic and reliable description of the energy demand of the various sectors. The modellers were able to investigate future energy technologies which best fitted local conditions and develop meaningful scenarios for in-depth analysis of some energy sectors. However, drawbacks of the model were indicated as: 1) an absence of systematic data collection on a local level, 2) a lack of disaggregated statistics on the use of energy carriers and 3) the assumption of a competitive market for all commodities (in equilibrium models such as MARKAL and TIMES). This meant there was a need for careful selection of external parameters by the modeller.

Table 2 presents the list and approach of studies which applied a regional/local MARKAL or TIMES model.

Table 2. Regional and local MARKAL/ TIMES models and their characteristics.

Model	Regional/local	Model type	Spatial scope	Lumpy investment
MARKAL [36]	Regional	LP	Basilica region (Italy)	---
MARKAL [37]	Local	LP	Potenza town and its surroundings (Italy)	---
MARKAL[38, 39]	Regional	MIP	Västra Götaland county (Sweden)	Bio-refineries and gas grid
TIMES[40]	Regional	Not mentioned	Basilicata region (Italy)	---
TIMES[35, 41]	Local	LP	Municipality of Pesaro (Italy)	---

Abbreviations: linear programming (LP), and mixed integer programming (MIP).

As Table 2 shows, the MIP feature was applied in only one case in the previous regional or local MARKAL and TIMES models: a regional MARKAL model [38, 39]. In the model, the lumpy investment option was limited to few conversion technologies and infrastructure options. Investment in large conversion technologies (such as large CHPs) was only allowed in larger DH systems in the studied region (see Table 2). The other regional or local models neither mentioned nor discussed MIP optimisation.

2.4 The main contributions of this thesis

This thesis contributes to the existing research in five main aspects:

The literature review shows that the techno-economic and carbon emissions impact of DH-industry interaction has been confined to a small geographical scope, including DH systems directly connected to industries. The infrastructure cost of DH-industry interaction has been fully or partially ignored. The first part of this thesis contributes to the field through studies investigating the impact of DH-industry interaction on costs, energy systems and CO_2 emissions. It is implemented through a system-wide perspective, which includes all DH systems and bio-refineries sharing the same local biomass markets. Moreover, the full cost of DH-industry interaction is included in the cost assessment.

The literature review shows that the techno-economic and carbon emissions impact of LEB area heating were confined to one or two heat supply options. They were carried out at a national level (implying that the local condition was partially ignored), or at a single-building level (which may lead to sub-optimisation). The second part of this thesis contributes to the field through studies investigating the impact of LEB heating on costs, energy systems and CO_2 emissions. It is implemented through a system-wide perspective which includes all buildings in an area (not just a single building), plus its close-by urban area DH system. This allows all three heat supply options to be compared with each other.

The overview of the research shows that some efforts were made to draw general conclusions in studies carried out based on DH system, industry and building cases (see [26] for DH-building interaction). This thesis contributes by developing a different method of analytical assessment by extensive sensitivity analysis of key parameters. This, in turn, allows general conclusions to be drawn, based on cases studied (**Papers I** and **III**).

The literature review shows that several studies applied optimisation models to assess DH-industry and DH-building interactions in the medium-to-long term. However, the models were static and unable to represent how the DH systems and power sector develop over time. This thesis contributes to the field by using two widely applied dynamic optimisation energy systems models to address this issue: MARKAL (**Papers I** and **II**) and TIMES (**Papers III** and **IV**).

Local/ regional energy system models best fit the DH systems studies, based on specific cases which capture local conditions. Few local/ regional MARKAL and TIMES models have been used in energy systems assessments. These models often applied LP to new investment, ignoring economy of scale. This thesis contributes to the field by applying one regional MARKAL model and by developing and applying one local TIMES model. The MIP optimisation is used in the MARKAL model for some new investment (**Papers I** and **II**) and in the TIMES model for all new investments (**Papers III** and **IV**), bearing in mind the economy of scale and the fact that some advanced technologies are not built at any capacity.

3 Methodology

This chapter describes the procedural approach of this thesis in assessing the system cost, energy system and carbon emission impacts of DH-industry and DH-building interactions. The approach is built on the research questions raised in Section 1.1. Figure 2 gives a schematic illustration of the applied methodology. The rest of this chapter outlines the approach in greater detail.

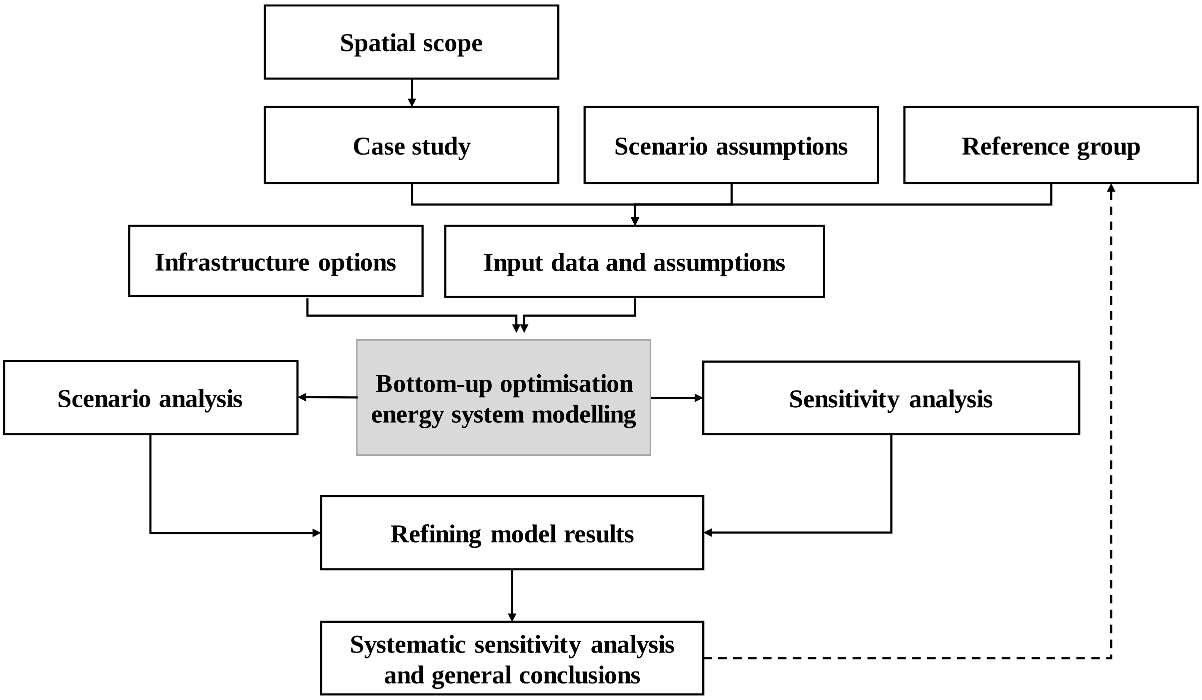

Figure 2. Applied methodology.

3.1 *Spatial scope*

In energy systems analysis, the choice of spatial scope (one important element of system boundary choices) can majorly affect the results and conclusion drawn. Taking a system thinking approach, any intervention in an energy system affects its surrounding. An intervention which appears to be an improvement (given a narrowly defined boundary) may not be seen as an improvement when the boundaries are extended [42].

DH-industry interactions through industrial EH use in DH systems would affect the use of local heat sources. In Sweden, biomass accounts for a large share of the fuel use in DH systems, in both HOBs and CHPs. Moreover, two common conversion technologies in DH systems are large-scale heat pumps and electric boilers. Consequently, industrial EH use is likely to affect electricity generation and biomass, as well as electricity use in DH systems. Regarding biomass, as current trade in it is mostly local, EH use in a DH system directly connected to an industry will likely impact neighbouring DH systems (if the amount of locally available, low-cost biomass is limited). Thus, an energy system analysis of DH-industry interaction (on a *regional* level) ought to provide comprehensive knowledge of changes in energy flows and carbon emissions. In this thesis and **Papers I** and **II,** DH-industry interaction is studied regionally, in a region of West Sweden (see Section 3.2). However, because electricity is transmitted over long distances, changes in local generation and use would affect not only electricity generation but also investment in new power plants somewhere in the international electricity market (a built margin). Therefore, this thesis and all its appended papers study the impact on carbon emissions of changes in electricity use and generation at a cross-border electricity system level.

As described in Section 2.2, an assessment of the DH-building interaction for providing heat in LEB areas (through a *large heat network*) ought to include individual LEBs and their relative locations (as with an *on-site* option), and a nearby urban area with an existing DH system. Consequently, the spatial scope should be extended to include both the LEB area and the nearby urban area DH system. This thesis and **Papers III** and **IV** study the interaction of DH with energy efficient buildings at a local/ municipal level, including an LEB area in Sweden with its close-by urban area.

Changes in the urban area DH system due to the *large heat network* would affect biomass (and electricity generation and use) in the urban area DH system. Thus, like the DH-industry interaction, the system perspective (for the energy flow and carbon emission assessments) ought to be expanded to include locally available biomass and the international biomass market in the short and long terms, plus the cross-border electricity system.

3.2 Cases

Studies of DH-industry interaction and DH-building interaction are largely based on the choice of specific cases. Firstly, DH systems differ in terms of size (heat supply capacity) and characteristics (fuel use and heat supply technology). Secondly, with regard to DH-industry interaction, collaboration between industry and DH companies varies as follows: in some cases, there is two-way collaboration between industry and DH systems, such as industrial EH utilisation in DH systems and DH use in industrial processes. In other cases, due to the technical limitations of industrial processes, these types of collaboration only occur in one direction (industrial EH use in DH systems). Regarding DH-building interaction, the heat demand profile, linear heat density and plot ratio differ between residential areas.

In this study, the case of DH-industry interaction is based on the current strong interest in large-scale EH from a cluster of chemical industries, for use in two local DH systems located in West Sweden (a one-way collaboration). The cluster and DH systems are described in Sections 3.2.1 and 3.2.2, respectively.

However, DH-building interaction is based on hypothetical cases constructed from data on three real LEB areas and three real DH systems. The LEB areas and DH systems are described in Sections 3.2.3 and 3.2.4, respectively.

3.2.1 Cluster of chemical industries in Stenungsund

A cluster of chemical industries is located near Stenungsund, a municipality in the VG Region approximately 50 km north of Gothenburg with a population of about 26,000 people [43]. It includes six production sites operated by five companies [24]: AGA, AkzoNobel, Borealis, Perstorp and INEOS. Current annual electricity and fuel use within the cluster is about 1.8 TWh and 4.9 TWh respectively (see [44] for a description of their fuel use and products). Most plants operate continuously over the entire year [24]. At present, a maximum heat extraction capacity of 235 MW for use in DH could be achieved since no heat is recovered within the cluster. However, by constructing a total utility network site and implementing energy efficiency measures, only 110 MW of heat (just under half the current potential) might be extracted for DH use [24].

When industry makes major investment in its facilities for totally different purposes, such actions may be interpreted by a DH company as a form of guarantee indicating a lower risk of shutdown in the near future [11]. 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” aims to complete the transition to renewable feedstocks; contributing to sustainable development of their products and recycling their plastics[39]. The implementation of these plans would likely decrease the risk of DH supply uncertainty.

3.2.2 Västra Götaland region

VG Region (Figure 3), is the second largest county in Sweden with a total population in 2017 of 1,623,400 (about 17% of Sweden's population) [43]. There is now strong interest in constructing a major heat network between the cluster of chemical industries located in Stenungsund (Section 3.2.1) and the Kungälv/Gothenburg DH systems in the Region. This DH-industry interaction has therefore been selected for this study. The region is divided into 49 municipalities, of which 37 have established local DH systems. Gothenburg, with its population of 536,800 inhabitants [43], is the largest city in VG. The first investigation into DH in 1946 led to continued development of the Gothenburg DH system, reaching its current status of 1,350 km [45] of DH network supplying some 3.5 TWh of heat. Between Gothenburg and Stenungsund lies the small town of Kungälv. Its DH system is currently based on a biomass CHP, supplying about 120 GWh of heat.

Figure 3. Geographical location of Västra Götaland, Stenungsund, Gothenburg and Kungälv.

3.2.3 Low-energy building areas

The three LEB areas were selected, starting with a low plot ratio area of 0.15 and representing a mainly residential area of primarily one-family houses. Two more dense areas were then selected, with plot ratios about five and nine times larger than the first area. Areas with these plot ratios were chosen as a good representation of the common range of plot ratios in residential areas in Sweden (such as 0.05- 2) [46].

<u>Mainly detached one-family houses</u>

The first real LEB area is located in the suburb of a small town in Halland County in West Sweden. Mainly constructed during 2011 – 2014, the area consists of 26 one-family houses, four small apartment buildings, six terraced houses, a nursing home for elderly people with 64 apartments and commercial buildings [47]. The total heated area is 15,300 m^2, the heat density is 27.2 MJ/m^2 and the plot ratio 0.15 [48]. All the buildings in the area were designed and built based on LEB requirements (< 45 kWh/ m^2/ year [47]). The total annual heat demand in the area, including space heating and hot-water demand, accounts for approx. 756 MWh (2720 GJ) [49, 50].

<u>Mainly multi-family buildings</u>

The second LEB area is located within the Falkenberg town in Halland County, Sweden and was constructed between 2008-2010. The area consists of four eight-storey, multi-family buildings with a total heated area of 10,208 m^2 and specific heat demand of 36.7 kWh/m^2/year [51]. This area characteristic provides the basis of the hypothetical case, with plot ratio of 0.73. Since the area is rather small in terms of total heated area, and to make it comparable with the other LEB areas in the calculations, the number of buildings in the model is multiplied by three (relative to the heat demand of the real LEB area) without changing the plot ratio. Thus, in this study, the total annual heat demand in this LEB area equals 4041 GJ.

<u>Mainly large multi-family buildings</u>

The third hypothetical case, with a plot ratio of 1.3, is inspired by a real LEB area located in the city of Munich, Germany. The area consists of 13 multi-family buildings with a total heated area of 28,550 m^2 and specific heat demand of 62 kWh/m^2/year. The measured annual heat demand in the area equals 6267 GJ [51].

3.2.4 District heating systems

To capture the scale effects and resource availability, three DH systems are selected: a small-town DH system, a medium one and a large one. Each has its own specific characteristics in terms of DH technologies and fuel use.

The LEB area providing input data for the area with plot ratio 0.15 is located close to a small town along the west coast of Sweden (Kungsbacka) with an existing DH system. This DH system was thus the inspiration for a hypothetical small-town DH system. In 2014, its total annual heat demand was 105 GWh. Due to DH network expansion, this heat demand increases by approximately 4 GWh [52] annually. The DH system is currently based on a biomass CHP plant, biomass HOB, oil HOBs and a heat pump.

The medium hypothetical DH system is inspired by the DH system in the larger town of Linköping and is based on a biomass HOB, oil HOBs, an electric boiler, a coal CHP, oil CHPs, municipal solid waste (MSW) CHPs and a biomass CHP. The total annual heat demand is 1312 GWh [53], which is assumed not to change over the studied time horizon.

The large hypothetical DH system, inspired by the DH system in the city of Gothenburg, has a total annual heat demand of 3177 GWh (assumed not to change over the studied time horizon). It is based on biomass HOBs, oil HOBs, natural gas (NG) HOBs, industrial excess heat, heat pumps, an electric boiler, NG CHPs, a biomass CHP and an MSW CHP [54].

3.3 Scenario assumptions

Explorative scenarios which broaden the scope of potential future climate policies address uncertainties regarding climate policy decisions and, consequently, energy markets. The 450ppm scenario in the World Energy Outlook (WEO) of the International Energy Agency (IEA) is in line with the goal of limiting the global temperature increase to 2 degrees, by capping the concentration of greenhouse gases. This scenario represents a stringent climate policy and has been identified as relevant in addressing the environmental sustainability of future energy systems. Referred to as BASE/450PPM, the scenario induces an increasing price (charge) on CO_2 emissions, resulting in decreasing fossil fuel prices while raising the price of renewable fuels in energy markets.

A second climate policy scenario has been identified as relevant for the purposes of this study. The New Policies/business-as-usual (BAU) scenario in IEA WEO is less ambitious but takes into account broad policy commitments and plans announced by countries. The 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.

3.4 Input data and assumptions

This thesis takes a DH-centred approach. Thus, the data it uses concerns DH systems; from heat sources to heat demand, their linked/potentially linked energy sectors and systems and their physical/political environment. The data on DH systems divides into two categories: 1) new investment in DH production technologies (which comes from two sources [55, 56]) and DH production technologies in existing DH systems (which comes from the environmental reports of DH systems companies, literature and statistics reported by Swedish District Heating). 2) data describing the heat demand of each building and maps of the LEB areas needed to design the DH distribution and transmission networks in **Papers III** and **IV** (which come from two sources [48, 51]) .

The data concerning DH linkage to energy sectors and systems divides into four categories: 1) industries with potential EH, 2) biorefineries, 3) buildings and 4) electricity systems, whereas data concerning DH physical/political environment divides into two categories: 1) energy markets and 2) climate policies.

Data describing industrial EH comes from two sources: 1) the analyses made by researchers involved in the reference group (see Section3.5) were used to represent chemical industries' EH extraction capacities versus their corresponding investment costs. 2) techno-economic data concerning the chemical industries and the Gothenburg/Kungälv DH systems heat connection (transmission pipeline), collected from the reference group and literature.

Data describing the techno-economic characteristics of the investment options for the biorefineries comes from scaling up of data from an existing biorefinery in the VG Region with a capacity of 20 $MW_{SNG\ (synthetic\ natural\ gas)}$.

Since buildings are represented in a less detailed way when assessing DH-industry interaction, only data on total heat demand and heat load profile of a typical year was sufficient. This data was collected from DH systems' environmental reports, plus literature and statistics from Swedish District Heating. For the assessment of DH-building interaction, additional data on buildings (including the heat demand of each building for a typical year and the map of the LEB areas) was collected from [55, 56]. This data was used to design the DH distribution and transmission networks in the LEB areas, which in turn were used to calculate the characteristics and costs of the DH networks. The heat demand data for each building also allowed for assumptions on individual heat production devices in the LEB areas.

Representation of the electricity system in the MARKAL model (including electricity prices and carbon emissions associated with the marginal electricity generation (built margin)) are outputs of the ELIN model [57] and ENPAC tool [58], in line with the corresponding climate policy scenarios in **Papers I** and **II**, respectively. However, the electricity system in the TIMES model in **Papers III** and **IV** is represented through assumptions and calculations based on data collected from [59], in line with the corresponding climate policy scenarios. The built margin in **Paper IV** depends not only on climate policy scenarios but also other factors affecting future electricity prices (and other considerations of the power companies). Thus, two paths are assumed for technological changes in the power sector: a “thermal power plants” (TPP) path and a “wind + gas turbines” (WGT) path.

Input data on energy markets, more specifically fossil fuel prices, is an output from three scenarios: the 450-ppm scenario, the Current Policies scenario and the New Policies scenario of the IEA's WEO reports in 2011 [60] and 2013 [61]. Input data on unrefined biomass (forest residues/wood chips) prices corresponds to two different system perspectives: a regional perspective and an international market one. In the appended papers, regional supply curves ([62, 63]) represent the regional market perspective while the output of the ENPAC tool [58] represents the international market perspective on biomass prices.

The perspective of climate policies such as the tradable green certificate (TGC) and emission trading systems (ETS) are national and international respectively. Since the scale of the energy systems of the VG Region and the LEB areas is sub-national, the TGC and ETS systems show effects similar to those of subsidies for renewable electricity and charges on CO_2 emissions. Thus, the data describing climate policies includes a CO_2 charge (tax), a renewable electricity subsidy and a transport biofuel subsidy. The CO_2 charges are also outputs of the three stated scenarios of the IEA's WEO reports [60, 61] and consistent with fossil fuel prices. The renewable electricity subsidy is based on historic TGC system cost levels and the transport biofuel subsidy is based on current biofuel tax exemptions.

3.5 Reference group

The energy system modelling in **Papers I-II**, was implemented in close collaboration with the following academic colleagues: 1) the researchers at the (former) Heat & Power Division, Chalmers (which addressed the cost of heat extraction within the cluster), 2) the Swedish Environmental Research Institutes (IVL), which assessed sustainability aspects and national environmental policies affecting the decision to build the large heat network and 3) the Research Institutes of Sweden (RISE), which designed market models to facilitate the necessary heat investments. There were also various stakeholders, such as the energy utility companies (which may own a future large heat network) and the chemical industries of Stenungsund. This collaboration was organised into two groups: 1) a Research Group including only the researchers and 2) a Working Group comprising all the stakeholders and researchers. The Research Group met continuously during the modelling 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 obtain feedback and generate new ideas.

The main research focus was the sustainability of the large heat network between the chemical industries and energy utility companies. 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 [64]). Three workshops were held to collect the principal aspects of sustainability, relevant to the construction of the large heat network: 1) an internal workshop, involving three researchers and 2) two external workshops with stakeholders, involving members of the Working Group for the modelling process, plus representatives of the public authorities and NGOs. Based on these workshops, the economic (long-term profitability and competitiveness) and environmental (climate change and primary energy use) aspects of sustainability were given high priority. The first, economic aspects, is addressed in **Paper I** and the second is assessed in **Paper II**.

3.6 Infrastructure options

In reality, the DH-industry and DH-building interactions become possible provided the required infrastructure is in place. This includes EH extraction and DH transmission for the DH-industry interaction, whereas DH transmission and distribution for the DH-building interaction. The following describes how the infrastructure options were represented in the models (Section3.7).

Paper I has two infrastructure options. These are introduced into the model one at a time. They are: 1) that either no investment in the Stenungsund – Kungälv (SK) and/or Stenungsund – Kungälv – Göteborg SKG pipelines will be made ("no connection"), or 2) that the operation of the SK and/or SKG pipelines will be possible from 2025, if investments in these pipelines are profitable ("connection").

Similar to **Paper I**, in **Paper II**: 1) either no SKG pipeline will be built ("no connection"), or 2) that the SKG pipeline is constructed and will be in operation from 2020 ("connection"). Since energy systems and CO_2 emission impacts of DH-industry interaction are assessed, a sunk cost is assumed for the SKG pipeline.

In **Papers III** and **IV**, three heat supply options to LEB areas exist: 1) *individual*, 2) *on-site* and 3) *large heat network*. These are also introduced to the model one at a time. Two of these need DH infrastructure: DH distribution in the on-site option and DH transmission and distribution in the large heat network option. The model is run in four modes to generate results for the three heat supply options as follows:

- For the *individual* and *on-site*:

Mode 1. Individual heat supply in the buildings in the LEB area (individual).
Mode 2. DH produced and used within the LEB area (on-site).

- For the *large heat network*:

Mode 3. DH produced for use within the nearby town.
Mode 4. DH produced in the nearby town for use in both the town and LEB area.

The cost-effectiveness threshold for the three heat supply options is examined in the model by varying the distances between the LEB areas and DH systems; from zero up to three km, in steps of one km.

3.7 Bottom-up energy systems modelling

The Following two models are applied: a regional MARKAL model for industrial EH use in DH systems (**Papers I** and **II**) and a local TIMES model for heat providing in LEB areas (**Papers III** and **IV**).

The following is a brief description of the models.

3.7.1 The MARKAL_WS model (Papers I and II)

In **Papers I** and **II**, the MARKAL_West Sweden (MARKAL_WS) model (developed and applied in [15, 16]), represents 37 municipal DH systems in the VG Region. Each DH system is described individually, with currently available DH production capacity and potential future investment options. In addition to HOBs and CHPs, the model also includes biorefineries with biofuels for transport as their main output. The model finds the lowest cost of meeting the exogenously defined DH demands for each DH system. Markets for electricity and transport biofuels are defined using exogenously assumed sale prices for these products.

Additional model development and updates were required for the SKG and SK and pipelines, plus the extraction of EH from the Cluster of Chemical Industries in Stenungsund (EH-CCIS). Investment in the pipelines and EH-CCIS extraction can only be made at discrete capacity levels. Furthermore, to capture the strong economies-of-scale characteristic of biorefineries, the technology is only available at discrete capacity levels (lumpy investment). Consequently, these investment options change the LP model into an MIP model.

In **Paper I**, the MARKAL_WS has a time horizon of 2010-2050, divided into nine model periods (so the length of each period is five years). The duration curve of DH is defined by four seasons plus day and night, so eight time-slices per year.

In **Paper II**, the model has a time-horizon of 2005-2030 divided into six time-steps, each representing five years. The duration curve of DH is defined by three seasons plus day and night, so six time-slices per year.

3.7.2 The TIMES_UH model (Papers III and IV)

For the purposes of this study, a local TIMES model, TIMES_UH (Urban Heating) was developed and applied. This model only represents the heat sector, implying that other sectors, (such as the power, residential and transport sectors) are exogenous. The TIMES model is driven by an exogenously given demand for heat, including space heating and hot water. The model's objective function is to minimise overall system costs for the entire horizon of 2014-2052, discounted against the reference year of 2014. The time horizon is divided into 10 time-periods with shorter lengths at the beginning (two periods of one year, 2014 and 2015 and one period of two years, 2016-2017) plus longer periods (five years) from 2018. Each year has been divided into eight time-slices, representing day and night in four different seasons. The model includes only one region, except for the *large heat network* option. For *large heat network*, the model includes two regions: an LEB area (Section 3.2.3) and one of the three DH systems (Section 3.2.4). All investment options for DH networks, DH technologies and individual heat devices in the LEB area and DH system can only be made at discrete capacity levels. Thus, these investment options change the linear model into an MIP model.

The general equation for the objective function is as shown in [34]:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} \left(1 + d_{r,y}\right)^{REFYR-y} . ANNCOST(r, y)$$

where:

- NPV is the net present value of the total cost for all regions (the objective function).
- ANNCOST(r,y) is the total annual cost in region r and year y.
- $d_{r,y}$ is the general discount rate.
- REFYR is the reference year for discounting.
- YEARS is the set of years for which there are costs, including: all years in the horizon, plus past years (before the initial period and if costs have been defined for past investments), plus a number of years after the end of the horizon (EOH) in which some investment costs are still being incurred, as well as the salvage value[1].
- R is the set of regions in the area of study.

ANNCOST in turn includes the following items:

- Capital costs incurred for investing into processes. These are first transformed into streams of annual payments, computed for each year of the horizon.
- Fixed and variable annual operation and maintenance (O&M) costs.
- Costs incurred for exogenous imports and domestic resource extraction.
- Revenues from exogenous export. Exogenous export earnings are revenues and have a minus sign in the cost expressions.
- Taxes and subsidies associated with commodity flows and process activities.
- The salvage value is the only cost element that remains lumped in the TIMES objective function. All other costs are annualised.

3.8 Refining model results

The model results are refined to generate the required parameters of interest to this thesis. This is done by inserting the results into the equations, described below.

---

[1] A *salvage value* of all investments still active at EOH and assumed to be accrued in the (single) year following the EOH. It is then discounted against the user-selected reference year.

In **Paper I**, the difference for each of the scenarios, in terms of heat supply technologies, total system costs and total CO_2 charges, between “connection” and “no connection” is assessed as:

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

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:

$$\text{System profitability} = -\,(\text{‘}\Delta\text{total system costs’} + \text{‘}\Delta\text{total } CO_2 \text{ charges’}) \quad (2)$$

Similar to **Paper I,** in **Paper II**, the equation (1) is used, but ‘ΔX’ presents the “connection” impacts on energy use and CO_2 emissions.

In **Paper III**, for each of the modes (Section3.6) and each scenario (Section3.3), the model generates future energy system developments and calculates the associated system costs. While the system cost of the individual and on-site options is directly calculated by the model (modes 1 and 2 respectively), the system cost of the large heat network option is obtained by inserting the model results in equation (3):

$$X_i\ (\text{Large heat network}) = X_i\ (\text{Mode } 4) - X_i\ (\text{Mode } 3) \quad (3)$$

where X is the system cost associated with heating buildings in the LEB areas and i represents the three DH systems.

The breakdown of cost components is calculated by inserting the model results in equation (4):

$$Y_i = \sum_{y \in YEARS} \left((Annualized\ capital\ cost) + (Annual\ fixed\ and\ maintenance\ cost) + (Annual\ running\ cost) \right) / \left(1 + d_{r,y}\right)^{y-REFYR} \quad (4)$$

where Y is the total distribution or transmission cost, discounted against the reference year.

Similar to **Paper III**, in **Paper IV**, the annual energy flows and CO_2 emissions associated with heating buildings in the LEB area are directly calculated (at each time period) for the individual and on-site options by the model (modes 1 and 2, respectively), while for the large heat network they are obtained by inserting the model results in equation (3), where X is the annual energy flows or CO_2 emissions associated with heating buildings in the LEB area and i represents the three DH systems.

So, the average annual energy flows and CO_2 emissions per unit of heated floor in the LEB area are calculated by equation (5):

$$W = \left(\sum_{j=1}^{10} (\text{X at period j}) * (\text{number of years in period j})\right)/\text{total number of years/heated floor area in the LEB area } [m^2] \quad (5)$$

3.9 Scenario and sensitivity analysis

In all the appended papers, the scenario analysis illustrates the possible impacts of DH interactions on energy systems, carbon emissions and system cost. As introduced earlier (Section3.3), rather than predicting the actual impacts, the two climate policy scenarios aim to show plausible results across a wide span.

In all the papers, the main idea of the sensitivity analysis cases is to assess the robustness of model results against parameter values whose future levels are uncertain and highly important to the DH systems' interactions with industry or buildings. Excepting these parameters, the sensitivity cases apply the same conditions as the two climate policy scenarios, one at a time. In **Papers I** and **III**, the sensitivity cases create a foundation for deeper analysis, as described in Section 3.10.

3.10 Systematic sensitivity analysis and general conclusions

This thesis has developed and applied a method to investigate the profitability/cost-effectiveness threshold of investments in the heat network required for the DH-industry and DH-building interactions in **Papers I** and **III** respectively (hereinafter called "systematic sensitivity analysis"). In this method, a matrix of sensitivity analysis is designed. The axes of the matrix consist of incremental change of parameters that are critical to the cost-effectiveness of the heat network. These are: 1) existing EH capacity in the base load of the Gothenburg DH system and deviation in investment costs for the heat network in **Paper I** and 2) scale of the urban area DH system and LEB area in **Paper III.** Accordingly, each element of the matrix represents either the profitability of various combinations of the sensitivity cases (in **Paper I**) or the system cost of the different heat supply options (in **Paper III**), in a ranking order.

The systematic sensitivity analysis plays other roles too. In **Paper I**, the systematic sensitivity analysis aims to deepen the sensitivity analysis of the network profitability whereas, in **Paper III**, it aims to investigate the threshold of cost-effectiveness for the *large heat network* option, by taking into account the distance between the LEB area and urban area DH system.

As mentioned earlier (Section 3.2), the energy systems, carbon emissions and system cost impacts of DH systems' interactions with industry and buildings are case-dependent. However, the systematic sensitivity analysis (in **Papers I** and **III**) may serve as a basis for drawing general conclusions, based on the studied cases. This is done by testing the model results under a wide range of changing parameters and conditions, so that each may represent some, if not all, the other DH systems, industries and LEB areas.

4 Reflection on the models and data used

The methodology developed and used in this study is governed by several factors, such as scope, data availability and the fact that DH systems are local energy systems. The following is a discussion on the choice of methods, models and data used.

4.1 Reflection on the models used

Optimisation models have limitations, such as perfect foresight (see [34]) and unrealistic linearity [65]. The first limitation, perfect foresight, extends to the entire model horizon, so that each agent has complete knowledge of the market's parameters, present and future [34]. Thus, these models are not necessarily a faithful forecasting tools for existing markets, especially in the short-term [66]. The second limitation, linear programming, is introduced to simplify complex optimisation problems. This assumption requires the objective function and all constraints to be linear which, in reality, they are not [65]. The problem of non-linear optimisation could be solved through MIP, in which some investments can be made at discrete levels [33].

There are several reasons that linear optimisation energy system modelling needs to be turned into MIP programming. Firstly, the fact that investments in infrastructure cannot be made gradually. In this study, investments in the DH transmission and distribution networks (as well as those in the heat extraction capacity of the cluster of chemical industries) can only be made at discrete capacity levels. Secondly, the fact that specific investment costs increase while conversion efficiencies decrease with decreasing capacity; and that investments in advanced technologies (such as biorefineries and CHPs) cannot be made at very small capacities (in other words, economies of scale). In this study, investments in biorefineries and all DH production technologies within municipalities can only be made at discrete capacity levels. Thirdly, some non-linearities can be made piecewise linear and solved using linear programming (LP) with much faster solution times. In this study, forest residues/wood chip supply curves (defining production cost versus regional potential) are modelled as stepwise variations in production. Heat load profiles of the DH systems in the models were also incorporated as stepwise seasonal variations.

The MIP optimisation is associated with some challenges: the flip-flop phenomenon is important to this study which, with a small change in assumptions, achieves a totally new set of results. As shown in **Paper IV**, the addition of a small amount of LEB area heat demand to the urban area DH system resulted in totally new investment in DH production. The problem was reduced by adding more constraints regarding new investment.

4.2 Reflection on the data used

For energy systems analyses of DH systems, regional and local models provide benefits by including more detail on locally important conditions. Such detail includes available heat sources, DH production plants, heat load profiles and techno-economics of DH distribution and transmission networks. However, many parameters such as energy markets, climate policies and the rest of energy systems have a national or international scope. Thus, data on these parameters needs to be given exogenously to the models. This, in turn, affects many assumptions in the model. In this thesis, different approaches were used to avoid biased assumptions. Firstly, the scenario and sensitivity analysis; secondly, collaboration with the reference group; thirdly, using the outputs of other models and tools (such as IEA WEO, ELIN and ENPAC).

In this study, only eight time-slices representing day and night in four different seasons were included in the MARKAL-WS and TIMES_HU models. This was because the aim (instead of yearly optimisation of the running of DH production plants) was to minimise the system cost of strategic DH planning for the industrial and building sectors in the medium-to long-term. This simplification opened the way to reducing the calculation time for model runs. This, in turn, enabled the inclusion of multiple cases and many sensitivity analyses. Thus, not only was it possible to generalise the model results to a large number of cases, but the robustness of the results could be tested against uncertain assumptions.

Data on the real heat load profile of 26 single-family houses (located in the LEB area and with a plot-ratio of 0.15) was entirely taken into account for the seasonal time-slices (four seasons) in the DH-building model, TIMES_UH. This assumption could well represent the load profile in the LEB areas. However, in the urban areas where the existing buildings do not necessarily comply with LEB requirements, it could result in over/under-estimation of the heat load for some seasons. Since the focus of this study was on the difference between each urban area with and without LEB area heating (rather than the absolute values in the urban areas), the error in the urban areas’ heat load was cancelled out.

5 Overview and discussion of the results

This chapter presents and discusses the main findings of the appended papers regarding DH-industry and DH-building interactions.

5.1 DH-industry interaction

The following subsections cover: the results of **Papers I-II** on energy systems (including energy flows and technologies) and environmental (CO_2 emissions); the 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; the profitability of investment in the large heat network. Firstly, the impacts on energy flows and technologies (at the regional and local levels) and impacts on CO_2 emissions (at local and cross-border electricity system levels) were assessed using a mid-term perspective. Secondly, the profitability of investment in the large heat network was assessed at regional level.

5.1.1 Energy flows

The model results show that the introduction of the large heat network between the cluster of chemical industries and Gothenburg/Kungälv DH systems increases EH use in the VG DH systems. The EH replaces fuel use in DH production, because it is a cheap source of energy compared to the other fuels (with the exception of municipal solid waste). The fuels replaced differ depending on scenario assumptions and time perspective. In this study, with its stringent climate policy scenario, EH replaces unrefined biomass (forest residues and energy crops) in the short-term, while in the mid-term it replaces NG. However, should future climate policies collapse, EH instead replaces unrefined biomass, NG and coal in the short-term, while in the mid-term it replaces only coal. The replaced fuels are ones which would have dominated the regional district heating systems, had the large heat network not been constructed under the applicable climate policy and time perspective.

In the short term, after introducing the heat network, biomass use shifts from heat to SNG production. At the same time, the EH delivered through the pipeline is insufficient to compensate for the reduced biomass use in the DH systems. Consequently, the use of electricity for heat pumps and NG increases in DH production to meet VG's heat demand.

5.1.2 CO_2 emissions

The changes in energy flows and technologies in the VG Region directly affect CO_2 emissions at the local level. These changes are also associated with indirect impacts, if the system and time perspective are extended. The changes in energy flows (because of, say, reduction in fossil fuel use) decrease CO_2 emissions, if the direct impacts on the DH systems of Kungälv and Gothenburg (*the local level*) are assessed.

In the stringent climate policy scenario of this study, changes in DH production technologies (such as the lower DH production in biomass CHPs) increase short-term CO_2 emissions at the cross-border electricity system level. This increase is due to the lower electricity generation in biomass CHPs being substituted for marginal electricity generation in NGCC (combined cycle) power plants.

In the stringent climate policy scenario, if we keep the system perspective of the cross-border electricity system but extend the time perspective into the mid-term, the changes in DH production technologies (such as lower DH production in NG CHPs and greater biorefinery production of transport biofuel) decrease CO_2 emissions. This reduction is due to lower electricity generation in NG CHPs and greater biofuel production in bio-refineries. So, the deficit electricity is generated by additional marginal electricity generation in more electrically efficient NGCC power plants (with an efficiency of 57%) while the biofuel replaces diesel in the transport sector.

5.1.3 Profitability of the large heat network

Investments in the large heat network, including heat extraction capacity at the chemical cluster and a 50km transmission pipeline (both at a capacity of 150 MW) are profitable in most assessed cases. The heat network allows for over 1 TWh/year EH utilisation in the DH systems of Gothenburg and Kungälv, replacing natural gas, electricity and biomass use in VG. The investments increase the cost of DH systems, but there is a major cost reduction due to lower CO_2 charges for avoiding the use of natural gas in DH production.

The sensitivity analysis indicates the large heat network would be profitable, even if heat demand in the VG Region were to decrease. Profitability increases if natural gas is phased out in VG’s DH systems and the investment costs for the heat network are lower.

Further systematic sensitivity analysis shows that the profitability of the heat network decreases substantially, if the existing oil refineries in Gothenburg continue supplying EH to Gothenburg’s DH system base load in the long term. In this case, if the investment cost of the heat network increases, the heat network is not profitable at all. Profitability also decreases if there is no regional competition for biomass between the DH systems and biorefineries. Future energy markets are also an important parameter. Lower fuel and electricity prices resulting from, say, solar and wind electricity generation, increase the profitability of the heat network.

5.1.4 Discussion

These results stress the importance of the methodology developed to conduct an energy system, system cost and carbon emissions assessment of the large heat network.

Firstly, 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 in regard to biomass use. Due to the existence of an alternative use for low-cost biomass, some changes occur outside the connected DH systems which cannot be captured at local level (such as biomass use in the transport sector). This finding implies that energy system decision-making may be better supported if interactions of energy carriers between the energy system and its surroundings are factored in, plus the importance of assessing local changes on a wider geographical scale.

Secondly, in this study, the dynamic energy system modelling has shed light on the short-to-long-term regional system impacts of a heat connection between a large chemical cluster and two DH systems. The model characteristics in this study are advantageous, since energy systems are by nature dynamic and the response to any intervention in the systems may differ over time.

Thirdly, in this study, the assumption of full or partial closure of oil refineries in Gothenburg is critical to the profitability of the large heat network. This is because existing EH sources naturally compete with Stenungsund's EH in the base load portion of the Gothenburg DH system.

Finally, the modelling results of the intersectoral approach (with biomass use in biorefineries assumed as an alternative to its use in CHPs and HOBs in the Region) show that investment in the heat network is profitable under various conditions. With a single-sector perspective (including only the stationary energy sector for biomass demand) represented by the DH systems in the Region, this investment becomes uncertain. In reality, given that there is an alternative use for the biomass, there will be an economic value associated with replacing it with EH. However, the magnitude of this value will likely be uncertain.

5.2 DH-building interaction

Buildings in new LEB areas require little heat even during cold days of the year. As described before (Section 2.2), individual heat devices in each building, (*individual*) and a low temperature district heating (LTDH) system in the area are two possible options so as to supply the required heat. The LTDH could be supplied by a local small DH system in the area, i.e. *on-site*, or by a heat connection to a nearby urban area with an existing DH system, i.e. *large heat network*.

This section presents and discusses the main findings of the appended papers in regard to DH-building interactions in LEB areas.

The results of **Papers III-IV** are as follows, concerning techno-economic and carbon emission impacts of a *large heat network* between a hypothetical LEB area and urban area cases compared with two other heat supply options in the LEB areas (*individual* and *on-site*):

Firstly, the cost-effectiveness of the *large heat network* option is compared with the *individual* and *on-site* options. This comparison is made for various combinations of the LEB area and urban area cases and for various distances between the LEB and urban area cases. The thresholds of the three heat supply options are thus identified. This section continues with an analysis of the cost components of the *large heat network* option.

Secondly, energy flows and carbon emission impacts of the *large heat network* option are compared with the *individual* and *on-site* options at local and global levels. This comparison is made for various combinations of the single-family LEB area and urban area cases, assuming that the LEB area is located within each of the urban areas.

5.2.1 Cost-effectiveness of large heat network

The model results show that, of the three heat supply options, the *large heat network* has the least cost independent of future climate policies and fuel and electricity prices if the LEB area is located in the urban area. The *large heat network* option is still the most cost-effective heat supply option if the LEB area is within 2-3 km of an urban area with a large DH system, including low-cost heat sources and DH production technologies. In LEB areas which include mainly single-family houses, the *on-site* option is the least cost-effective heat supply. By contrast, for LEB areas in this study which have mainly large or small apartment buildings (LEB areas with a plot ratio above 0.73), the *individual option* is the least cost-effective heat supply.

The analysis of the cost components of the *large heat network* option illustrates that the DH distribution and transmission costs dominate the total system cost in the *large heat network* option. This implies that fuel and electricity prices, as well as CO_2 charges in the 450PPM and BAU scenarios, cannot significantly influence the results of the *large heat network* option.

5.2.2 Energy flows and carbon emissions

From the model results on the *large heat network* option, marginal changes in an urban area's DH demand (due to connection of the LEB area to the urban area DH system) could affect the future path of the systems. The effects are complex and depend not only on climate policies but also on the urban area DH system's size. In the medium and large DH systems, where a diversified basket of fuels and heat sources are combined with DH production in CHPs, the effects on the energy flows can be strong. This is because any change in heat production of CHPs is associated with significant change to their fuel input and electricity output. One change which might occur is that the cost-effectiveness of waste heat production in CHPs (a by-product of times when it is profitable to generate more electricity) varies after providing LEB heating. While changes in utilised fuel in CHPs affect local carbon emissions, changes in electricity output from CHPs affect global carbon emissions which, in turn, depend on climate policies and the path of technological changes to the electricity system.

In this study (using the 450PPM scenario), connecting the LEB area to the large DH system reduces heat production in the natural-gas CHP plant which, in turn, greatly reduces natural gas use and electricity generation in the corresponding urban area. At local level, changes in carbon emissions are straightforward; the reduced use of natural gas use decreases local carbon emissions. By contrast, the impacts at global level are complex and depend on the substituted (marginal) electricity generation somewhere else in the electricity system. The reduced electricity generation increases global emissions in the model, in both TPP and WGT paths.

In the small DH system, where heat production occurs in biomass boilers and large heat pumps, providing LEB heating leads to increased use of biomass and electricity. These changes do not affect the local carbon emissions as biomass is assumed to be carbon neutral in this study and the electricity is not locally generated. However, depending on the alternative use of biomass and marginal electricity generation (which, in turn, depend on climate policy) these changes affect global emissions. With the 450PPM scenario, increased use of biomass limits alternative use of biomass in coal power plants, resulting in increased global carbon emissions. In the same scenario, increased use of electricity leads to increased global carbon emissions, in both the TPP and WGT paths.

The model results on the *individual* and *on-site* options show that impacts on energy flows and carbon emissions are similar to the *large heat network* option in the small DH system.

5.2.3 Discussion

The system-wide perspective (on assessing the impact of providing LEB area heating on economics, energy systems and carbon emissions) allowed comparison of three distinct heat supply options: a *large heat network*, an *on-site* and an *individual* one. The model results showed the importance of including not only individual LEBs and LEB areas in the assessments, but also the nearby urban area DH system. The result otherwise might be sub-optimisation. There again, modelling the impacts on the urban area DH systems introduced great uncertainty, making it difficult to give clear recommendations based on the study. These uncertainties are smaller in urban areas with small DH systems and where DH production often occurs in HOBs and heat pumps.

The scale effects of both LEB areas and DH systems were taken into account for the economic assessment, so as to generalise the model results to a larger number of cases. However, for providing LEB area heating, only the scale effects of DH systems on energy systems and carbon emissions impacts were included. One reason for this was that, based on the results, the system cost of *the large heat network* option was relatively close to the *individual* option in LEB areas with very low plot ratios (and mainly single-family houses). Thus, these LEB areas were selected for further energy system and carbon emission assessments. Another reason was that neither the total heat demand (ranging from 2.7-6.3 TJ) nor the DH distribution and transmission heat loss varied significantly between the LEB area cases. Thus, the energy system and carbon emission impacts of just one LEB area case can be generalised to different LEB area cases.

6 Conclusions

This thesis investigates potential future DH systems' interactions with industries and buildings. It includes method development and its application to specific cases in Sweden. To this end, two bottom-up optimisation energy system models of MARKAL and TIMES were developed and applied. This chapter presents the main conclusions drawn under each of the questions raised in Section 1.1.

Does DH-industry interaction through a large heat network contribute to both system profitability and carbon emissions reduction? How does the choice of system perspective affect the outcomes?

A large heat network between the cluster of chemical industries (located in Stenungsund) and the Kungälv/Gothenburg DH systems (in the VG Region) were selected to study DH-industry interaction, in which EH from industries could be used in the DH systems. Regional, bottom-up, dynamic energy system optimisation modelling (MARKAL_WS) is applied to investigate the system profitability, energy system and carbon emission impacts for the DH-industry interaction case.

The optimisation results of **Paper I** show that the large heat network investments (including heat extraction capacity within the chemical cluster and the heat pipeline between Stenungsund and Kungälv/Gothenburg, at capacity of 150MW) depend on the scenario assumptions and the energy system perspective applied. The results illustrate that the profitability of the heat network depends on future CO_2 emissions charges, fuel and electricity prices and biomass markets. If the competition for regional biomass is taken into account (and other EH sources in the vicinity of the DH systems do not compete in the base-load portion of the DH systems' heat supply) investment in the large heat network will likely lead to an overall reduction in long-term system costs in the VG Region.

The results of **Paper II** show that the large heat network would lead to more EH usage exceeding 1 TWh/year and, in turn, less use of biomass, fossil fuel and electricity in the DH systems. The greater use of EH is likely to weaken the competitiveness of biomass and natural gas CHPs in the mid-term and heat pumps in the long-term. These changes would lead to lower electricity generation in the short term and electricity use in the long term, while opening up opportunities in the Region for earlier production of transport biofuel.

At the local level, since EH utilisation would replace fossil fuels, its use in the Kungälv/Gothenburg DH systems would result in lower local CO_2 emissions. However, taking a cross-border electricity system perspective, if the interactions between DH systems and the power and transport sectors are taken into account, CO_2 emissions would increase in the short-term while decreasing in the mid-term.

In general, in the cases of one-way cooperation between an EH source industry and a DH system (only using 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 that are replaced will differ between DH systems. EH replaces CHP plants in many DH systems, resulting in reduced electricity generation within the DH systems. This, in turn, results in increased generation from marginal electricity technologies elsewhere.

Long-distance transmission of excess heat in a heat network requires major investment. Such investment can become profitable if the excess heat replaces DH supplies that are largely based on fossil fuels. It is less likely to become profitable if other major sources of excess heat are located closer by and if there is an abundance of low-cost biomass available in the region. Whereas stringent climate policies (associated with higher CO_2 charges) are likely to increase the profitability of investments, the higher investment cost of the heat network (due to, say, higher interest rates) would reduce such profitability.

Is DH-building interaction through a large heat network associated with lower costs and carbon emissions compared to the other heat supply options to LEB areas? How does the choice of system perspective affect the outcomes?

Three options for providing heating to LEB areas are investigated: a *large heat network* option, an *on-site* option and an *individual* one. In the *large heat network* option, heat is produced in a nearby urban area DH system and transmitted to the LEB area by pipeline. The *on-site* option consists of a stand-alone local DH system within the LEB area. Both the *large heat network* and *on-site* options include a low-temperature DH system in the LEB area. The *individual* option represents installation of a heat production device in each building. The *large heat network* option in this study represents the DH-building interaction. To incorporate the scale impacts, hypothetical cases were constructed, based on data from three real LEB areas and three real DH systems. A local bottom-up dynamic energy system optimisation model, TIMES_UH, was developed and applied to investigate the system cost, energy system and carbon emission impacts of the DH-building interaction. Distances from 0-3 km, in steps of 1 km, are taken into account between the LEB areas and DH systems to examine cost-effectiveness thresholds between the three heat supply options.

From the model results in **Paper III**, providing LEB area heating from a nearby urban area DH system through a *large heat network* is associated with the lowest system cost over the modelled time horizon. Since this result depends on several circumstances, the cost-effectiveness threshold of a *large heat network* is investigated in comparison with the other two options. It is shown that the *large heat network* always has the lowest cost if the distance between the urban area DH system and the LEB area is zero. This implies that the LEB area is within or adjacent to the DH network. If specific conditions are met regarding climate policies and the scale of the DH system and LEB area, the *large heat network* still has the lowest cost. For instance, given stringent climate policies (450PPM in this study) and the existence of a large DH system in the nearby urban area (associated with low-cost heat sources such as industrial EH and municipal waste incineration), the lowest system cost is a *large heat network* of a couple of km in length to LEB areas (where the plot ratio is less than about 1 and linear heat density is less than 4 GJ/m/yr).

The model results indicate that a large share of the *large heat network* system cost relates to the cost of infrastructure; thus, climate policies cannot significantly change the model outcomes. However, stringent climate policies (corresponding to higher CO_2 charges) could slightly improve the cost-effectiveness threshold of the *large heat network* compared to the *on-site* and *individual* options.

From the model results in **Paper IV**, the energy system and carbon emission impacts of the *large heat network* option are complex. This is because it imposes a small additional heat demand on the urban area DH system. These impacts depend on the urban area DH system and climate policy. The impacts of the *large heat network* are likely to be more complex, given a large or medium-sized DH system in the local urban area (where the DH supply includes many different technologies which can be affected by changing demand). In reality, the small additional heat demand will likely lead to different DH production investment, depending on decision makers' perception of the future and a range of motives.

The system-wide perspective in this study aims to take into account the indirect impacts of the heat supply options. These impacts are important; they correspond to the cross-border electricity system and alternative use of biomass. They also add to the complexity of the carbon emission impacts of the *large heat network* option. This is because of uncertainty regarding the future electricity system and use of alternative biomass.

From this study, it cannot be concluded that LEB area heating using the *large heat network* option is associated with lower carbon emissions than the other options. However, it can be concluded that a comprehensive assessment of the carbon emission impacts of providing LEB area heating needs to consider local conditions, such as a nearby urban area DH system.

The final general conclusion of the first question is that the investment in industrial EH extraction and transmission to the DH systems is profitable and leads to lower global carbon emissions in most cases studied. Moreover, the second question is that, where the threshold for the *large heat network* option for LEB area heating applies, the distance extends given low-cost heat sources (such as EH and municipal waste CHP in the base load portion of the urban area DH system). Combining these results indicates that achieving various goals for increasing energy efficiency and climate change mitigation could be made easier by the interaction of DH systems with industry and energy-efficient building areas.

How can the DH interactions with industry and buildings be modelled so as to accurately represent the local and case-specific characteristics and, specifically, what opportunities and challenges are there with MIP optimisation energy systems modelling at the local level?

In **Papers I** and **II**, the case of DH-industry interaction in the VG Region of Sweden is represented in the regional MARKAL_WS model. In addition to the 37 DH systems in the region, the model also includes biorefineries. This allows representation of the competition for biomass use between the heat and transport sectors. The necessary infrastructure for the DH-industry interaction (large heat network), such as the extraction of EH from the chemical industries in Stenungsund and EH transmission to the Kungälv/Gothenburg DH systems, are included as conversion technologies. This allows the model to represent their costs and efficiencies. The large heat network and biorefineries are modelled at discrete capacity levels, which turns the linear model into an MIP optimisation model. Then, the energy system and carbon emission impacts (plus the profitability of the large heat network) are assessed through MIP programming, minimising the total system cost for the 37 DH systems to meet the heat demand. Moreover, the systematic sensitivity analysis (initially used for in-depth profitability analysis of the key parameters of the large heat network) allows for generalisation of the results from the studied case.

In **Papers III** and **IV**, several cases of DH-building interactions in Sweden are represented in the local TIMES_UH model. In addition to the three heat supply options in LEB areas, three LEB areas, three urban area DH systems and four different distances between these are included in the model, so as to take scale effects into account. Since the study has a local perspective on the heat sector, all new investment in DH production, DH distribution and transmission and individual heat devices in buildings are modelled at discrete capacity levels, turning the model into an MIP optimisation model. The energy system, carbon emission and system cost impacts of the three heat supply options are then assessed through MIP programming, minimising the total system cost of each heat supply option. Moreover, the systematic sensitivity analysis (initially used to investigate the cost-effectiveness threshold of the heat options in the LEB areas) allows the results of the studied cases to be generalised.

In this study, the use of regional/local MARKAL and TIMES models is associated with opportunities and challenges. These allow local conditions (in terms of available heat sources, DH production technologies, DH distribution and DH and EH transmission technologies) to be represented. However, many parameters (such as energy markets, climate policies and the rest of the energy systems) have a national or international character, so data regarding these parameters needs to be provided to the models exogenously. This, in turn, concerns many assumptions in the model.

The linearity characteristic of bottom-up optimisation models may become a drawback to accurate modelling of new investments. Firstly, at the local level, it would make no sense to invest in some conversion technologies (such as CHPs and biorefineries) at very small capacities. Secondly, investment in the infrastructure (which either takes place or does not take place) is made at discrete capacity levels. The “lumpy” investment feature of the MARKAL and TIMES models which transforms a linear optimisation model into an MIP optimisation model, describes conversion technologies which are subject only to investment in specific size increments.

However, the MIP optimisation is associated with some drawbacks. For instance, it may lead to a flip-flop problem as shown specifically in **Paper IV**. In this study, the addition of a small amount of LEB area heat demand to the large and medium urban area DH systems results in totally new investment in DH production. This adds to the complexity of the carbon emission impacts of the large heat network option for heat provision in LEB areas.

7 Future research

This thesis has assessed the carbon emission and economic impacts of large-scale industrial EH for direct use in the distribution networks of DH systems. The potential for utilising short or long-term heat storage capacities within DH systems or industries leads to greater EH use in DH systems. A future study might include short or long-term heat storage capacities 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.

There are other larger or smaller industrial EH sources in the VG Region in comparison to the industrial cluster EH. 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 therefore be: “could heat connections between several DH systems offer opportunities to capture the potential of industrial EH for DH purposes within the VG Region?” The environmental and economic impacts of large DH systems can be assessed at regional level to answer this question.

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 use of additional EH in DH systems would likely reduce the will to implement them. There are also investment costs associated with implementing energy efficiency measures and constructing heat extraction capacities for DH systems within the cluster, plus construction of the long-distance pipeline for EH utilisation in the DH systems. The optimised level of EH availability for DH systems should be assessed. A capacity-cost model has been developed by researchers at the former 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 could be identified by linking the MARKAL_WS model and the capacity-cost model.

The results of this study are currently being 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. The results are also being used at Research Institutes of Sweden (RISE) to design market models to facilitate the necessary heat investment. We acknowledge that the energy systems modelling applied in this study is not sufficient for environmental assessment of a large heat network. Life cycle assessment (LCA) is a broad environmental assessment tool, but does not take economic and social aspects into account. LCA also results in a static model. Thus, a combination of tools (such as energy systems modelling and LCA) might provide broader knowledge and assist the decision-making processes.

This thesis has assessed the carbon emission and economic impacts of three heat supply options for provision of heat in LEB areas. In the on-site and large heat network options, the heat storage capacities corresponding to new investments in solar collectors were limited to day-night storage tanks. In a future study, short or long-term heat storage capacities might be included in the TIMES_UH model, to assess the cost-effectiveness threshold of the on-site and large heat network options and any resulting carbon emission impacts.

For the individual option, a limited number of heating devices were included in the optimisation model: a biomass boiler, a brine-to-water heat pump and an electric boiler. A research question might be: “could a combination of devices (such as a PV, plus an electric boiler plus a day-night heat storage tank) affect the cost-effectiveness threshold of the individual option?

In this thesis, small LEB areas, including a limited number of buildings, resulted in low annual heat demand. This, in turn, showed flip-flop results when the large heat network option was investigated through the local MIP optimisation model (TIMES_UH). For future study, further modelling efforts are required to minimise or resolve this flip-flop problem. One way might be to substitute larger areas with a lot of LEBs. Another might be to limit lumpy investments to a small number of technologies for which non-linearities are particularly important.

Acknowledgments

I am grateful to my academic supervisors, Erik Ahlgren and Tomas Ekvall, whose encouragement, guidance and support helped me develop an understanding of the subject and structure my research. Thanks also to Martin (Börjesson) Hagberg, co-author of **Paper II**, who contributed valuable discussion and helped me understand the MARKAL model.

Thanks to my colleagues at the Energy Technology Division for providing a pleasant working atmosphere and especially to my colleagues at the Energy Systems Research Group, for providing a good forum for discussing energy systems analysis issues. Special thanks to Shivika Mittal for valuable discussion and helpful inputs.

Thanks to my parents and sisters for their encouragement and support and special thanks to my mother for caring for my daughter whilst I was writing this thesis. Thanks to Felicia for making me happy. To Johan, thank you for your support. And to Magnus, many thanks for always being there for me. Thank you for the opportunity of loving you as your wife.

This thesis was conducted at the Division of Energy Technology, the Energy and Environment Department, Chalmers University of Technology. I am grateful to the following financial sponsors of this study:

Paper I — 40% by the Swedish Energy Agency and 60% by participating stakeholders (Business Region Gothenburg, West Sweden Region, the industries within the Stenungssund Chemical Industry Cluster, plus the Gothenburg, Kungälv and Stenungsund DH utilities).

Paper II — FORMAS and E.ON.

Paper III — Swedish Energy Agency and the multi-partner 4DH project, led by Aalborg University.

Paper IV — Swedish Energy Agency and the multi-partner 4DH project, led by Aalborg University, the J. Gust. Richert Foundation and the Adlerbertska Research Foundation.

References

1. EC, *An EU Strategy on Heating and Cooling*. 2016, EUROPEAN COMMISSION: Brussels.

2. Werner, S., *International review of district heating and cooling.* Energy, 2017. **137**: p. 617-631.

3. Werner, S., *District heating and cooling in Sweden.* Energy, 2017. **126**: p. 419-429.

4. Lund, H., et al., *4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems.* Energy, 2014. **68**: p. 1-11.

5. Sjödin, J. and S. Grönkvist, *Emissions accounting for use and supply of electricity in the Nordic market.* Energy Policy, 2004. **32**(13): p. 1555-1564.

6. Epstein, J.M., *Why Model?* Journal of Artificial Societies and Social Simulation, 2008. **11**(4): p. 12.

7. Djuric Ilic, D., et al., *Introduction of large-scale biofuel production in a district heating system - An opportunity for reduction of global greenhouse gas emissions.* Journal of Cleaner Production, 2014. **64**: p. 552-561.

8. Holmgren, K., *Role of a district-heating network as a user of waste-heat supply from various sources - the case of Göteborg.* Applied Energy, 2006. **83**(12): p. 1351-1367.

9. Lund, H., *Large-scale integration of wind power into different energy systems.* Energy, 2005. **30**(13): p. 2402-2412.

10. Lidberg, T., T. Olofsson and L. Trygg, *System impact of energy efficient building refurbishment within a district heated region.* Energy, 2016. **106**: p. 45-53.

11. Grönkvist, S. and P. Sandberg, *Driving forces and obstacles with regard to co-operation between municipal energy companies and process industries in Sweden.* Energy Policy, 2006. **34**(13): p. 1508-1519.

12. Thollander, P., I.L. Svensson and L. Trygg, *Analyzing variables for district heating collaborations between energy utilities and industries.* Energy, 2010. **35**(9): p. 3649-3656.

13. Gustafsson, M., et al., *CO2 emission evaluation of energy conserving measures in buildings connected to a district heating system - Case study of a multi-dwelling building in Sweden.* Energy, 2016. **111**: p. 341-350.

14. Marszal, A.J., et al., *On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark.* Renewable Energy, 2012. **44**(0): p. 154-165.

15. Åberg, M., et al. *Large-scale introduction of new residential district-heating loads to increase renewable electricity generation in CHP plants*. in *World Renewable Energy Forum, WREF 2012, Including World Renewable Energy Congress XII and Colorado Renewable Energy Society (CRES) Annual Conferen*. 2012.

16. Åberg, M. and D. Henning, *Optimisation of a Swedish district heating system with reduced heat demand due to energy efficiency measures in residential buildings.* Energy Policy, 2011. **39**(12): p. 7839-7852.

17. Nässén, J. and J. Holmberg, *On the potential trade-offs between energy supply and end-use technologies for residential heating.* Energy Policy, 2013. **59**: p. 470-480.

18. Weinberger, G., S. Amiri and B. Moshfegh, *On the benefit of integration of a district heating system with industrial excess heat: An economic and environmental analysis.* Applied Energy, 2017. **191**: p. 454-468.

19. Jönsson, J. and J. Algehed, *Pathways to a sustainable European kraft pulp industry: Trade-offs between economy and CO2 emissions for different technologies and system solutions.* Applied Thermal Engineering, 2010. **30**(16): p. 2315-2325.

20. Persson, U. and S. Werner, *Heat distribution and the future competitiveness of district heating.* Applied Energy, 2011. **88**(3): p. 568-576.

21. Gebremedhin, A. and B. Moshfegh, *Modelling and optimization of district heating and industrial energy system - An approach to a locally deregulated heat market.* International Journal of Energy Research, 2004. **28**(5): p. 411-422.

22. Klugman, S., M. Karlsson and B. Moshfegh, *Modeling an industrial energy system: Perspectives on regional heat cooperation.* International Journal of Energy Research, 2008. **32**(9): p. 793-807.

23. Karlsson, M., et al., *Regional energy system optimization - Potential for a regional heat market.* Applied Energy, 2009. **86**(4): p. 441-451.

24. Morandin, M., R. Hackl and S. Harvey, *Economic feasibility of district heating delivery from industrial excess heat: A case study of a Swedish petrochemical cluster.* Energy, 2014. **65**: p. 209-220.

25. Åberg, M., J. Widén and D. Henning, *Sensitivity of district heating system operation to heat demand reductions and electricity price variations: A Swedish example.* Energy, 2012. **41**(1): p. 525-540.

26. Åberg, M., *Investigating the impact of heat demand reductions on Swedish district heating production using a set of typical system models.* Applied Energy, 2014. **118**: p. 246-257.

27. Karlsson, K.B., S. Petrovic and R. Næraa, *Heat supply planning for the ecological housing community Munksøgård*. 2015, Proceedings of the 10th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2015).

28. Möller, B. and H. Lund, *Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system.* Applied Energy, 2010. **87**(6): p. 1846-1857.

29. Milan, C., C. Bojesen and M.P. Nielsen, *A cost optimization model for 100% renewable residential energy supply systems.* Energy, 2012. **48**(1): p. 118-127.

30. Fishbone, L.G. and H. Abilock, *MARKAL, a linear-programming model for energy systems analysis: technical description of the BNL version.* International Journal of Energy Research, 1981. **5**(4): p. 353-375.

31. ETSAP, *Energy Technology Systems Analysis Program*. http://www.etsap.org/index.asp.

32. Gargiulo, M., *Getting started with TIMES-VEDA, Version 2.7*. 2009, Energy Technology Systems Analysis Program (ETSAP).

33. Lolou, R., G. Goldstein and K. Noble *Documentation for the MARKAL family of models. Energy Technology Systems Analysis Programme*. 2004.

34. Loulou, R., et al., *Documentation for the TIMES Model-PART I*. 2016: Available at: http://www.iea-etsap.org/web/Documentation.asp.

35. Comodi, G., L. Cioccolanti and M. Gargiulo, *Municipal scale scenario: Analysis of an Italian seaside town with MarkAL-TIMES.* Energy Policy, 2012. **41**(Supplement C): p. 303-315.

36. Salvia, M., et al., *Approaching the Kyoto targets: A case study for Basilicata region (Italy).* Renewable and Sustainable Energy Reviews, 2004. **8**(1): p. 73-90.

37. Cosmi, C., et al., *Environmental and economic effects of renewable energy sources use on a local case study.* Energy Policy, 2003. **31**(5): p. 443-457.

38. Börjesson, M. and E.O. Ahlgren, *Cost-effective biogas utilisation – A modelling assessment of gas infrastructural options in a regional energy system.* Energy, 2012. **48**(1): p. 212-226.

39. Börjesson, M. and E.O. Ahlgren, *Biomass gasification in cost-optimized district heating systems-A regional modelling analysis.* Energy Policy, 2010. **38**(1): p. 168-180.

40. Di Leo, S., et al., *Energy systems modelling to support key strategic decisions in energy and climate change at regional scale.* Renewable and Sustainable Energy Reviews, 2015. **42**: p. 394-414.

41. Comodi, G., et al., *Local authorities in the context of energy and climate policy.* Energy Policy, 2012. **51**(Supplement C): p. 737-748.

42. Midgley, G., I. Munlo and M. Brown, *The theory and practice of boundary critique: Developing housing services for older people.* Journal of the Operational Research Society, 1998. **49**(5): p. 467-478.

43. SCB, *Befolkningsstatistik (Population statistics)*. 2017, Statistiska centralbyrån (Statistics Sweden): Örebro, Sweden.

44. Hackl, R., S. Harvey and E. Andersson, *Total Site Analysis (TSA) Stenungsund*, in *Research project report*. 2010, Chalmers University of Technology

45. GöteborgEnergi. *District heating in Göteborg (Fjärrvärmen i Göteborg)*.

46. Werner, S. 2016, Energy Technology, Halmstad University, Personal communication: Halmstad

47. Nielsen, C.K., M. Haegermark and J.O. Dalenbäck. *Analysis of a navel solar district heating*. in *EuroSUN 2014*. 2014. Aix-les-Bains (France): International Solar Energy Society.

48. Christensson, N. 2015: Eksta Bostads AB, Kungsbacka, Sweden.

49. Jimmefors, H. and J. Östberg, *Energy performance and indoor climate investigations in the passive house residential area Vallda Heberg*, in *Department of Civil and Environmental Engineering*. 2014, Chalmers University of Technology: Gothenburg.

50. Fahlén, E., et al., *Vallda heberg- The largest passive house area in Sweden with renewable energy (Vallda Heberg – Sveriges största passivhusområde med förnybar energi)*, in *LÅGAN Report* 2014: Gothenburg, Sweden.

51. Dalla Rosa, A., et al., *Toward 4th Generation District Heating: Experience and Potential of Low-Temprature District Heating*, in *Annex X Final report*. 2014, IEA DHC/CHP.

52. Statkraft. *Kungsbacka District Heating*. Available from: http://www.statkraft.com/energy-sources/Power-plants/Sweden/Kungsbacka/ (accessed 2015-05-20).

53. Difs, K., et al., *Biomass gasification opportunities in a district heating system*. Biomass and Bioenergy, 2010. **34**(5): p. 637-651.

54. GöteborgEnergi. *Environmental reports [Miljörapporter]*. 2014; Available from: http://www.goteborgenergi.se/Privat/Kundservice/Informationsmaterial/Miljorapporter (accessed 2015-11-02).

55. Danish Energy Agency and Energinet.dk, *Technology Data for Energy Plants*. 2014, Danish Energy Agency and Energinet.dk: Copenhagen.

56. Nohlgren, I., et al., *Electricity from new and future plants [El från nya och framtida anläggningar] 2014* 14:40, Editor. 2014, Elforsk AB, Swedish Energy Research Centre [Svenska Elföretagens Forsknings- och Utvecklings]: Stockholm.

57. Odenberger, M., J. Kjärstad and F. Johnsson. *Prospects for CCS in the EU energy roadmap to 2050*. in *Energy Procedia*. 2013.

58. Axelsson, E. and K. Pettersson, *Energy price and Carbon Balances Scenarios tool (ENPAC) – a summary of recent updates*. 2014, Chalmers

University of Technology: Göteborg, Available at: https://publications.lib.chalmers.se/publication/194812-energyprice-and-carbon-balances-scenarios-tool-enpac-a-summary-of-recent-updates.

59. IEA. *Power Generation in the New Policies and 450 Scenarios*. 2014; Available from: http://www.worldenergyoutlook.org/weomodel/investmentcosts/ (accessed 2015-11-02).

60. IEA, *World Enegy Outlook 2010*. 2011, International Energy Agency: Paris.

61. *World Energy Outlook 2013*. 2013, IEA (International Energy Agency): Paris.

62. Athanassiadis, D., et al., *Marginalkostnader för skörd av grot och stubbar från föryngringsavverkningar i Sverige (Marginal costs for harvesting branches and stumps of regeneration fellings in Sweden)*. 2009, Swedish University of Agricultural Sciences.

63. Athanassiadis, D. 2012, Swedish University of Agricultural Sciences, Personal communication: Umeå.

64. Zamagni, A., et al., *Blue Paper on Life Cycle Sustainability Analysis. CALCAS Report D20*. 2009.

65. Sterman, J.D., *A Skeptic's Guide to Computer Models.* In Barney, G. O. et al. (eds.), Managing a Nation: The Microcomputer Software Catalog, Westview Press, Boulder, 1991.

66. Lolou, R., P.R. Shukla and A. Kanudia, *Energy and Environment Policies for a Sustainable Future- Analysis with the Indian MARKAL Model*. 1997, Delhi: Allied Publishers Ltd.