THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A Methodology for Identifying Transformation Pathways for Industrial Process Clusters: Toward Increased Energy Efficiency and Renewable Feedstock

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Heat and Power Technology
Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

The European process industry is facing major challenges. Modern, large-scale production facilities in other parts of the world are often more efficient. Furthermore, limited access to inexpensive shale gas from North America has led to an additional disadvantage for the European industry. At the same time, the European Union (EU) has implemented policy instruments aiming at increasing the costs for emitting Greenhouse Gases (GHG) in order to curb global warming.

According to the International Energy Agency (IEA), the only measure that decreases GHG emissions and at the same time achieves economic, environmental and societal goals is increasing energy efficiency. Clusters of industrial production plants often offer considerable opportunities to increase efficiency at the total site level. Another option for the process industry is to tap into new markets in order to stay competitive. The interest for biomass based products has increased lately due to societal expectations for sustainable development and renewable feedstock based products.

This work presents a framework methodology that can provide guidance to the process industry in order to manage this transformation in an efficient way. Process integration tools are used to identify common measures to improve energy efficiency at a site-wide scale. This targeting procedure is followed by a detailed procedure for design and evaluation of practical energy efficiency measures. This step should be performed in close collaboration with experts from the industrial cluster in order to present solutions that can overcome some of the main barriers for the implementation of common energy efficiency measures. The knowledge obtained during this targeting and design process can also be used to identify favourable ways to integrate biomass based processes that can replace fossil with biogenic feedstocks and utilise existing infrastructure. In most chemical processes, there is usually excess process heat that cannot be utilised internally. In the last stage of the framework methodology developed in this work, the opportunity to export industrial excess heat should be investigated. This includes an assessment of the quantity of available heat, the economic feasibility and the competition between internal integration and the export of heat.

The framework methodology is demonstrated via a case study of a chemical cluster in Sweden.

Keywords: total site analysis, process integration, energy efficiency, biorefinery, district heating

Appended papers

This thesis is based on the work contained in the following papers:

I. Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA).
Hackl R, Andersson E and Harvey S (2011)
Energy, 36(8): 4609-4615

II. Applying exergy and total site analysis for targeting refrigeration shaft power in industrial clusters.
Hackl R and Harvey S (2013)
Energy, 55: 5-14

III. Design strategies for integration of biorefinery concepts at existing industrial process sites: Case study of a biorefinery producing ethylene from lignocellulosic feedstock as an intermediate platform for a chemical cluster
Hackl R and Harvey S
Accepted for publication in “Process Design Strategies for Biomass Conversion Systems" textbook to be published by John Wiley & Sons, Inc. in 2015
(A similar version of this book chapter is available in the proceedings of the 6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, 25 – 29 September 2011)

IV. Framework methodology for increased energy efficiency and renewable feedstock integration in industrial clusters
Hackl R and Harvey S (2013)
Applied Energy, 112: 1500-1509

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

VI. From heat integration targets toward implementation – A total site analysis (TSA)-based design approach for heat recovery systems in industrial clusters
Hackl R and Harvey S
Manuscript to be submitted to *Energy*

Co-authorship statement

Roman Hackl is the main author of papers I-IV and VI. Professor Simon Harvey supervised the work in all papers. Eva Andersson co-supervised the work in Paper I and was involved in the data collection and analysis. Process simulations and a portion of the process integration work in Paper III is based on a MSc thesis[1] by Maria Arvidsson and

[1] Arvidsson, M. & Lundin, B., 2011. Process integration study of a biorefinery producing ethylene from lignocellulosic feedstock for a chemical cluster. Master’s Thesis. Göteborg: Chalmers University of Technology. Available at: publications.lib.chalmers.se/records/fulltext/140886.pdf.

Björn Lundin, which was supervised by Roman Hackl. Associate Professor Matteo Morandin is the main author of Paper V. Roman Hackl contributed input data, was active in formulating the problem and methodology, analyzing the results and writing portions of Paper V.

Related work not included in this thesis

- Total Site Analysis (TSA) Stenungsund
  Hackl R, Andersson E and Harvey S (2010)
  Research project report, Heat and Power Technology, Chalmers, Sweden.
  Available through Chalmers Publication Library (CPL)
  publications.lib.chalmers.se/records/fulltext/local_131484.pdf

- Opportunities for Process Integrated Biorefinery Concepts in the Chemical Cluster in Stenungsund
  Hackl R and Harvey S (2010)
  Research project report, Heat and Power Technology, Chalmers, Sweden.
  Available through Chalmers Publication Library (CPL)
  publications.lib.chalmers.se/records/fulltext/local_131485.pdf

- TSA II Stenungsund - Investigation of opportunities for implementation of proposed energy efficiency measures
  Andersson E, Frank P-Å, Hackl R, and Harvey S (2011)
  Research project report, Heat and Power Technology, Chalmers, Sweden.
  Available through Chalmers Publication Library (CPL)
  publications.lib.chalmers.se/records/fulltext/local_155735.pdf

- Applying process integration methods to target for electricity production from industrial waste heat using Organic Rankine Cycle (ORC) technology
  Hackl R and Harvey S (2011)
  In Proceedings of WREC – the World Renewable Energy Congress, Linköping, Sweden, 8–13 May 2011, Vol. 7, pp. 1716-1723

- From fossil to biogenic feedstock - Exploring Different Technology Pathways for a Swedish Chemical Cluster
  Jönsson J, Hackl R, Harvey S, Jensen C and Sandoff A (2012)
  In Proceedings of the 2012 ECEEE Industrial Summer Study, Arnhem, The Netherlands, 11-14 September 2012

- Identification, cost estimation and economic performance of common heat recovery systems for the chemical cluster in Stenungsund
  Hackl R and Harvey S (2014)
  Research project report, Heat and Power Technology, Chalmers, Sweden.
  Available through Chalmers Publication Library (CPL)
  publications.lib.chalmers.se/records/fulltext/187164/187164.pdf

- Bridging barriers for multi-party investments in energy efficiency – A real options based approach for common utility systems design and evaluation
  Jönsson J, Hackl R, Harvey S, Jensen C, Sandoff A, Schaad G, Furberg A and Haggärde M (2014)
  Proceedings of the 2014 ECEEE Industrial Summer Study, Arnhem, The Netherlands, 2-5 June 2014

Table of Contents

1 Introduction

This chapter provides background information for this PhD project. Drivers for Energy Efficiency (EE) in industry are identified; additionally, industrial clusters are defined, the concepts of industrial symbiosis and eco-industrial parks are introduced and the role of clusters in EE and the integration of processes based on renewable feedstocks are described.

1.1 Background

The industrial sector is one of the main users of energy in the European Union (EU) and worldwide. The sector's consumption of primary energy carriers accounts for approximately 26% of the total primary energy use in the EU. This portion is approximately the same share as the two other main users, i.e., the residential and road transport sectors (see Figure 1). [1]

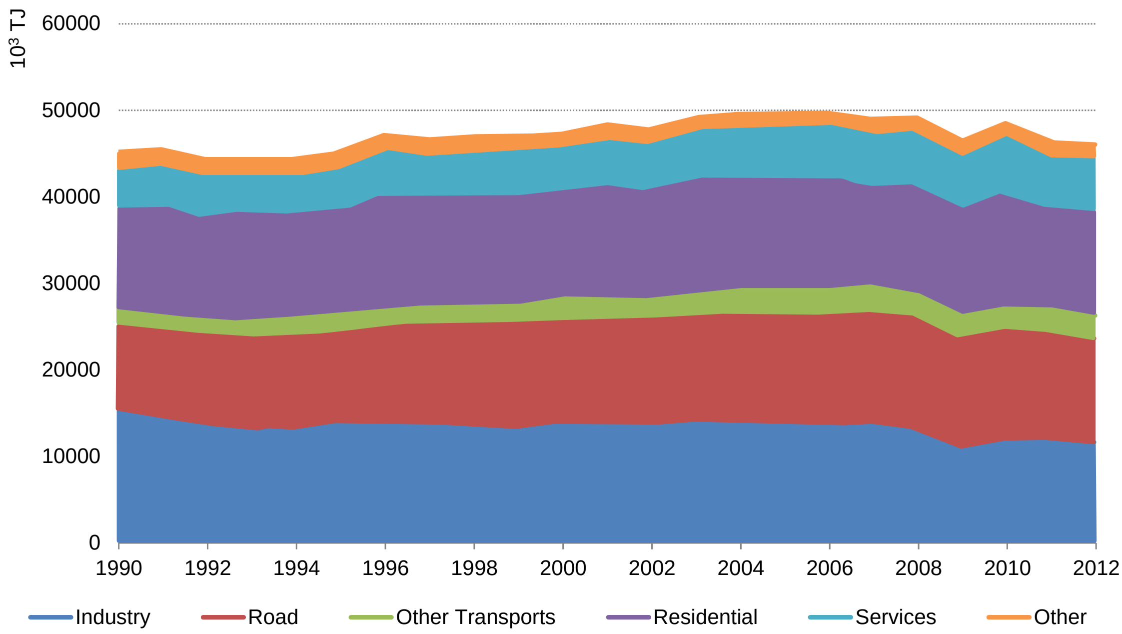

Figure 1 Total energy use (including electricity) between 1990 and 2012 by sector within the EU-28 [1]. Energy carriers, such as naphtha or natural gas, which are converted into non-energy products, e.g., petrochemicals, are included in the energy use of the industrial sector.

Energy in the industrial sector is used for a wide variety of purposes, e.g., heating, cooling, refrigeration, air conditioning, processing, assembly and lighting. Energy use is strongly related to GreenHouse Gas (GHG) emissions. Consequently, the emissions of GHGs in the EU are largest from the three aforementioned sectors; industry is ranked second after the transportation sector, with approximately 1,000 Mt-$CO_{2\text{-equ}}$/y of GHG emissions in 2010[2]. Most GHG emissions are caused by direct combustion of fuels, which accounts for approximately 60% of the total industrial GHG emissions [2], whereas approximately 40% of industry-related emissions are caused by energy transformation.

Due to the decline in domestic fossil resources, primary energy supply produced within the EU is steadily decreasing, with the exception of renewables (see Figure 2). However, the overall energy demand is relatively stable (Figure 1).

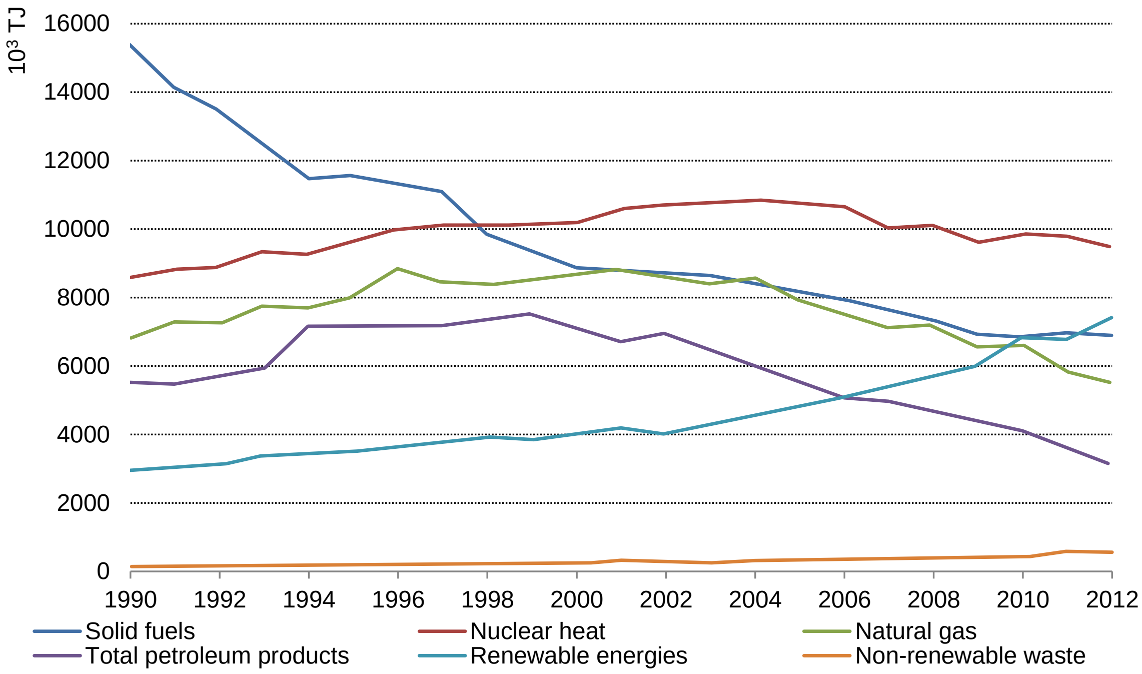

Figure 2 Primary energy supply produced within the EU-28 [1].

Thus, energy imports to the EU that are necessary to offset the energy demand increase the EU's energy dependence. For example, imports of natural gas have doubled in the past decade, and in 2012, these imports accounted for approximately 66% of the total natural gas consumption. The general trend in the EU is toward increased imports of fossil fuels and, to a lesser extent, biofuels. [1]

As noted above, the industrial sector contributes significantly to the total energy use and related emissions of GHGs, which affect both environmental and energy security. According to the Intergovernmental Panel on Climate Change (IPCC) [3], global GHG emissions must be reduced by 40-70% compared with the 2010 levels by 2050 and continue to decrease thereafter to curb the global temperature increase at 2 °C.

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[2] Incl. indirect emissions from energy transformation, e.g., electricity generation.

Furthermore, the International Energy Agency (IEA) has noted that increased end-use efficiency for fuel and electricity is critical for reaching the 2 °C goal [4]. Cellulosic biomass, which can replace fossil fuels and fossil feedstock in industrial production processes, can also contribute to reaching this goal [5].

High efficiency industrial production processes are extremely important to remain competitive. Rapid changes in the political atmosphere and energy costs in different regions of the world place pressure on energy security and competitiveness.

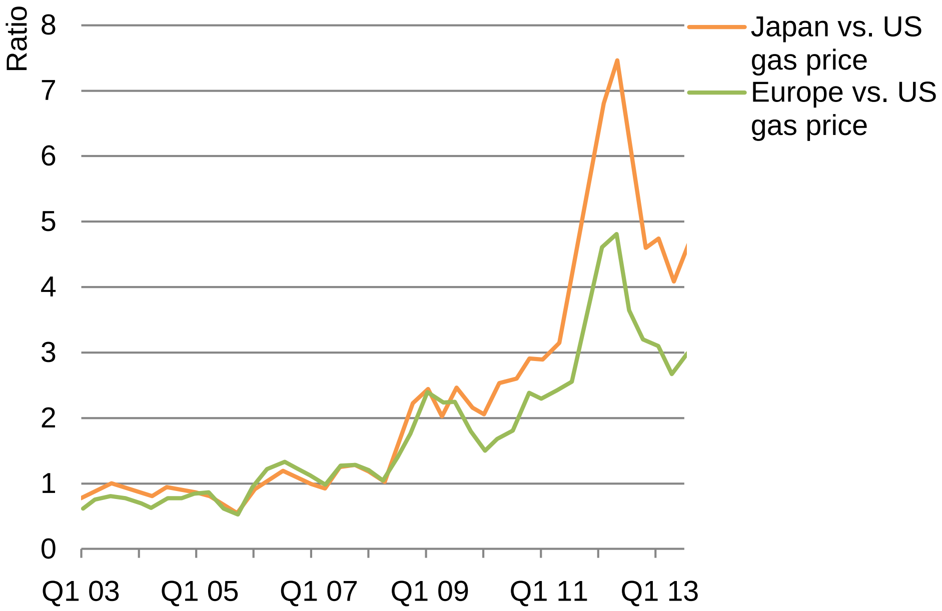

Figure 3 Japanese and European natural import prices relative to the US natural gas spot price [6]. European prices are weighted average price of imports at the German border. Japanese prices are for deliveries of LNG to import terminals. US prices are Henry Hub.

One example of rapid local-scale changes in energy costs is the so-called "shale gas revolution" in the US, which led to a competitive advantage for natural gas consumers in the US compared with other parts of the world. The ratio of natural gas import prices in Europe and Japan to the US spot price is illustrated in Figure 3. The ratio has increased considerably in recent years, resulting in a 3 times higher natural gas price in Europe (almost 5 times higher in Japan) compared with the US at the end of 2013. According to the latest IEA World Energy Outlook 2013, this ratio is likely to decrease in the future [6]; however, natural gas prices will remain considerably higher in Europe and Japan compared with the US. These costs are putting pressure on energy-intensive industries in Europe [6]. Furthermore, the construction of modern, large-scale production facilities in regions such as Asia has resulted in productivity advantages that the generally older, smaller facilities in Europe struggle to match [7]. Increased energy end-use efficiency is an important part in counteracting these economic disadvantages since it decreases both dependence on energy imports and the amount of GHG emissions.

Despite the current low price for carbon emissions, the implementation of the European Emissions Trading System (ETS) is another (future) driver for industrial EE. The ETS includes 11,000 power stations and industrial installations in 31 countries, including approximately 45% of the EU-28 total GHG emissions [8]. The limited availability of GHG emission allowances increases the costs of using energy, which makes investments in EE a viable option to decrease energy use and avoid GHG emissions.

As stated in a current report by the ECN [9], rising cost associated with GHG emission will provide incentives for companies to invest in EE measures, although only to a certain price level. Research shows that despite their economic viability, not all EE measures are implemented. The authors suggest using direct policies, such as introducing an EE obligation or using ETS auction revenues to fund EE programs. In addition, methodologies that assist industry in setting energy savings targets and identifying specific EE measures, including basic design considerations and economic evaluation, must be developed to bridge the gap between the potential for cost-effective energy savings and the actual level of their implementation.

As noted above, increased EE can assist with simultaneously achieving economic, energy security and environmental objectives. Therefore, increased EE is an important building block when planning future energy systems. Methods to identify and tap the potential energy savings of industrial processes and the efficient integration of processes based on renewable feedstocks are critical to achieving these goals.

The European Chemical Site Promotion Platform, a forum promoting new investments in Europe’s chemical clusters, argues that the formation and strengthening of chemical clusters in Europe is one of the main factors to ensure that chemical production remains competitive in Europe [10].

1.2 Industrial clusters in the chemical industry

One definition of clusters in an economic context is formulated by Porter [11]: *“Clusters are geographic concentrations of interconnected companies and institutions in a particular field, linked by communalities and complementarities.”* Porter later states the following: *“A cluster allows each member to benefit as if it had greater scale or as if it had joined with others without sacrificing its flexibility.”*

According to this definition, clusters in the chemical industry are agglomerates of chemical companies that are interconnected in some manner. Examples of possible interconnections include:

- Common logistics infrastructure, e.g., a common port or railway;
- Interconnected material flows, e.g., one company’s product is another company’s feedstock;
- Common utility infrastructure, e.g., steam/electricity generation and distribution;
- Shared labor pool; and
- Shared facilities, e.g., administration and research.

In her work regarding the economic and environmental aspects of integrated chemical production sites, Kimm [12] identified benefits attained by chemical clusters due to strong integration. To utilize the advantages offered by integrated chemical production, methodologies are needed to identify and implement this strong integration.

This work focuses on chemical clusters and their opportunities to improve competitiveness as well as decrease fossil resource consumption and GHG emissions. In the following section, two applications of the concept of industrial clusters from the field of industrial ecology are described.

1.3 Industrial symbiosis and eco-industrial parks

According to Chertow [13] "*industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity.*" Eco-industrial parks are an application of industrial symbiosis in which companies in geographic proximity are in "symbiosis", exchanging and sharing resources, including materials, energy, water, information and infrastructure [12]. The concept may involve the direct utilization of waste/by-product material streams of one unit at a neighboring plant, the use of excess process heat that cannot be utilized at the unit where it is generated at another plant or the sharing of common energy equipment, such as CHP plants and utility infrastructure.

One example of an eco-industrial park is located in Kalundborg, Denmark. Here, the collaboration between a power station, an oil refinery, a biotechnology company, a producer of plasterboard, the city of Kalundborg and a soil remediation company has led to increased environmental and economic efficiency, e.g., an estimated annual reduction of CO_2 emissions by approximately 130 kt and annual savings of approximately 15 million US$ [14]. Moreover, other benefits, e.g., personal, equipment and information sharing, have been identified [13].

Several tools are available to promote the creation and improvement of industrial symbiosis and eco-industrial parks. In this work, a framework methodology based on process integration tools is developed to systematically identify, design and evaluate heat integration opportunities among industrial facilities in geographic proximity. The framework methodology also enables the identification of renewable feedstock-based processes that can be integrated with existing clusters to improve economic performance and reduce GHG emissions.

In the following section, advantages and challenges of chemical clusters are discussed, which is followed by a more specific description of the implications of clustering chemical production sites on EE and the potential for integration of renewable feedstock-based processes.

1.4 Advantages, opportunities and challenges of chemical clusters

Kimm [12] investigated the advantages of integrated chemical production sites. Short distances between production plants enable the direct utilization of by-products or intermediates as feedstock for neighboring processes without additional transport. Direct product transfer by pipeline decreases safety risks from sea, rail or truck transport and transport costs and related emissions.

Energy is another important aspect of integration in chemical clusters. Chemical processes require heat and electricity to operate sub-process units, such as evaporation, condensation, and compression. Heat to chemical processes is typically provided by an energy carrier, such as steam, which is generated via the combustion of fuel in a boiler. A more energy-efficient method to provide process heat is the co-generation of heat and (electric) power in a combined heat and power (CHP) plant. These plants are typically more cost-effective at larger scales. A CHP plant in a small stand-alone chemical production site is typically not cost effective, whereas CHP plants providing heat and electricity to a chemical cluster provide these utilities more efficiently (less overall emissions) and at lower costs.

Heat Integration (HI) also offers significant opportunities for EE within larger clusters. Whereas stand-alone plants are limited to HI within one process, HI within a chemical cluster can be far more extensive. If excess heat from one process can supply heat to another via, e.g., a steam or another utility network, HI can lead to substantial primary energy savings.

Another advantage of chemical clusters is related to both energy and material transfer. Direct material transfer can enable heat savings due to the possibility of transferring hot materials. For example, in a stand-alone unit, the product must be cooled/liquefied for transportation. At the receiving site, the feedstock must be heated/evaporated to achieve suitable process conditions. Direct material integration can reduce the utilities consumed in these stages.

By-products that cannot be utilized in another process and must be incinerated can be utilized more efficiently in a chemical cluster. Single process plants might not be able to use the additional heat generated from by-product incineration, whereas clusters can use this heat. Moreover, by-product fuels can replace fuels in CHP plants for supplying heat and electricity to chemical clusters, leading to additional efficiency gains.

Depending on the processes used at a chemical site, the need for infrastructure may vary. In general, installations such as those required for the energy supply (e.g., steam, electricity, and natural gas), material and utility distribution (e.g., material pipeline, steam, water, and electricity networks), waste management (e.g., waste water treatment and waste incineration) and transport (e.g., road, sea, and rail infrastructure) can be utilized more efficiently or might only be available at larger scales. Moreover, the costs for services, including engineering, IT and communications, analytics, and safety (e.g., fire brigade and site security), benefit from economies of scale, which are provided by chemical clusters.

Another important advantage of chemical clusters compared with single, stand-alone plants is based on the opportunities for information and knowledge sharing and access to a common labor pool. The proximity of the individual companies and their employees being involved in common projects leads to an exchange of knowledge and experience that promotes the development of the entire cluster. Furthermore, clusters have a larger demand for skilled labor and other services. Therefore, the regional importance of clusters increases. Meanwhile, a climate conducive to education, research and other services related to the cluster activities is created.

Despite the advantages that chemical clusters offer to companies in geographical proximity to each other, these opportunities are rarely exploited to their full extent. To remain competitive with clusters in other growing markets, such as Asia, European clusters must increase their productivity. In general, plants in Europe are older and do not benefit from the economies of scale that are achieved by new large production facilities in Asia. Changes across entire production facilities and companies in contrast to traditional single company investments are necessary to obtain significant productivity improvements [7].

Joint investments in measures to improve productivity within a cluster result in a larger degree of complexity compared with investments of single companies. One potential difficulty is competition between companies involved in the investment because there is often a limited culture of collaboration, which makes it difficult for project partners to work together. Joint investments require the long-term strategies of all partners to interlock for the investment to occur. Business models for joint investments are another issue. Instead of focusing on benefits for the entire cluster, companies tend to put their own interests first [15].

Clusters differ depending on their geography, size and interaction between the participating companies. In the following section, aspects of EE via improved HI on a site-wide scale and efficient integration of renewable feedstocks are highlighted.

1.5 Energy efficiency and integration of renewable feedstocks in the context of chemical clusters

From an EE perspective, the short distances between companies located in a cluster enables the exchange of materials, heat and cooling between the different process plants. Therefore, the overall EE of the cluster can be increased. A production plant that generates excess heat at a temperature that prohibits its use within its own plant boundaries can export this heat to a neighboring plant. This transfer reduces the need to produce the same amount of heat in a utility boiler, which saves primary energy.

Methodologies based on HI targeting tools for single sites have been developed that allow for the targeting of such energy collaboration opportunities, namely, Total Site Analysis (TSA) [16]. However, one of the many potential barriers in implementing such collaborative measures is the ownership structure of the cluster. If the constituent plants have different owners and operate in different markets with different business cycles, adopting common EE measures can present major challenges. Hence, it is important to also assess the potential for EE improvements if each plant adopts measures solely at its own site and uses this assessment as a benchmark for collaborative EE measures.

In addition to improving EE in existing processes, another option to improve the competitiveness of chemical clusters discussed in this work is the biorefinery concept, which represents a method for substituting fossil hydrocarbon feedstock in processes that produce synthetic products and liquid fuels using renewable raw materials. A wide range of renewable feedstock materials can be converted into value-added products and thus substitute fossil feedstocks. For example, the raw materials that can be used as feedstock for a biorefinery are crops and residues, lignocellulosic material, municipal solid waste and algae. Biorefineries apply a wide range of technologies to separate the biomass inputs into their building blocks, such as hydrogen, carbohydrates and proteins, which are subsequently converted into value-added products [17].

The integration of a biorefinery process within a chemical cluster can be advantageous compared with stand-alone operations for the following reasons:

- Utilization of existing infrastructure e.g., ports, railways, roads, boilers, piping, and storage;
- Excess heat from certain biorefinery components (e.g., excess steam from a gasification unit) can partially offset the heat demands in other parts of the cluster;
- Excess heat from the cluster can be used in biorefinery processes, such as biomass drying and biogas reactor heating;
- Biorefinery products can be used directly as feedstock in the cluster (e.g., syngas and ethanol), thus eliminating the need for transport, while the direct delivery of warm products can conserve energy; and
- Biorefinery operations can capitalize on existing knowledge regarding the operation of chemical processes.

The consequences of implementing both EE measures and a biorefinery in a chemical cluster are illustrated in Figure 4. The energy and material flows into, within and out of a chemical cluster with a low degree of integration are shown on the left side of Figure 4. Large amounts of fossil feedstocks, fuels and electricity are imported and converted into products and large amounts of excess heat. An illustration of measures to decrease the clusters' environmental footprint and improve efficiency is presented on the right side of Figure 4. The following major changes are suggested:

- More efficient use of excess heat;
- Integration of biorefinery processes to decrease the clusters' fossil feedstock dependence;
- Decreased import of fossil feedstocks, fuels and electricity; and
- Export of by-products.

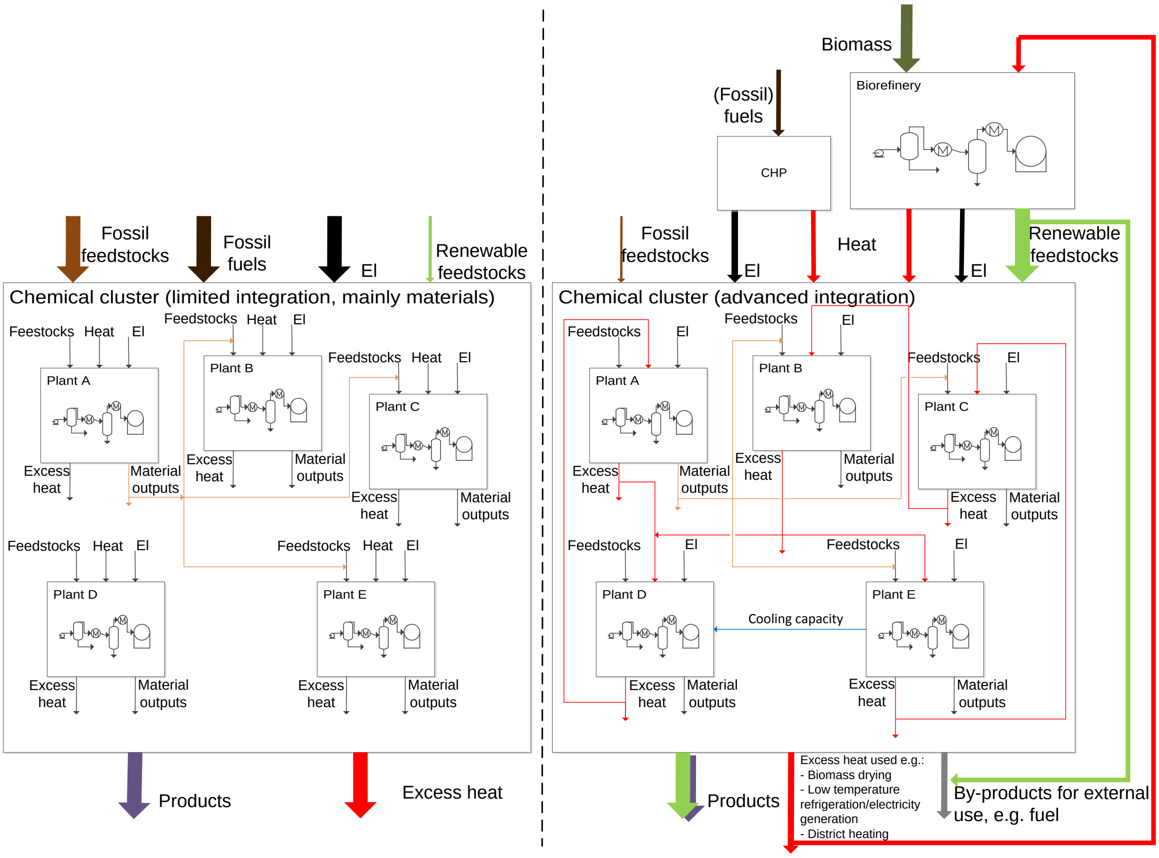

Figure 4 Left: Illustration of energy and material flows in a chemical cluster with a low degree of integration (no HI, limited materials integration). Right: Energy and material flows in an industrial cluster with a high degree of integration (heat and material integration), a CHP for delivering heat and electricity, and integrated on-site processing of renewable feedstocks (biorefinery concept).

These improvements can be accomplished by:

- Increased EE of single plants;
- Increased EE by site-wide energy collaboration, whereby companies send excess heat and cooling capacity to other plants for optimal re-use;
- Implementation of process-integrated biorefinery units;
- Increased utilization of low-grade excess heat, which cannot be recovered directly within the cluster, e.g., extended district heating (DH), low-temperature refrigeration/electricity generation, heat pumping and biomass drying; and
- Increased co-generation.

This work presents a framework to investigate opportunities for systematically implementing such improvements.

1.6 Appended papers

A general overview of the papers included in this thesis is presented and illustrated in Figure 5.

In **Paper I,** the methodology used for identifying site-wide HI opportunities within an existing industrial cluster is presented. The methodology, which is called TSA, is illustrated with a case study of a chemical cluster in Sweden. The paper is based on an extensive project report that is not included in this thesis [18]. **Paper II** presents an extension of the methodology applied in **Paper I** to identify heating, cooling and related shaft work savings targets using advanced HI. The same cluster is used to illustrate the methodology.

In **Paper III**, a design strategy for integrating advanced biorefinery processes with existing industrial clusters is developed and illustrated for a biorefinery producing ethylene from lignocellulosic biomass.

The methodologies used and the results obtained in **Papers I, II and III** are used to describe a framework methodology that simultaneously targets EE and replaces fossil feedstocks with biomass in industrial clusters. This framework methodology is established in **Paper IV**.

In **Paper V**, a targeting approach for delivering industrial excess heat to DH systems is presented. The economic conditions for exporting industrial excess heat at different levels of cluster internal heat recovery are investigated. Moreover, consequential CO_2 emissions due to heat recovery within an industrial cluster versus exporting excess heat to a DH network are investigated.

Paper VI extends the TSA methodology by creating a detailed flexible design for common site-wide heat recovery systems in industrial clusters with or without common energy infrastructure. The methodology is presented and illustrated in a case study of the same cluster used in the previous papers.

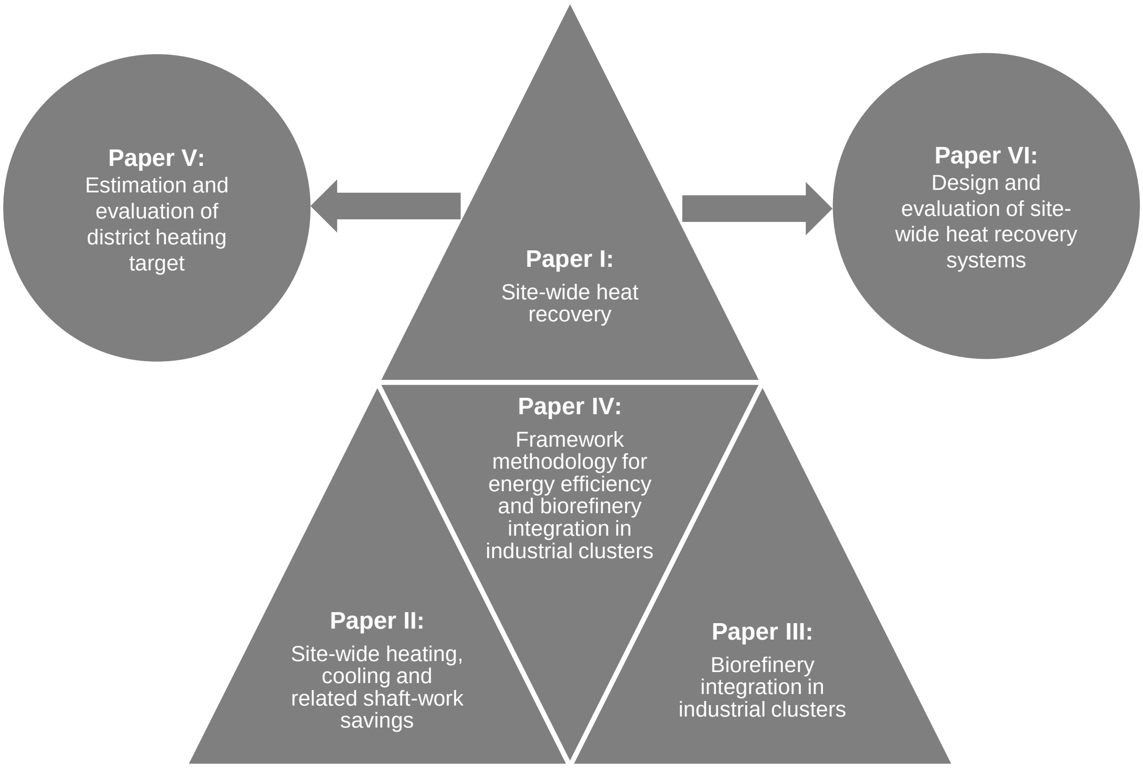

Figure 5 Overview of the appended papers and their relation.

1.7 Thesis outline

The relevant scientific literature is presented in Chapter 2, which provides an overview of the development and current status of methods and tools for improving EE in industrial clusters and the integration of new bio-based processes. At the end of this chapter, research needs are identified. Based on these needs, the objectives and scope of this thesis are described in Chapter 3. Chapter 4 provides a detailed overview of the methods used in this work, and the methodologies developed in this work and their application to a case study are presented in Chapter 5. In Chapter 6, the main findings of this work are summarized, and the primarily conclusions are discussed. Chapter 7 discusses potential sources of error and uncertainty and their implications on this work, and Chapter 8 outlines interesting future areas of research in the field of process integration with a focus on industrial clusters.

2 Literature review and research needs

This chapter presents an overview of the current scientific literature on EE in industrial clusters and the integration of biorefinery concepts with existing (industrial) infrastructure. Thereafter, the research needs that were identified based on the literature review are described.

2.1 Literature review

The scientific literature includes both papers on methodologies and case studies targeting improved EE in industrial clusters. Developing methodologies for identifying implementation strategies for site-wide EE measures remains a necessity. There are a limited number of papers discussing methods for the practical implementation of EE measures in real industrial clusters. The literature on biorefinery integration with chemical clusters is limited to studies investigating different biorefinery processes and their internal integration potential or integration opportunities with other single process plants, e.g., gasification plants that co-generate fuels, heat and electricity integrated with industrial processes, such as pulp and paper mills, or local DH networks.

2.1.1 Total site analysis and exergy analysis for heat integration targeting

TSA represents a set of tools developed for targeting HI on a chemical site level. Since its introduction by Dhole and Linnhoff [19], TSA has been significantly developed by, e.g., Raissi, who extended the methodology by introducing the site composite and site utility grand composite curves and applied TSA to greenfield, site expansion and retrofit projects [16].

Hui and Ahmad [20] developed a methodology for the optimal design of total site utility systems that combines the principles of traditional pinch analysis and exergy analysis. Transferring heat from a utility to a process stream implies a certain amount of exergy loss due to the temperature difference between the two streams. Hui and Ahmad utilized exergy analysis for steam (hot utility) costs to determine the optimal utility system configuration for an entire site. The methodology can be applied to chemical sites with a common utility system to increase efficiency.

Klemeš et al. [21] summarized the results of 5 different studies in the petroleum, chemical and pulp & paper industries in which TSA was applied to target EE. Their results indicated that the identified heat savings resulted in fuel and emissions savings of up to 20% and 50%, respectively. HI via a utility system often exhibits considerable effects on the power generation potential of a chemical site. At large chemical sites, power is co-generated when supplying heat. HI decreases heat consumption and related power generation in CHP systems.

Maréchal and Kalitventzeff introduced a methodology for targeting and synthesizing site-scale utility (including co-generation and refrigeration) systems using mathematical programming techniques to minimize the energy supply costs of an entire site [22]. The methodology was applied to a case study that suggested an approximately 36% reduction in operating costs at the investigated site. They also developed a method for targeting utility systems that accounts for multi-period operation; thus, this approach considers temporal changes in utility demands at the different plants within an entire site [23].

Matsuda et al. [24] first applied the TSA methodology to one of the largest, centrally integrated chemical clusters in Japan. Despite relatively well-integrated single plants, a large potential for heat savings through the use of site-wide measures was identified. In this study, TSA tools were applied to visualize changes to the utility systems at the investigated sites that are necessary to achieve the targeted heat savings. Project ideas resulting from this analysis were described in their paper; however, no detailed design for measures that realize the potential heat savings was presented. In another case study, the methodology was applied to an industrial area in Thailand, where the TSA revealed an energy savings target of 28% [25].

Becker and Maréchal [26] proposed a methodology for targeting and optimal integration at industrial sites. The methodology accounts for the fact that not all units are able to exchange heat directly, which makes it necessary to introduce heat transfer units, such as hot water heat recovery systems. The optimal placement of energy conversion units, e.g., CHP and heat pumps, was also investigated.

Pouransari et al. [27] applied techniques based on process integration to develop a methodology for EE improvements at large chemical sites. The methodology uses different levels of detail in data acquisition (e.g., black, grey, white box and simple/detailed model analysis); moreover, they illustrated the quality improvements due to the use of more detailed data acquisition. Single processes and total site integration were investigated, illustrating that larger efficiency gains can be achieved by site-wide HI. Multi-objective optimization indicated that a detailed representation of all units is not always necessary to identify the most beneficial retrofit options for a given process. Pouransari and Maréchal [28] proposed a targeting approach for solving the heat load distribution problem for large industrial sites. The approach identifies feasible near-optimal solutions that are compatible with the Minimum Energy Requirement (MER) of the heat load distribution problem while simultaneously reducing the complexity of the problem. The approach was illustrated using a case study.

Bandyopadhyay et al. [29] incorporated the concept of assisted heat transfer. Self-sufficient pockets in the Grand Composite Curve (GCC), which indicate opportunities for process internal heat exchange in pinch analysis, are exploited to supply heat to other processes at the site. The authors showed that it was possible to increase site-wide HI by not removing the pockets from the GCC. The methodology can be applied to identify the site utility levels and target potential energy savings and co-generation.

The work of Varbanov and Klemeš [30] extended the traditional total site HI approach to include intermittent renewable energy sources, such as solar, wind, biomass and renewable waste streams, for a site's energy system.

Stijepovic and Linke [31] proposed a methodology to target waste heat recovery and reuse in industrial zones by identifying specific waste heat recovery options via existing utility systems. The methodology aims at identifying optimal recovery and reuse techniques for excess heat and accounts for the distance between plant units within an industrial zone. Only the generation and transfer of hot utilities of a quality already present in one of the utility systems within the industrial zone are considered; no new utilities are introduced. Hot utilities generated from excess heat are assumed to be transferred to the utility system of another plant, whereas changes to the hot utility/process interface are not considered. The approach was extended to also include heat and power co-generation [32].

A recent paper by Varbanov et al. [33] introduced an individual-ΔT_{min} approach that accounts for changes in heat transfer characteristics for different processes. In the traditional approach, an average ΔT_{min} is used for all heat exchange processes throughout a site to estimate the potential heat savings. This new method allows distinct ΔT_{min} values for intra-process, process-to-utility and utility-to-process activities to be identified, which allows for a more realistic estimate of the site's heat recovery potential.

Wang et al. [34] presented a methodology that accounts for the distance between the plants when targeting total site HI. Heat losses, pump power and piping costs are the major factors that affect total costs when process heat is recovered across different plants, which are represented in the suggested targeting procedure. The authors illustrated the methodology using a case study. In another paper, Wang et al. [35] extended their methodology by investigating different connection patterns (e.g., parallel, series or split) when constructing pipeline infrastructure across several plants. Issues regarding the choice of heat transfer fluid (steam/hot water) for site-wide heat recovery were also addressed.

Boldyryev et al. [36] suggested an approach to target the minimum heat transfer area for site-wide heat recovery. The cost optimal utility temperature level is determined by dividing the area between the hot and cold process streams in the composite curves into enthalpy intervals and calculating the utility temperature that results in the minimum heat transfer area for each interval. Based on this approach, the utility temperature with the overall minimum heat transfer area can be identified.

Liew et al. suggested approaches to address several total site related HI issues, such as water sensible heat [37], variable energy supply and demand [38] and plant layout [39]. A retrofit framework for total site heat recovery networks was also proposed by the authors [40]. The presented algorithm focuses on identifying EE improvements at industrial sites with a central utility system. The approach was demonstrated using a case study.

A large consumer of power in chemical processes is refrigeration. Linnhoff and Dhole [41] developed a methodology that extended pinch analysis to the design of low-temperature processes. The authors combined pinch analysis with exergy concepts. The main goal of the method is to achieve a more in-depth understanding of how to design a refrigeration system and a Heat eXchanger (HX) network to achieve low energy requirements. Linnhoff and Dhole introduced the Exergy Grand Composite Curve (EGCC) as a tool to target decreased exergy losses and suggested a short-cut method to estimate shaft power requirements based on exergy flows. They also demonstrated the application of the concept for evaluating the effects of process changes on shaft power consumption.

Umeda [42] proposed a combined exergy/pinch analysis approach for HI targeting. Dhole and Linnhoff [19] presented a summary of TSA tools and demonstrated a combined TSA and exergy analysis approach. The authors presented targeting procedures to identify the optimal use of fuel, co-generation and process cooling. They also suggested a methodology for the overall design and analysis of low-temperature processes [43]. The methodology is based on the EGCC approach introduced in their earlier work. Case studies conducted by the authors identified average shaft power savings of 15% compared with a traditional pinch analysis-based approach.

Several authors have applied the aforementioned combined exergy/pinch analysis approach to target EE measures in single plant industrial case studies. Fritzon and Berntsson [44] demonstrated the approach at a slaughter and meat processing plant and found that 10% to 16% of the shaft power currently used for refrigeration could be saved by improving the current systems using measures identified by the combined exergy/pinch analysis. Panjeshahi et al. [45] applied the concept for targeting improved EE at an ammonia production plant. The authors determined optimal temperature levels for the refrigeration systems that resulted in potential shaft power savings of 15%.

Hirata and Kakiuchi [46] studied the integration of adsorption heat pumps driven by excess heat to replace cooling capacity in refrigeration systems in an ethylene production process, achieving shaft power savings of approximately 12% in the existing refrigeration systems.

Fabrega et al. [47] performed an exergetic analysis of the refrigeration system in a steam cracker plant. In their study, the equipment with the highest rates of exergy destruction was identified; they suggested measures that could reduce exergy destruction by approximately 13%.

Ataei [48] presented a case study regarding the combined use of pinch and exergy analysis to decrease the power consumption of an olefin plant. Moreover, Ghorbani and Salehi [49] applied a combination of pinch and exergy analysis to design the refrigeration cycle for natural gas liquefaction.

Maréchal and Favrat [50] used the exergy concept combined with a pinch-based approach to study the optimal integration of energy conversion systems. The authors determined the minimum exergy demand for a process considering the exergy demand caused by the minimum temperature difference (ΔT_{min}) due to heat exchange, the exergy deficit above the pinch point, the exergy excess between the pinch point and the ambient temperature and the exergy demand for refrigeration. Based on this approach, the optimal integration of energy conversion systems was determined to minimize energy costs or exergy losses.

Aspelund et al. [51] extended pinch analysis and exergy principles to design sub-ambient temperature processes by incorporating pressure-based exergy in the targeting and design procedure.

Marmolejo-Correa and Gundersen identified challenges related to using exergy efficiency as a performance indicator for the design of low-temperature processes. The authors identified a lack of standardization and an incorrect understanding of the exergy transformation inside the process or unit operation as the factors that explain why exergy efficiencies are difficult to use for this type of study. Marmolejo-Correa and Gundersen [52] proposed mathematical expressions to represent the internal exergy transfer for processes operating at sub-ambient temperatures. A new graphical approach to directly obtain exergy targets when designing low-temperature processes [53] and processes that operate both above and below ambient temperatures [54] was also developed.

2.1.2 Integration of advanced biorefinery processes with industrial clusters

A large body of literature on the development, design and process integration of biomass-based fuels and chemical production processes is available. Most studies have assumed stand-alone operation and/or the integration of different energy conversion technologies, such as co-generation, whereas other studies have considered HI with, e.g., a local DH system to increase the biorefinery efficiency. Several investigations have been conducted regarding the integration of biomass-based processes with existing industrial process plants.

Integration with a conventional oxo synthesis plant was studied by Arvidsson et al. [55]. Two cases were investigated: a) natural gas as feedstock for synthesis gas production was replaced by biomass-derived natural gas via thermal gasification and b) synthesis gas of suitable quality was directly produced from gasified biomass. Process simulation and integration were used to investigate the efficiency of the new processes under different integration scenarios. The study showed that HI with the existing plant was advantageous from an EE perspective.

Holmgren et al. [56] studied the integration of biomass-based methanol production connected to the same petrochemical cluster used in the case study presented in this thesis. In the case study, it was assumed that the excess steam from the gasification/methanol synthesis plant was used to replace steam from the cluster's boilers. Moreover, the availability of excess heat from the cluster for biomass drying was also quantified. Different scenarios for the cluster's future heating demands were investigated. The results of the study showed that biomass gasification systems integrated with existing industrial processes exhibited a larger potential for reducing GHG emissions than stand-alone units.

Hannula and Arpiainen [57] investigated the production of light olefins and biofuels via methanol from gasified biomass. Different aspects of integrating parts of the process with an existing olefin cracker plant were discussed, including the integration of heat/materials and equipment sharing.

Brau and Morandin [58] investigated the integration of two biomass-to-hydrogen process concepts with an existing oil refinery. The concepts were based on indirect and direct gasification; different technologies were used for gas upgrading and treatment. Several integration configurations were evaluated in terms of energy and exergy efficiency and environmental impacts via a fossil CO_2 balance. The authors showed that the performance of the two biomass-to-hydrogen concepts could be improved by up to 11% in EE and 9% in exergy efficiency through heat integration.

Heyne et al. [59] investigated the benefits of integrating a gasification-based biorefinery with an existing power production plant. A biomass gasification unit producing synthetic natural gas was integrated with a biomass CHP plant. The importance of properly conducted HI was highlighted in this study. Power production from a well-integrated plant was shown to be as much as 10 times larger than in a less integrated scenario.

An overview of different aspects related to biorefineries is provided in the evolving e-book entitled “Systems Perspectives on Biorefineries”, by Sandén [60]. Researchers from Chalmers University of Technology cover a range of aspects that are important for the implementation of biorefineries, including biomass availability, the optimal location of biorefineries, potential GHG emission reductions and biorefinery efficiency.

2.2 Research needs

Based on the aforementioned literature review, research needs regarding the further development of current methodologies for identifying EE opportunities in industrial clusters and integrating renewable feedstocks are highlighted below.

Single plants in clusters that are not centrally integrated typically have their own utility systems consisting of

- Boilers or CHP plants supplying heat (and power);
- Steam distribution/condensate collection systems with plant-specific utility levels;
- Other hot utilities (e.g., hot oil) at plant-specific temperature levels;
- Cooling water; and
- Refrigeration systems.

All of these systems are suitable for single plants (e.g., utility temperature/pressure levels and condensate purity), which are not necessarily the same throughout an entire cluster. Current tools and studies have not considered this aspect of clusters and their inherent difficulties and limitations.

Current TSA-based tools for targeting EE in industrial clusters are based on the analysis of large, highly integrated chemical sites, where site-wide utility systems and infrastructure are already in place and the sites are centrally managed by a site entity. In these clusters, large CHP plants typically supply heat (and power) to the common utility systems. To increase EE, current methodologies are primarily used to identify opportunities for heat recovery or increased co-generation assuming coherent site-wide utility levels.

Mathematical programming approaches, which are used to target total site HI, become increasingly complex as company-, plant- or even HX-specific constraints are considered. Examples of such constraints include differing long-term strategies that cause EE to be prioritized differently by each company, different maintenance schedules that influence the time window during which site modifications can be conducted or HXs being viewed as “difficult” to replace due to space, control or other constraints. A more flexible semi-automated approach can be used to consider a wider range of constraints in real retrofit situations.

It is not realistic to consider retrofitting an entire cluster of chemical production plants for maximum site-wide heat recovery at a single point in time. Instead, it is more realistic to consider implementing a series of EE projects over a given period of time. Traditional graphical and mathematical programming approaches target an optimal heat recovery system and provide limited guidance on how to gradually plan investments to achieve this optimal situation. In practice, perfect integration is difficult to achieve, especially at the scale of an entire chemical cluster with many constraints, as discussed previously. Based on the optimum system, a sequence of small site-wide HI projects must be defined to initiate inter-company collaboration. If correctly planned, these projects will lead to a gradual evolution of the site topology toward the optimal system. An engineering methodology to specifically determine these projects is necessary. It is important to translate targets into specific, implementable systems to convince stakeholders of the viability of site-wide HI. A flexible and pedagogical approach should be developed. Proposing heat recovery systems that only realize a small portion of the total heat recovery potential but are less complex can be a starting point for extensive systems if the initial small project demonstrates the feasibility of successful collaboration.

The utilized methodologies must also account for the investment needs and visualize the economic and GHG emission reduction performance of the HI systems to justify investments.

In recent studies, the combined exergy/pinch analysis approach on a total site level has primarily focused on investigating heat recovery measures via common steam or other hot utility systems. As an extension to available methods, the site-wide recovery of cooling capacity via common cold utility systems using refrigerants across different plants and companies and resulting shaft power savings should also be addressed.

Biorefinery integration with existing installations currently focuses on single processing plants. Integration with clusters of different types and utility infrastructures has only been investigated on a higher systems level, where excess heat from a biorefinery replaces heat in the cluster. A new approach for more detailed integration of a biorefinery with an industrial cluster is necessary. Current and future HI scenarios should be considered to investigate close integration of both the biorefinery and cluster and to determine a suitable utility system for the biorefinery that enables this integration.

The aim of this work is to address the aforementioned issues by developing a holistic framework for EE in industrial clusters that also enables the investigation of efficient biorefinery integration opportunities.

3 Objectives and scope

In this chapter, the main objectives of this work are described and the scope of this thesis is defined.

3.1 Objectives

The overall objective of this work is to develop a methodology to identify cost-effective measures for decreasing the energy demands of industrial clusters, which also enables the identification of favorable methods to integrate biorefinery operations that replace fossil with renewable feedstocks. A high level of EE is considered an important factor for achieving this goal. Traditional HI tools provide targets for improved EE. On a site-wide scale, numerous integration measures must be implemented to achieve these targets. To provide decision makers with the necessary information on concrete EE projects, it is necessary to determine a range of suitable projects for the specific site.

The primary goals of the methodological framework to be developed are as follows:

1. Target the most efficient utility system to minimize the energy demands in an industrial cluster;

2. Identify measures to achieve this overall EE target (considering process heating/cooling and refrigeration process);

3. Develop a flexible implementation strategy for EE measures under challenging business conditions, e.g., multi-company collaboration;

4. Identify renewable feedstocks and processes suitable for decreasing the dependence on fossil resources and quantifying integration advantages; and

5. Assist in designing utility systems for new biorefinery processes that can be integrated with an industrial cluster.

The tools developed in this work should provide the flexibility required to consider a wide range of site-specific conditions.

3.2 Scope and limitations

A methodology for HI within an existing industrial cluster and the energy efficient integration of new biomass-based processes is presented and illustrated in a case study of a chemical cluster in Sweden.

To perform a proper analysis of an entire chemical site, a vast amount of data is needed; therefore, significant data gathering and close collaboration with companies is necessary. As a result, the case study is limited to one chemical cluster.

A major environmental benefit of implementing EE measures in the chemical industry is decreased GHG emissions because fuel combustion for utility generation and electricity imports are both avoided. Quantifying GHG emissions is also important from an economic perspective because current and future attempts to reduce carbon emissions, such as the ETS, will results in an additional incentive for implementing EE measures [8]. In this work, environmental consequences of HI are limited to lifecycle GHG emission reductions due to avoided fuel consumption in cluster boilers. The effects of avoided emissions of other harmful substances are not assessed. Moreover, emissions caused by the construction and installation of EE equipment as well as end-of-life emissions are not accounted for in this work.

Procedures for estimating investment costs that have an accuracy of +/- 30% are applied. More detailed estimates are not performed because the methodology presented in this work is intended to provide input to decision makers who decide on whether more detailed design studies should be conducted.

Process simulation of a generic biorefinery process and a methodology for evaluating integration opportunities with an existing chemical cluster are both demonstrated. In this work, no comparison to overall GHG emissions is performed because the goal of the methodology is to compare different integration strategies for the same biorefinery process. Instead, the differences between integration strategies in terms of EE are quantified.

Potential valorization of excess heat from the cluster is limited to a study assuming a DH system as a potential user of the heat. Parts of the methodology presented in this study can also be applied to other heat recovery technologies, such as low-temperature electricity generation or biomass drying. Moreover, the economic potential and changes in CO_2 emissions due to exporting excess heat from a cluster are assessed. Applications to the technologies discussed here are not demonstrated in this work.

In Chapter 7, additional sources of error and uncertainty in the methodology are discussed.

4 Methods

This chapter describes the methods on which the framework methodology is based and presents the background data used in this work. Moreover, the assumptions made to perform the economic and GHG emission evaluations are presented. The methods described here are based on pinch technology, which is widely used to target EE. Specific tools to target single processes, total sites, as well as greenfield or retrofit projects are available within pinch technology.

4.1 Pinch technology

Pinch technology was introduced by Bodo Linnhoff at the University of Leeds during the late 1970s [61] and has been developed further at several institutions, including the University of Manchester Institute of Science and Technology (UMIST). An updated version of the original user guide for pinch analysis was published by Kemp [62]. Several studies have shown that energy savings of 20-40% can often be achieved using Pinch Technology [63].

Streams in industrial processes are often heated or cooled to fulfill the process requirements. Therefore, heat is added or removed, respectively, which is achieved by heat exchange with hot and cold utility streams or by transferring heat between hot process streams that must be cooled and cold process streams that must be heated. To achieve these exchanges in an energy-efficient manner, pinch technology can be applied to target the minimum heating and cooling demands of a process and design HX networks.

Pinch technology provides a set of tools that are widely applied in process integration to target increased EE. Typical applications include the following:

- Energy targeting;
- HX area targeting;
- Cost targeting;
- Utility selection;
- Co-generation targeting;

- HX network design;
- Integration of energy conversion technologies, such as heat pumps and refrigeration systems; and
- Integration of energy intensive equipment, such as distillation columns. [62,64]

Several tools and their applications are described below.

The method is used both in grass-root and retrofit projects. In this work, a framework for improving EE in existing process industries is developed. Therefore, only the procedure for retrofit projects is described here.

4.1.1 Stream data collection

Data extraction for targeting existing processes is not always a straightforward process. Data consistency is important to obtain useful targets and suggest practical improvements. Kemp [62] provided the following guidelines for data extraction:

- Use the highest temperature heat that is available for the hot streams and the lowest temperature necessary to heat the cold streams;
- Do not divide streams unless it is necessary;
- Avoid non-isothermal mixing in the energy targeting phase; and
- If available, use more accurate stream data around the pinch point.

4.1.2 Composite curves

Composite Curves (CC) are important graphical tools for achieving insights about the characteristics of thermal flows within a process. In order to construct these curves, the first step is to identify the hot streams in the process which need to be cooled and the cold streams that need to be heated. After this identification, the temperature characteristics of all hot streams are combined to construct a single composite curve by defining temperature ranges that are distinguished by changes in the overall rate of enthalpy change with temperature. Streams within each temperature range are then combined into a composite hot stream. The same procedure is applied to all cold streams. Both composite curves are plotted together in one diagram that depicts the temperature versus the heat flow (*T*-*Q*-diagram; see Figure 6).

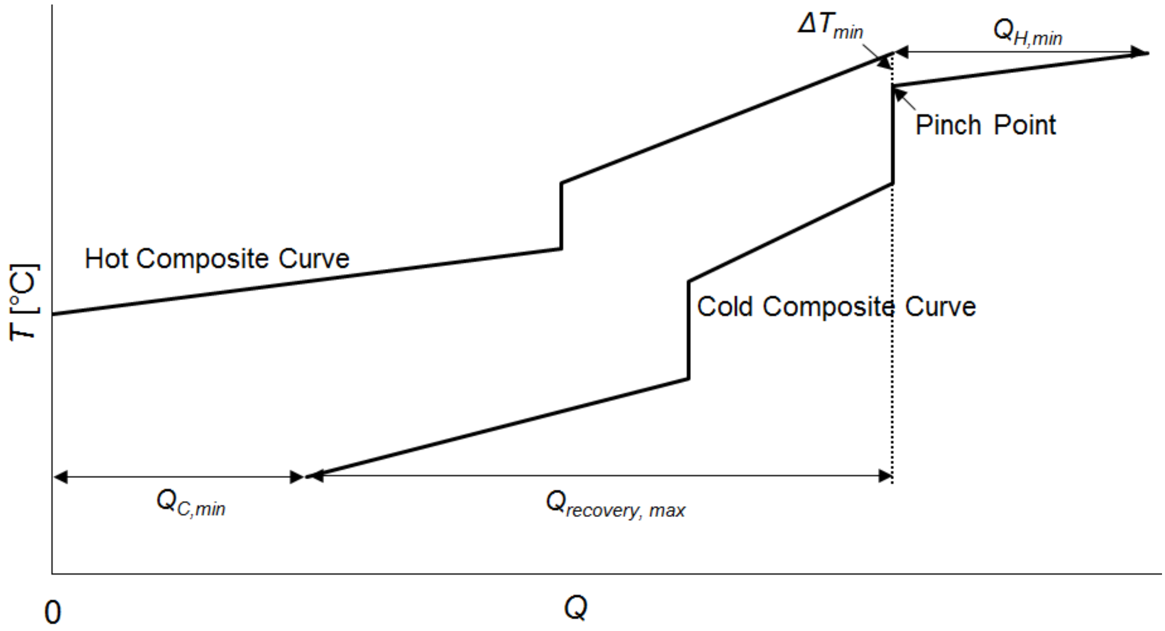

Figure 6 Composite curves showing the pinch point and energy targets [65].

Feasible heat exchange between the two curves, i.e., between the streams from which the curves are constructed, is only possible where the hot composite curve is hotter than the cold composite curve. Therefore, the region where the two curves overlap shows the potential heat recovery from the process, $Q_{recovery, max}$. If the two curves intersect, the cold composite curve must be shifted to the right to maintain a minimum temperature difference ΔT_{min} as a driving force. The point at which the distance between the curves on the temperature axis is ΔT_{min} is the so-called pinch point. The diagram shows the minimum heating and cooling demand ($Q_{H, min}$ and $Q_{C, min}$, respectively) of the system for ΔT_{min}, which are represented by the non-overlapping areas in the diagram.

ΔT_{min} represents an economic trade-off between capital costs and operating costs (hot/cold utility costs). For an initial HX network design, it is often assumed that no HX between hot and cold streams results in a lower temperature difference than ΔT_{min}.

The pinch point divides the CCs into two parts, i.e., above and below the pinch point. Above the pinch point, the system has a net deficit of heat, whereas below the pinch point, a net excess of heat occurs. Three rules for the design of HX networks can be established based on this configuration:

- Heat must not be removed from process streams located above the pinch point,
- Heat must not be added to process streams located below the pinch point and
- Heat must not be transferred through the pinch point.

In this work CCs are used to determine $Q_{H, min}$ and $Q_{C, min}$ for the individual processes. Moreover, the principles of CC construction are used to construct the curves used for TSA (see section 4.2.2).

4.1.3 Grand Composite Curve

Another diagram derived from the stream data and used in pinch technology is the GCC. The entire process is divided into temperature intervals. The diagram shows the heat supply and demand in each of these temperature intervals. A positive slope indicates a heat demand, whereas a negative slope indicates a heat surplus. This surplus can be transferred downward to streams with heat deficits. The GCC is used for various purposes, including the following:

- Selection of appropriate hot and cold utility levels and loads; and
- Identification of opportunities for integrating energy conversion technologies, such as heat pumps and combined heat and power units.

Figure 7 shows an example of a typical GCC with suggestions for utility levels, heat pump integration and internal heat exchange (pockets) [64]. The temperature (*T** in Figure 7) represents a shifted temperature, which is considered to account for the temperature difference necessary for exchanging heat between hot and cold streams. Stream temperatures are shifted by a certain value; for cold streams, the temperature is shifted upward, whereas for hot streams, the temperature is shifted downward.

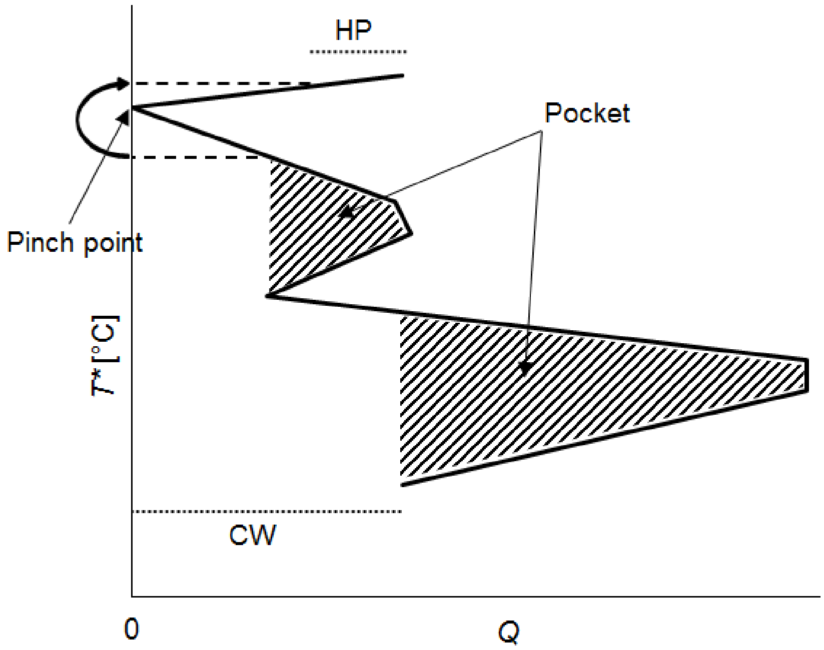

Figure 7 Example GCC with hot/cold utility levels, heat pump integration and internal heat exchange.

The shaded areas represent self-sufficient pockets, where process heat can be directly utilised to heat cold streams. The placement of hot and cold utilities is shown in Figure 7 (HP steam and CW). The GCC can be used to investigate opportunities for integration of energy conversion technologies such as a heat pump. For example, Figure 7 shows how heat from below the pinch point can be pumped to above the pinch and used to substitute hot utility. Thereby heat from below the pinch, where there is a net excess of heat, is utilized above the pinch.

In this study, pinch analysis is used to identify the minimum heating and cooling demands of single process plants to provide an overview of the potential energy savings in case site-wide heat recovery is not considered. The GCC is also applied to estimate the available amount of excess heat from a cluster to be utilized in a biorefinery.

4.1.4 Background/foreground analysis

An extension to the GCC approach is the so-called background/foreground analysis, which is useful for determining the HI potential of separate processes or sub-processes. The GCCs of two processes/sub-processes are created and presented into the same diagram.

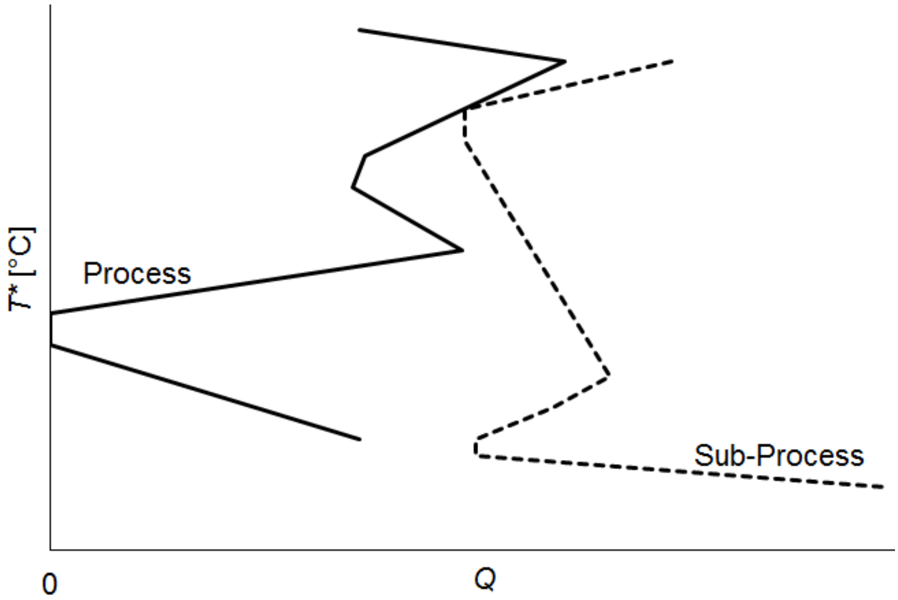

Figure 8 Illustration of background/foreground analysis between a process and a sub-process.

An illustration of such a diagram is shown in Figure 8. This representation can be used to investigate possibilities for delivering/receiving heat to/from each process. Figure 8 shows how excess heat from the main process (solid line) can be delivered to the sub-process (dashed line). The amount of heat that can be transferred between the processes corresponds to the overlap of the two curves. The tool can also be used to determine process parameters in one or both processes that can be adjusted to increase their overlap and improve HI. Modifications that can be identified by this procedure include pressure changes in distillation columns to enable the utilization of excess process heat.

In this work, background/foreground analysis is applied to estimate the integration potential of different processing steps in a biorefinery process.

4.1.5 Retrofit targeting procedure

The following procedure is typically followed when using pinch technology to investigate opportunities for retrofitting an energy system in an industrial process and to reduce external utility requirements:

- Define the stream system to be investigated;
- Gather stream data from appropriate sources (e.g., starting temperature T_{start}, target temperature T_{target}, and heating/cooling loads Q);
- Select the minimum acceptable temperature difference for heat exchange ΔT_{min};
- Use pinch analysis targeting tools to determine the minimum hot and cold utility demands and potential for maximum internal heat exchange;
- Determine the present heating and cooling demands from available process data and quantify the target for heat recovery enhancement;
- Identify process modifications to increase HI;
- Identify pinch rule violations in the existing heat exchanger network;
- Identify opportunities for integrating energy conversion technologies;
- Suggest a set of possible modifications to the existing HX network that eliminate or reduce pinch violations;
- Calculate investment costs for the suggested changes and analyze their economic performance [66];
- Repeat the procedure for different values of ΔT_{min}; and
- Identify a reduced set of retrofit options for detailed engineering investigations.

4.1.6 Area and cost targeting for DH delivery

A simplified procedure based on the area targeting approach described by Smith [64] is applied to estimate the number and area of HXs necessary to collect and export excess heat from a chemical cluster to a regional DH network. Based on the number and area of HXs, the related investment costs for exporting DH can be estimated based on standard cost estimation procedures.

The number and size of heat exchangers is determined by assuming vertical heat transfer between the hot (process) and cold (DH water) composite curves. The area between the hot process stream profile and DH water profile is divided into enthalpy intervals ΔH_h (Figure 9). The HX area necessary to transfer heat from the hot process to the DH water profile in each interval is estimated as follows:

$$A_{\Delta Hh} = \frac{\Delta H_h}{U \cdot F \cdot \Delta T_{ml,h}}, \qquad \text{Eq. (1)}$$

where U is the overall heat transfer coefficient estimated based on the fluid properties on both sides of the HX, fouling factors and tube thickness, F is a factor to account for non-ideal countercurrent flow in the HX, and $\Delta T_{ml,\,h}$ is the logarithmic mean temperature difference between the hot and cold streams in the interval (Figure 9).

For each enthalpy interval h of ΔH_h, the number of heat exchangers required to transfer heat from the hot process stream profile to the DH water is assumed to be the number of process streams present in that enthalpy interval. The area A_h of each of these HXs is estimated by equally distributing the total area in the interval $A_{\Delta Hh}$ across all HXs. The purchasing cost of a heat exchanger unit is estimated via the generalized cost equation found in Ref. [67]. More detailed assumptions on the cost targeting procedure are provided in **Paper V**.

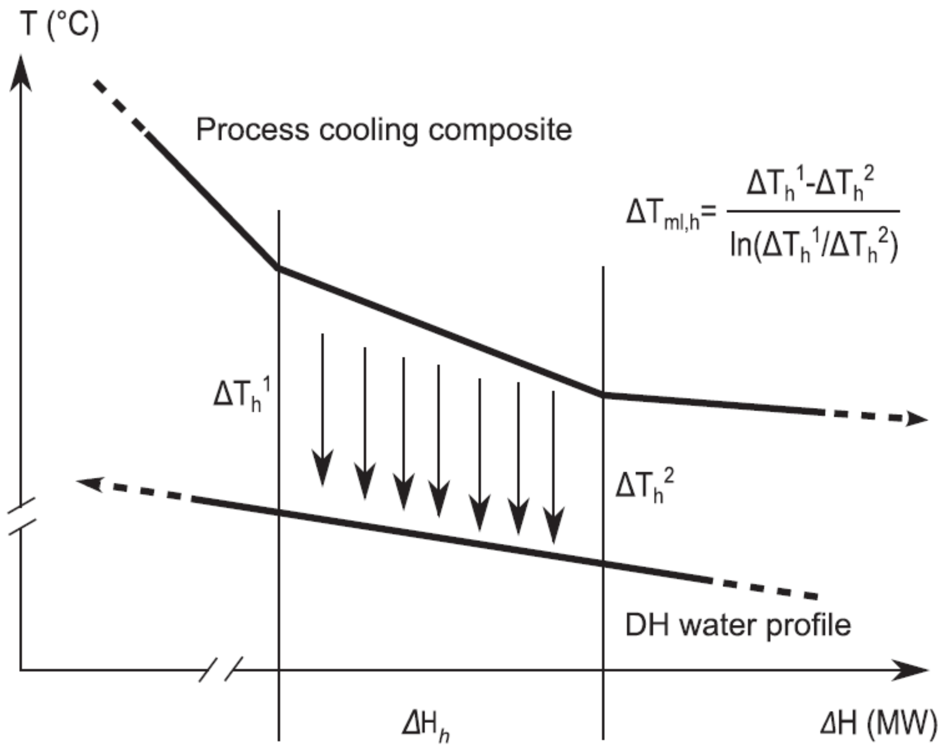

Figure 9 Vertical heat exchange between a hot process stream profile and DH water profile.

4.2 Total Site Analysis

TSA represents an extension of the pinch analysis method and is typically applied to industrial sites to target increased EE via a common utility system. Due to a number of factors, such as long distances between individual plants, different operation times, plant safety, direct heat exchange between different plants is difficult to achieve. TSA is used to investigate opportunities for integrating the individual heating and cooling demands of different processes at a total site. Excess heat from one process plant is transferred to a common utility (e.g., steam, hot water, or hot oil) and delivered using the common utility system to processes with a heat deficit. The TSA method enables targets to be established based on the amounts of hot utility generated and used by the combined individual processes, the amount of heat recovery in a common hot utility system, the steam demand from the boilers and the co-generation potential [68]. The approach can also target changes in the utility system that increase EE by increasing heat recovery and co-generation.

4.2.1 Data collection approaches for TSA

Data collection for TSA studies is time consuming; therefore, practitioners have defined different approaches that can be used to conduct studies at different levels of detail. These approaches are briefly discussed below. The necessary data for each process stream include T_{start}, T_{target}, Q and the respective utility (if the stream is currently heated or cooled by a utility).

<u>White box approach or detailed pinch:</u>
Detailed stream data for all process heating and cooling demands for each plant are collected. Thereafter, complete CCs and GCCs can be constructed for the total site. Moreover, the minimum hot and cold utility demands for each process can be determined.

<u>Grey box approach:</u>
For each plant, only the process-utility interface is considered; process-process heat recovery is ignored. Only process streams that are heated/cooled by utilities are considered in the analysis based on their T_{start}, T_{target} and Q. The current level of process/process HI within each single plant is accepted as is; however, the grey box approach identifies opportunities for transferring heat between plants and changes in the process-utility interface that lead to increased heat recovery.

<u>Black box approach:</u>
The process (stream) is represented by data for the corresponding utility streams in heaters and coolers. Other utility users, such as steam tracing or tank heating, are often represented as black boxes [69].

Figure 10 illustrates the three approaches. It is <u>important that all utility usage and potential demands are included</u> when conducting a TSA study [70].

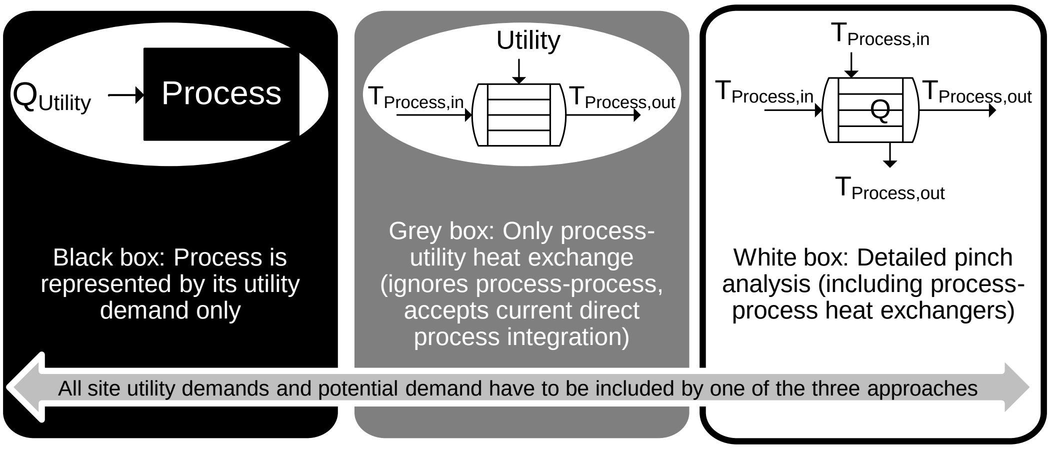

Figure 10 Illustration of the different data collection approaches in TSA.

The decision of whether and at which level of detail (i.e., which of the three approaches above should be selected) to include processes, sub-processes or specific streams depends on several factors and must be decided prior to data collection. There are several issues that must be considered, including the following:

- Existing heat recovery measures: The current level of heat recovery within a process might be accepted and therefore streams included in process-process HXs are disregarded from data collection.

- Size of the streams: Heat recovery that utilizes minor streams might not justify investment in new HXs and the related increase in complexity and other related costs;

- Intermittency: Heat recovery that involves processes, sub-processes or streams that only operate over limited time periods are less likely to justify investment; and

- Process requirements: Utility streams that are particularly important for the processes include the expansion of utility steam to supply mechanical power to the process at all times and the steam demand for direct steam injection to the process.

4.2.2 Total Site Profiles and Total Site Composite Curves

Process source/sink profiles can be constructed based on the collected data. By matching these profiles, the maximum potential for heat recovery is identified. Direct heat exchange across several plants is difficult to achieve. In order to illustrate the interaction of the thermal process streams with the utility systems and to identify the potential for heat recovery via the utility system utility profiles matching the process source/sink profiles are plotted. In this work, a minimum temperature difference (ΔT_{min}) of 10 K between the process and utility streams is chosen. The so-called Total Site Profiles (TSP) are subsequently obtained (left side of Figure 11), which enables the analysis of how heat is supplied to and removed from the processes by different utilities. The site utility profiles are developed from process stream lists that represent the utilities used to cool/heat each process stream.

To determine the maximum amount of heat recovery possible at the total site scale by heat exchange through the combined utility system, the total site profiles are shifted until the hot and the cold utility curves intersect (right side of Figure 11). This point is the so-called site pinch, which limits the amount of heat that can be recovered by the utility system. The overlapping curves to the right in this figure are the so-called Total Site Composites (TSC). The TSCs show the minimum amount of heat that must be externally supplied to the processes as hot utility ($Q_{heating}$), which is illustrated in Figure 11. Therefore, $Q_{heating}$ is directly related to the boiler fuel requirements.

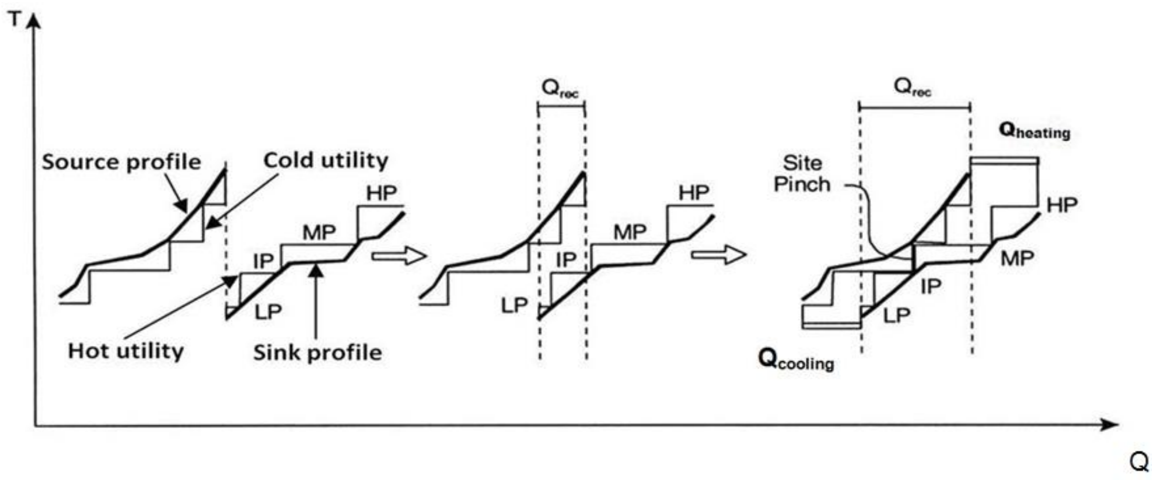

Figure 11 Left: Total Site Profiles. Right: Total Site Composites [20].

The cooling demand ($Q_{cooling}$) in Figure 11 represents the amount of heat that must be discharged from the processes. The TSPs and TSCs can be used to identify changes to the utility system that improve the total site HI through the utility system. Utility system changes include replacing steam by introducing new steam levels, utility (often steam) generation from recovered process heat at higher levels, process stream heating using utilities (often steam) at lower levels [20] or introducing a hot water circuit [71].

In addition to HI, TSA can also be applied to target increased co-generation. Electricity can be generated by expanding steam between different steam levels. TSA provides knowledge regarding the level at which steam can be recovered from the processes and used for process heating. This information can be used to target co-generation by applying Carnot efficiency curves, which is analogous to the approach described in section 4.3.

4.3 Targeting for decreasing exergy losses

Traditional pinch analysis and TSA primarily focus on targeting HI potential and related fuel savings. Primary energy savings achieved by HI measures that reduce the cooling capacity in refrigeration systems cannot be directly evaluated using regular tools. Therefore, the exergy concept using curves based on Carnot efficiency can be applied in combination with pinch analysis, which enables the targeting of shaft power savings in low-temperature processes.

Exergy is defined as the maximum theoretical useful work (shaft work or electrical work) that can be obtained as two systems interact to equilibrium or the minimum theoretical useful work required to bring matter to a specified state [72]. The main difference between conventional and combined exergy pinch analysis/TSA is that the *y*-axis of the CC, GCC, TSP and TSC exhibit Carnot efficiencies using corrected temperatures instead of the actual temperatures. Carnot efficiency is defined as $\eta_c = 1 - T_{ref} / T$ (T_{ref} = reference temperature). An example of such a diagram is presented in Figure 12, which shows the interaction of hot process streams with a cold utility system below the ambient temperature.

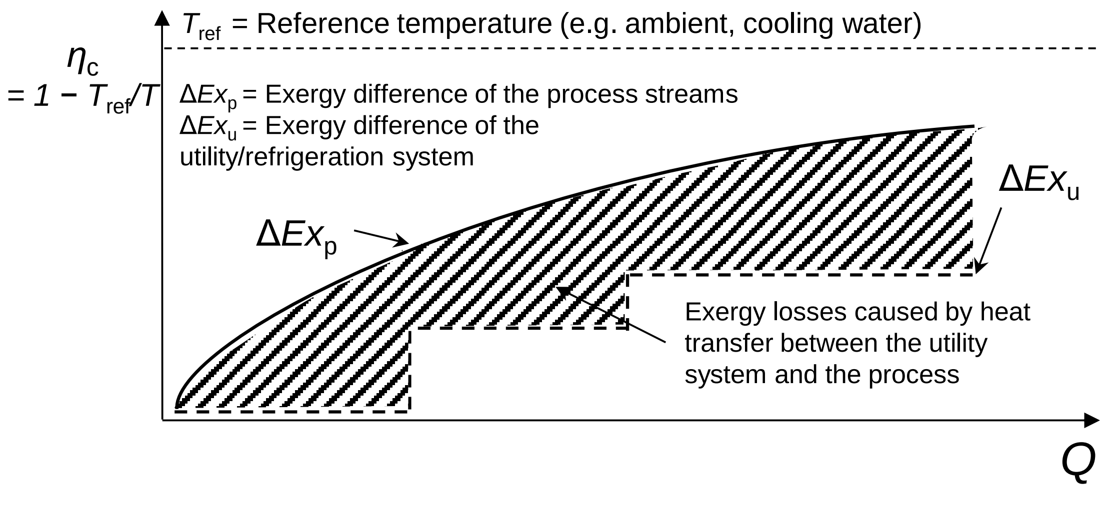

Figure 12 A schematic example of an exergy CC showing the CC of the process (solid line), the CC of the utility system (dashed line), and the resulting exergy flow rate difference between the process streams and utility.

Using Carnot efficiencies with corrected temperatures instead of the actual temperatures is advantageous because sources of exergy flow rate losses can be easily identified in a graphical manner and quantified by integrating the areas between the curves without the need for time-consuming process simulations of the given case.

The following procedure is applied to construct the profiles shown in Figure 12:

- Collection of relevant stream data (e.g., T_{start}, T_{target}, Q, and the type of utility);
- The process stream profile can be plotted using T_{start}, T_{target} and Q for each stream according to the description provided by Kemp [62];
- The utility profile is plotted in the same manner using T and Q of the utilities used for heating/cooling the plotted process streams;
- A suitable T_{ref}, e.g., the CW temperature, is defined; and
- The process stream and utility profiles are plotted in the exergy $\eta_{\mathrm{c}} - Q$ – CC (TSC and TSP) diagram.

The area between the respective curve and reference temperature line in the exergy CC represents the exergy flow rate that must be supplied to achieve the desired target temperature. The area between the upper solid line and reference temperature line represents the exergy flow rate difference between the process streams ΔEx_{p}, which is the minimum exergy input necessary to cool the process streams to their target temperature. A utility system that is able to reach this minimum exergy input requires an infinite number of utility levels and that ΔT_{min} between the process and utility system be infinitely small. The area between the lower dashed line and reference temperature line represents the exergy input to a real utility system designed to cool the given process. The area between the process (solid) line and utility system (dashed) line can be considered as exergy flow rate losses caused by the utility systems' design (e.g., cooling temperature levels or temperature differences). The presented curves can be used to target reductions in exergy flow rate losses by identifying changes in the design of the utility system that result in a decrease in exergy flow rate losses, which is achieved by modifying the curves to decrease the area between the utility and process curves.

In this work, the curves are applied to target decreased exergy flow rate losses by optimizing refrigerant use and decreasing exergy flow rate losses using site-wide recovery of refrigeration.

Estimating shaft power targets based on exergy savings targets

The methodology for targeting decreased exergy flow rate losses is described above. To establish a target value, it is necessary to translate the exergy savings into shaft power savings using an appropriate exergetic efficiency (η_{ex}) for the utility/refrigeration cycle. The exergetic efficiency is defined as follows:

$$\eta_{ex} = {}^{\Delta Ex_u}\!/_{P}\,, \qquad \text{Eq. (2)}$$

where P represents the actual shaft power for the investigated process at a certain operating point. Changes in η_{ex} caused by deviation from the operating point are not accounted for by this approach. The actual shaft power is obtained by measurements or process simulation if measurements are not available. ΔEx_u is the exergy flow rate difference in the utility/refrigeration system, which is obtained from exergy pinch curves of the real refrigeration system operating at the same conditions used to determine P. Once determined for the investigated system, η_{ex} can be used to estimate effects on the shaft power demand due to changes in the process, HX network and refrigeration systems. η_{ex} accounts for friction and other losses in the refrigeration system.

4.4 Economic and GHG emission evaluation

To evaluate the economic status and GHG emission reductions caused by introducing the process changes and new technologies identified in this work, measures of economic and GHG emission reduction performance are determined as follows.

4.4.1 Economic evaluation

A simple Pay-Back Period (PBP) is used to select promising heat recovery system designs:

$$PBP = \frac{Cost_{Inv}}{CF_{avg}}, \quad \text{Eq. (3)}$$

where PBP is the time until the invested capital is recovered. Projects with shorter PBPs are more attractive in terms of limited risk. For retrofit projects, the PBP represents the ratio between the total investment costs ($Cost_{inv}$) and the annual average cash flow (CF_{avg}), which corresponds to the improvement in the annual mean operating costs.

The Net Present Value (NPV) can be calculated for selected designs according to the following relationship:

$$NPV = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i)^n}. \quad \text{Eq. (4)}$$

Table 1 shows data and assumptions for the economic evaluation. NPV is a measure of the profitability of a project that represents the sum of the present values of each individual annual cash flow. Time is accounted for by applying a discount rate to the annual cash flow CF_n. Economically more attractive projects have a larger positive NPV. Projects with a negative NPV are not profitable.

The ratio of NPV to $Cost_{inv}$ is used to provide a more complete picture of the economic performance of the different selected heat recovery measures.

In the case of heat recovery investments, CF_n represents the operating cost savings in each year over the project's economic lifetime. Cash flows in the beginning of a project typically include investment costs.

The Discounted Cash Flow Rate Of Return (DCFROR) is another economic indicator that is used to compare the performance of investments. The DCFROR represents the interest rate at which the NPV of an investment is equal to 0 over its economic lifetime. The DCFROR is particularly suitable for comparing investments of different sizes because it indicates how efficient the invested capital is used.

Table 1 Data for economic evaluation.

Economic lifetime	15 y*
Discount rate, *i*	11%*
HP steam price	400 SEK/MWh**
Electricity price	600 SEK/MWh***
Maintenance + Operation	2% of the total fixed capital, HW pump power; 2% of the total heat savings
Additional operation cost savings	CW pumping; 2.5% of the CW savings

*According to discussions with company experts for EE investments.
**The steam produced from natural gas in boilers (η_{boiler}=0.9); the natural gas import price for Europe in 2020 (IEA, 2013) is 292 SEK/MWh$_{LHV}$; the distribution cost is 12%; the tax is 25 SEK/MWh$_{LHV}$; and the charge for GHG emissions is 44 SEK/t.
***Expected price according to plant energy experts.

In this work, a DCFROR of at least 10% is assumed as the investment criteria to determine economically feasible systems delivering DH from a chemical cluster to a regional DH network.

4.4.2 Evaluation of reductions in GHG emissions

To give an indication of how improved EE impacts emissions and resource consumption of chemicals production GHG emissions savings by EE measures and overall efficiency of biorefinery processes under different integration scenarios are calculated using procedures and assumptions described below.

4.4.2.1 Reductions in GHG emissions due to EE measures

Reductions in GHG emissions due to EE measures are estimated assuming that increased heat recovery leads to reduced firing of natural gas in utility boilers (lifecycle GHG emissions are assumed to be 248 kg$_{CO2equ}$/MWh) assuming a boiler efficiency of 0.9 and an annual operating time of 8,000 h/year. GHG emissions associated with avoided/additional electric power usage are accounted for by assuming a combined cycle with natural gas as a power producer, 394 kg$_{CO2equ}$/MWh. [73]

4.4.2.2 Performance indicator for biorefinery HI opportunities

To compare different biorefinery process integration alternatives, the overall EE ($\eta_{overall}$) of the processes is calculated as follows:

$$\eta_{overall} = \frac{\dot{m}_{ethylene} \cdot HHV_{ethylene} + \dot{m}_{excess\,solid\,residues} \cdot HHV_{excess\,solid\,residues} + \dfrac{\dot{W}_{el}^{-}}{\eta_{el,ref}}}{\dot{m}_{biomass,in} \cdot HHV_{biomass} + \dot{m}_{yeast} \cdot HHV_{yeast} + \dot{Q}_{Fuel\,to\,ethylene\,reactors} + \dfrac{\dot{W}_{el}^{+}}{\eta_{el,ref}}} \quad \text{Eq. (5)}$$

This equation provides a method for investigating the performance of bio-based processes integrated with an existing energy system on a primary energy basis. Electricity ($\dot{W}_{el}$) and other energy carriers and feedstocks used as by-products and/or input to the processes are considered.

Only net energy flows are considered, which means that $\dot{W}_{el}$ can only be part of the numerator or denominator. $\dot{W}_{el}^{-}$ denotes the net electricity generated, whereas $\dot{W}_{el}^{+}$ is the net electricity consumed by the processes. Distribution losses when exporting/importing electricity are not considered [74]. $\eta_{el,ref}$ is the conversion efficiency of the reference energy system, which is used to estimate the primary energy demands of the processes or the amount of primary energy replaced in the reference system. Estimating the efficiencies of the reference system in a future scenario is extremely complex. A tool developed at the division of Heat and Power Technology at Chalmers is used for this estimation [75]. In this case, the marginal technology for electricity generation is assumed to be coal combustion with an efficiency of 0.46[3] by 2020 [77] based on the Higher Heating Value (HHV) of coal. The HHVs for the different energy carriers are used for all combustible flows in the system. The HHVs are given in **Paper III**. The HHV of yeast is estimated to be 21.6 MJ/kg in Aspen Plus[4].

[3] The reference gives the efficiency based on a lower heating value (LHV) (0.48); therefore, the efficiency is adjusted for the difference between the HHV (23.968 MJ/kg) and LHV (22.732 MJ/kg) for coal [76].

[4] Aspen Technology, Inc., Burlington, Massachusetts, USA

5 Results – Developed methodologies and case study application

In this chapter, the methodologies developed to target, identify, design and evaluate site-wide EE measures via cluster internal integration and the export of excess process heat and the integration of new bio-based processes with existing industrial clusters are described. In combination with the established tools presented in Chapter 4, a framework methodology is developed that is illustrated using an industrial case study.

5.1 Case study overview

In this section, an overview of the chemical cluster and the biorefinery used as a case study to illustrate the framework methodology is presented.

5.1.1 The chemical cluster in Stenungsund

The chemical cluster used as a case study is located in Stenungsund, which is on the west coast of Sweden. The cluster is Sweden's largest agglomeration of its kind. The companies involved and their main products include AGA Gas AB (producing industrial gases), Akzo Nobel Sverige AB (producing amines and surfactants), Borealis AB (producing ethylene, propylene and polyethylene), INEOS Sverige AB (producing polyvinyl chloride) and Perstorp Oxo AB (producing specialty chemicals). At the heart of the cluster is a steam cracker plant that is run by Borealis. This plant delivers both feedstock and fuel gas to most of the other plants.

Each plant has its own utility system. Currently, there is only a minor collaboration in terms of heat exchange between the different plants. Therefore, there is no coordination between plant sites regarding the choice of utility levels. The cluster is a representative example of industry agglomerations that operate independently and have not tapped the efficiency gains offered by site-wide heat integration. Therefore, the cluster is highly suitable to illustrate the framework methodology developed in this work.

An overview of the locations of the individual companies, including material and energy flows across the cluster, is provided in Figure 13.

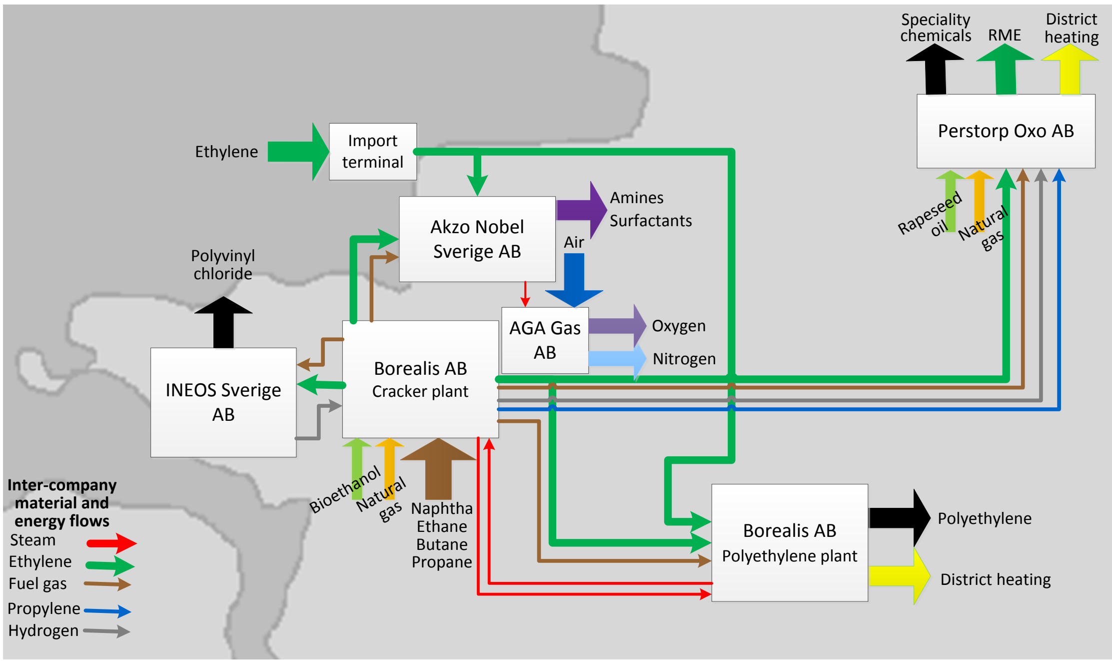

Figure 13 The chemical cluster in Stenungsund, including material and energy flows between the individual plants [78].

Thirteen different steam levels (ranging from gauge pressure of 85 bar to 1 bar), 3 different hot water systems, hot oil and flue gas heating together with water, air and refrigerant cooling are operated within the cluster. Table 2 shows the utilities used for process heating/cooling and heating and cooling recovery; the corresponding heat loads and amounts of heat that must be covered by external heat/cooling from the boilers and refrigeration systems are also presented. The total external heating demand of the cluster is $Q_{gen} - Q_{consumed} = 122.1$ MW; the external cooling demand is 632.8 MW. Approximately 10 MW of excess heat from two plant sites is currently dedicated for delivering heat to a local DH system.

The companies have recently announced a common vision called “Sustainable Chemistry 2030”, which intends to increased collaboration regarding energy savings, increased use of renewable resources and decreased overall emissions.

Table 2 Utilities currently used for heat/cooling recovery and process heaters/coolers.

Utility	T [°C]	Q_{gen} [MW][1]	$Q_{consumed}$ [MW][2]	$Q_{gen} - Q_{consumed}$ [MW]
Steam 85 bar	300	50.8	1	49.8
Steam 40 bar	250	42	43.2	−1.2
Steam 28 bar	230		6.3	−6.3
Steam 20 bar	215	29	38.5	−9.5
Steam 14 bar	200	15.2	12.7	2.5
Steam 10 bar	184	22.1	21	1.1
Steam 8.8 bar	178	27.3	91	−63.7
Steam 7 bar	168		15.3	−15.3
Steam 6 bar	163		14.2	−14.2
Steam 4 bar	150	26.1	2.2	23.9
Steam 2.7 bar	140	13	4.7	8.3
Steam 2 bar	131	55.3	128.4	−73.1
Steam 1 bar	119	0.6	8.4	−7.8
Hot oil	277		1.9	−1.9
Hot water	160-50	9	13.3	−4.3
Flue gas	1400		10.4	−10.4
Sum of hot utility		290.4	412.5	**−122.1**
Chilled water	4-7		5	−5
Refrigerant C3/9 °C	9	27.7	32.5	−4.8
Refrigerant C3/–21 °C	–21	1.2	20.5	−19.3
Refrigerant C3/–40 °C	–40		38.3	−38.3
Refrigerant C2/–62 °C	–62		0.9	−0.9
Refrigerant C2/–84 °C	–84		7.3	−7.3
Refrigerant C2/–100 °C	–100		1	−1.1
Sum of refrigerant		29	100.6	−76.7
CW			472.8	−467.8
Air			88.2	−88.2
Sum of cold utility		29	662	**−632.8**

[1] Heating/cooling generated from hot/cold process streams

[2] Heating/cooling consumed in process heaters/coolers

5.1.1.1 Plant and process data collection for process integration studies

Plant data were collected in close collaboration with plant experts. The data are chosen to represent the current processes, including already scheduled process modifications at expected average capacity operations, to determine a representative picture of the plant operations. Real-time and historical process data, documented process and design data and process simulations are used. For the analysis illustrated in this work, it is important to include all utility consumption in the processes. 360 process streams with a heat load exceeding 300 kW and requiring utility heating and cooling are included in the case study (grey box approach). These limitations were determined after discussions with plant energy experts. It is deemed unlikely that HXs with a load of less than 300 kW would be included in a retrofit. Moreover, streams that are currently involved in direct heat exchange to recover process heat are regarded as being unlikely to be changed in the future.

To account for utility consumption of all process streams, the current utility consumption at each utility level is determined; moreover, the difference between the current consumption and the sum of the utility consumption found from process streams is included in the data (black box approach).

Utilities and corresponding process streams that cannot be changed due to process restrictions, such as extremely high temperatures achieved using flue gases in direct-fired cracking furnaces, are not included in the stream data.

Some major compressors at the cracker plant are driven by steam turbines that co-generate mechanical power. After discussions with plant experts, the turbine steam consumption and the current turbine back-pressure are regarded as process requirements. All steam consumption must be included in the TSA. Therefore, in the stream/utility data, the steam consumption of the turbines is included as the heat load difference between the steam entering and leaving the turbine at the temperature level of the turbine back-pressure.

5.1.1.2 Refrigeration systems

Most of the refrigeration within the cluster is performed via two interconnected vapor-compression refrigeration systems, i.e., propylene (C3) and ethylene (C2) compression refrigeration systems, both of which are located at the steam cracker site (see Figure 14). The propylene system’s four-stage compressor is driven by a steam turbine (steam expansion from a gauge pressure of 85 to 8.8 bar) and delivers refrigeration cooling at three levels (i.e., 9 °C, –21 °C, and –40 °C). The shaft power requirement of the propylene refrigeration system is approximately 21 MW, depending on the production capacity, the feedstock mix and other process parameters of the cracker plant.

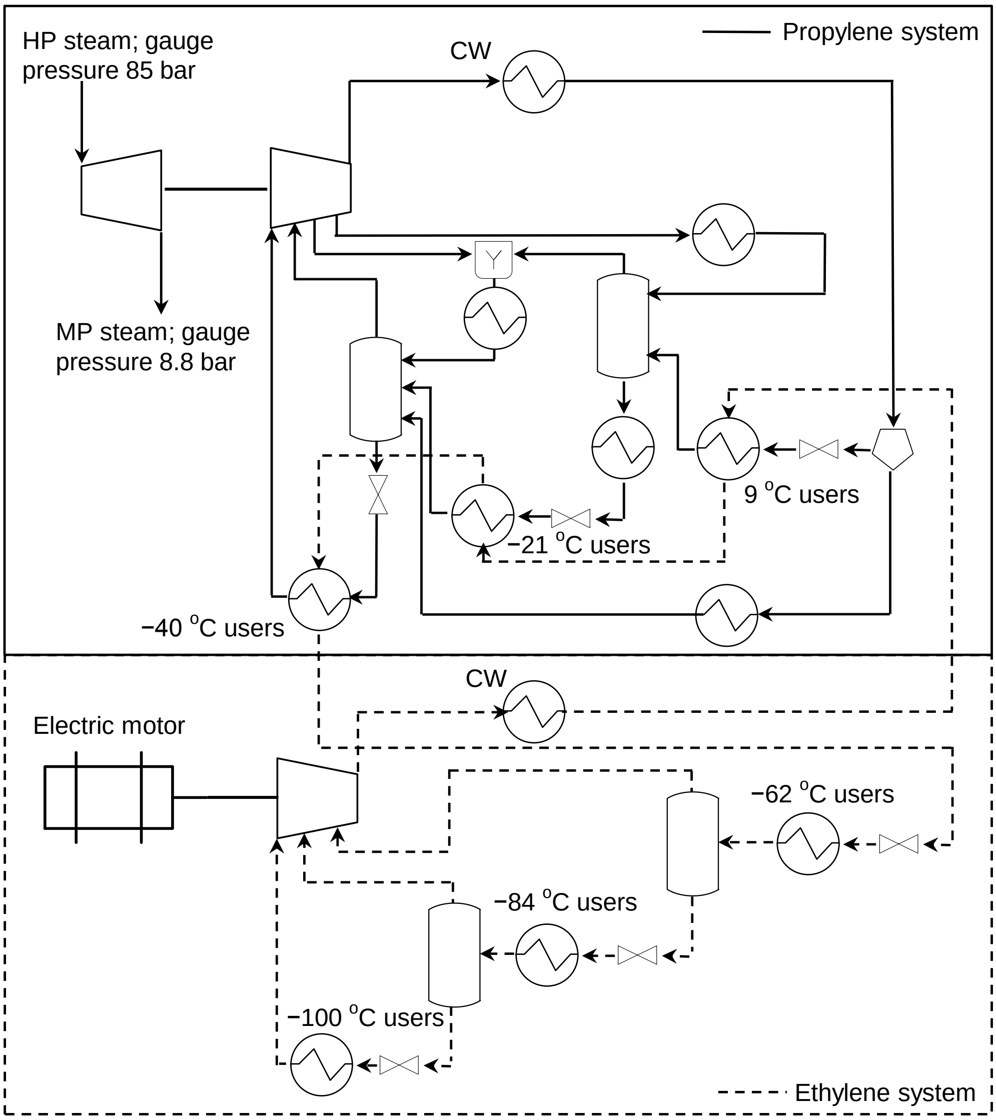

Figure 14 Process flow diagram of the propylene and ethylene refrigeration systems at the cracker plant.

The compressor of the ethylene refrigeration system is driven by an electrical motor. The typical electric power requirement of the system is approximately 4 MW, which accounts for approximately 10% of the total electricity consumption of the cracker plant. Cooling is delivered at three levels (i.e., –62 °C, –84 °C, and –100 °C).

5.1.2 Introduction of biomass-based ethylene feedstock

The chemical cluster consumes a large amount of ethylene (polymer grade with a purity 99.95 mol-% [79]), of which 200 kt/year are imported and approximately 500 kt/year are produced in the steam cracking plant, which is primarily fed with ethane and naphtha. As a first step in decreasing the dependence of the cluster on fossil feedstock, the imported ethylene can be replaced by biomass-based ethylene. This initial step toward renewable feedstock does not affect the operation of the cluster. The olefins produced by the cracker can be replaced by renewable olefins at a later date.

Figure 15 illustrates different possible conversion routes for the production of ethylene (and olefins) from biomass. To illustrate the suggested design strategy, one production route, namely, the catalytic dehydration of bio-ethanol, is used as a case study in this work.

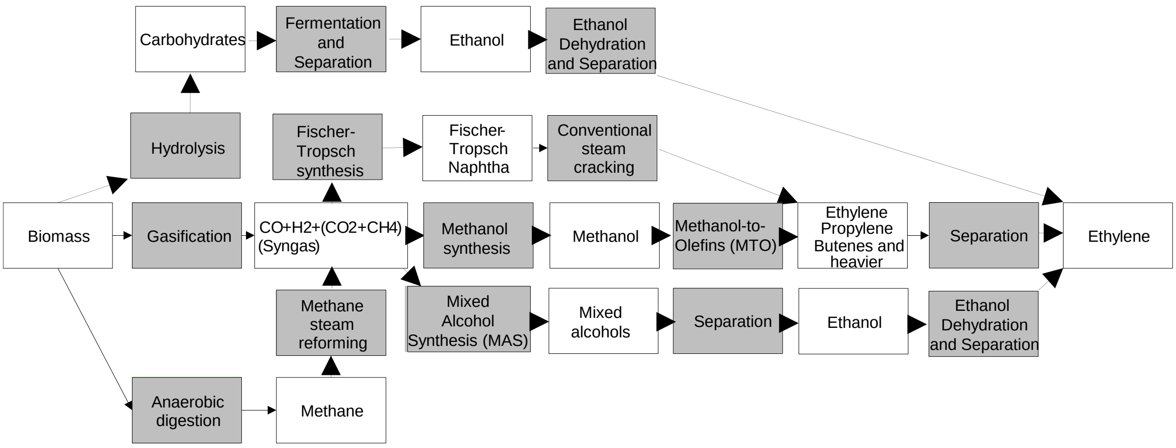

Figure 15 An overview of possible biomass-to-ethylene production routes adapted from Ref. [80–83].

This work investigates the potential heat savings that can be achieved by integrating an ethanol production plant based on the fermentation of lignocellulosic feedstock and an ethanol dehydration plant producing ethylene with an existing chemical cluster.

5.2 Overview of the framework methodology

The framework methodology is based on a holistic representation of the energy system of the overall cluster. Figure 16 shows an overview of how several process integration tools are combined in the framework methodology.

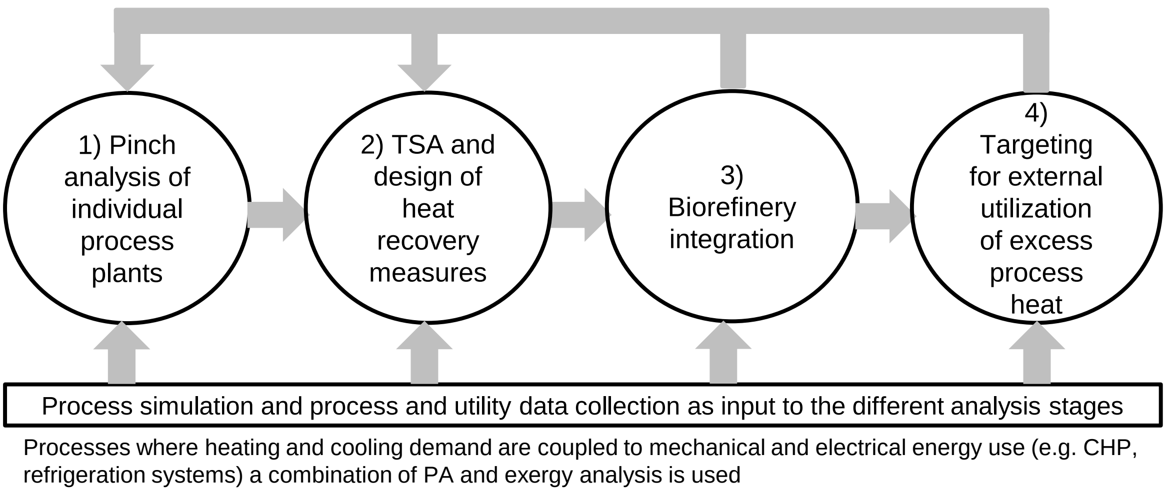

Figure 16 Illustration of the framework methodology.

In the first step, data for individual process heating and cooling demands are collected. The level of detail at which a single plant is investigated must be determined at this point (i.e., black, grey or white box approach) [70]. Pinch analysis provides HI targets for single processes and input to further analysis stages.

In the second step, the collected data are analyzed using TSA tools. Total site heating and cooling profile curves are produced to provide an overview of heat flows within the total site's energy system. Opportunities for the exchange of utility flows between plants can be identified using these curves. A detailed analysis of the TSA curves allows the user to identify potential HI improvements that require a common site-wide utility system. Therefore, the theoretical minimum overall hot and cold utility demands can be determined. Several practical measures to approach this minimum can be subsequently designed according to the algorithm developed in this work. Changes in heating and cooling demands or utility levels are often coupled to the shaft power demand/production (e.g., reduced refrigeration requirements decrease the shaft power required to drive the refrigeration system compressors, whereas reduced hot utility demand decreases the co-generation potential). A combination of pinch analysis and exergy analysis should be used to assess the total savings of hot and cold utilities and the effects on shaft power consumption/generation.

In the third step, opportunities for integrating biorefinery processes are investigated. The knowledge of the current energy system of the cluster and the potential for further site-wide integration (determined in steps one and two) are the basis for identifying opportunities for energy-efficient biorefinery integration. Process simulation is used to obtain mass and energy balances for the biorefinery process. The efficiency gain that could be achieved by integrating a biorefinery with the existing cluster is quantified by first conducting a pinch analysis for the single biorefinery process. Then, a total site analysis is performed for the integration with the cluster. This procedure should be performed for several promising biorefinery concepts to identify the most suitable concept for integration with the existing cluster. However, due to the large amount of data necessary to perform this analysis, the integration of only one biorefinery concept is presented in this work to illustrate the procedure.

Regardless of the level of HI, there is always some excess heat rejected from the processes that cannot be utilized within the cluster. Therefore, the external utilization of excess heat is investigated in the fourth step. In this work, DH is assumed to be a potential consumer of excess process heat. Thermal streams that currently and after site-wide HI discharge heat to the atmosphere (via CW or air cooling) are regarded as potential sources for delivering DH to a local DH system. Because the best use of industrial excess heat depends on the economic value of DH and the environmental performance of reference DH production technology, it is necessary to assess the competition between the uses of excess heat. In this framework, the competition between internal/site-wide HI and the export of excess process heat is investigated. The economic feasibility and environmental viability of delivering DH are evaluated by considering different levels of internal HI.

5.3 Heat integration targeting of single process units

The pinch analysis results for each of the six individual constituent plants within the chemical cluster are shown in Table 3.

Table 3 Minimum heating and cooling demands of the constituent plants within the chemical cluster assuming a global ΔT_{min} of 10 K.

Plant/Site	Minimum heating demand [MW]
Plant A	1
Plant B	17.3
Plant C	5.5
Plant D	0
Plant E	20.6
Plant F	27.6
Sum	**72**
Current sum	**122**
Potential savings	**50**

Comparing the sum of the minimum heating demands for the plants based on current common hot utility consumption (Table 2) indicates a potential saving of approximately 50 MW of hot utility. This potential can be used as a benchmark and should be compared with the site-wide heat recovery target to determine the added value of introducing site-wide heat recovery systems instead of separately improving EE in each plant.

5.4 Heat integration targeting in industrial clusters without a common utility infrastructure

In this section, the TSA methodology is applied to the chemical cluster in Stenungsund. The first part of this section describes how heat recovery measures are identified and a maximum heat recovery utility system is designed. The first part of this section is based on **Paper I**. Then, in section 5.4.4, a practical design methodology is introduced to define heat recovery projects that can utilize the potential for site-wide heat recovery in the cluster. The latter part of this section is based on **Paper VI**.

5.4.1 Methodology development

An overview of the overall methodology for site-wide HI is shown in Figure 17. In the first stage, a TSA is conducted for the cluster using both TSPs and TSCs. Matching process stream profiles yields the largest potential for heat recovery. However, direct heat exchange between separate plants is difficult to achieve when site-wide heat recovery is targeted. Therefore, the current utility systems in the cluster are represented by TSPs and TSCs. Based on this representation, modifications to the utility systems are identified to target the maximum heat recovery within the cluster. This stage yields information suggesting that changes to the clusters’ utility systems and process/utility interface are necessary to realize the MER at the total site scale.

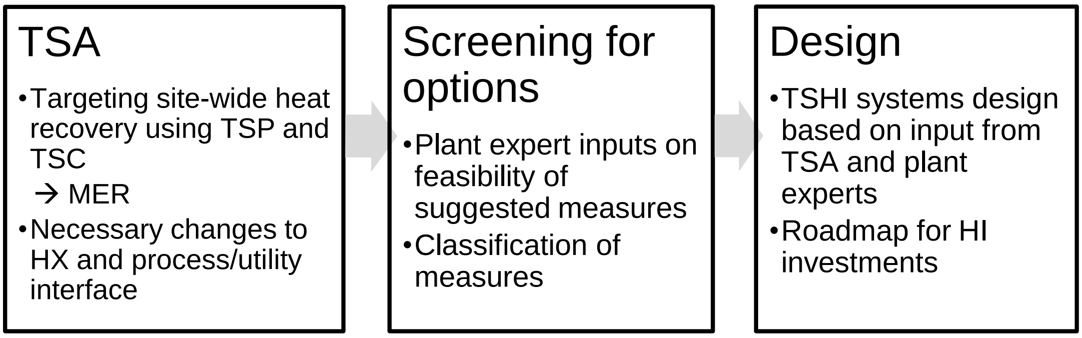

Figure 17 Overview of the methodology.

Achieving the maximum heat recovery target across an entire cluster with no or limited existing common utility infrastructure would demand a nearly complete reconstruction of the utility systems and HX networks. To obtain a starting point for the design of common heat recovery measures in the second stage of the procedure, plant experts are consulted with the results of the first stage. A list of HXs that potentially are affected by the construction of the utility system identified in the first stage is presented to plant process and energy experts. The experts are asked to consider several aspects, including the expected costs, space issues, location, process control for replacing each HX. This is used for categorizing the HXs. In the following, design phase changes to the process/utility interface that are deemed easier than other changes are prioritized when designing heat recovery systems.

5.4.2 Analysis of the current utility system

Figure 18 shows TSCs for the chemical cluster. The TSCs represent cold and hot process streams (solid lines) and cold and hot utility curves (dashed lines).

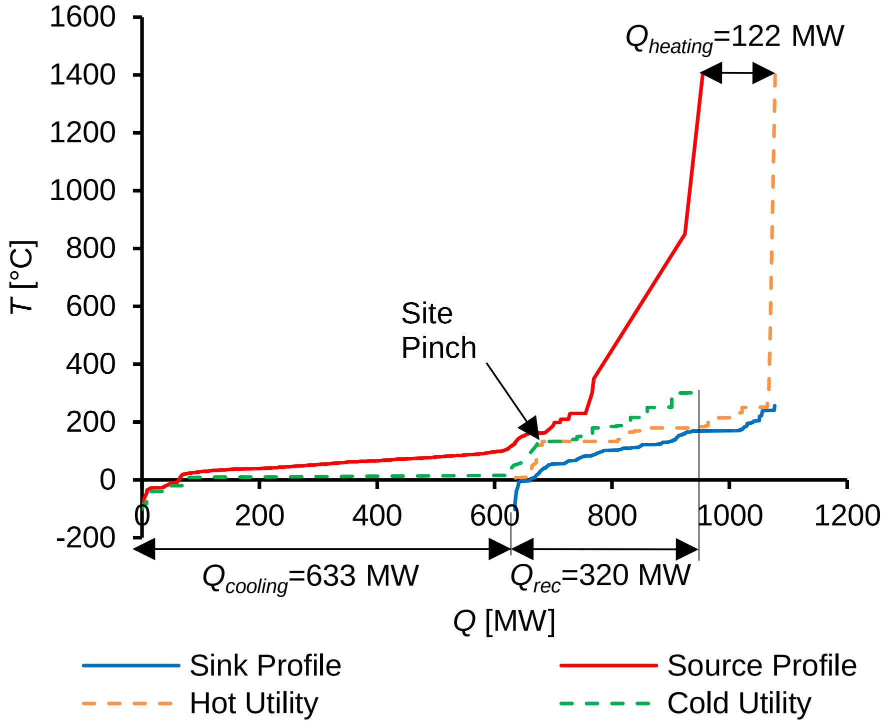

Figure 18 TSCs for the chemical cluster in Stenungsund based on the utility system.

As described previously, the minimum heating and cooling requirements for the total site can be determined from the TSCs, i.e., $Q_{heating}$=122 MW and $Q_{cooling}$=633 MW. Figure 18 also shows the site pinch, which limits further heat exchange through the utility system. In this case, the site pinch is located at 133 °C at the LP steam level. The overlap of the source and sink profiles (and the respective utility profiles) represents the amount of heat recovery by the utility system (320 MW).

5.4.3 Improvements to the total site utility system

In this section, the systematic procedure applied to increase site-wide HI via a common utility system is presented using TSPs and TSCs:

- The TSCs of the current utility system (Figure 18) exhibit a large temperature difference between the hot utility curve and sink profile (especially at temperatures below the site pinch).

  → This leads to high exergy losses because the process streams are heated with utility at higher temperatures than necessary.

- The source profile indicates that there is heat available (currently discharged) at suitable temperatures to supply heat to the cold process streams. Heat from hot process streams can be recovered in the circulating hot water system and delivered to cold process streams (between 50 °C and 100 °C).

  → A detailed analysis indicates that 2 bar (g) steam that is used for process heating could be replaced by hot water.

Implementation of such a circuit results in modified curves (see Figure 19) in which the resulting site pinch is shifted and the overlap of the TSCs is increased. These changes can be seen by comparing $Q_{heating}$ in Figure 18 and Figure 19. Introducing a hot water circuit results in the following changes:

- Increased recovery of process heat to generate hot water between 50 °C and 100 °C; and

- Savings of 51 MW steam at 2 bar (g).

A new site pinch is created, which indicates that no further HI is possible. Figure 19 shows that there remain hot and cold process streams available that are at a suitable temperature for heat recovery using a hot water circuit. However, in practice, the new site pinch implies that if more than 51 MW of 2 bar (g) steam is replaced with hot water, there will be an overall excess of 2 bar (g) steam. This is because there will still be the same amount of 2 bar(g) steam recovered from process heat, but there is less demand since steam for heating purposes is replaced by hot water.

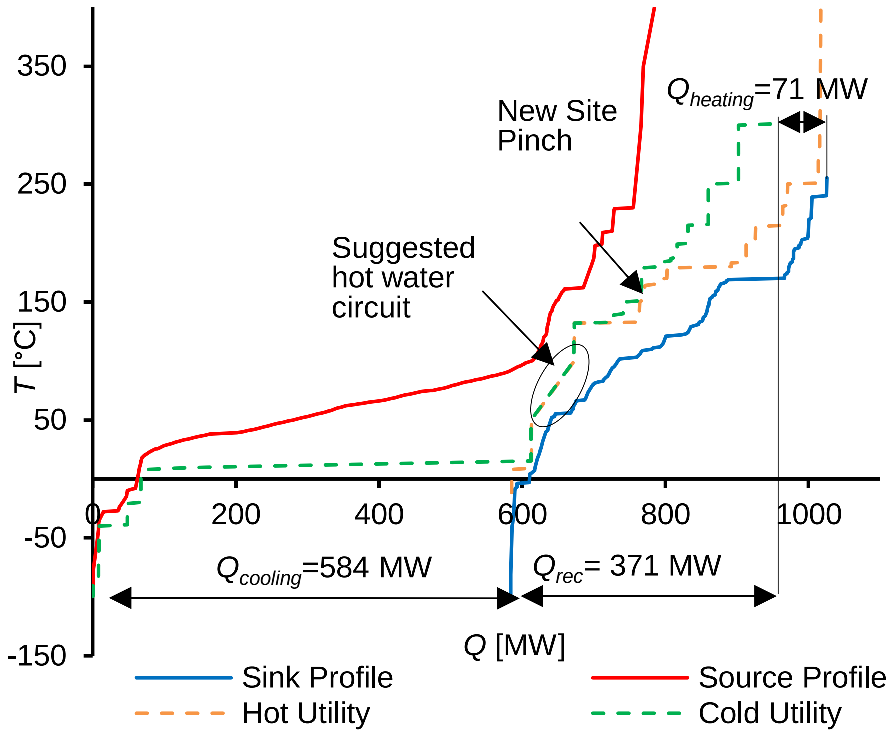

Figure 19 TSCs after introducing a new hot water heat recovery circuit.

Further increases in heat recovery require additional shifts in the site pinch, which can be achieved as follows:

- Modify the operating conditions of certain heat exchangers. In this work, the focus is on heat exchangers that do not require steam at a level higher than 2 bar (g) (see sink profile in Figure 19) $\rightarrow$ the steam level in these heat exchangers can be decreased $\rightarrow$ the demand for 2 bar (g) steam is increased;

- Proceed as above until another site pinch is created, which makes it necessary to either lower the steam level in the heat exchangers using higher pressure steam or steam from excess process heat can be recovered at higher levels;

- Both modifications make it possible to shift the site pinch and increase the overlap of the TSCs;

- The TSCs in Figure 19 also indicate the possibility for increasing the generation of 2 bar (g) steam from recovered excess process heat (see Figure 20); and

- The maximum theoretical HI is achieved when ΔT between the source profile/cold utility and hot utility/sink profiles approaches ΔT_{min} (here, ΔT_{min}=10 K).

The TSPs corresponding to the maximum energy recovery achieved using the aforementioned modifications are shown in Figure 20. The dotted lines show the current hot and cold utility profiles, whereas the dashed lines show the suggested utility system. The overall savings is 129 MW.

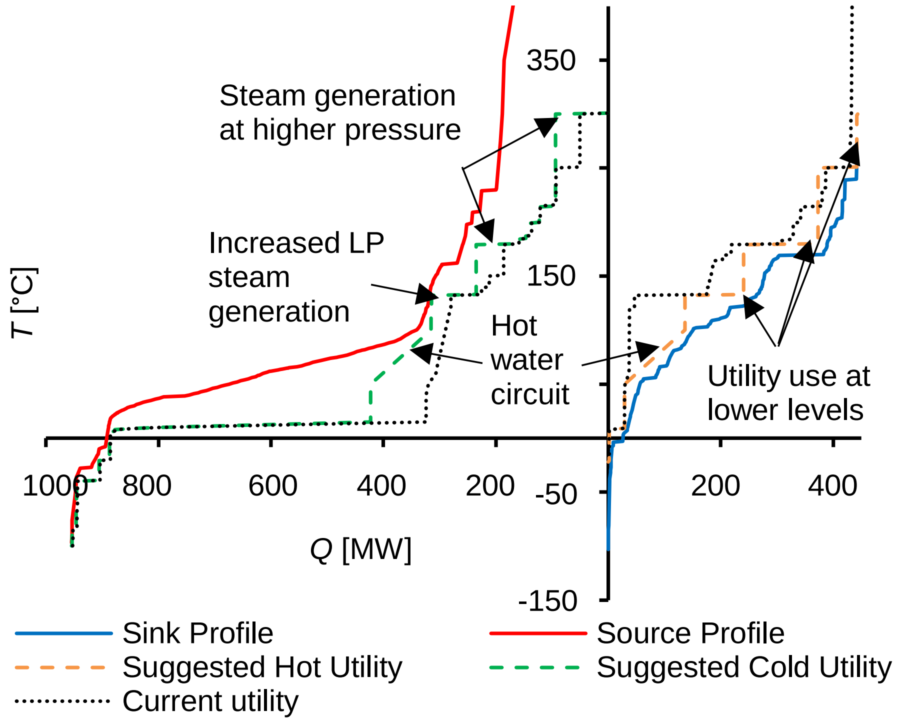

Figure 20 TSPs after introducing a utility system for maximum heat recovery.

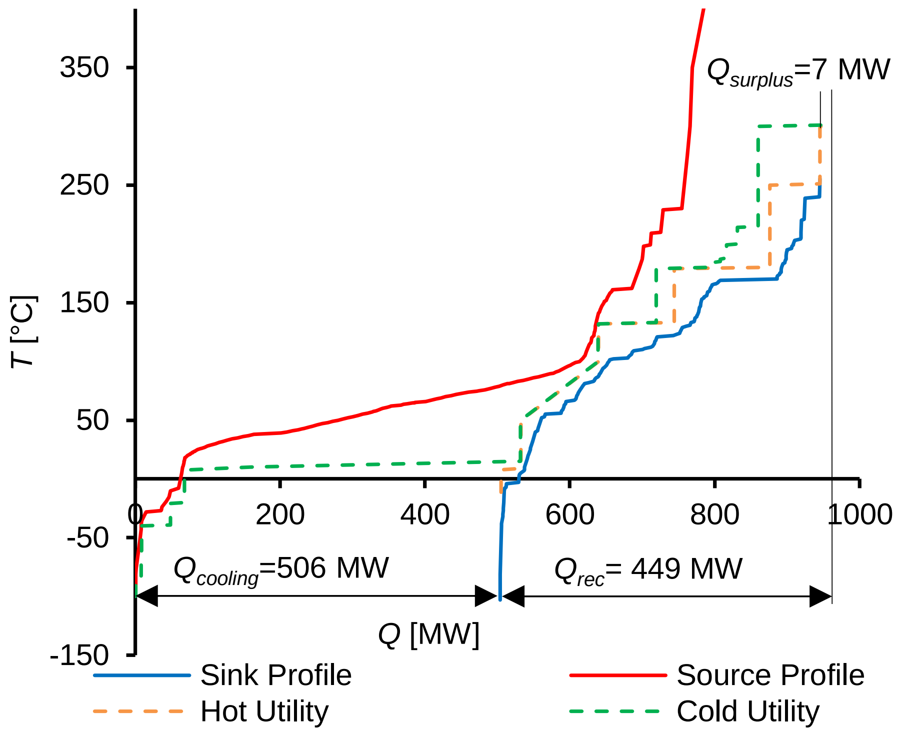

Figure 21 TSCs after introducing a utility system for maximum heat recovery.

This result implies that the site's current external utility demand of 122 MW can be completely covered by recovered process heat that is distributed via an interconnected utility system. Additionally 7 MW of excess steam would be available as illustrated by $Q_{surplus}$ in Figure 21.

5.4.4 Design for implementing site-wide heat recovery measures

The design procedure developed and the case study results presented in this section are based on **Paper VI**.

5.4.4.1 Design procedure

The overall design procedure can be divided into a preparatory phase and the design algorithm. The preparatory phase consists of the following steps:

1. Target TSHI using TSPs and TSCs to identify utility systems that achieve the MER of the cluster;
2. Screen for practical options by consulting plant experts to discard those that are considered to be highly expensive and/or technically infeasible;
3. Apply TSA using the options that remain after the screening phase to determine temperature levels of utilities used for heat recovery and to target the amount of heat recovery that can be achieved when considering the remaining process streams after the screening phase;
4. Identify limitations and all necessary investments to realize the heat recovery target;
5. Calculate fixed capital costs for HXs that are included in the common heat recovery systems; and
6. Rank the new HXs according to their costs per unit of heat.

After these steps, the heat recovery systems are designed based on the following algorithm presented in Figure 22.

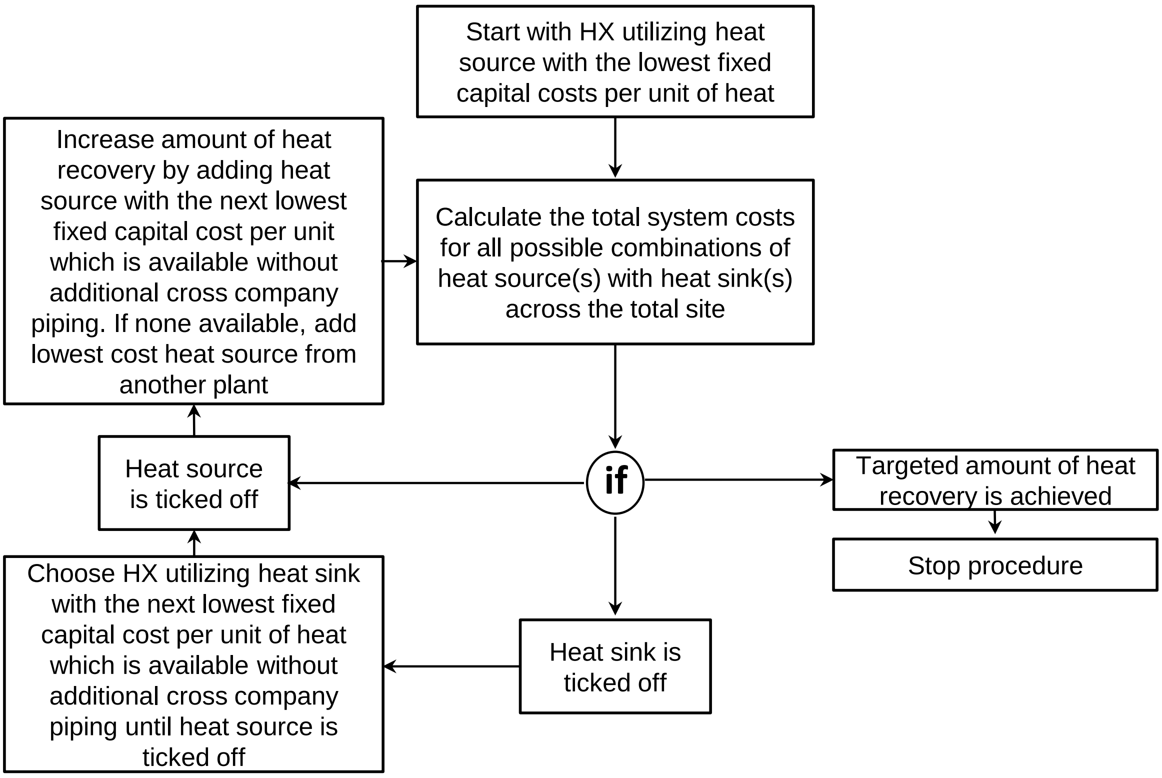

Figure 22 Illustration of the overall design procedure.

Detailed assumptions and background data on the cost estimation for heat recovery systems can be found in **Paper VI**.

The procedure presented in Figure 22 results in a wide range of different heat recovery systems. By systematically increasing the amount of heat recovery due to the addition of heat sources and sinks without (if possible) additional cross-company piping, the number of companies involved in each heat recovery system remains low, which leads to heat recovery systems that are potentially easier to implement. This conclusion is particularly important because cross-company collaboration and the control of heat recovery systems across several processes are considered constraints on site-wide HI.

When designing systems that do not achieve the heat recovery target, one must allow for future expansion toward a utility system that achieves the MER. By following the suggested procedure, it is guaranteed that the heat recovery systems are based on each other, allowing for step-wise expansion. The complexity of the suggested systems can gradually be increased, allowing the companies to obtain a larger portion of the heat recovery target with more sophisticated heat recovery systems. The HI target identified during the TSA is considered the ultimate goal.

5.4.4.2 Case study application

A qualitative evaluation of the suggested measures is conducted with the assistance of plant experts to assess the feasibility of the measures, to consider practical constraints and obtain a starting point for the design process. The measures are sorted into three categories:

- Possible, with moderate changes: Only new HXs with increased areas must be modified. No changes to other equipment are necessary. There is sufficient available space to conduct the modifications; no additional pipe racks are needed.

- Technically feasible: Changes to other process equipment must be conducted in addition to modifying the heat exchangers because, e.g., there is a lack of space, additional pipe racks must be installed, or heat exchangers are difficult to reach (e.g., top condensers or heat exchangers placed high above ground level).

- Not feasible: The suggested measures are not possible for other process reasons.

This evaluation indicates that 60 MW of the targeted savings can be achieved with moderate changes, although 110 MW of savings are technically feasible. These values should be compared with the theoretical heat recovery target of 129 MW identified in the TSA targeting study.

Based on the outcomes of this initial screening stage, several heat recovery systems are designed for different levels of heat recovery following the algorithm suggested in Figure 22.

Necessary equipment, practical limitations and constraints that are important for the design and final costs of common heat recovery systems are illustrated in Figure 23 and described below.

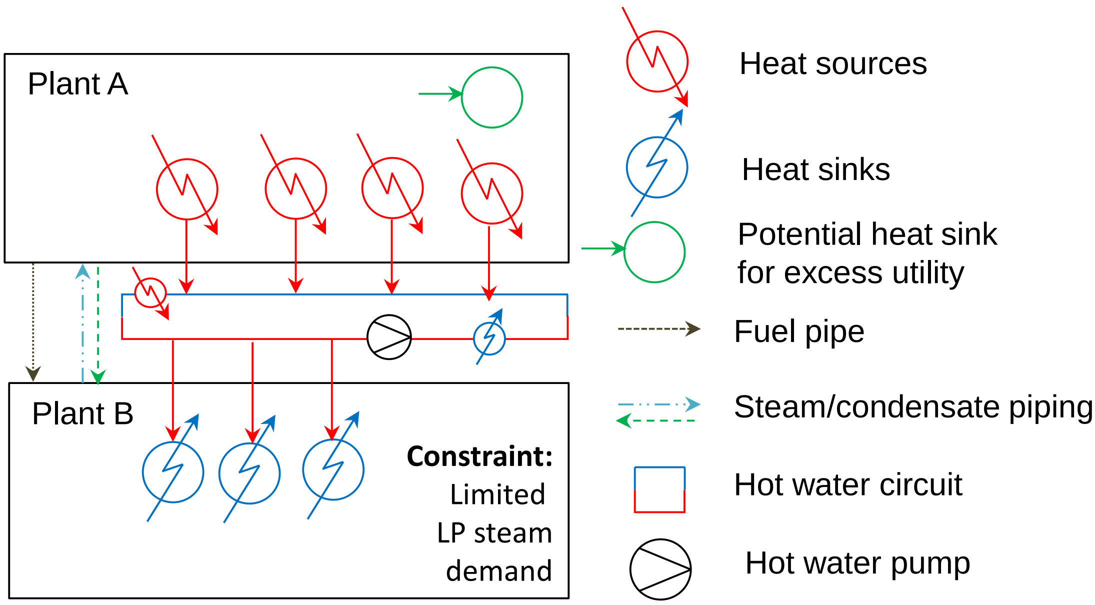

Figure 23 Example of two plants and the components necessary for implementing a common site-wide heat recovery system.

Practical limitations and assumptions:

- To achieve primary energy savings, it is necessary that recovered heat replaces utilities that are generated by fuel combustion in boilers; utility replaced by recovered heat that does not directly decrease the fuel demand must be redistributed to a plant where it can replace boiler utility;
- Once demand for excess utility is met at all plants, further heat recovery does not lead to primary energy savings; in this case, the maximum demand for excess utility is 53.8 MW;
- By-products that must be incinerated must be redistributed if the boiler steam demand falls below a certain level due to heat recovery, preferably to a plant with existing co-generation potential;
- 10% heat losses in the HW circuits are compensated for by adding process heat [84]; and
- HW piping is assumed to collect and distribute HW in parallel.

Necessary investments:

- HXs delivering heat (heat sources) to a common utility (HW) system;
- HXs receiving heat (heat sinks) from a common utility (HW) system;
- Backup HXs that supply and extract heat to and from the common utility (HW) circuit (in case of temperature and/or load fluctuations caused by, e.g., production capacity changes or plant shut-downs in the common HW systems);
- HW pipe circuit between the different plants to transfer heat;
- Steam piping between the plants to transfer excess steam between plants;
- Fuel piping to transfer excess by-product fuel between the plants;
- New HXs that can utilize excess hot utility created when process heat recovery is increased (in case utility generation cannot be directly controlled by decreasing the boiler load, e.g., due to safety regulations, i.e., boiler at stand-by of minimum boiler load, or excess process heat); and
- HW pumps.

Selection of site-wide heat recovery systems for a detailed economic evaluation

Figure 24 shows the estimated PBP for several heat recovery systems identified by applying the procedure illustrated in Figure 22. Large investments are necessary because there is nearly no existing common utility infrastructure within the cluster. The fixed costs for this infrastructure are rather high, which explains why the PBP decreases rapidly from approximately 7.6 to 2.4 years when increasing the amount of heat recovery from 1.4 to 20.7 MW. Thereafter, the PBP is rather stable when the amount of heat recovery is increased further. A sudden increase in the PBP occurs above 23.8 MW of heat recovery because it is necessary to invest in a fuel pipe between Plants F and D. The estimated PBP is then relatively constant between 3 to 4 years; a minimum PBP (3.2 years) occurs at

30.6 MW of heat recovery. The PBP increases slightly up to 3.9 years for a heat recovery of 53.8 MW due to the increased complexity of the systems.

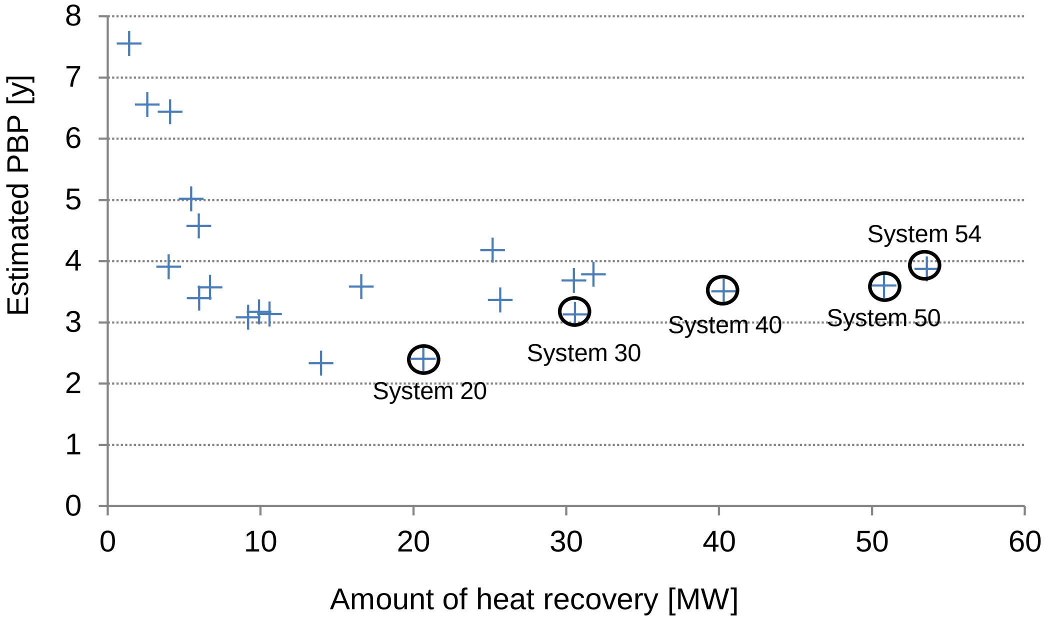

Figure 24 PBP for different heat recovery systems.

Once a certain heat recovery threshold is reached, HXs that currently use MP or HP steam must be converted to LP steam to increase the demand for excess LP steam. Above 40.3 MW of heat recovery, the demand for low-pressure steam at plant F is met, and an additional steam pipe between Plants D and E is required.

Several systems are chosen for more detailed analysis based on their PBPs. Promising heat recovery systems (i.e., Systems 20, 30, 40, 50 and 54) are indicated in Figure 24. The numbering reflects the amount of heat recovered. The PBPs for these systems are the shortest for their corresponding heat recovery rates. Therefore, these systems are investigated in more detail with respect to economic performance and the potential for reducing GHG emissions.

Increased complexity

Figure 25 illustrates the number of new HXs that must be installed depending on the amount of heat recovery. Each data point represents a heat recovery system. Systems with the shortest PBP are considered at each heat recovery level. At low levels of heat recovery, the number of new heat exchangers is relatively constant between 3 and 6 HXs; however, the number of new HXs increases rapidly when the amount of heat recovery is increased. Moreover, the number of plants participating in the heat recovery systems increases with the targeted amount of heat recovery.

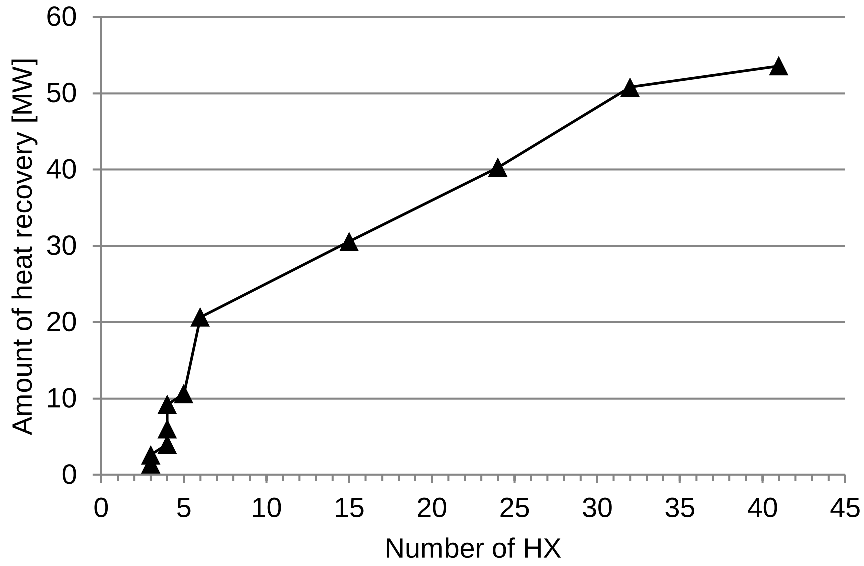

Figure 25 Amount of heat recovery as a function of the number of new HXs for systems with the shortest estimated PBPs.

Increased complexity and interdependency often represents a barrier for heat recovery projects. A roadmap of projects is suggested to overcome this issue. Here, one system is selected as a starting point, e.g., System 20. If proven successful, this system can be extended toward more complex systems that recover more heat.

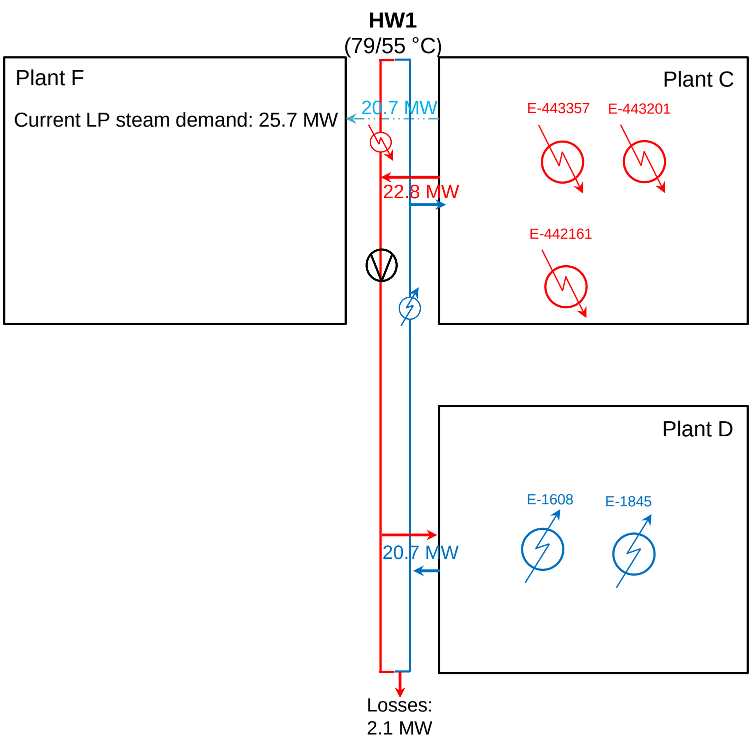

Figure 26 Example of a heat recovery system (System 20) as a result of the suggested methodology; see Figure 23 for the legend.

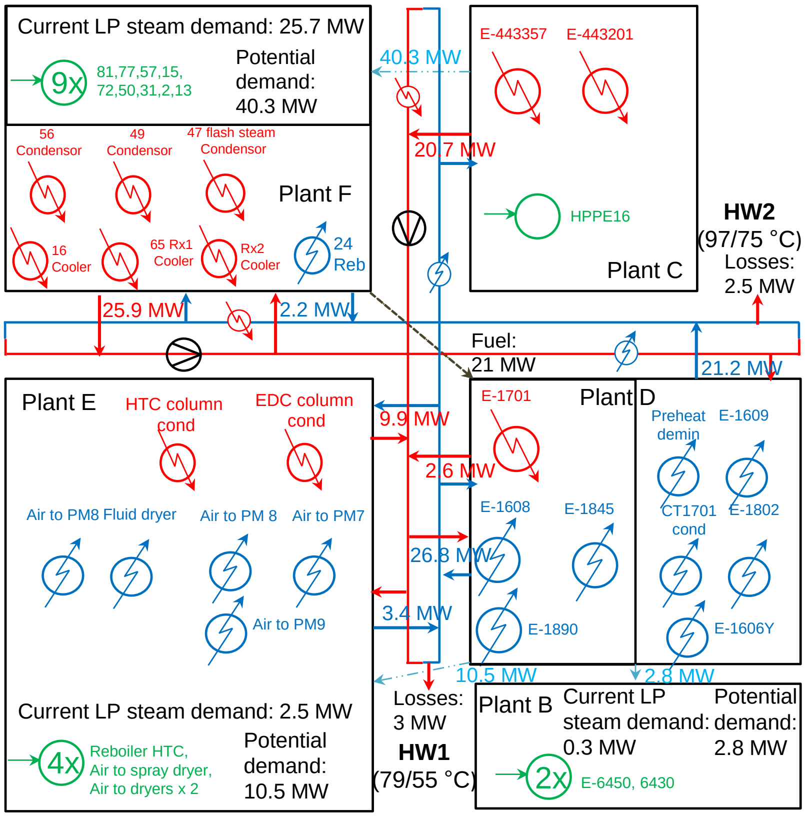

Figure 27 Example of a heat recovery system (System 54) as a result of the suggested methodology; see Figure 23 for the legend.

Economic evaluation

Table 4 presents the most important results of the economic evaluation and the achieved reductions in GHG emissions using the selected heat recovery systems, which can be used by decision makers. Despite the lower risk (lower total investment, shorter PBP and higher NPV_{15}-to-total investment ratio) and complexity (fewer companies involved and fewer process interdependencies) of projects achieving lower heat recovery, these projects exhibit a significantly lower NPV_{15} and are thus less profitable in the long run. Moreover, for the assumed market conditions, the NPV_{15} is 575 MSEK for System 50. This result means that System 54 is less profitable and bears larger risk (i.e., lower NPV_{15}-to-total investment ratio), which makes it unattractive compared with System 50. However, this result can change depending on several facts, including changes in GHG emissions and fuel costs, which are investigated in a sensitivity analysis described in **Paper VI**.

Table 4 Economic performance and reductions in GHG emissions for site-wide heat recovery systems.

TSHI system	Heat savings [MW]	Total investment [MSEK]	No. of collaborating companies	PBP [y]	NPV_{15} [MSEK]	NPV_{15}/total investment	Avoided GHG emissions [kt/y]	% of total cluster CO_2 emissions
System 20	20.7	153	2	2.4	312	2.04	47	5.2
System 30	30.6	289	2	3.1	392	1.36	70	7.7
System 40	40.3	425	2	3.5	469	1.10	92	10.2
System 50	50.8	549	3	3.6	575	1.05	116	12.9
System 54	53.6	620	4	3.9	564	0.91	122	13.6

Based on the data presented in Table 4, it is advantageous to begin energy collaboration throughout the cluster by first implementing a smaller system with both a low NPV_{15} and low risk, such as System 20, which can be expanded to a larger system with a higher NPV_{15} in the future. In this case, some additional investment (approximately 41 MSEK) is necessary to make System 20 ready for further expansion, namely, larger HXs, larger pipes (HW and steam) to transfer the future amount of heat across the plants and larger HW pumps to provide the capacity for future expansion.

The decision regarding which project to invest in must be based on the companies' short- and long-term strategies and their ambitions to decrease GHG emissions.

5.5 Combined shaft work and HI targeting of industrial refrigeration systems in industrial clusters

The methodology and case study presented in this section are based on **Paper II**.

5.5.1 Methodology development

The methodology for targeting reduced exergy losses (see section 4.3) is extended and applied to estimate a target for site-wide recovery of cooling capacity and the associated consequences for shaft power consumption in the refrigeration systems.

The following procedure is applied:

- Stream data collection for cold process streams below the ambient temperature from the different plants (e.g., T_{start}, T_{target}, Q, and the type of hot utility); and

- The process stream and current hot utility profile are plotted using an exergy CC diagram (see section 4.3).

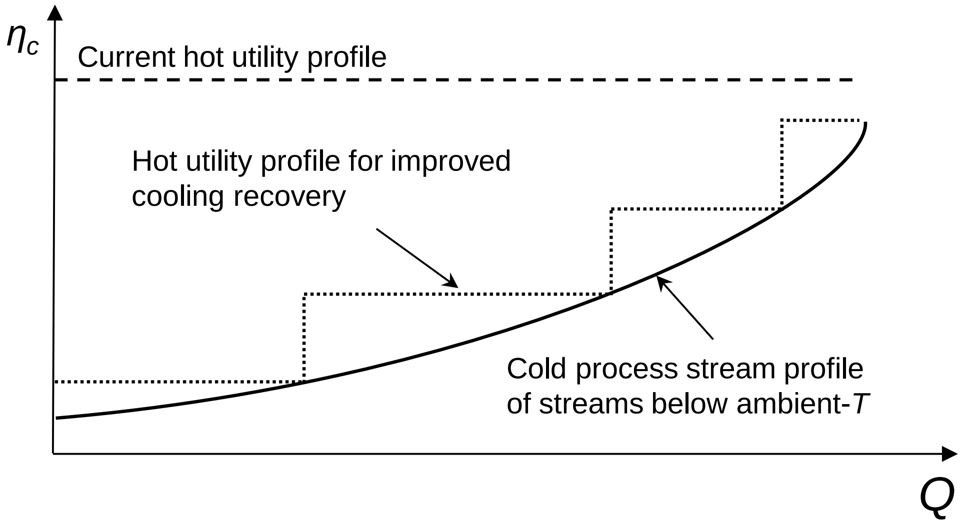

Figure 28 Illustration of the targeting procedure for site-wide recovery of cooling capacity from cold process streams (solid line) below the ambient temperature; current hot utility (dashed line) and the utility system when recovering cooling capacity (dotted line).

Figure 28 illustrates the process for estimating the recovered cooling capacity. The figure can be explained as follows:

- The area between the current hot utility (dashed line) and the process stream profile (solid line) represents the exergy flow rate loss caused by the current utility system;
- Because only streams below the ambient temperature are included in the process stream profile, it is possible to recover cooling capacity;
- The temperature levels of the refrigeration utility system present at the site are retained (dotted lines in Figure 28); and
- An improved refrigeration recovery utility system is designed; the system's potential for recovering cold utility is determined by activating a utility pinch against the cold process profile at each utility level.

→Therefore, a target for the recovery of cooling capacity can be determined as follows:

- The recovered cooling capacity replaces refrigerant from the refrigeration systems; and
- The corresponding decrease in exergy flow rate losses can be calculated because this decrease corresponds to the exergy necessary to generate the recovered cooling capacity.

5.5.2 Case study application

In this section, the results for applying the tools described in sections 4.3 and 5.5.1 to the chemical cluster in Stenungsund are discussed. Shaft power savings are targeted by the improved utilization of refrigerant and site-wide recovery of cooling capacity.

5.5.2.1 Improved utilization of refrigerant for increased energy efficiency

One approach to decreasing exergy losses caused by the current refrigeration system designs and thus increase their energy efficiencies is to improve the manner in which cold utility is used in the process.

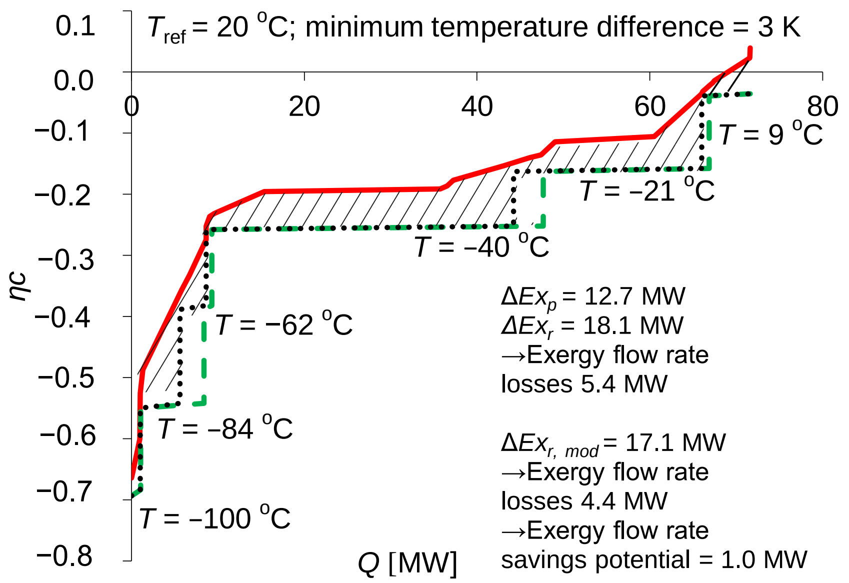

Figure 29 Exergy CCs showing the improved utility profile (dotted line) at the current cold utility levels and the current utility profile (dashed line).

Figure 29 illustrates the design of an improved cold utility system (dotted line). The area between the current refrigeration system and the process curve corresponds to a total exergy loss of 5.4 MW due to the manner in which heat is transferred from the process streams to the cold utility system. The current cooling levels are maintained; however, the cold utility is used at the maximum possible temperature. Therefore, the area between the utility and process curves is decreased (ΔEx_r of the current refrigeration system = 18.1 MW; $\Delta Ex_{r,\ mod}$ of the suggested refrigeration system = 17.1 MW), which corresponds to avoided exergy losses of approximately 1 MW (Figure 29).

The exergetic efficiency (η_{ex}) for the system investigated in this work is 0.66 based on the measured shaft power data obtained for the targeted refrigeration systems. Accounting for η_{ex}, shaft power savings of approximately 1.5 MW can be achieved using the suggested changes to the utility system, which corresponds to approximately 5.4% of the total shaft work consumed in the refrigeration systems. Additional savings can be obtained by increasing the number of refrigerant levels and changing the temperature levels of the existing refrigerant levels, which is considered a more unlikely measure because it involves extensive changes to the compressors and to a numerous heat exchangers; these components must be redesigned for new utility temperature levels.

5.5.2.2 Increased recovery of low-temperature utility

The left side of Figure 30 shows the hot process streams (solid line) and cold utility profile (dashed line). The right side of Figure 31 shows the cold process streams (solid line) and current hot utility (dashed line) used for process heating. The area between the curves (striped) represents the total exergy loss caused by the transfer of heat between the utility system and process streams.

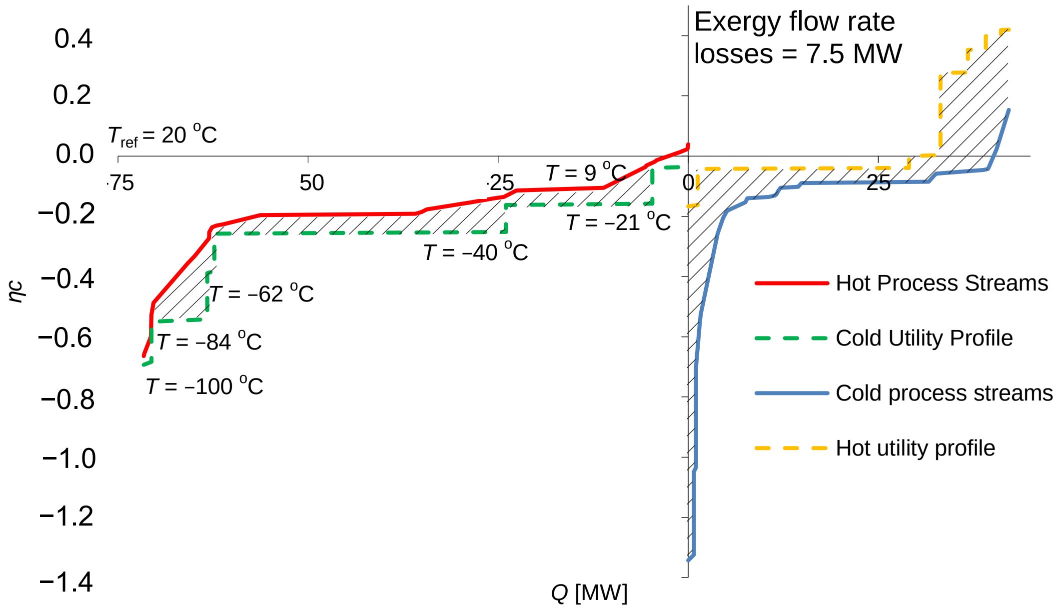

Figure 30 Exergy TSPs showing the process streams at the steam cracker plant cooled by refrigerants and the cold utility profile (left). The cold streams below the ambient temperature and the respective hot utility profile for the total site are also shown (right).

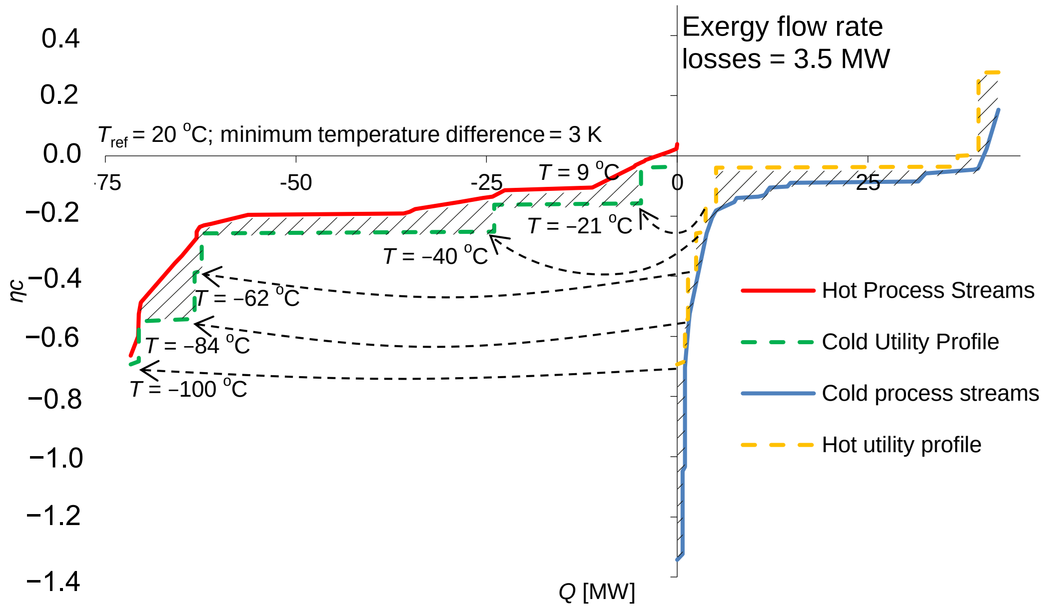

Figure 31 Exergy TSPs showing the process streams at the steam cracker plant cooled by refrigerants and the cold utility profile (left). The cold streams below the ambient temperature and a suggested improved hot utility profile are also shown (right).

On the right side of Figure 30, there is a large gap between the hot utility profile and cold process streams, which means that the exergy losses due to heat transfer are high and that there is a potential for the recovery of cooling capacity. Therefore, a utility system utilizing optimal (from an exergy point of view) cooling loads (retaining the cluster's existing cold utility levels) is designed. This system is shown on the right side of Figure 31. The area between the curves is decreased such that the sum of exergy losses is decreased from 7.5 to 3.5 MW.

It is possible to decrease the exergy losses in the cooling system by 1.63 MW by changing the utility system to recover more cooling capacity from the cold process streams while maintaining the current utility levels. Accounting for η_{ex} (which is equivalent to 0.66), this decrease corresponds to a shaft work of 2.5 MW, which represents approximately 10% of the total shaft work consumption of the cooling systems.

In the improved hot utility system that uses several heat exchangers, the utility steam should be replaced with a refrigerant to recover cooling capacity. In addition to relieving the refrigeration systems, this measure results in an additional savings of approximately 6.3 MW of utility steam at pressure levels between 1.8 and 28 bar (g).

5.6 Process integration of advanced biorefinery processes with existing industrial clusters

The process integration strategy and case study results presented in this section are based on **Paper III**. Detailed process descriptions, input data, assumptions for the process simulations and detailed process simulation results for the biorefinery processes can also be found in **Paper III**.

The goals of studying the integration of a biorefinery with a chemical cluster are as follows:

- Estimating the potential energy savings and resulting overall EE improvement that can be achieved through varying degrees of HI within the biorefinery processes and with the chemical cluster; and
- Estimating the biomass feedstock requirements to produce the specified amount of ethylene. Results of this analysis are provided in **Paper III.**

5.6.1 Integration strategy

Process simulation and pinch technology tools are used to systematically investigate opportunities for improving EE improvement. Thus, the focus of this portion of the study is on a holistic approach to the entire process instead of improving single process steps. In this work, the approach illustrated in Figure 32 is adopted.

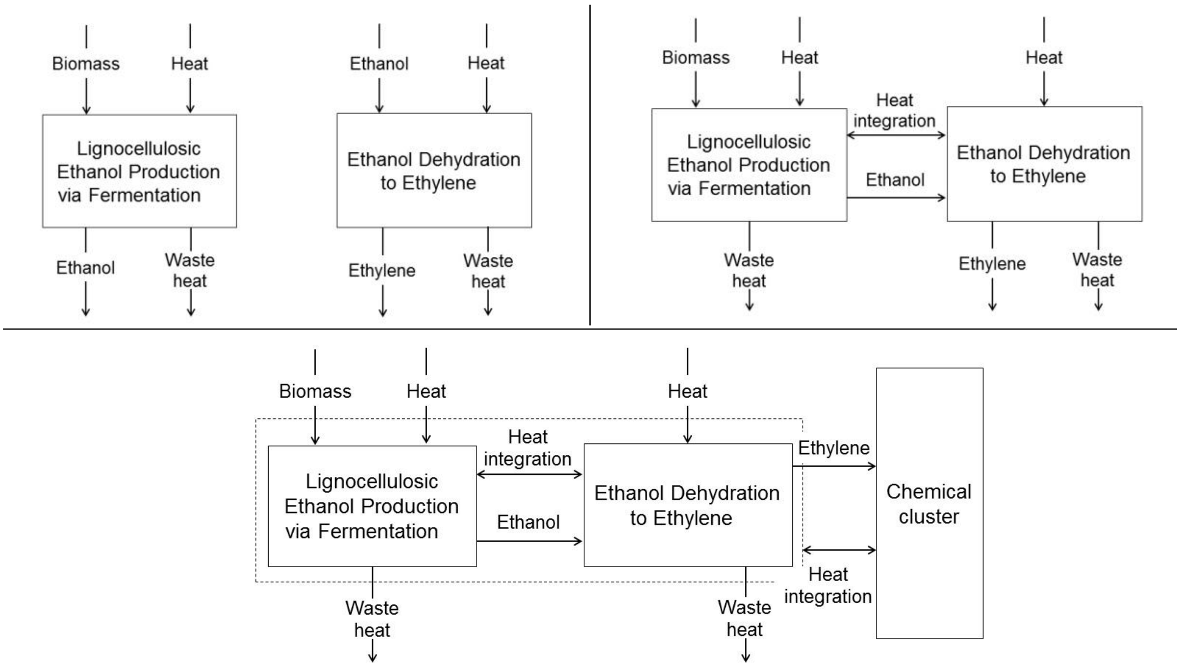

Figure 32 Illustration of possible process integration options; upper left: base case with no integration between ethanol and ethylene process; upper right: heat and material integration between the two processes; and lower: heat and material integration and design of a utility system to enable site-wide process integration.

Lignocellulosic ethylene production can be divided into two steps: 1) lignocellulosic ethanol production and 2) ethanol dehydration to ethylene production. To identify EE opportunities, pinch analysis is performed using HI at three different levels with increasing degrees of integration. On the first level (Case I), the two processing steps are investigated separately; no integration between the two processes is considered. In practice, this is the case if both processes are at different locations. This case represents the reference case to which the following cases are compared. At the second level (Case II), the material integration (i.e., ethanol is directly delivered in the gaseous phase from the production of lignocellulosic ethanol to the ethanol dehydration process) and HI of the two processes are investigated. In practice, this level requires that the two processes are co-located. At the third level (Case III), the integration potential of the combined lignocellulosic ethylene process with the existing chemical cluster through a common utility system is estimated using the results obtained in **Paper I**. The energy targets determined using pinch analysis assume that direct heat exchange is possible between all process streams across the entire site. The new plant must be integrated with the cluster's utility system to transfer heat within the biorefinery and with the existing cluster. Currently, the cluster has no common utility system. In **Paper I**, several measures to increase the cluster's EE via site-wide energy collaboration are identified; a common utility system is suggested in this publication. The suggested utility system is assumed to estimate the side-wide HI potential between the ethylene production plant and chemical cluster.

For each case, the potential for exporting excess solid fuel, co-generation of electricity in a CHP plant and the electricity consumption are estimated based on process simulation; the results are presented in Table 5.

The different process integration levels are compared by quantifying the minimum process energy requirements ($Q_{heating,\ min}$ and $Q_{cooling,\ min}$) for a plant with an annual ethylene production of 200 kt and by estimation of the overall EE at the different process integration level.

5.6.2 Integration of separate ethanol and ethylene production processes (Case I)

Direct steam injection in the pre-treatment steps of the ethanol production process (51.2 MW) and direct steam to the ethylene reactor (25.1 MW) are not included in the HI analysis because this steam usage is a process requirement and cannot be replaced by heat exchange with other process streams. These amounts of steam must be added to cover the total steam demand of the processes.

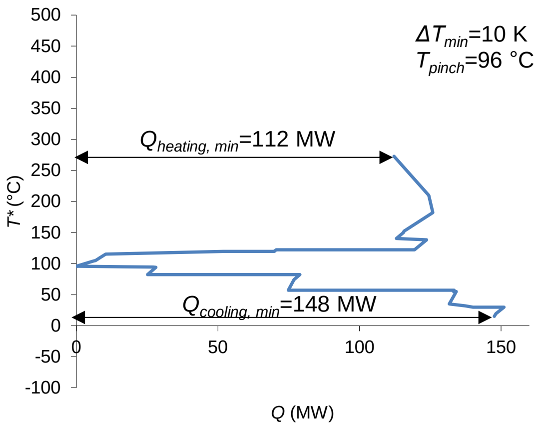

Figure 33 GCC for the ethanol production process from lignocellulosic biomass; direct stream injection of 51 MW in the pre-treatment steps is considered a process requirement. Therefore, this stream is not included.

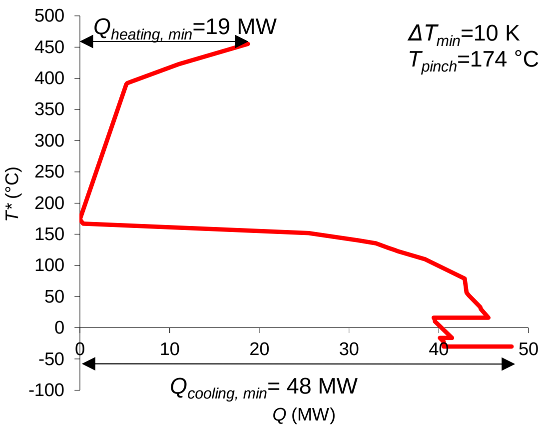

Figure 34 GCC for the ethanol dehydration process; direct steam injection of 25 MW to the ethylene reactor is considered a process requirement. Therefore, this stream is not included.

On the first integration level, lignocellulosic ethanol production and the ethanol dehydration process are investigated separately. Figure 33 shows the GCC for the ethanol production process. Assuming a global ΔT_{min} of 10 K, the minimum heating and cooling demands for the ethanol production process are 112 and 148 MW, respectively. The pinch temperature of the process is 96 °C. Moreover, a large fraction of the heating demand occurs at a temperature of at least 117 °C (i.e., for ethanol purification). Large sources of excess heat include the condensers used in the purification stage and the cooling demand of the hydrolysis and fermentation processes.

The GCC for the ethanol dehydration process is shown in Figure 34. The minimum heating and cooling demands are 19 and 48 MW, respectively. The pinch temperature for the process is 174 °C, which is considerably higher than the pinch temperature for the ethanol production process (i.e., 96 °C). The GCC below the pinch point is relatively flat, indicating the presence of a large amount of excess heat. Therefore, excess heat from the dehydration process can likely be used to offset a portion of the heating demand of the ethanol production process.

The total minimum heating and cooling demands of the two processes are 131 and 196 MW, respectively.

5.6.3 Material and heat integration of the two processes (Case II)

Material integration implies that ethanol is directly delivered to the ethanol dehydration plant in the vapor phase, which results in some changes in process and energy flows in both processes. Therefore, the cooling demand in the rectifier column in the ethanol process is decreased by approximately 14.3 MW, whereas the demand for preheating the ethanol feed to the dehydration reactor (approximately 4.3 MW) is eliminated; the heating demand in the furnace of the ethylene plant is decreased by approximately 8.7 MW.

A background/foreground analysis of the two processes is performed to illustrate HI opportunities and estimate the potential utility saving. Figure 35 shows the analysis of the combined processes. There is an opportunity to recover 44.5 MW of excess heat in the ethanol dehydration process and deliver it to the ethanol production process.

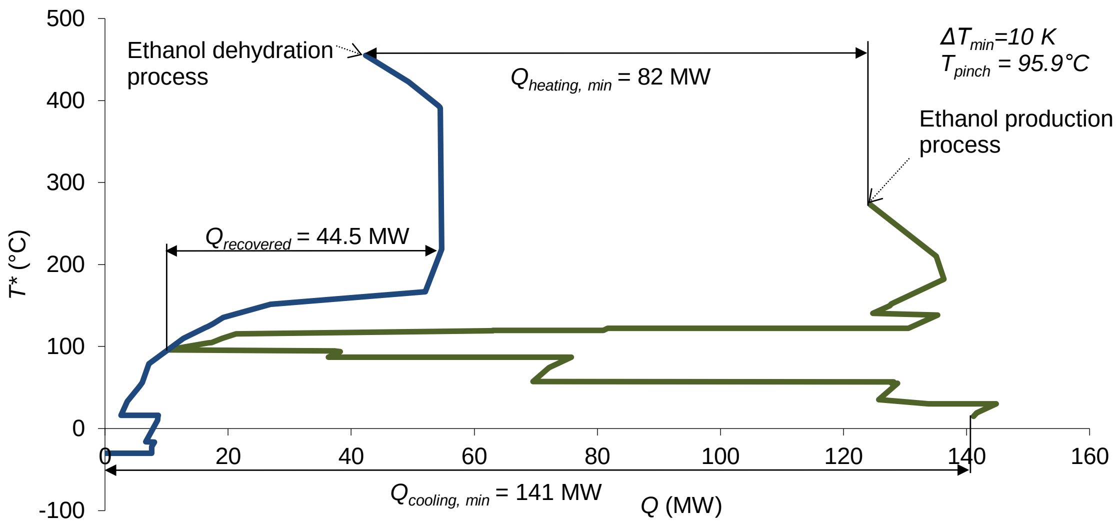

Figure 35 Background/foreground analyses of ethanol production and the ethanol dehydration process; direct delivery of ethanol between the processes is accounted for in the stream data.

As a result, there is an opportunity to reduce the total minimum heating demand for the combined processes from 131 to 82 MW via both material integration and HI (i.e., a reduction of 49 MW compared with the case of two separate processes). Similarly, there is an opportunity to reduce the total minimum cooling demand from 196 to 141 MW (corresponding to a reduction of 55 MW) via both material integration and HI of the two processes.

5.6.4 Integration opportunities with the existing chemical cluster (Case III)

The GCCs shown in Figure 35 represent the minimum heating and cooling demands of the biomass to ethylene production plant. In this case, it is assumed that direct heat exchange between process streams is possible across the entire biorefinery plant. In practice this might not be entirely feasible. A large portion of process heating and cooling is performed via the utility system. TSA is applied to design a utility system for a process that enables both a high amount of heat recovery within the process and HI with the existing chemical cluster.

In **Paper I**, a common utility system for heat recovery and process heating is suggested that mainly consists of 4 steam levels [i.e., 85, 40, 8.8 and 2 bar (g)] and a hot water circuit (see Figure 20). By applying these utility levels to the new biomass-to-ethylene process, the TSCs depicted in Figure 36 are obtained. The TSCs show the amount of external hot and cold utility, i.e., $Q_{heating}$=103 MW and $Q_{cooling}$ = 164 MW. External heating demands of 78.4 and 1.2 MW are covered by 2 and 8.8 bar (g) steam, respectively.

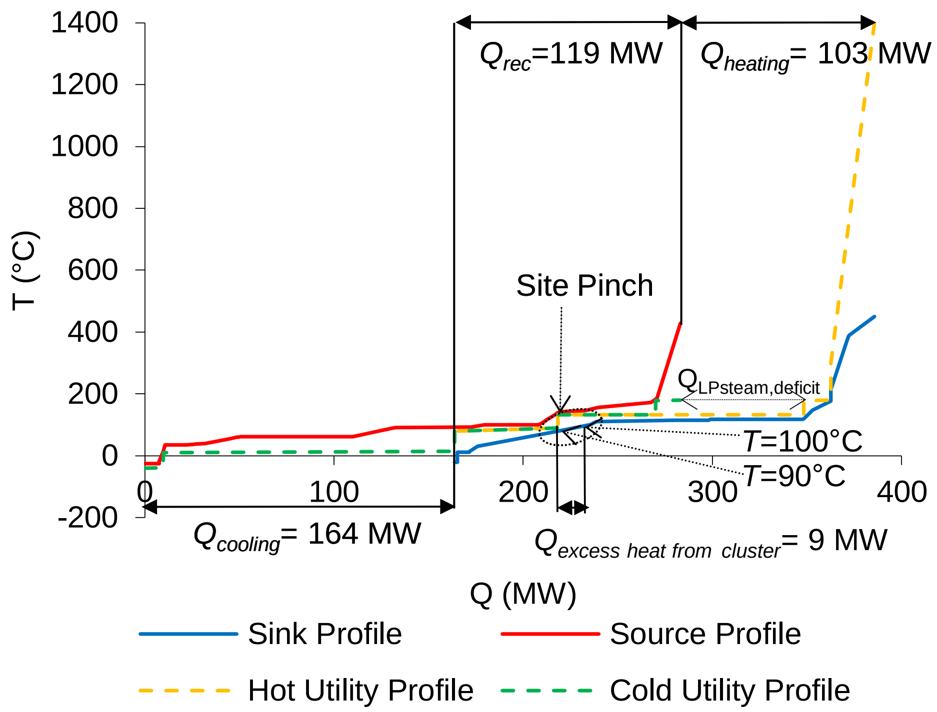

Figure 36 TSC for the biomass-to-ethylene plant.

The minimum heating and cooling demands are compared with the results from the pinch analysis study (see section 5.6.3) because pinch analysis assumes direct heat exchange between process streams with a constant ΔT_{min} of 10 K, whereas heat recovery through the utility system requires a higher temperature difference (i.e., ΔT_{min} accounts for the difference between the source profile and cold utility and between the hot utility and sink profile). Therefore, it is not possible to achieve the same amount of heat recovery that is attainable via direct heat exchange. Another reason for the lower heat recovery is related to the nature of the utility steam system. Because of the constant temperature of the condensing steam and the evaporating water used for process heating and cooling, a site pinch is created (see Figure 36) that hinders increased heat recovery.

The dotted circle close to the site pinch in Figure 36 indicates a large gap between the hot utility curve and sink profile, which means that a utility with a lower temperature could be used for process heating. Figure 37 shows the temperature level and amount of excess process heat available after maximum HI within the cluster using an improved utility system. The GCC contains the hot process and the utility demands for process heating of the cluster's improved common utility system. The graph provides an estimate of the amount of heat available from the processes after the maximum amount of process heat is recovered using the improved common utility system. Excess heat (23 MW) is available at temperatures exceeding 110 °C. As indicated in Figure 36, there is a heating demand of 9 MW at temperatures between 90 °C and 100 °C in the biorefinery process, which means that a portion of the excess heat from the cluster can be used for heating streams in the biorefinery. The use of this excess heat results in savings of 9 MW of 2 bar (g) steam from the CHP plant, reducing the external hot utility demand of the ethylene process to 94 MW. As indicated in Figure 36, the biorefinery has a deficit of LP steam of approximately 78 MW, which represents an important aspect of these results, especially for integrating this process with other petrochemical sites that have excess LP steam. In the latter case, the excess LP steam can be utilized in the biorefinery and increase EE.

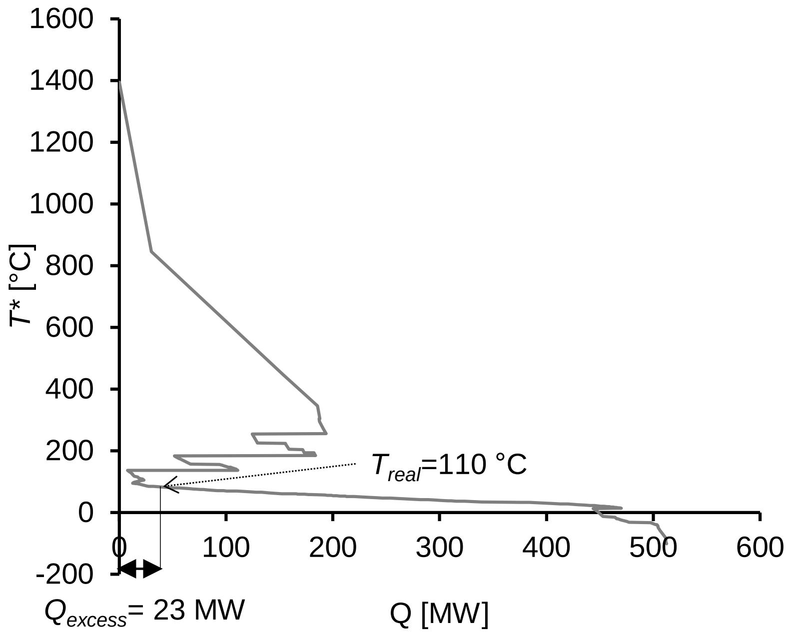

Figure 37 GCC representing the transfer of heat from hot process streams to an improved utility system in the chemical cluster, which is used to determine the amount of additional excess heat that can be delivered to the biorefinery.

5.6.5 Performance assessment of heat integration opportunities

Table 5 shows the flows of energy to and from the biomass-to-ethylene production processes considering the different levels of process integration. The level of HI has a strong effect on the amount of excess solid residues and electricity that can be exported from the processes, which consequentially influences the overall EE. The largest net amount of electricity that can be exported from the site occurs for Case 1 even though the amount of excess solid residues is smallest for this case.

Table 5 Energy inputs and outputs and the overall energy efficiencies for different levels of process integration.

	Case I Base case with separate processes	Case II Integrated mass and heat processes	Case III Integration with existing site
Outputs:	[MW]	[MW]	[MW]
$\dot{m}_{ethylene} \cdot HHV_{ethylene}$	307	307	307
$\dot{W}_{el}^{-}$	56	46	51
$\dot{m}_{excess\,solid\,residues} \cdot HHV_{exce}$	86	123	103
Inputs:			
$\dot{m}_{biomass,in} \cdot HHV_{biomass}$	749	749	749
$\dot{m}_{yeast} \cdot HHV_{yeast}$	9	9	9
$\dot{W}_{el}^{+}$	35	38	38
$\dot{Q}_{NG}$	16	8	8
$\eta_{overall}$	56.4%	58.3%	57.1%

In this case, more heat is needed for process heating, resulting in a larger potential for co-generating electricity. Meanwhile, a larger portion of the solid residues must be combusted to supply heat to the processes. Overall, this alternative exhibits the lowest overall EE. Case II exhibits the highest overall EE.

Cases I and II assume the possibility for direct heat exchange throughout the respective site. Case III assumes that heat exchange occurs via a common utility system that enables heat exchange with the existing chemical cluster. Assuming heat transfer via a utility system increases the necessary temperature difference for heat recovery, which explains why the overall EE in Case III is slightly lower than for Case II, although Case III provides a more realistic target.

Furthermore, Figure 33 to Figure 36 indicate that there is excess process heat available at temperatures suitable for delivery to a DH network. Finding use for the available excess process heat could further increase the overall EE of the processes. In the following, a targeting approach for DH delivery from industrial sources is presented.

5.7 Targeting for export of excess heat from industrial clusters to a district heating network

The methodology developed and the case study results presented in this section are based on **Paper V**.

5.7.1 Methodology development

Pinch technology tools are applied to determine the potential for delivering excess heat from the cluster to a regional DH network. Exporting excess heat from the cluster to a regional DH system must be evaluated with respect to the potential for internal HI within the cluster. This competition is investigated by comparing the potential for DH delivery of the current non-integrated cluster with the case in which the identified heat recovery measures [85] (that achieve approximately 50% of the heat recovery target identified in Paper I; see section 5.4.3) are implemented. In the latter scenario, all heat sources selected as “possible with moderate changes” (determined according to the screening stage described in section 5.4.4.2 and presented in Ref. [85]) are not considered as being available for DH production. The detailed methodology and the results of this study are presented in **Paper V**.

<u>CO_2 emissions from DH that are produced from industrial excess heat</u> are calculated as follows:

$$e_{ehDH} = e_{fuel} \cdot \frac{\text{Fuel demand avoidable by HI}}{\text{DH delivery capacity target}} \qquad \text{Eq. (6)}$$

CO_2 emissions from industrial excess heat must be allocated to account for the possibility of avoiding these emissions using internal HI. In a chemical cluster in which heat recovery is not maximized, an unnecessarily large amount of heat is cascaded from the boilers to the cold utility system; this heat is potentially available for DH. To account for these inefficiencies in the heat recovery systems, CO_2 emissions are allocated to the share of the DH consisting of heat that could be internally recovered within the cluster.

Natural gas is assumed to be fuel with specific emissions (e_{fuel}) of approximately 217 kg/MWh [75]. The “fuel demand avoidable by HI” considers the fuel that could be saved by implementing internal heat recovery measures within the chemical cluster (approximately 150 MW_{fuel} if all possible TSHI measures are implemented). The “DH delivery capacity target” is the amount of DH delivered to the DH system in the specific cases investigated herein.

To <u>estimate the economic potential for DH delivery</u> from the cluster, it is assumed that the heat is delivered to the clusters’ battery from the location at which the DH company receives the heat. Two levels of DH prices are assessed, a low value (i.e., 100 SEK/MWh) and a high value (i.e., 700 SEK/MWh), based on representative average sales price to DH consumers in Sweden.

The calculation algorithm is as follows:

1. Candidate excess heat streams, which are streams that are currently cooled by CW or air and not retained for internal heat recovery within the cluster, are identified;
2. The DH capacity target is calculated by superimposing the DH water curve with the process cooling composite curve;
3. Hot process streams are sorted based on the size of their potential contribution to DH delivery; and
4. For each DH capacity value in the range, the following steps are executed:
    a. The cooling composite of hot process streams that should be used for DH delivery is constructed (following the order identified in point 3), which are then superimposed onto the DH hot water profile;
    b. Enthalpy intervals in the CC diagram are identified;

c. For each enthalpy interval, the total heat transfer area and estimated number of heat exchangers are determined;
d. The total investment cost is calculated; and
e. The annual DH delivery that satisfies the investment criteria is calculated (DCFROR of 10%).

5.7.2 Case study results

In the following, the main results of the case study performed for the chemical cluster in Stenungsund are presented and discussed.

5.7.2.1 Potential for DH delivery

Figure 38 shows the DH delivery potential from the cluster for the case in which current HI is accepted and no additional internal heat recovery measures are considered.

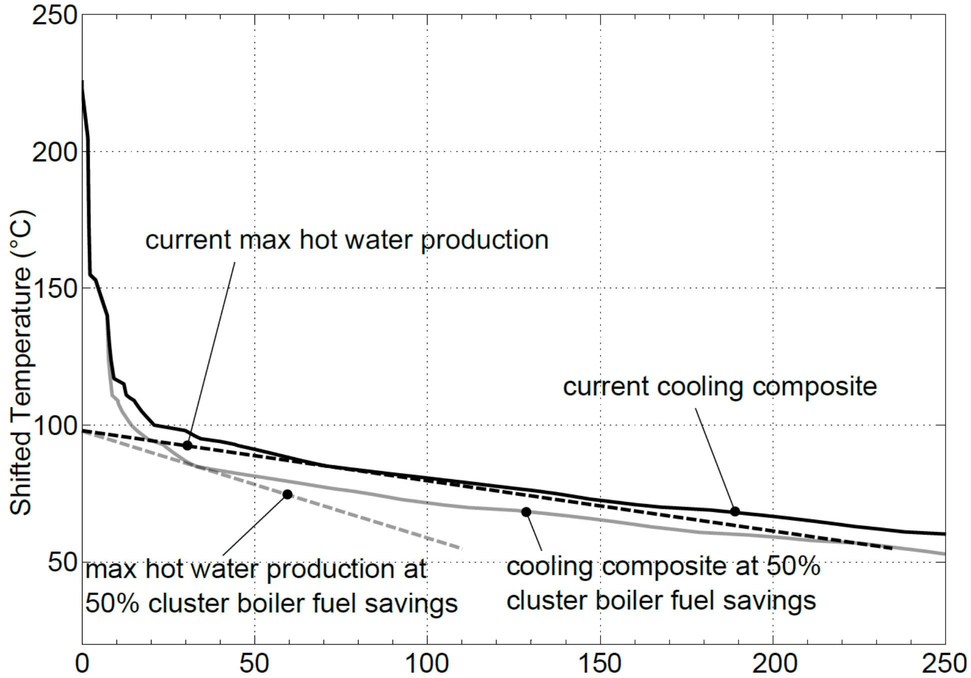

Figure 38 Cluster DH delivery potential considering current (black curves) and internally heat-integrated (gray curves) cases.

The figure also shows the potential for a case in which site-wide HI (resulting in savings of approximately 50% of the cluster's boiler fuel consumption for hot utility production) is assumed.

The potential for delivering DH from the cluster assuming the current state of HI is approximately 235 MW (black dashed line). Assuming increased internal heat recovery, the potential decreases to approximately 110 MW (gray dashed line). Interestingly, the decrease in DH potential when comparing the current case with the integrated case is larger (approximately 125 MW) than the heat savings (approximately 75 MW_{fuel}, corresponding to approximately 60 MW_{heat}) that can be achieved by internal site-wide HI. This decrease is due to the change in shape of the cooling composite because many of the hot streams involved in site-wide heat recovery measures are at relatively high temperatures and are especially suitable for DH delivery.

Figure 39 illustrates the number of process streams delivering DH. With the exception of Plant A, the curves for the individual plants and the cluster are initially relatively steep, which means that using only a few streams can offset a large portion of the DH capacity target. The pinch point between the cooling composite and HW production profile is determined by only a few of the process streams; only a few of the other streams are used to preheat water from the DH return temperature to the pinch point.

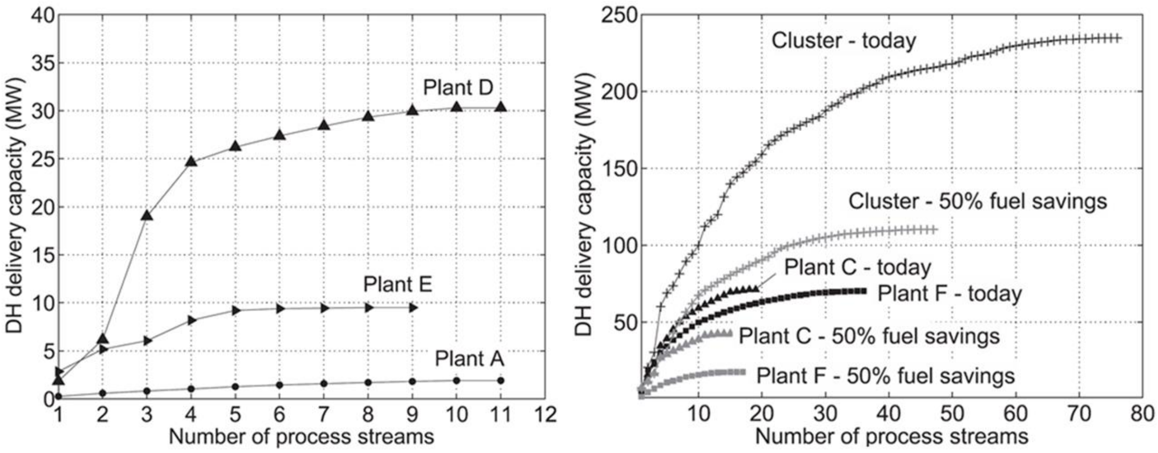

Figure 39 Number of process streams delivering DH.

The contribution of other thermal streams to the increased capacity is small. For example, only 76 process streams out of the available 173 streams are used to deliver the entire DH potential of approximately 235 MW using the current HI. In this case, only 14 streams are required to deliver half of the potential amount.

5.7.2.2 Allocation of CO_2 emissions with DH delivery

Table 6 shows the potential for delivering DH from the cluster, the fuel demand for hot utility generation and the resulting allocation of specific CO_2 emissions for DH.

Table 6 DH export potential, cluster's fuel demand for hot utility generation and allocated specific CO_2 emissions for DH in the two different internal integration cases.

Local HI	0	50%
Heat collection system	site-wide	site-wide
Max DH export (MW)	235	110
Cluster natural gas (MW)	150	75
Specific DH CO_2 emissions (kg/MWh)	139	148

The results show that the specific CO_2 emissions from exporting DH are smaller for the case in which no HI of the cluster is assumed. This result is due to the large decrease in the potential for DH delivery in the integrated case compared with the non-integrated case. However, it is important to consider which type of DH generation technology is replaced by the industrial excess heat. If a natural gas boiler (specific emissions of approximately 217 kg/MWh) is replaced, it is advantageous to deliver industrial excess heat. If other CO_2 lean technologies, such as natural gas or biomass-fired CHP, are used, it is advantageous to use excess heat for internal heat recovery within the cluster, which will lead to reduced firing of natural gas boilers. Moreover, different technologies are replaced during different periods of the year in DH systems; therefore, it is important to consider the total reduction in CO_2 emissions that can be achieved over the course of an entire year.

5.7.2.3 Economic feasibility

The results of the economic feasibility study are shown in Figure 40, Figure 41 and Figure 42. For each level of installed DH capacity (x-axis), the amount of annual DH delivery that must be guaranteed at a high and low price for DH to achieve a DCFROR of 10% is shown. The range of conditions that fulfill the investment criteria is indicated by the shaded area between the curves.

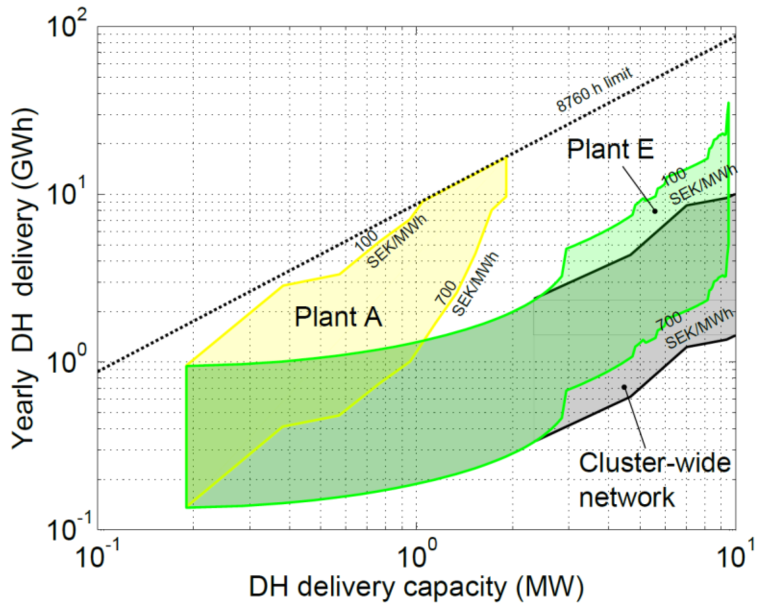

Figure 40 DH delivery capacity versus the yearly DH delivery needed to reach a DCFROR of 10% at different DH prices for different plants (color) and the entire chemical cluster (black) assuming no internal HI.

Figure 40 shows the results for the case in which no site-wide HI is considered. DH delivery from Plant A suggest that larger yearly DH delivery is required for an equal DH price, which makes this a less interesting option than DH delivery from Plant E. The same holds when comparing DH delivery from Plant E with other plants in the cluster or with a site-wide heat collection system for capacities up to 2 MW.

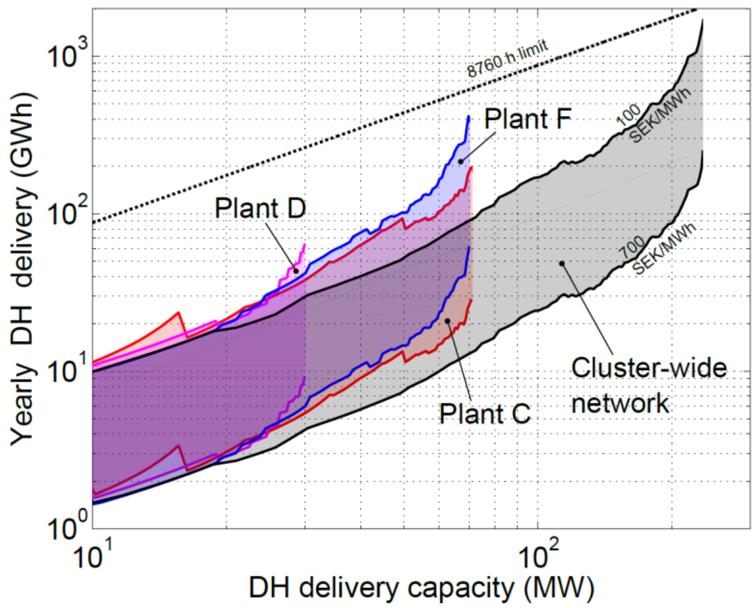

Figure 41 DH delivery capacity versus the yearly DH delivery needed to reach a DCFROR of 10% at different DH prices for different plants (color) and the entire chemical cluster (black) assuming no internal HI.

Figure 41 shows that the site-wide network exhibits the most favorable results. The lowest annual heat delivery needed to reach the investment criteria throughout the entire range of installed DH delivery capacities is indicated. Plants C, D and E exhibit comparable results. Plant D exhibits the most promising results up to an installed capacity of approximately 15 MW. At higher capacities, Plant C is found to be the most cost-effective single plant for delivering DH.

The curves become steeper with increased installed DH delivery capacity. For the case of a site-wide network, the annual revenues (i.e., yearly DH delivery) required to achieve a similar rate of return must increase substantially to counterbalance the large investment in heat exchangers for capacities exceeding 100 MW. This effect is even stronger above 200 MW. As the installed capacity approaches the target DH capacity (approximately 235 MW), it is necessary to utilize nearly all of the relevant cluster excess heat sources for DH delivery, including extremely small and expensive sources.

Figure 42 shows the results in the case of site-wide HI. For most installed capacities, cluster-wide DH delivery is the least expensive option. Moreover, in this scenario, a higher annual DH delivery is required to achieve the target DCFROR of 10%, which is because site-wide HI and DH delivery utilize hot process streams within the same temperature range. Moreover, streams that are particularly suitable for both site-wide HI and DH delivery (due to their high heat contents and high temperatures) are assumed to be used for internal integration and are not available for DH. Therefore, more process streams are required to achieve the same DH capacities relative to the conditions without integration, which increases the investment costs.

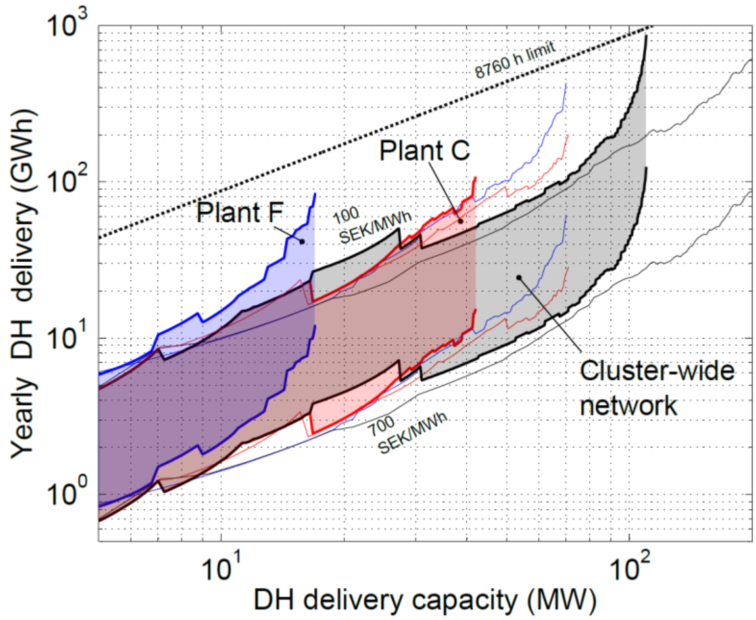

Figure 42 DH delivery capacity versus the yearly DH delivery needed to reach a DCFROR of 10% at different DH prices for different plants (color) and the entire chemical cluster (black) assuming site-wide HI (which saves 50% of the current fuel used for hot utility demand). The thin lines represent DH delivery assuming no HI.

6 Conclusions and discussion of the main findings

The transformation of existing industrial production sites and processes toward more energy-efficient production and less fossil feedstock dependence must be conducted in a systematic and efficient manner. The work presented herein describes how a set of process integration methods can be used to obtain a holistic assessment of the energy system in an industrial cluster and, based on this assessment, identify ways to achieve increased EE and transition from fossil toward renewable feedstocks.

Pinch technology is used to target minimum heating and cooling demands of single process plants and identify specific measures to decrease the use of hot and cold plant utilities. The results from pinch analysis studies of individual processes provide guidance for efficiency improvement investments at one site and can be used as input for site-wide HI studies using TSA tools. The HI target can be largely increased if the system boundaries are expanded from single to total site integration.

Based on a mapping of the energy systems within the existing cluster, suitable biorefinery concepts and feasible methods to deliver excess process heat for external use, e.g., as DH, can be identified following the procedures described in this work.

<u>The general conclusions</u> from the presented work are as follows:

- Investments in EE at one site are often not feasible because they result in an excess of low-quality utility at the specific site. Clusters often consist of several plants with different plant owners. Plant operators typically have no detailed knowledge of the energy and material flows in their neighboring plants. The approach used in this work is a method to make all plant operators aware of common HI opportunities and their associated efficiency gains. By considering the entire cluster, it is possible to determine a method for improving the redistribution of recovered utility, which leads to an overall increase in EE for the entire cluster.
- The step-wise design approach for HI systems enables a roadmap of HI investments to be created that begins with less complex systems (recovering a small amount of the total heat recovery target) and moves toward strongly integrated, complex systems (recovering a larger amount of heat). Because collaboration among companies is not always simple, beginning with a simple system that can be expanded when proven successful can assist in initiating site-wide HI opportunities.

- Exergy composite curves can be used for rapidly identifying and evaluating the consequences of local measures for decreasing shaft power in a compression refrigeration system. The methodology can be applied to determine optimal utility loads and evaluate the effects of demand changes between different utility levels on the refrigeration shaft power consumption.

- Combining total site profiles and exergy analysis is shown to be a useful method of determining targets for recovering cooling capacity at a site-wide level and simultaneously evaluating the potential for refrigeration shaft power savings based on these measures. The methodology can be applied to all industries that operate refrigeration systems to target shaft power savings via the recovery of cooling capacity from cold process streams, e.g., cryogenic distillation reboilers and storage tanks.

- There are many different biorefinery concepts available. Meanwhile, biogenic feedstock is limited and expensive. Biorefineries differ strongly with respect to their heating, cooling and electricity demands. The suggested holistic approach can be used to compare the integration of different biorefinery concepts with an existing industrial cluster and to identify the most suitable biorefinery from a process integration perspective. The approach also enables the identification of utility systems configurations that maximize opportunities for HI within the biorefinery and within the encompassing industrial cluster.

- The suggested approach can be used to investigate the integration of advanced biorefinery concepts with a site-wide utility network that can lead to several advantages, such as economies of scale, because a biorefinery delivering feedstock to several plants can have a larger production volume. Also sharing large investments can decrease the risks involved in implementing new technology.

- In addition to HI, other potential synergies between the existing plants can be identified using the suggested approach. Excess capacity in the existing cluster (e.g., in boilers or refrigeration systems) can be identified. Moreover, possible uses for this capacity within the new process can be investigated. Alternatively, excess heat from the biorefinery can instead be used in the cluster, thereby avoiding expensive boiler capacity addition.

- Regardless of the level of HI, there is always some excess heat rejected from the processes. If available, DH systems can act as sinks for excess process heat. As highlighted in this work, the current and future status of HI within an industrial cluster strongly affects the amount of DH available, its costs and CO_2 emissions. The procedure applied in this work can be used to target economically feasible DH delivery from industrial clusters.

- Targeting internal (site-wide) HI should be conducted simultaneously with targeting alternative options for utilizing excess process heat, as both strongly influence each other regarding economic feasibility and CO_2 emissions consequences.

This analysis is possible if a holistic approach is applied where energy and material flows throughout an entire site are considered; this knowledge can be used to integrate the most suitable biorefinery process to minimize resource consumption and costs and export excess process heat, which will further increase the EE of the cluster.

During this research project, other factors that are important for collaboration across company borders (beyond the technical feasibility) were identified. One of the challenges of using the proposed methodology is to investigate long-term development plans for such clusters. Each company within a cluster has more or less far-reaching plans for future development of its own plant; such plans should be included in the TSA effort. However, data collection is a complex process, especially if there are uncertainties in the data and potential future plant developments are not clearly defined. Other factors include the ownership structure of the companies, the design of business models that promote collaboration across company borders, and policies supporting the implementation of EE measures and renewable materials.

7 Discussion of sources of error and uncertainty

Engineering assumptions and simplifications are necessary to limit the complexity and the scope of this work. The use of certain assumptions and simplifications is explained herein. The consequences on the methodology developed and the results obtained in this work are also discussed.

The process stream data used in this work are based on the average steady-state operation of the processes within the cluster. Heating/cooling demand fluctuations and temperature changes might occur depending on several factors, including the production rate or product mix. It is also assumed that all processes run simultaneously at the given capacity. These uncertainties are considered acceptable in the targeting phase, which is the aim of the methodology presented in this work. Nevertheless, more detailed investigations must be performed when designing the suggested HI measures to provide suitable back-up heating and cooling capacity for guaranteeing stable process operations at all times.

The processes included in the analysis might still be in the commissioning phase; therefore, process design data must be used, which do not necessarily reflect true operation conditions of the processes. Whether the design data reflect real process operating conditions must be considered when concrete heat recovery systems are designed.

Considering certain process plants, streams or portions of individual processes with less detail ("black box") when conducting TSA increases the uncertainty because some HI opportunities may not be identified. Data collection is critical and must be conducted with care to not disregard major improvements prior the analysis.

Considering the design procedure developed in this work, there is no guarantee that a global optimum heat recovery system can be identified. This is not the main goal of the procedure. Instead, the objective of this work is to identify feasible, flexible and simple systems that can be expanded from small systems to systems achieving the MER.

Based on the exergy targeting methodology presented herein, it is not directly possible to allocate the actual shaft power savings between the ethylene and propylene refrigeration cycles because these two systems are interconnected. Therefore, an evaluation of the actual potential for steam and electricity savings must be performed on a case-to-case basis and cannot be generalized.

In the case study of the biorefinery investigated in this work, the process design and data used for process simulation are based on literature data because no large-scale unit of this type has been constructed to date. Therefore, the stream data obtained for EE targeting are subject to uncertainty that may also affect the results presented for the overall efficiency of ethylene production via the suggested processes.

In this work, a single cluster and one biorefinery concept were considered to illustrate the framework methodology. To obtain more general and comparable results, the framework methodology should be applied to other clusters; different biorefineries should be investigated to identify the most suitable scenario.

When targeting DH delivery from the cluster, it is assumed that piping costs are proportional to the heat exchanger purchasing costs. Therefore, it is implied that the final arrangements of the heat exchanger units in the different solutions are equally complex. However, this assumption is not necessarily the case for all plant types and sizes, which introduces additional uncertainty in the results because piping costs of a large network are expected to increase exponentially when the maximum production target is pursued.

Another uncertainty in the proposed targeting procedure is that the vertical heat transfer approach overestimates the number of heat exchanger units, while a smaller heat transfer area per unit is obtained. This error occurs because process streams typically belong to more than one enthalpy interval; therefore, one heat exchanger unit could be constructed to offset a larger load than a single enthalpy interval found in the composite curve diagram. As a result, the investment in heat exchangers is overestimated because the fixed cost of equipment per unit of heat becomes large for low heat transfer areas. The design of an optimal heat exchanger network should apply more advanced techniques than those used herein.

When allocating CO_2 emissions to industrial excess heat the maximum heat recovery target for TSHI is assumed as “fuel demand avoidable by HI”. Whether or not this assumption is realistic has to be discussed on a case-to-case basis. The case study presented in this work is a first step towards a more detailed study on the utilization of excess process heat from the cluster in Stenungsund.

8 Future research

Until now, the framework presented assumes stable, simultaneous operations of all participating plants. To obtain a more realistic heat recovery target and to determine the necessary utility generation capacity in case of temporal variations in heat recovery, heat demand variations throughout the cluster should be included in future analyses.

The framework methodology presented in this work should be applied to other industrial clusters/complexes to improve the general applicability and further refine the methodology.

To identify suitable bio-based alternatives to current fossil-based products and production processes, different biorefinery processes should be investigated for integration with the chemical cluster in Stenungsund. As shown in Figure 15, there are several other production pathways for ethylene (olefins) production using biomass as feedstock. Moreover, increased end-product recycling and a potential method for integrating such recycling within the cluster should be investigated to improve the resource efficiency of chemical production.

In future work, the framework methodology should be extended by applying a life cycle based approach to optimise emissions and resource consumption when aiming for HI, renewable feedstock integration and increased external utilisation of excess process heat. For HI investments, this means that emissions from construction of necessary infrastructure should be taken into account. For renewable feedstock integration (indirect) land-use change, emissions from biomass production and product use should be accounted for. When investigating export of excess process heat to a district heating network, it is necessary to further refine the methodology for allocating CO_2 emissions from industrial excess heat used for district heating. Alternative uses of excess process heat should be investigated, such as electricity generation from low temperature heat or biomass drying, since district heating is not always a viable option. The influence of different aspects such as heat demand fluctuations and future internal heat demand/supply changes due to site modifications should also be considered in future investigations.

This aforementioned issue can be addressed by developing more sophisticated methods to address long term process investment strategies and their effects on future process changes, plant retirement or site expansion in the data collection phase to obtain a representative set of data on which HI and biorefinery integration studies can be based.

The approached applied in this work is advantageous because it facilitates interaction with stakeholders, which is a critical factor in achieving the actual implementation of possible measures. However, there is also a need to further develop generic optimization tools that are able to scan many possible options once suitable superstructures are defined. Also a more detailed investigation of non-energy benefits of site-wide HI, such as increased production capacity without the need for new boilers should be conducted.

Nomenclature and Abbreviations

Abbreviations

CC	Composite Curves
CEPCI	Chemical Engineering Plant Cost Index
CF_{avg}	Average Annual Cash Flow
$Cost_{Inv}$	Total Investment Cost
CHP	Combined Heat and Power
C2	Ethylene (Refrigeration System)
C3	Propylene (Refrigeration System)
DCFROR	Discounted Cash Flow Rate Of Return
DH	District Heating
EE	Energy Efficiency
EU	European Union
IEA	International Energy Agency
GCC	Grand Composite Curve
GHG	GreenHouse Gas
HI	Heat Integration
HW	Hot Water
HX	Heat eXchanger
MER	Minimum Energy Requirement
NPV	Net Present Value

PBP	Simple Pay-Back Period
SEK	Swedish Kronor
TSA	Total Site Analysis
TSC	Total Site Composites
TSP	Total Site Profiles

Symbols

A	Area [m^2]
D	Diameter [m]
ΔEx_p	Exergy Flow Rate Difference in the Process [W]
ΔEx_r	Exergy Flow Rate Difference in the Refrigeration System [W]
$\Delta Ex_{r,mod}$	Exergy Flow Rate Difference in the Modified Refrigeration System [W]
ΔEx_u	Exergy Flow Rate Difference in the Utility System [W]
ΔH	Enthalpy Change [W]
P	Actual Shaft power [W]
Q	Heat Load [W]
ΔT_m	Logarithmic Mean Temperature Difference [K]
ΔT_{min}	Minimum Temperature Difference [K]
T_{ref}	Reference Temperature [°C]
T_{start}	Starting Temperature [°C]
T_{target}	Target Temperature [°C]
U	Overall Heat Transfer Coefficient [kW/m^{2}K]
$\dot{W}_{el}$	Electric Power [W]
η_{ex}	Exergetic Efficiency [-]
$\eta_{overall}$	Overall Energy Efficiency [-]

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