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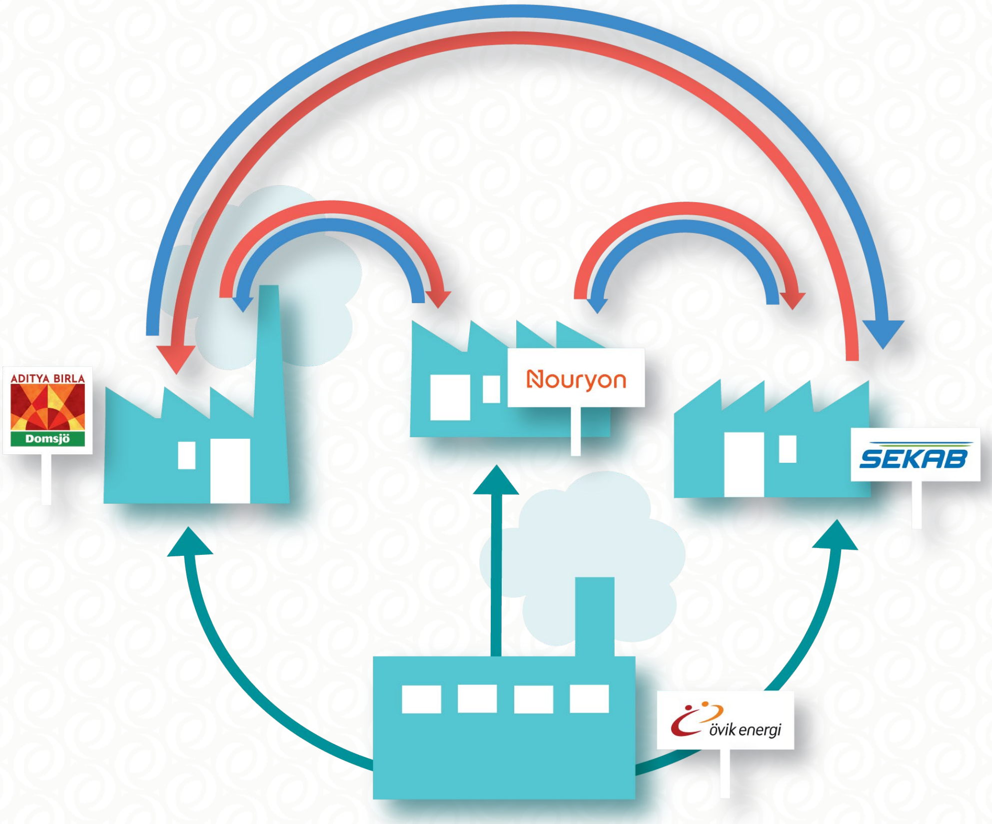

Energy Integration of Domsjö Biorefinery Cluster

Based on a total-site analysis, two energy integration alternatives and one additional energy system change are presented. The practical heat recovery potential is about 15 MW for the total site, of which about 10 MW are located within one of the industries. Alternatively, about 7 MW of utility steam could be replaced by district heating. These measures are estimated to have good economic performance. Furthermore, steam production capacity is released, which enables increased production from the site without investments in new steam boilers.

Sofia Klugman, Simon Harvey (Energy Technology, Chalmers), Johanna Nilsson, Roman Hackl, Kristina Holmgren

In cooperation with Chalmers University of Technology

Author: Sofia Klugman, Simon Harvey (Energy Technology, Chalmers), Johanna Nilsson, Roman Hackl, Kristina Holmgren
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IVL Swedish Environmental Research Institute Ltd.
P.O Box 210 60, S-100 31 Stockholm, Sweden
Phone +46-(0)10-7886500 // www.ivl.se

Preface

Pinch analysis is an efficient method for investigating the energy use at industrial sites and finding the potential for heat recovery and optimal utility use. In this study, a bio refinery cluster consisting of one wood pulp production facility, two bio-chemical facilities and one energy facility are analysed with pinch analysis from a total site perspective. This report is the final report for Work Package 2 in a project named *Analysis and evaluation of energy integration in bio refinery clusters from a system perspective*, which also includes energy system modelling of an industrial site in Sundsvall. Further analysis regarding economic performance, reduction of carbon dioxide emissions as well as analysis of introduction of new biorefinery processes will be performed during year 2019.

The study was funded by the Swedish Energy Agency, Formas and the Swedish Environmental Protection Agency via the SIVL foundation together with the Domsjö site industries involved in the task: Domsjö Fabriker, Nouryon, SEKAB and Övik Energi.

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Summary

This report presents the results of a case study performed at the Domsjö biorefinery cluster in Örnsköldsvik with the aim to identify energy savings opportunities through heat recovery and changes to the site utility mix. The biorefinery cluster in Domsjö includes plants run by Nouryon (former Akzo Nobel Functional Chemicals), Domsjö Fabriker (Aditya Birla), SEKAB Biofuels & Chemicals AB and Övik Energi.

The initial step was to conduct an inventory of all process streams heated or cooled by hot or cold utility. Heat exchangers which exchange heat and cold between two internal process media are not included in the study, but only heat exchangers that use steam or water to heat or cool. Furthermore, all heat sources and sinks were classified into three categories, according to their suitability for modifications in order to achieve heat savings. The main focus of this report is on heat sources and sinks for which such modifications are expected to incur moderate to medium level costs. Within the cluster, there are 22 such heat sources currently cooled by cooling water (24 MW), and 25 heat sinks heated by 22 bar(g) steam (3 MW) or 7 bar(g) steam (53 MW).

After that, the mix of hot utility used to provide heat at the site was analysed. The analysis showed that the energy use within the Domsjö biorefinery cluster has significant potential for improvements. In many locations, utility is supplied at an unnecessarily high temperature level. 22 bar(g) is only necessary in one heater with a load of 100 kW. The demand for 7 bar(g) steam could be reduced even further if an additional utility level (e.g. 3 bar(g)) was introduced. However, most such changes would require modifying or replacing the existing steam turbine unit, and such modifications were out of the scope of this study. The alternative to replace 7 bar(g) steam with district heating showed to have the potential to replace at least 7 MW steam. This alternative was selected for further economic and environmental analysis.

The results for the total site analysis was that the maximum heat recovery potential is 15 MW. A circulating hot water loop operating between 40 °C and 120 °C could be implemented to achieve this heat recovery potential. The heat recovery potential accounts to approximately 10 % of the total steam use at the site. The remaining cold demand would be 8.5 MW and the remaining heat demand 41 MW.

It was found that a great part of the total potential energy saving can be achieved by measures at Domsjö Fabriker, 10 MW of 15 MW. In this case as well, a circulating hot water loop operating between 40 °C and 120 °C could be implemented to achieve this heat recovery potential. Hence the case with Domsjö Fabriker as a separate plant were chosen for further analysed. Internal recovery at Nouryon and SEKAB contributes by minor heat recovery potentials and were therefore not analysed further.

The result of heat integration of each of the separate plant sum up to a total heat recovery potential of 11 MW. Hence, the heat integration potential is larger and thus the minimum heating and cooling demand lower if heat integration between the plants is allowed. The heat integration potential increases by 4 MW if site-wide heat exchange is allowed.

A total of three alternatives where selected for further economic and environmental performance analysis:

1. Heat recovery within the total Domsjö biorefinery cluster (15 MW)
2. Heat recovery within the separate plant Domsjö Fabriker (10 MW)

3. Replacement of 7 MW use of 7 bar steam with district heating (involves Övik Energi, Domsjö Fabriker and Nouryon)

Preliminary economic estimations show that heat integration within Domsjö Fabriker only has a shorter payback period than site-wide heat integration, 5 years and 10 years respectively. The main reason for this is that the additional 5 MW of site-wide heat recovery requires a substantially higher number of modifications to the heating and cooling utility exchangers. No further analysis was conducted to identify the techno-economic optimum levels of heat exchange in both cases.

From an energy systems perspective, the heat integration alternatives are double sided. Use of wood fuels is reduced, which could be used to substitute fossil fuels elsewhere if wood fuels are a limited resource. However, renewable electricity generation is decreased, requiring additional generation elsewhere.

To summarise, all the three energy alternatives which have been analysed achieve good economic performance. From a climate-change perspective, substitution of 7 bar(g) steam with district heating is particularly attractive since this leads to increased electricity generation from renewable resources. In addition, all cases considered release up to 15 MW of steam production capacity. This could enable increased production without requiring investments in new steam boilers. Alternatively, this capacity could be used to completely (or partially) offset the steam requirements of a new process plant at the Domsjö site. Also, an opportunity could be to produce more lignin for sale instead of burning the sulfate liquor in the recovery boilers. To use the released steam capacity to a new process plant is further elaborated in the next phase of this study.

Sammanfattning

I denna rapport presenteras resultaten av en fallstudie utförd vid Domsjö bioraffinaderikluster i Örnsköldsvik med syfte att identifiera energibesparingsmöjligheter genom värmeåtervinning och ändringar av användningen av tryck och temperatur på servicemedia. Bioraffinaderiklustret i Domsjö omfattar anläggningar som drivs av Nouryon (tidigare Akzo Nobel Functional Chemicals), Domsjö Fabriker (Aditya Birla), SEKAB Biofuels & Chemicals AB och Övik Energi.

Det första steget var att göra en inventering av alla processflöden som värms eller kyls. De procesströmmar vars värme- och kylbehov uppfylldes genom intern värmeväxling beaktades inte, dvs denna studie undersökte inte potentiella energibesparingar som skulle kunna uppnås genom att göra ändringar i värmeväxlarnätverket hos de befintliga anläggningarna. Vidare klassificerades alla värmekällor och -sänkor i tre kategorier efter deras lämplighet för modifieringar för att uppnå värmebesparingar. Huvudfokusen i denna rapport handlar om värmekällor och -sänkor för vilka sådana förändringar förväntas leda till måttliga till medelstora kostnader. Inom klustret finns det 22 sådana värmekällor som för närvarande kyls av kylvatten (24 MW) och 25 sådana värmesänkor som upphettas med 22 bar (g) (3 MW) eller 7 bar (g) ånga (53 MW).

Därefter analyserades blandningen av ånga som användes för uppvärmning. Analysen visade att energianvändningen inom Domsjö bioraffinaderikluster har en betydande potential för förbättringar. På många ställen levereras ånga vid en onödigt hög temperaturnivå. 22 bar (g) som används hos Nouryon är endast nödvändig i en värmare med en effekt på 100 kW. Efterfrågan på 7 bar (g)-ånga skulle kunna reduceras vidare om en ytterligare användningsnivå (t ex 3 bar (g)) infördes. De flesta sådana förändringar skulle emellertid kräva modifiering eller ersättning av den befintliga ångturbinen, och sådana modifieringar är utanför ramen för denna studie. Ett alternativ är att ersätta 7 MW 7 bar (g)-ånga med fjärrvärme. Detta alternativ valdes ut för ekonomisk och miljömässig fördjupning.

Två alternativ för förbättrad värmeintegration studerades, I) värmeintegreringen av var och en av de separata anläggningarna inom Domsjö-klustret utan att tillåta värmeväxling mellan företag och II) värmeintegration över hela klustret, där överskottsvärme från heta processflöden överförs till en ny värme/kylkrets och används för att täcka det sammanlagda värmeunderskottet på hela anläggningen.

Vid analys av värmeintegration i separata anläggningar antogs direkt värmeöverföring mellan processflöden med en minsta temperaturskillnad på 20 K. Den totala värmeåtervinningspotentialen när de tre anläggningarnas potential adderas är 11 MW, varav 10 MW ligger inom Domsjö Fabriker.

Även för det fall där en indirekt värmeväxling inom hela området tillåts genom en ny värme/kylkrets antogs en minsta temperaturskillnad på 20 K. I detta fall är den uppskattade potentialen för värmeåtervinning 15 MW. Därmed ökar värmeintegreringspotentialen med 4 MW om värmeväxling över företagsgränser är tillåten. Värmeintegreringspotentialen utgör ungefär 10 % av den totala ånganvändningen på området.

De tre alternativ som valdes för fördjupad ekonomisk och miljömässig studie var:

1. Värmeintegration för hela bioraffinaderiklustret (15 MW)
2. Värmeintegration inom Domsjö fabriker (10 MW)
3. Ersätta ånga med fjärrvärme (7 MW)

Preliminära ekonomiska uppskattningar visar att värmeintegrationen inom endast Domsjö Fabriker har en kortare återbetalningsperiod än helhetsintegrerad värmeintegration, 5 år respektive 10 år. Huvudskälet till detta är att den extra värmeåtervinningen på 5 MW kräver ett väsentligt högre antal modifieringar av värmeväxlare. Ingen ytterligare analys utfördes för att identifiera de tekniskt ekonomiska optimala nivåerna av värmeväxling i båda fallen.

Ur ett bredare energisystemperspektiv uppvisar de två värmeintegrationsalternativen olika för- och nackdelar. Användning av träbränslen reduceras, vilket medför att de kan användas för att ersätta fossila bränslen på annat håll om träbränslen är en begränsad resurs. Förnybar elproduktion minskar emellertid, vilket kräver ytterligare elproduktion på annat håll.

Sammanfattningsvis har alla de tre energialternativen som har analyserats goda ekonomiska förutsättningar. Ur ett klimatperspektiv är ersättning av 7 bar (g) ånga med fjärrvärme särskilt attraktiv eftersom det leder till ökad elproduktion från förnybara resurser. De studerade alternativen innebär att upp till 15 MW ångkapacitet frigörs. Detta skulle kunna möjliggöra ökad produktion utan att det krävs investeringar i nya ångpannor. Alternativt kan denna kapacitet användas till att helt eller delvis kompensera ångbehovet till en ny bioraffinaderiprocess på Domsjö-området. Ytterligare ett alternativ vore att producera mer lignin istället för att bränna all sulfitlut i sodapannorna.

1 Introduction

1.1 Background

Industry is one of the major consumers of energy worldwide. In Sweden industrial energy use represents about 40 % of the total final energy use, see Figure 1[1].

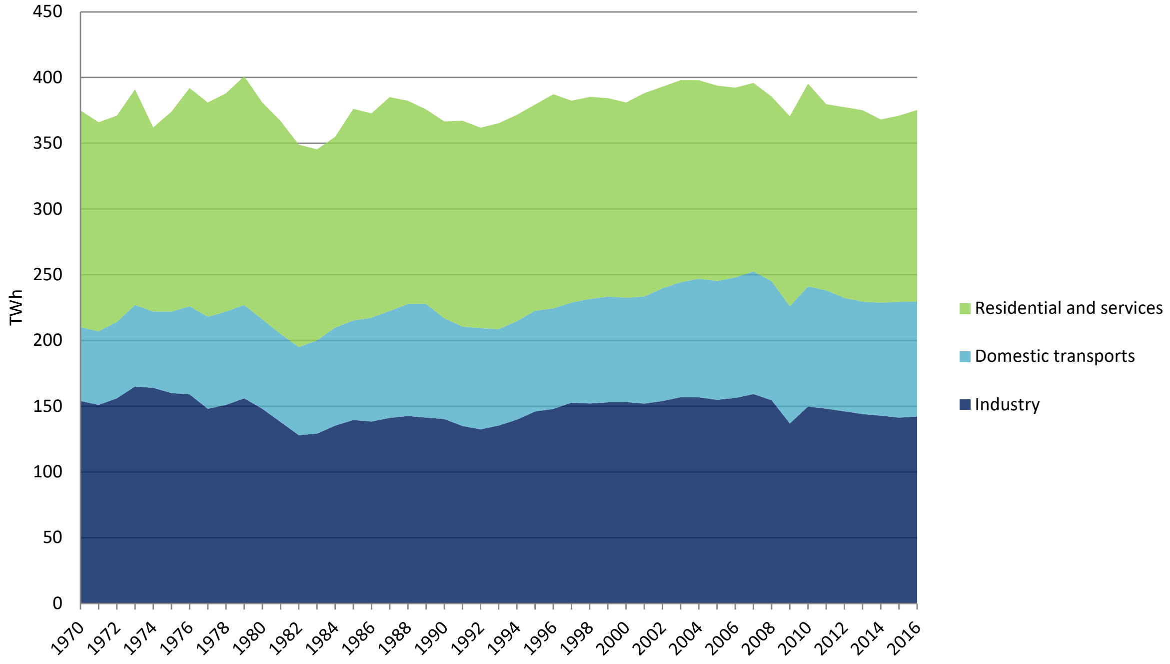

Figure 1 Total final energy use, by sector, in Sweden from 1970 to 2016 [TWh]. (Swedish Energy Agency, 2018)

Furthermore, the breakdown by sector of energy use in the industry is rather unique for Sweden compared to other countries, given the dominating position of the forest industry sector, see Figure 2. More than half of the final energy use in the industrial sector is allocated in the industries of pulp and paper together with wood production.

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[1] Swedish Energy Agency, 2018. Energy in Sweden, facts and figures 2018 (Excel document). http://www.energimyndigheten.se/en/facts-and-figures/statistics/

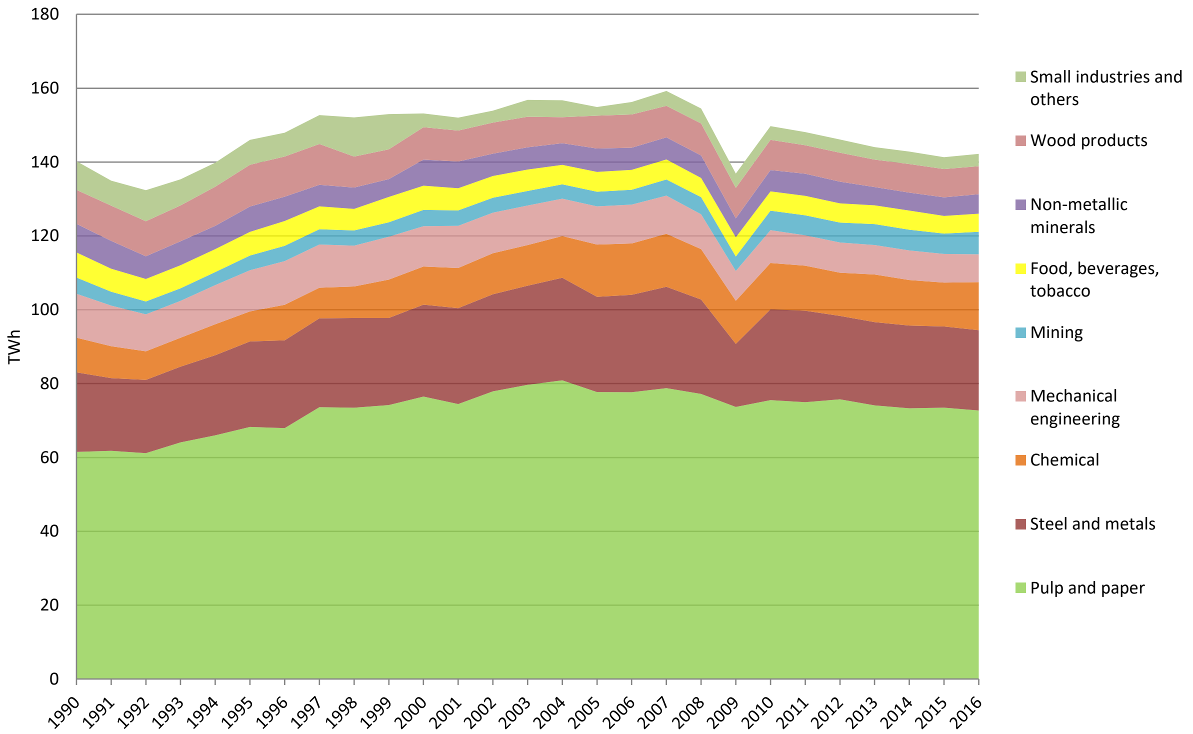


Figure 2 Final energy use in the industrial sector, by industry, in Sweden from year 1990 to 2016 [TWh]. (Swedish Energy Agency, 2018)

In the industrial sector, energy is used for e.g. heating, cooling, refrigeration, air conditioning, processing, assembly and lighting. Industrial energy efficiency improvement is often mentioned as an important measure to decrease among others environmental impacts such as natural resource consumption and CO_2 emissions, while at the same time achieving economic and energy security objectives. Furthermore, industrial energy efficiency plays an important role in planning future energy systems. Different, proven methods to identify and realize energy efficiency targets exist and are constantly developed further.

1.2 Aim and Scope

The biorefinery cluster in Domsjö, Örnsköldsvik, has been targeted in order to evaluate the potential for energy cooperation between several companies at the same industrial site.

The objective of this study is to perform a total site analysis based on pinch analysis in order to quantify the site-wide potential for increased energy efficiency at the biorefinery cluster in Domsjö. The first step of the method was identifying process streams that are heated or cooled with utility in order to find possibilities for increased integration between utility systems of the plants. Furthermore, additional energy system changes were studied based on a helicopter view of the biorefinery cluster.

The study also aims to suggest practical ways to achieve a more integrated utility system in order to increase energy savings, based on the results of the total site analysis. Since the current utility system includes steam turbine cogeneration, an important goal of the project is to quantify the impact of possible changes to the total site utility system on the cogeneration potential.

The study also aims at increasing knowledge about the biorefinery cluster, which can be used as a basis for further studies.

The case was analyzed using tools in the form of total site analysis, scenarios and energy- and carbon dioxide balance calculations in a life-cycle perspective. Strengths, weaknesses and general applicability of the tools were discussed and communicated broadly to forest industry and related stakeholders.

2 Process and utility systems description

The biorefinery cluster in Domsjö includes the companies Nouryon (formerly Akzo Nobel Functional Chemicals), Domsjö Fabriker (Aditya Birla), SEKAB Biofuels & Chemicals AB and Övik Energi. In the following subsection the main processes and major material- and energy flows in and out from the cluster as well as within the cluster are described. The material- and energy flows in and out from the biorefinery cluster are shown in Figure 3. The material- and energy flows between the companies are shown in Figure 4.

The overall steam system in the biorefinery cluster is presented in Figure 5. The units in the steam system that are associated with the greatest possibilities to reduce costs or increase incomes within the energy system are marked with red rings. A list of both hot and cold utilities used in the biorefinery cluster is found in Appendix A.

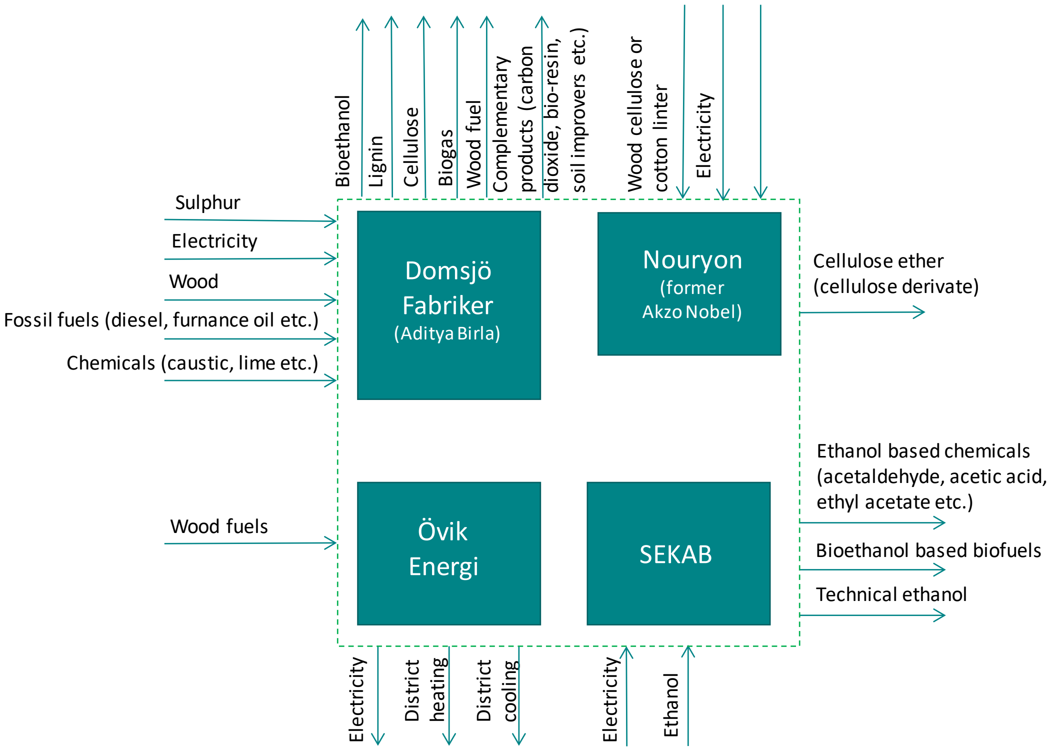


Figure 3 Major material- and energy flows in and out from the Domsjö biorefinery cluster.

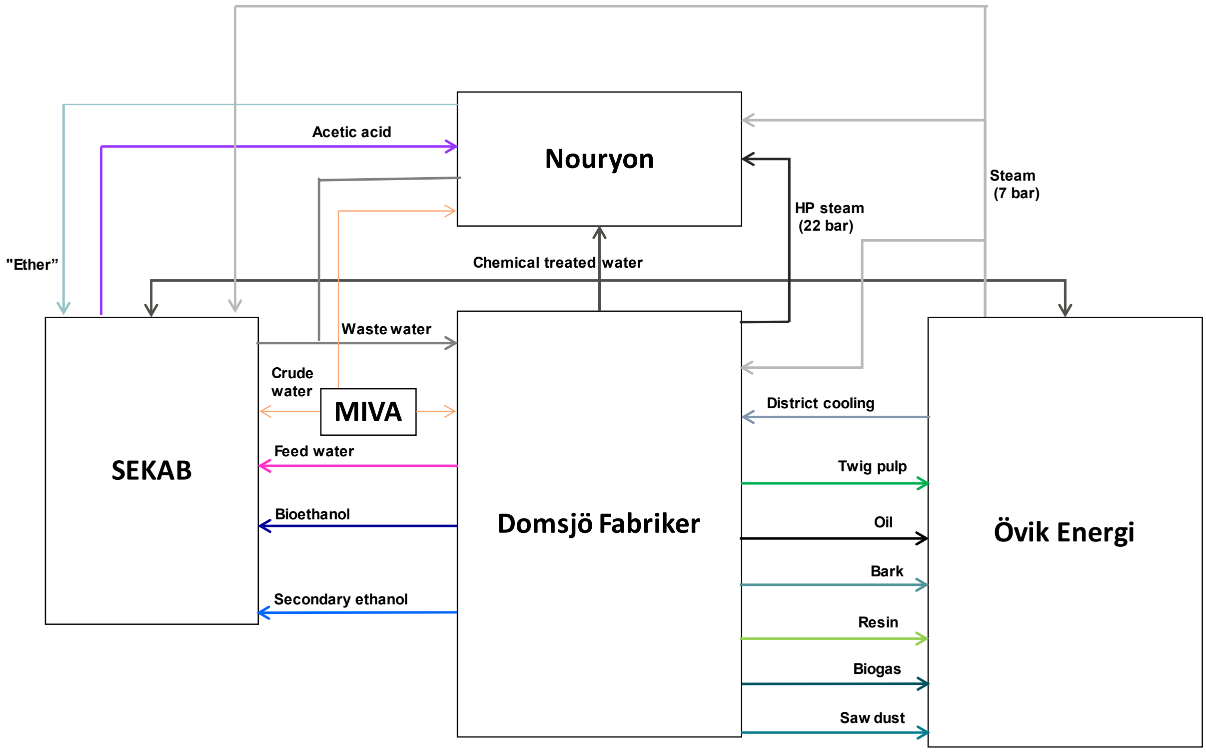


Figure 4 Major material- and energy flows in the Domsjö biorefinery cluster.

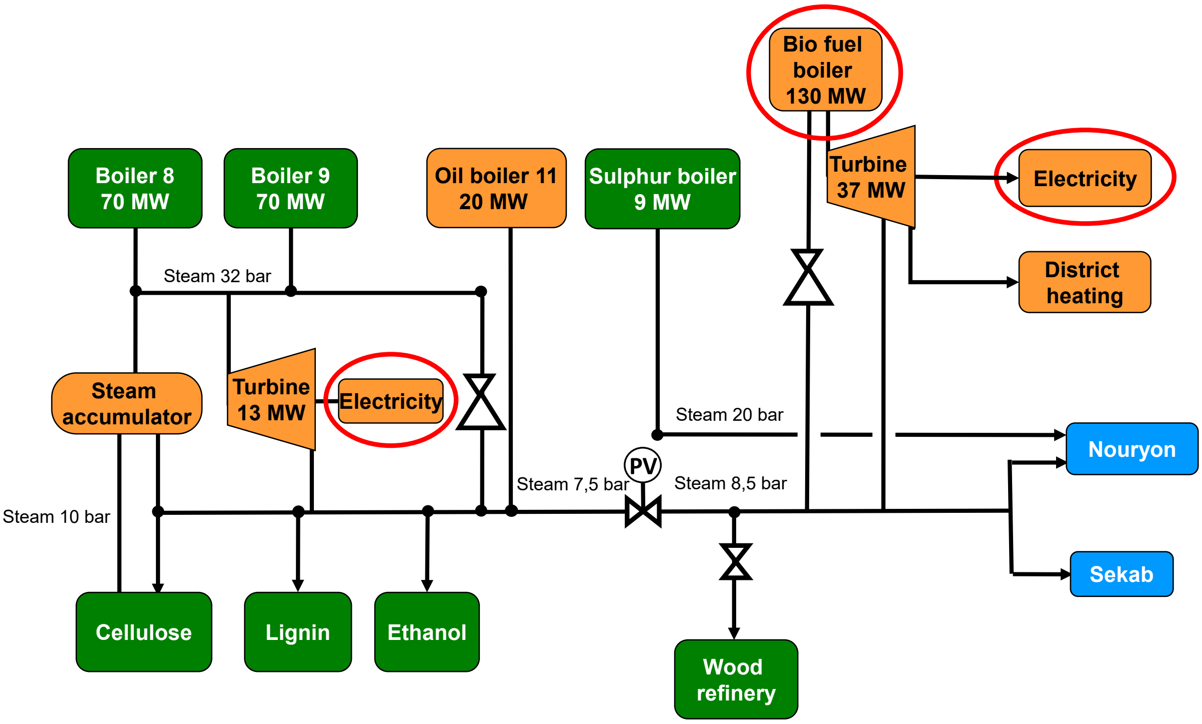


Figure 5 The overall steam system in the Domsjö biorefinery cluster. Green = Owned by Domsjö Fabriker, Orange = Owned by Övik Energi. The locations of the most promising opportunities to reduce costs or increase incomes within the energy system are marked with red rings.

2.1 Nouryon

2.1.1 Products and processes

Nouryon (formerly Akzo Nobel Functional Chemicals) at the Domsjö site produces a cellulose derivative (cellulose ether) which is mainly used as thickener in water-based paint and different types of building products (plaster and filler). Nouryon uses wood cellulose and cotton linter as raw material in the process. Pure cellulose is insoluble in water, but the process produces a water-soluble product.

The plant consists of three production lines with a total of five synthesis reactors and three lines for downstream treatment of the product. The cellulose used by Nouryon is bought from suppliers outside the Domsjö biorefinery cluster.

The production of cellulose derivate can be divided in the following process stages:

1. Cellulose grinding,
2. Synthesis,
3. Washing and dewatering,
4. Drying,
5. Grinding/screening,
6. Blending and packaging.

The synthesis takes place in reactors that are run on a batch-wise basis. In the synthesis, the cellulose reacts with sodium hydroxide, ethylene oxide and ethyl chloride and/or methyl chloride. The other stages (washing, dewatering, drying and grinding) are run on a continuous basis. Depending on the desired quality of the product, different chemicals can be added to the raw material in the synthesis.

The gases from reactors and de-aeration of tanks with ethyl chloride are sent to a recovery unit where primarily the ethyl chloride can be recovered and reused in the process. The gases which are not condensed are sent to a RTO (Regenerative Thermal Oxidation)-plant where they are oxidized to CO_2 and water before being discharged to the atmosphere.

Nouryon does not have its own plant for purification of the industrial waste water. The cleaning of the waste water is performed in the Domsjö Fabriker plant.

2.1.2 Utility System

The hot utilities at Nouryon include steam at pressure levels 22 bar (g) and 7 bar (g) as well as glycol water and hot water.

The cold utility is river water with a temperature varying from +0.2 °C in winter to +20 °C in summer months.

2.2 Domsjö Fabriker (Aditya Birla)

2.2.1 Products and processes

Domsjö Fabriker AB (Aditya Birla) is a sulfite pulp mill that converts softwood into the main products cellulose, bioethanol and lignin. The mill also produces complementary products, such as carbon dioxide, biogas, bio-resin and soil improvers.

The wood is debarked, chipped and screened, and then fed together with cooking chemicals into the digesters. The bark and saw dust are sold as fuel to Övik Energy. After cooking the cellulose is washed and screened and the resin is extracted. Subsequently, it is bleached with hydrogen peroxide in the closed-loop bleach plant. The bleached cellulose is dried, sheeted and packed in bales.

During the cooking process hemicellulose and lignin are dissolved. The hemicellulose is then fermented and distilled into bioethanol. In the fermentation process, both bioethanol and carbon dioxide are produced. Carbon dioxide is sold to AGA and used as feedstock for production of carbonic acid. The lignin is processed in the cooking process before being dried to a powder and packed.

In the recovery boiler cooking chemicals are recycled and energy in the form of steam is produced which is used in the all the other processes.

The main markets for cellulose are Europe, Indonesia, India and China. The cellulose can be used in viscose for textiles and hygiene products, tablets for pharmaceuticals, thickener and cellophane. The lignin from the process is shipped to customers in over 60 countries around the world. The lignin is used in concrete additives, binders in the mineral and food industries and additives for geotechnical drilling. The bioethanol is delivered to SEKAB for on-site production of green chemicals. The bioethanol can be used as cooling agent for heat pumps, in raw material for chemicals, paint additive, biofuel and screen washer fluid.

The production capacity and the production level year 2016 of Domsjö Fabriker are shown in Table 2.

Table 1 Production capacity and production in Domsjö Fabriker year 2016

Product	Production capacity [ton]	Production year 2016 [ton]
Cellulose	230 000	202 556
Lignin	120 000	88 143
Bioethanol	20 000	17 395

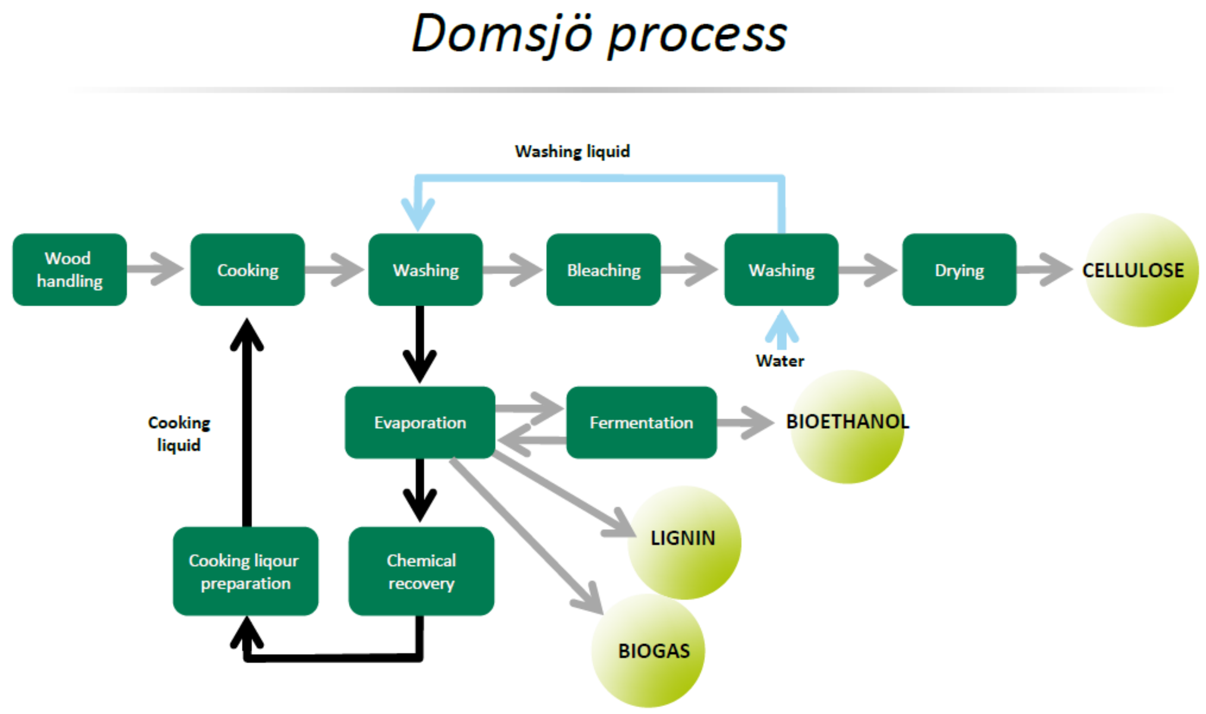


Figure 6 Domsjö sulfite pulp process. (Source: Domsjö Fabriker)

In year 2016, the total amount of steam used in the processes at Domsjö Fabriker was approximately 1,000 GWh, which correspond to approximately 140 MW steam use. Of this, purchased steam from Övik Energi was 176 GWh, while the vast part origined from the recovery boilers. Electricity use during the year amounted to 219 GWh. Electricity production in the turbine at the plant of Domsjö Fabriker was 34 GWh. In the biological treatment plant, bacteria break down organic materials into e.g. biogas. The facility is one of the largest producers of biogas in Sweden. In year 2016, Domsjö Fabriker produced approximately 11 million Nm^3 (normal cubic metres) of biogas (approximately 78 GWh). 80 % of the biogas origins from Domsjö Fabriker, 16 % from Nouryon, and 4 % from SEKAB. The biogas is recovered and used as energy source for lignin drying and generation of electricity and steam.

In year 2016, the energy consumption was 6.7 MWh per tonne of pulp produced. Around 96 % of the energy consumption originates from renewable fuels.

Table 2 Fuel consumption by type

Fuel Consumption by type	**2016**
Purchased fuels	
Heavy fuel oil and Light fuel oil [GWh]	15
Sulfur [GWh]	40
Own-produced fuels	
Biogas [GWh]	78
Brown Liquor Solids [GWh]	1 050
Total [GWh]	1 183

The main raw materials are wood and sulfur. Table 4 below shows the quantity of material used by type for production of specialty cellulose, lignin and bioethanol.

Table 3 Raw material used at the mill year 2016

Raw Material	2016
Wood [M m^3sub]	1 272 500
Sulfur [tons]	7
Sulfur dioxide [tons]	20
Sodium hydroxide [tons]	31
Hydrogen peroxide [tons]	16

2.2.2 Utility System

As described in Figure 5, the steam pressure levels at Domsjö are 32, 20, 10, 7, 3 bar (g) and 0.1 bar (g). Steam of 32 bar (g) is fed into the turbine. The other steam levels are used in the production processes. However, the steam of 20 bar (g) is delivered to Nouryon.

The steam is produced in the two recovery boilers (70 MW each) and the Sulfur boiler (9 MW) at the Domsjö site, and in a biomass-fired boiler at Övik Energi's neighbouring site. The recovery boilers are fed with waste liquors and heavy fuel oil whereas the biomass boiler is fed with bark and saw dust from Domsjö Fabriker and additional fuels (forest residues/wood chips and peat).

The Sulfur boiler is fed with Sulfur (imported to the cluster) and waste chemicals from the recovery boilers.

The Sulfur boiler produces steam at 20 bar (g) and most of it is sold to Nouryon whereas a smaller fraction is reduced to 7 bar (g) and is used in the 7 bar utility system.

The two recovery boilers produce steam at 32 bar (g) level but the steam is partly reduced to 10 bar (g) which is the steam level used in the digesters, and partly to 7 bar (g) steam. Part of the high pressure steam produced in the recovery boiler is fed through a turbine (owned by Övik Energi) which produces both electricity and 7 bar (g) steam. Most of the produced 7 bar (g) steam is used in the cellulose production, a smaller fraction is used in the bioethanol and in the lignin production processes.

In addition, 7 bar steam is bought from the biofueled plant owned by Övik Energi, see section 2.4.

In the Domsjö Fabriker utility system process steam at 0.1 bar (g) is also used along with flash steam, flash condensate and scrubber water.

The cold utilities used in the Domsjö Fabriker include river water (unpurified) and chemically purified water. The temperature varies by season.

2.3 SEKAB Biofuels & Chemicals AB

2.3.1 Products and processes

SEKAB develops and produces ethanol-based chemicals such as acetaldehyde, acetic acid and ethyl acetate. SEKAB is also a manufacturer of bioethanol-based biofuels and technical ethanol. SEKAB works with catalytic processes in which the ethanol raw materials react. SEKAB uses the ethanol produced by Domsjö Fabriker but also imports ethanol (by ship) from other producers worldwide.

2.3.2 Utility System

SEKAB uses mainly 7 bar (g) steam as utility for heating their processes. The steam is produced in the biomass boiler owned by Övik Energi.

For cooling purposes SEKAB uses river water, which has a varying temperature between 0.2 °C in winter months and peaking at +21°C in summer.

2.4 Övik Energi

2.4.1 Products and processes

Hörneborgsverket is a CHP plant in Örnsköldsvik, owned by Övik Energi. The plant uses biofuels to produce steam at 7 bar (g), district heating and electricity. In Table 5 the production in year 2016 is shown.

Table 4 Heat and electricity production in Hörneborgsverket, Övik Energi, year 2016

	2016
District heating [GWh]	262
Steam, 7 bar (g) [GWh]	283
Electricity [GWh]	141

The plant consists of a steam boiler and a steam turbine with installed capacities of 130 MW and 40 MW, respectively. The fuel consists of bark, forest residues (tops and branches), peat and wood chips. Approximately one third of the fuel origins from Domsjö Fabriker.

The biomass fuel is sent to the plant and is combusted in the steam boiler. The steam is expanded in the turbin to 7 bar (g) steam and district heating for the city of Örnsköldsvik. The 7 bar (g) steam is sent to the steam network that supplies the nearby industries (Nouryon, SEKAB and Domsjö Fabriker). Alfa values (amount of electricity per heat production) of the turbine are approximately 20 % for steam production, and 50 % for district heating production.

Övik Energi produces steam to the nearby industries Nouryon, SEKAB and Domsjö Fabriker. Nouryon and SEKAB get all their 7 bar (g) steam demand from Övik Energi. Domsjö Fabriker produces most of their own steam in their recovery boilers, and only a minor part is delivered from Övik Energi, about 23 %. The steam is primarily produced in Hörneborgsverket, but also in a gas/oil boiler at the Domsjö site when needed.

In addition to the turbine at Hörneborgsverket, Övik Energi also owns the turbine at the Domsjö site which is fed with steam from the recovery boilers of Domsjö Fabriker. Övik Energi obtains green certificates for all the electricity generated in the turbine at Hörneborgsverket, and for 28 % of the electricity generated in the turbine at the Domsjö site.

Furthermore, Övik Energi supplies district cooling in two systems, one for the central parts of the city Örnsköldsvik and one for Domsjö Fabriker, SEKAB and also Hörneborgsverket.

3 Methodology

This section of the report covers the basic principles of pinch analysis and total site analysis used to estimate the opportunities for saving hot utility at the Domsjö biorefinery cluster site. The method builds upon visual analysis of curves characterizing the heating and cooling requirements of process streams within the cluster. The same curves can also be used to identify opportunities to improve the mix of hot utilities selected to provide heat.

3.1 Pinch Analysis

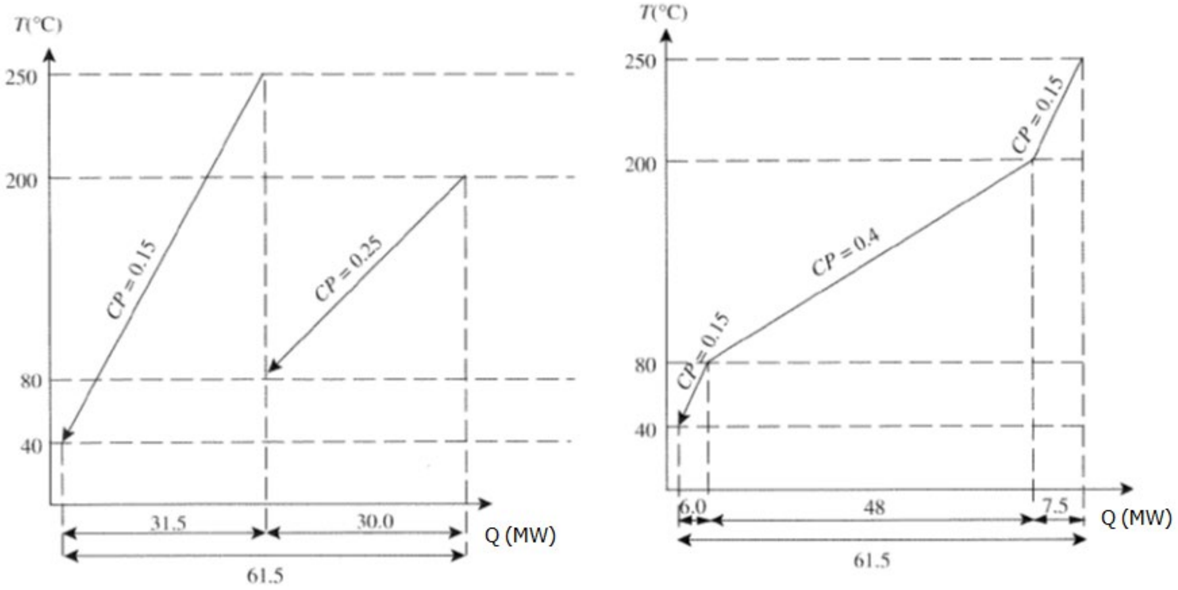
Material streams in industrial processes often need to be heated (heat sinks, hereafter referred to as *cold streams*) or cooled (heat sources, hereafter referred to as *hot streams*) to satisfy the process requirements. This is achieved by adding or removing heat to process streams by heat exchange with hot and cold utility streams or by transferring heat between hot and cold streams. Pinch analysis can be used to establish targets for the minimum heating and cooling demands of a process, for a given value of the minimum acceptable temperature difference for heat exchanging (ΔT_{min}). Pinch analysis also determines the so-called pinch point temperature (T_{pinch}) which divides the process stream system into two distinct zones. Above the Pinch Point, the process stream system constitutes a net heat sink, and only hot utility is required to operate the process. Conversely, below the Pinch, the process stream system is a net heat source, requiring only external cooling. Once the energy targets are established and the location of T_{pinch} is determined, pinch analysis methodology also provides guidelines for the design of Heat Exchanger (HX) networks that can achieve the energy targets. Application of Pinch technology has been shown to be able to achieve utility savings of 20-40% (Heck et al., 2009). A detailed overview of the methodology is provided in Kemp (2007) and Smith (2016).

The methodology can be used to target process heat integration opportunities and increase energy efficiency in both grass-root and retrofit situations. Typical applications include:

- Energy targeting;
- Heat exchanger area targeting;
- Cost targeting;
- Utility selection;
- Co-generation targeting;
- Heat exchanger network design;
- Integration of energy conversion technologies, such as heat pumps and refrigeration systems; and
- Integration of energy intensive equipment, such as distillation columns.

Composite Curves

One of the important steps in pinch analysis is generating the Composite Curves. All hot and cold streams included in the analysis are characterized by their heating or cooling load, as well as the start and target temperature of the stream being heated or cooled. For the hot streams, it is then possible to add together the heat loads of all streams existing over any given temperature range. In this way, a single *composite curve* can be produced and plotted in a Temperature/Heat Flow diagram. The construction of the composite curve is illustrated in Figure 7 for a simple stream system with two hot streams with heat capacities (i.e. mass flow*C_p, denoted *CP* in the figure) equal to 0.15 and 0.25, respectively. Note that the hot composite curve represents a heat source, i.e. streams that must be cooled. The corresponding composite curve is hereafter referred to as the *cooling composite*.



The hot streams plotted separately

The hot composite curve

Figure 7 Construction of hot composite curves for two-stream system. From Smith (2016)

The cold composite curve (hereafter referred to as the *heating composite*) can be constructed in a similar manner. The curves can then be positioned horizontally relative to each other, in the same plot. If the curves are not overlapped at all, all cooling of hot streams must be accomplished by cold utility, and all heating of cold streams must be accomplished by hot utility. If utility consumption is to be minimized, as much heat as possible should be recovered from the hot streams and used to heat the cold streams, i.e. the curves must be overlapped as much as possible. The possible overlap is limited by the minimum allowable temperature difference for heat exchanging (ΔT_{min}). The procedure is illustrated in Figure 8 for a four stream system with two hot and two cold streams, and ΔT_{min}=10°C. The figure shows how the selection of ΔT_{min} determines the location of the pinch point, and the energy targets, i.e. the minimum need for external cooling ($Q_{C,min}$), minimum need for external heating ($Q_{H,min}$), as well as the maximum amount of heat that can be recovered (Q_{Rec}).

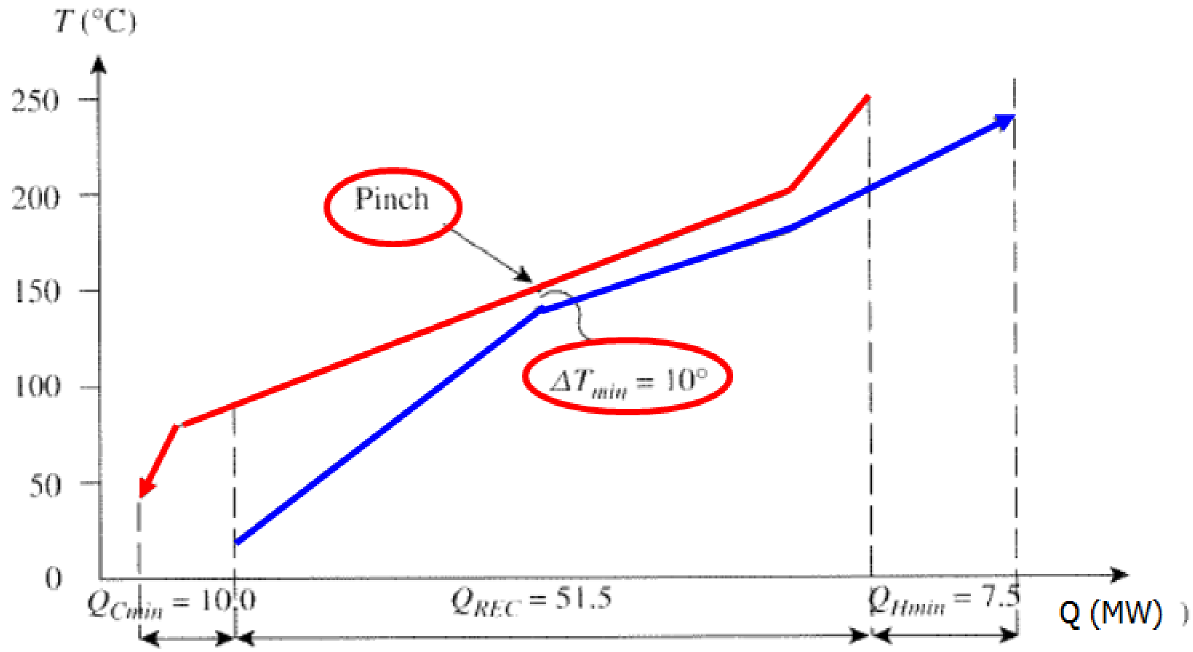


Figure 8 Composite curves for four stream system and ΔT_{min} = 10°C. From Smith (2016)

3.2 Total Site Analysis (TSA)

Pinch Analysis was initially developed for analysis of individual process plants. However, many process plants are located close to other process plants, and it is therefore of interest to investigate opportunities for integrating energy flows of several plants with the objective of achieving energy savings that are greater than the sum of the energy savings that could be achieved by the individual plants. Total Site Analysis (TSA) is an extension of pinch analysis that can be used to identify energy savings opportunities for multiple plants, as described in Klemes et al. (1997). TSA can also be used to identify changes to the site's utility systems in order to reach the targets identified for the minimum heating and cooling demand. Furthermore, TSA can be applied to target for increased co-generation of electric power (Bandyopadhyay et al., 2010)).

By using TSA it is possible to integrate the individual heating and cooling demands of different processes at a total site. Excess heat from one process can be used as heat source in another using a common utility system. Excess heat is transferred to a common utility (e.g. steam, hot water, hot oil) and then transferred to processes with a heat deficit by the common utility system, as described by e.g. Bagajewicz and Rodera (2001).

3.2.1 Heat exchanging constraints in TSA studies

When conducting a TSA study, it is important to decide upon the constraints for heat exchanging to be considered for the analysis. In many cases, unconstrained heat exchanging between different plants is not an option, and it is common to consider only heat recovery options in which heat is exchanged between plants through the utility system, since this does not change the topology of the individual plants. Such constraints will determine the level of detail of process data required to proceed with the study. In practice, three types of approaches are commonly adopted:

- Unconstrained heat exchanging: if no constraints are placed on heat exchanging, all site-wide options for increasing heat recovery can be considered. This approach is essentially equivalent to pinch analysis in which the system boundary is widened to include all individual processes. This approach allows the user to quantify the theoretical target for site-wide heat recovery.
- Semi-constrained heat exchanging: in this case, the layout of each individual process is accepted as it is, including the existing heat exchanger network and the level of heat recovery within the plant. Only process streams that are heated/cooled by utilities are considered in the analysis based on their T_{start}, T_{target} and load Q. If relevant, certain such heat sources or sinks can be excluded from the analysis for operational reasons. It is assumed that heat is transported from one plant to another by utility streams. No changes are allowed to the layout of the individual process plants. However, it is assumed that the site-wide utility system can be adapted so as to increase heat recovery. This approach was adopted by Hackl (2014) for investigating energy savings opportunities within the chemical complex in Stenungsund.
- Highly-constrained heat exchanging: this approach is similar to the semi-constrained approach discussed above. However, in this case, changes to the site-wide utility system are not allowed. This type of approach has been used primarily for investigating options for increased power generation in back-pressure steam turbine systems, in which excess steam from one plant is expanded down to a lower pressure and used to partially cover the steam requirements of a neighbouring plant, thereby off-loading the receiving plant's boiler. For more information about this approach, see Zhu and Vaideeswaran (2000).

3.2.2 Composite curves for TSA studies

In this study, we focus on the semi-constrained heat exchanging approach. The first step is to create composite curves for the process streams being heated and the process streams being cooled. It can also be of interest to include the composite curves of the hot and cold utility streams that deliver the heating and cooling needs of these streams.

Once the composite curves are available, further analysis is possible following pinch analysis methods. In particular, the following targets can be established:

- Heat recovery targets: the maximum amount of heat that can be recovered can be estimated by maximizing the overlap between the heating and cooling curves, for a given value of ΔT_{min}. It is also possible to handle additional constraints resulting from the temperature profiles of the medium selected for transferring the heat if direct heat transfer is not an option.
- Optimized Utility levels and loads. Once targets for increased heat recovery have been established, it is also possible to use the curves to optimize the utility loads, and to investigate the benefits of adjusting utility levels and/or introducing new levels. It is assumed that the specific cost of utility heat increases with temperature. The cost-optimal loads can be determined by starting with the lowest temperature utility. The load is maximized for the specified value of ΔT_{min}. The procedure is repeated for next utility level, and so on until the heating requirements are fully covered.

3.2.3 Estimation of investment costs for heat recovery measures

The investment costs for heat recovery measures were estimated according to the method described in Hackl and Harvey (2013, 2015). The method is based upon the concept of heat exchanger area targeting described in Kemp (2007). The estimated area cost was then used to calculate the equipment cost based on the procedure described in Smith (2016). Investment costs were updated to 2017 levels using the CEPCI index value for 2017 (591). Finally, the basic equipment costs were adjusted using cost factors to correct for materials of construction, design pressure and design temperature, as well as standard installation cost factors. The procedure is further described in Appendix B.

4 Results

In this chapter composite curves corresponding to the current utility use in process heaters and coolers are presented firstly for the three separate industrial plants and then for the total site. The current utility use is analysed in terms of optimality, i.e. no unnecessarily hot utility should be used for low temperature heating purposes. If possible, a more efficient use of utility is suggested, either through optimisation of the use of existing utility levels or by introducing utility at a new temperature level.

In the analysis, the options which have the potential to reduce costs or increase incomes are prioritised. Hence, the possibilities to reduce the amount of purchased fuel and increase the electricity production have been the main focus of this work.

In Chapter 5, the selected measures are further analysed regarding their economic potential and potential to reduce CO_2 emissions.

The streams which are relevant in the heat integration alternatives are listed in Appendix A, Table 13. As discussed in the previous section, the semi-constrained approach was adopted, i.e. we focused our analysis on process streams currently heated or cooled by hot and cold utility streams. Furthermore, the utility heat exchangers were classified into three categories, according to their suitability for modifications to achieve heat savings:

- Category A: modifications possible at moderate costs
- Category B: modifications are possible, but complicated to implement and higher investment costs are expected
- Category C: modifications are not possible due to process constraints, or costs are expected to be prohibitively high.

This study focuses primarily on improvements that relate to modifications of Category A and B utility exchangers.

4.1 Internal heat integration of the separate plants

In the following the heating and cooling composite curves of the three industrial plants within the Domsjö cluster are presented. The stream data included for the site profiles are limited to streams that are not already involved in heat recovery at the plants and are running on a continuous basis, which means that approximately 30 % of the steam use is represented in the curves. For each plant the theoretical minimum hot and cold utility demands are determined. A minimum temperature difference of 20 K is assumed. In the diagrams cold and hot process streams are presented (blue and red curves), as well as the corresponding cold and hot utility curves (black and brown curves).

4.1.1 Internal heat integration at Nouryon

Nouryon has five synthesis reactors of which two (reactor 1 and 2) are planned to be replaced within the near future and where local heat recovery will increase the efficiency. The other three reactors also show a potential for local heat recovery since the heating/cooling circuit is run alternatively for cooling and heating during each batch cycle. Internal heating and cooling loads for these reactors were therefore not included in the analysis. The five reactors also have a cooling demand via the condensers and this cooling demand for reactors 3-5 was included in the analysis.

At Nouryon there is also a local utility system using glycol water recovering heat and distributing heat to different processes that is not included in the analysis since this is already a way to improve the heat recovery at the site.

The site composite curves for the current situation at the Nouryon site at Domsjö are shown in Figure 11. It can be observed that 22-bar steam is used to a high extent, also for process heat demand at temperatures below 150 °C. 3.9 MW of the total heating demand of 4 MW require heat below 150 °C, for which 7-bar steam or lower is sufficient.

Figure 12 shows the results of the energy targeting analysis for the given value of ΔT_{min}. As shown in the figure, it is possible to overlap the heating and cooling composite curves by 0.66 MW, which thereby is the maximum potential for internal heat recovery for the given value of ΔT_{min}. A new utility of about 30 – 70 °C could be used for this purpose (not shown in the figure). All of the cooling demand could be supplied by this new utility but 3.3 MW of the heat demand would still remain. However, this alternative is not further analysed due to the small amount of heat recovery in relation to the potential of the total site analysis which is 15 MW (see Chapter 4.2).

Furthermore, 1 MW of the streams have a heating demand below 72 °C which could be supplied by district heating which is 82 °C at the lowest during the year. An alternative utility mix in which district heating replaces as much 22 bar steam as possible is illustrated in Figure 11.

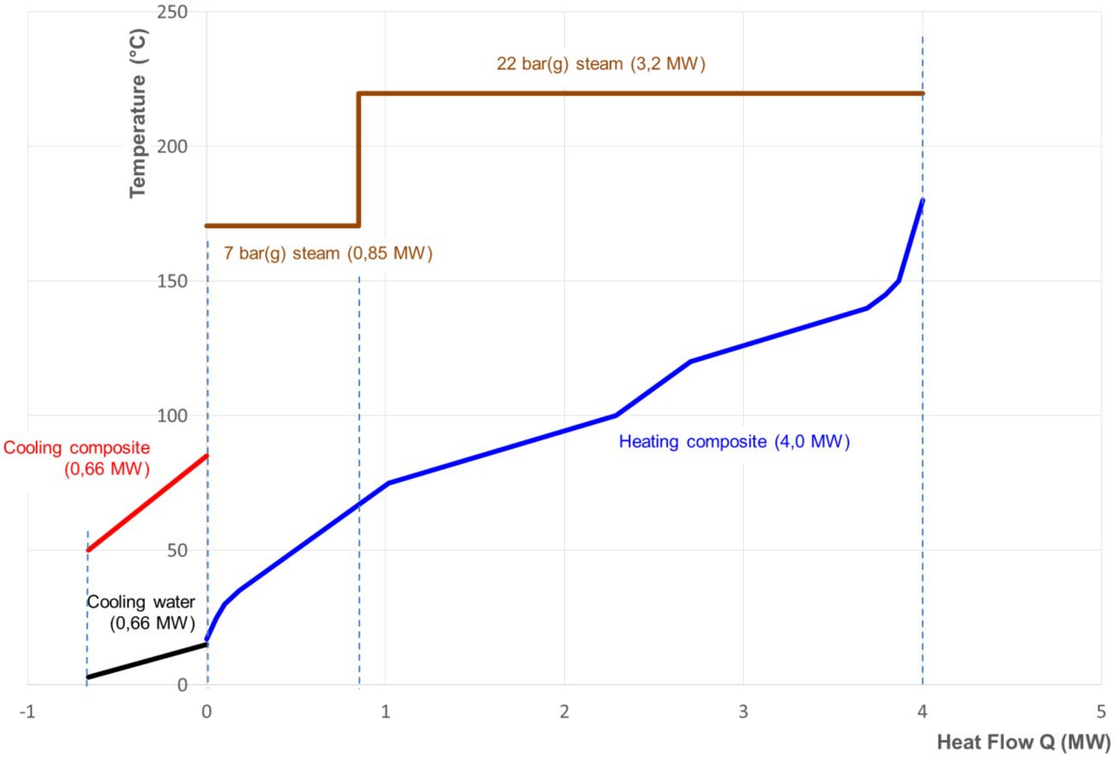


Figure 9 NOURYON. Heating and cooling composites and the current utility mix (category A + B heat exchangers only).

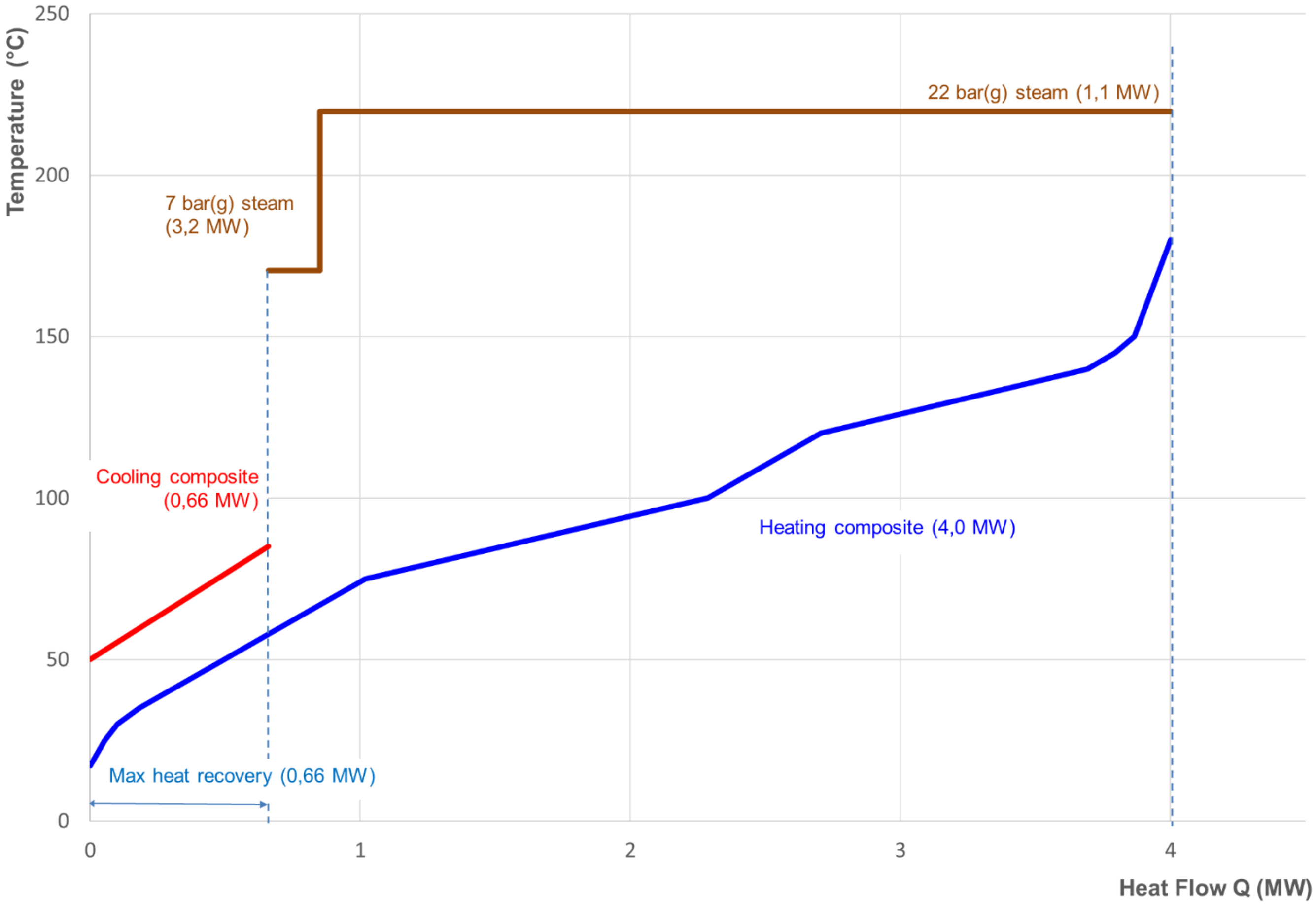


Figure 10 NOURYON. Heat recovery potential and utility loads (current utility levels, category A + B heat exchangers only).

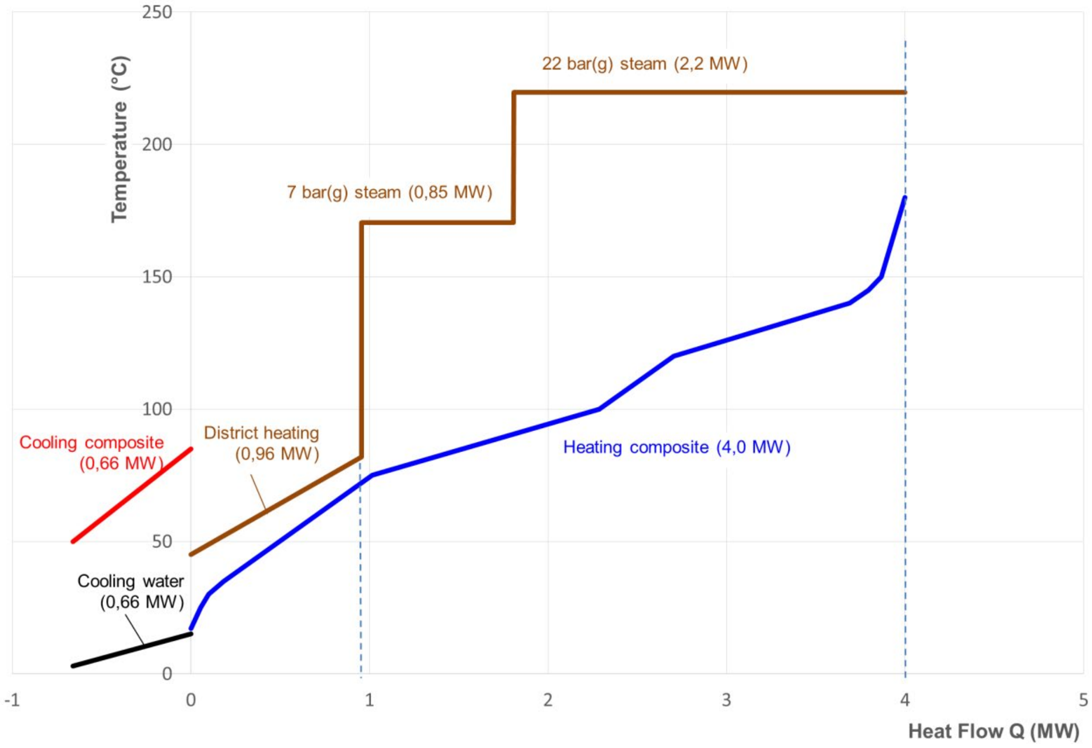


Figure 11 NOURYON. Max heat delivery from district heating water. Other utility levels unchanged. 7 bar utility load restricted to current load. No heat recovery. Category A + B exchangers only.

4.1.2 Internal heat integration at Domsjö Fabriker

The current heating and cooling composites of Domsjö Fabriker are presented in Figure 12. 7 bar steam is used as hot utility for all the streams with heat demand. However, about 38 MW of the 42 MW heat demand require temperatures below 134 °C and could be supplied with 3 bar steam or utility at even lower temperature.

Figure 13 shows the results of the pinch analysis energy targeting. The heating and cooling composites could overlap by 10 MW at most, which is the maximum potential for internal heat recovery. A new utility of about 40 – 120 °C could be used for this purpose (the turquoise line in Figure 13). If all this heat recovery potential is realised, the remaining cooling demand would be 1 MW and the remaining heat demand would be 32 MW. The conclusion of this is that a substantial part of the potential heat recovery for the entire biorefinery total site, 10 MW of 15 MW (see Chapter 4.2), is located at Domsjö Fabriker.

At Domsjö Fabriker, 6.3 MW of the heating demand requires temperatures below 72 °C and could therefore be heated with district heating which is 82 °C at the lowest during the year. This alternative is illustrated in Figure 16.

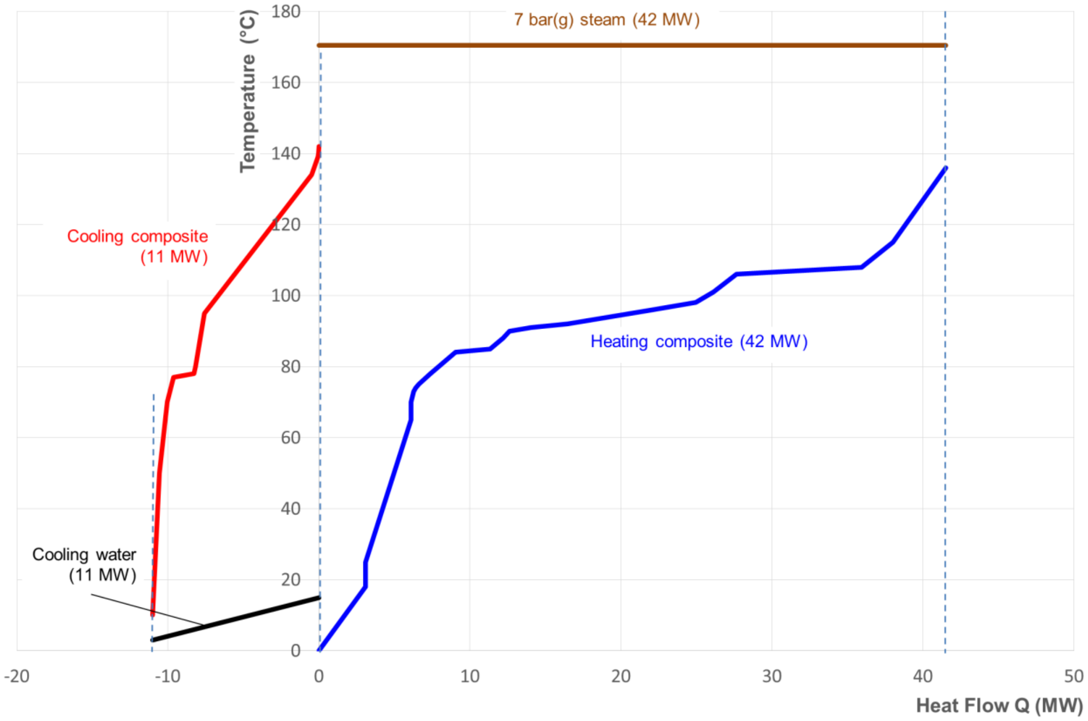


Figure 12 DOMSJÖ FABRIKER. Heating and cooling composites and current utility mix (category A + B exchangers only)

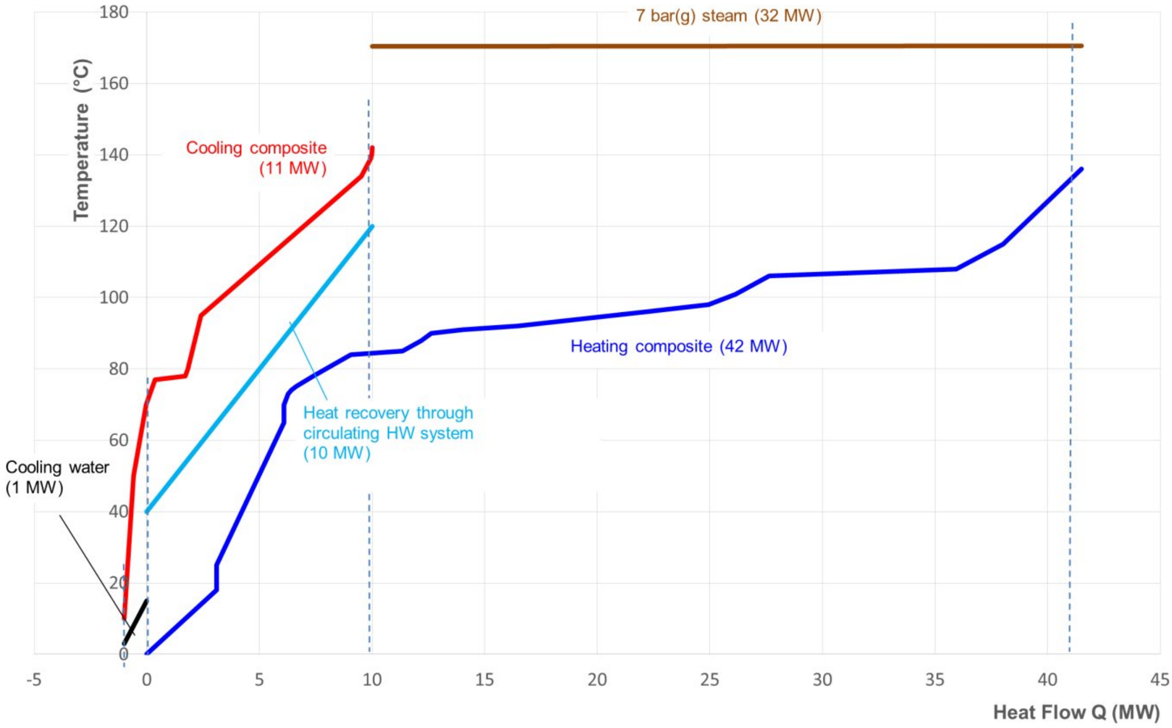


Figure 13 DOMSJÖ FABRIKER. Maximum heat recovery through circulating HW + utility mix. Existing utility levels. Category A + B exchangers only.

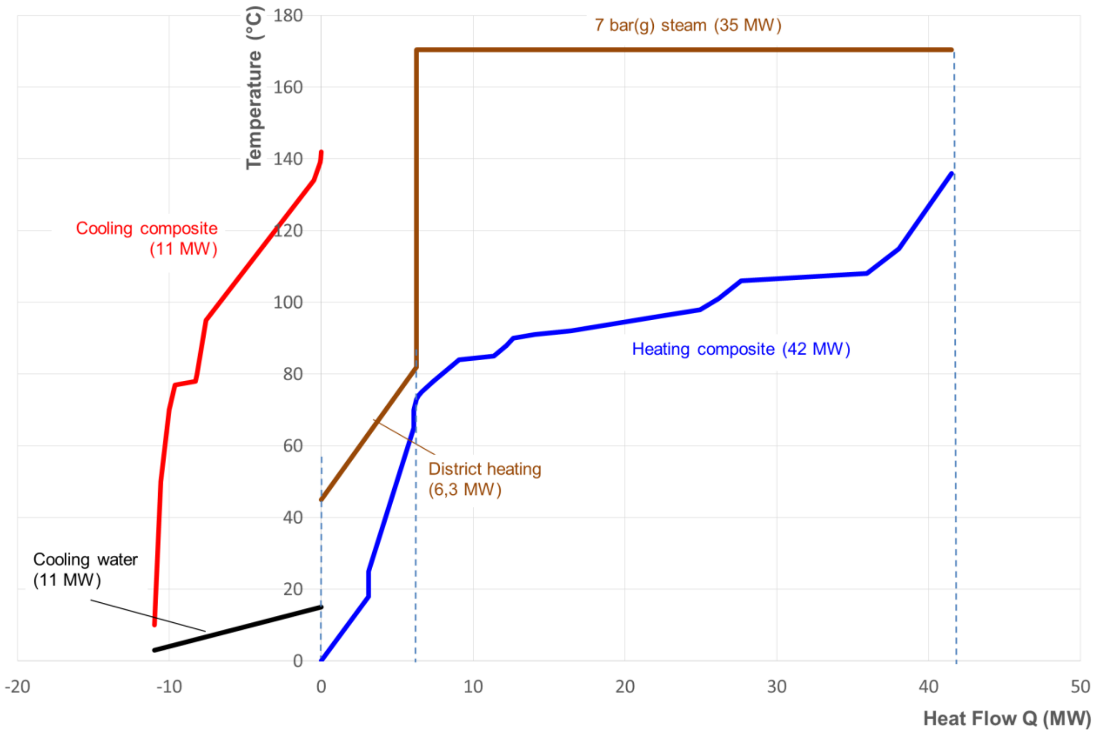


Figure 14 DOMSJÖ FABRIKER. Max heat delivery with district heating water. Other utility levels unchanged. No Heat recovery. Category A + B exchangers only.

4.1.3 Internal heat integration at SEKAB

In the case of SEKAB some processes were not considered since they are not run continuously but batch-wise. The site heating and cooling composites for the remaining streams at SEKAB are presented in Figure 15. 7 bar steam is used as hot utility for all the heating demands even though 3 bar steam would be sufficient. However, since the temperature demands exceed 72 °C, district heating could not replace steam for these demands.

Figure 18 shows the results of the pinch analysis for SEKAB. The figure shows clearly that the potential for internal heat recovery at the SEKAB site is very small.

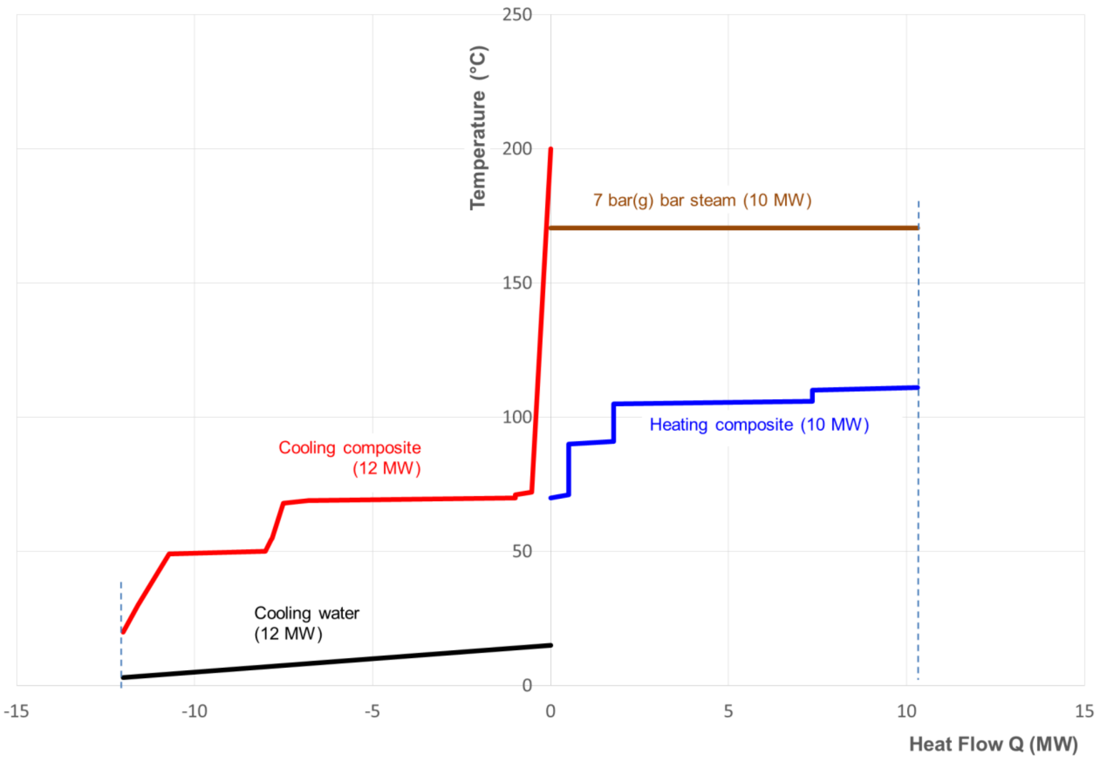


Figure 15 SEKAB. Heating and cooling composites and current utility mix (category A + B exchangers only).

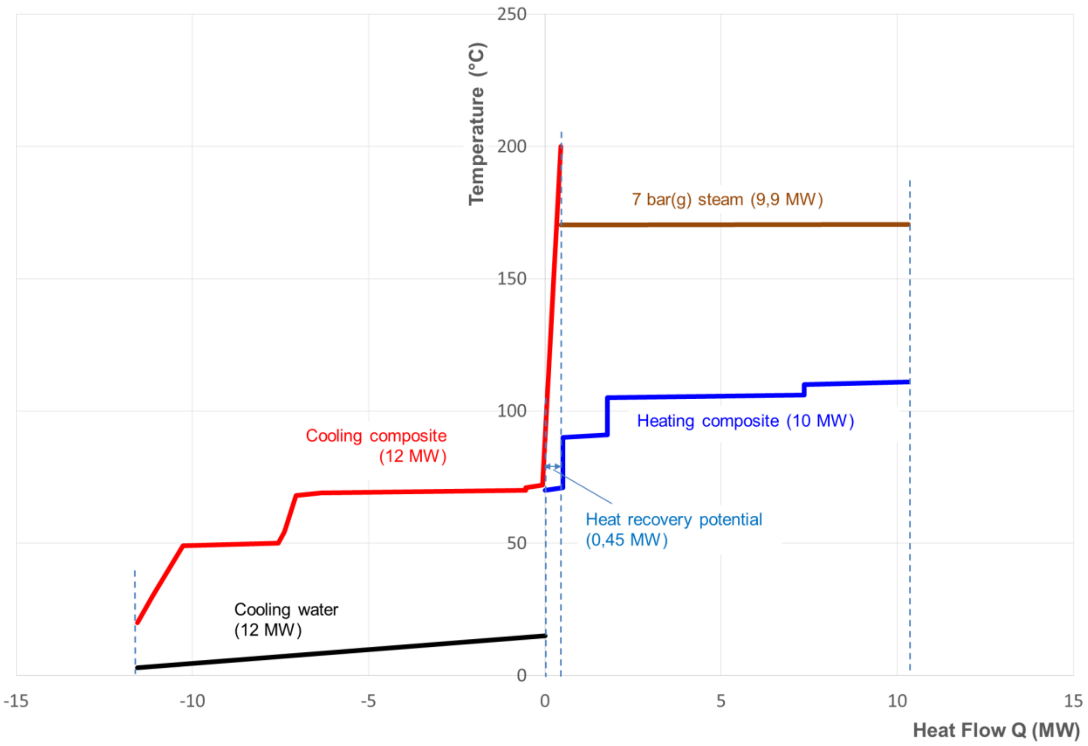


Figure 16 SEKAB. Heat recovery potential + utility loads (current utility levels, category A+B exchangers only).

4.1.4 Summary of internal heat integration potential analysis for separate plants

Table 6 provides an overview of the heating and cooling demands for each individual plant within the Domsjö biorefinery cluster. The table shows the potentials for heat recovery as well as the potential to substitute steam hot utility with district heating.

It is seen that a great part of the total potential energy saving can be achieved by measures at Domsjö Fabriker, 10 MW of 15 MW. Hence the case with Domsjö Fabriker as a separate plant will be further analysed in Chapter 5 regarding economic performances and potential for CO_2 emission reduction. Internal recovery at Nouryon and SEKAB contributes by a minor heat recovery potentials and are therefore not analysed further.

Table 5 Minimum heating and cooling demands, maximum heat recovery and potential of district heating use at the separate plants within the Domsjö biorefinery cluster assuming a global ΔT_{min} of 20 K.

Plant	Current heating demand	Current cooling demand [MW]	Minimum heating demand [MW]	Minimum cooling demand [MW]	Maximum heat recovery [MW]	Potential for district heating use [MW]
Nouryon	4.0	0.7	3.3	0	0.7	1
Domsjö Fabriker	42	11	32	1	10	6.3
SEKAB	10	12	12	10	0.45	0
Sum	**56**	**24**	**47**	**11**	**11**	**16**

4.2 Total site analysis of the biorefinery cluster

In this section, total site analysis is performed for the Domsjö biorefinery cluster in order to find the potential for synergies between the industrial plants at the site.

In all related figures, the heating and cooling composites are presented (blue and red curves) as well as the corresponding and cold and hot utility composite curves (black and brown curves). *Process cooling* is shown in the left side of the graphs. In order to remove heat from the hot process streams, it is transferred to the cold utility curve. *Process heating* is shown in the right-hand side of the figures. Hot utility is used to deliver heat to the cold process streams. Using the curves, the total cooling and heating demands can be determined, as well as the amount of heat discharged to the environment by e.g. cooling water, the potential for site-wide heat recovery as well as the hot utility requirements.

The stream data included for the site profiles are limited to streams that are not already involved in heat recovery at the plants and are available on a continuous basis. Also, the streams which are considered impossible to change (Category C according to the classification discussed in the introduction of this Chapter) are excluded in the analysis.

Figure 17 shows the heating and cooling composites and the corresponding utility composites for the entire biorefinery cluster. In accordance with the analysis of the separate plants, it is found that unnecessarily hot utility, steam at 7 bar, is used to supply most of the heating demand. Steam at 3 bar or lower would be enough for 52 MW of the 56 MW heat demand.

Figure 18 illustrates how the utility mix shown in Figure 17 can be modified. Two new hot utilities are introduced: 3 bar(g) steam and district heating water.

Figure 19 shows the results for the total site energy targets. The maximum heat recovery potential is 15 MW. A circulating hot water loop operating between 40 °C and 120 °C could be implemented to achieve this heat recovery potential. The remaining cold demand would be 8.5 MW and the remaining heat demand 41 MW.

In Figure 20 the potential to use district heating is illustrated. About 7 MW of the heating demand requires temperatures below 72 °C and could therefore be heated with district heating which is 82 °C at the lowest during the year. Note that this a modest estimation. More of the heating demand could be supplied by the higher district heating temperature which is used other parts of the year. In addition, it could be possible to use another temperature to the industries than the city.

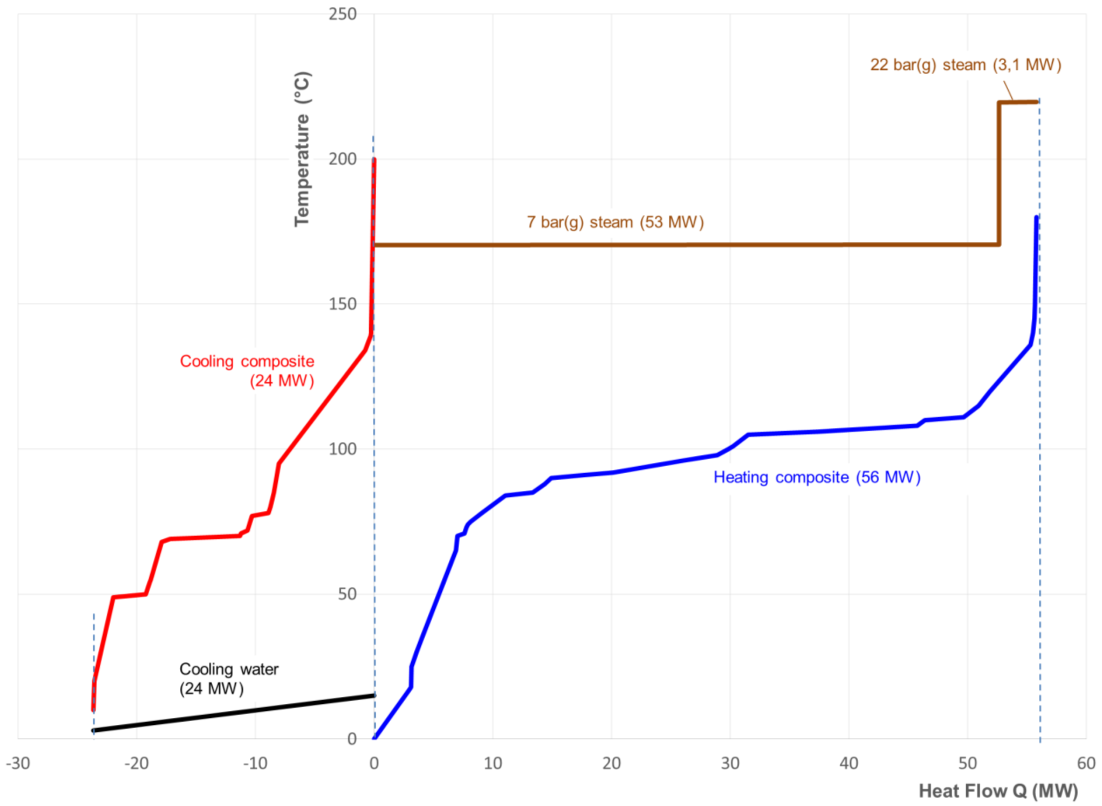


Figure 17 BIOREFINERY CLUSTER. Heat and cooling composites and current utility mix (category A + B exchangers only).

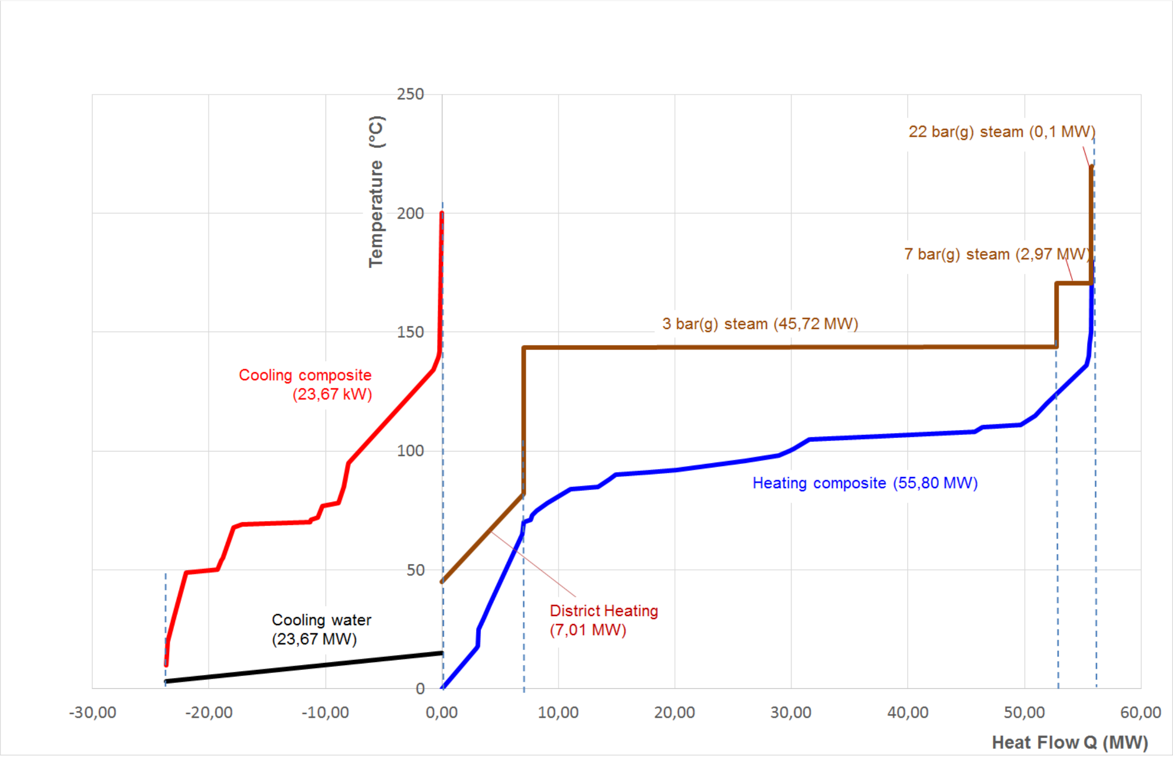


Figure 18 Modified hot utility mix for the stream system considered in Figure 17.

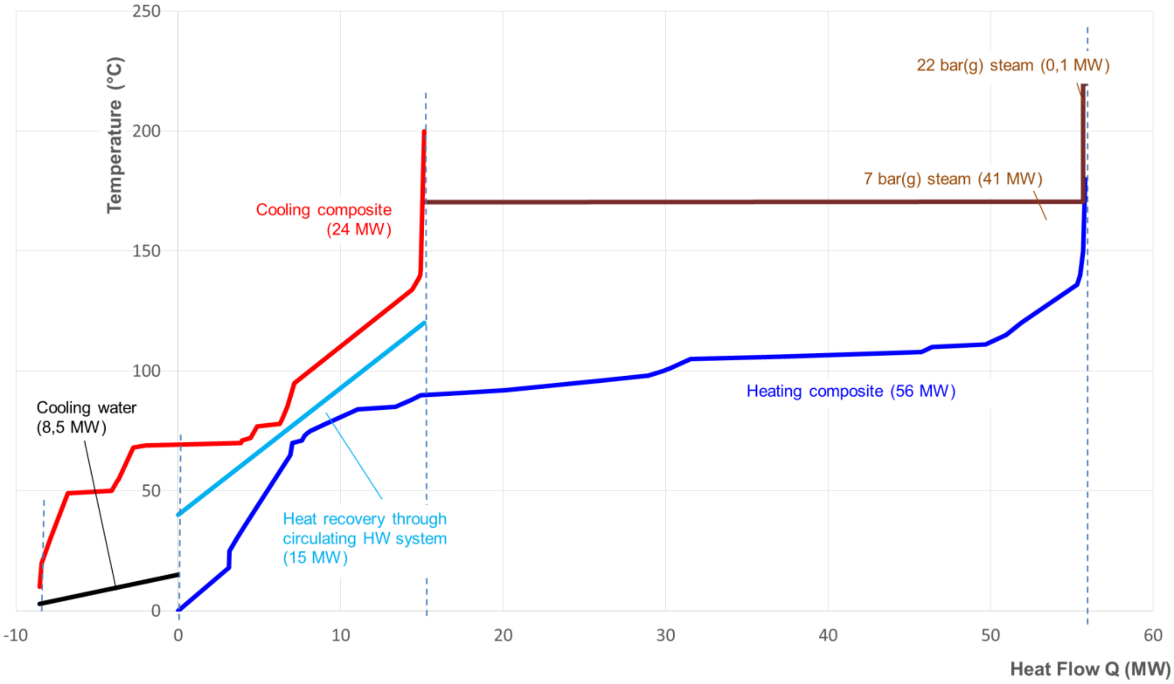


Figure 19 BIOREFINERY CLUSTER. Max heat recovery through circulating HW + utility mix. Existing utility levels only (category A + B exchangers only).

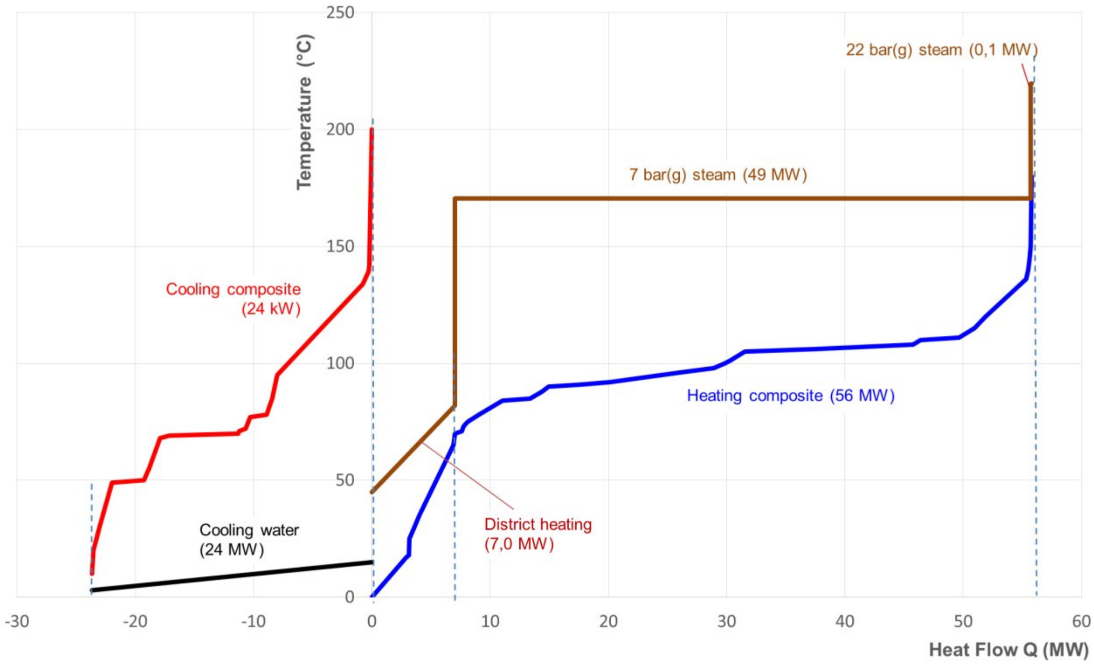


Figure 20 BIOREFINERY CLUSTER. Max heat delivery from district heating water. Other utility levels unchanged. No heat recovery. Category A + B exchangers only.

4.3 Summary of the results

The heat recovery potential for the total Domsjö biorefinery cluster is about 15 MW. Of this, 10 MW could be realised by internal heat recovery within Domsjö Fabriker. The remaining 5 MW requires that heat is integrated between all three industrial plants at the site. In both cases a new utility between 40 °C and 120 °C needs to be introduced. 15 MW and 10 MW, accounts for somewhat less than 10 % of the total steam use in the cluster and Domsjö Fabriker respectively.

Furthermore, the results show that high temperature utility is often used to provide heat for low temperature purposes. There is therefore a potential to switch to lower cost utilities. For example, at least 7 MW 7 bar steam could be replaced by district heating from Övik Energy, thereby increasing the potential to cogenerate electric power in Övik Energy's CHP plant. Since this potential is estimated with the lowest district heating temperature, 82 °C, which is used during the summer, a higher potential should be found during the other seasons.

Due to the size of the impact, these three alternatives are selected to be further analyses in Chapter 5.

5 Estimation of economic performance and potential for CO_2 emission reduction of the proposed energy measures

In this chapter three energy measures are evaluated with respect to their economic performance and potential for carbon dioxide emission reduction. The following measures were selected:

- Heat recovery within the total Domsjö biorefinery cluster (15 MW)
- Heat recovery within the separate plant Domsjö Fabriker (10 MW)
- Replacement of 7 MW use of 7 bar steam with district heating (involves Övik Energi, Domsjö Fabriker and Nouryon)

The economic performance of the measures was estimated using the price assumptions shown in Table 7. Table 8 presents the assumptions regarding technical performance and energy system operation that are used in the estimations.

Note that the economic performance has only been studied on total site-level. The consequences for each company have not been considered. Neither has a business model for sharing costs and benefits been suggested. Furthermore, only the direct consequences for the energy system, such as reduced fuel demand and reduced or increased electricity production has been taken into account in the calculations. Other opportunities that could arise when the steam demand is reduced are not calculated for. These opportunities are discussed in Chapter 6 Discussion and conclusions.

Also, note that the three measures are partly competing. If district heating is introduced a vast part of the potential for heat recovery is removed.

The estimation of the number of full load hours per year is illustrated in Figure 22. The steam demand throughout the year is shown. Approximately 7,000 full load hours were estimated. This number is used for calculation of energy demand consequences for the alternative energy integration measures. The potential was calculated in terms of capacity in MW. By multiplication with the number of full load hours the energy saving is calculated in MWh per year.

Figure 23 shows the steam delivery from Övik Energi to Domsjö Fabriker for one year. For 85 % of the hours of the year, the steam delivery exceeds 10 MW. In the economic estimations, this is used for calculating the fuel reduction and reduction of electricity generation at Övik Energi if the steam demand is reduced.

The part of steam which originates from the recovery boilers at Domsjö Fabriker is assumed to still run through their turbine even though the steam demand is reduced. This is because of the necessity to run the recovery boilers for process chemical recovery purposes. Hence, even though the steam demand is reduced, there will be no reduction of electricity generation in that turbine.

Table 6 Price assumptions

Description	Assumption	Unit	Comments
Electricity price	300	SEK/MWh	Average price on the Nord Pool spot market (for SE3), 2017[2]
Electricity certificate price	130	SEK/MWh	Average price, 2017[3]
Wood fuel price	182	SEK/MWh	Average price of woodchips excl. tax, 2016-2018[4]
Sulfate liquor price	0	SEK/MWh	
Cooling water price	0.5	SEK/m^3	
Hot water piping cost	10 000	SEK/m	

Table 7 Technical assumptions and energy system operation assumptions

Description	Assumption
Alpha value (power-to-heat ratio) for steam production (Övik Energi)	0.2
Alpha value (power-to-heat ration) for district heating production (Övik Energi)	0.35
Share of hours of the year when steam delivery exceeds 10 MW from Övik Energi	85 %
Full load production hours during the year	7,000 h/year
Fuel efficiency for steam generation (Övik Energi)	80 %

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[2] Energimyndigheten, Energiläget i siffror 2018

[3] Energimyndigheten, ET 2018:7 En svensk-norsk elcertifikatsmarknad, Årsrapport för 2017

[4] Energimyndigheten, Prisstatistik biobränslen

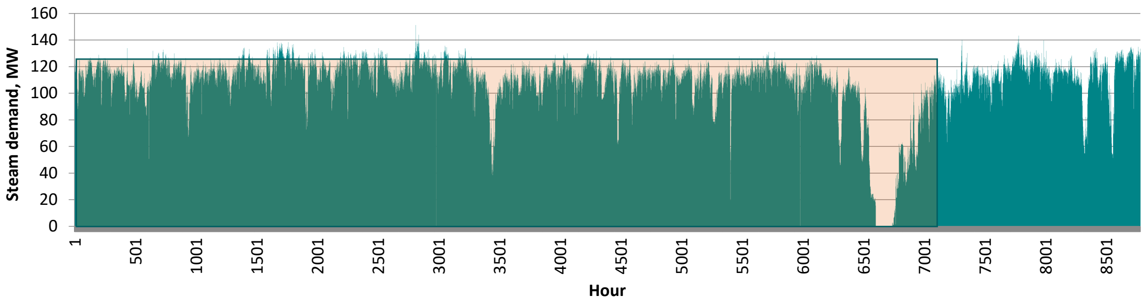

Figure 21 Steam demand for the production at Domsjö during one year. In light orange the approximation of full load hours is illustrated.

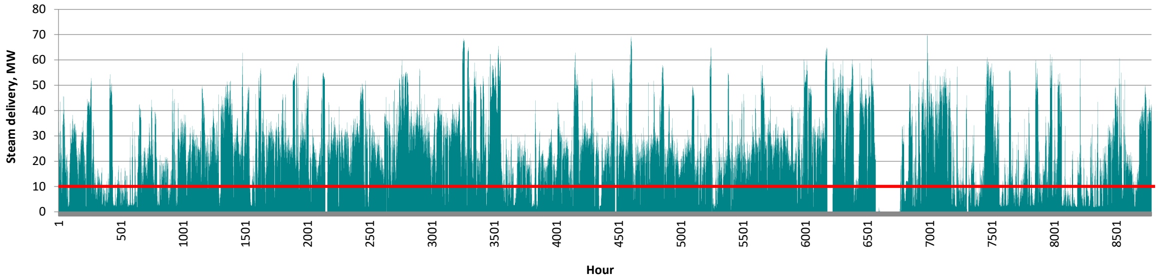

Figure 22 Steam delivery from Övik Energi to Domsjö Fabriker during one year.

5.1 Heat recovery within the Domsjö biorefinery cluster (15 MW)

Regarding the alternative with heat integration measure within the biorefinery cluster, the energy saving potential was estimated to be 15 MW. The energy saving of 7 bar utility steam is assumed to come primarily from Övik Energi's CHP plant. This is because the recovery boilers at Domsjö are used for base load steam generation and steam from Övik Energi is used to cover additional load when needed. A consequence of decreased use of 7 bar steam is decreased fuel demand at Övik Energi, mainly purchased biofuels and thus a reduced cost. Also, the electricity production in the CHP plant will decrease and cause a loss of income from sold energy. A schematic of the consequences is shown in Figure 24.

The fuel reduction is estimated to 100 GWh/year, which corresponds to a cost reduction of about 18 million SEK. The reduced electricity generation is about 16 GWh/year which corresponds to a loss of income of about 7 million SEK.

The required investment cost is estimated to 114 million SEK, which includes replacing or upgrading 36 heat exchangers as well as new piping. In Table 13 in Appendix A, the heat sources and heat sinks which are affected are listed. The payback period for this alternative is estimated to be 10 years.

The potential for carbon dioxide emission reduction is double-sided. The reduced demand of solid biofuels enables biofuels to replace fossil fuels elsewhere, which reduces carbon dioxide emissions. On the other hand, renewable electricity production will decrease which may lead to increased use of fossil electricity as a consequence which increases carbon dioxide emissions.

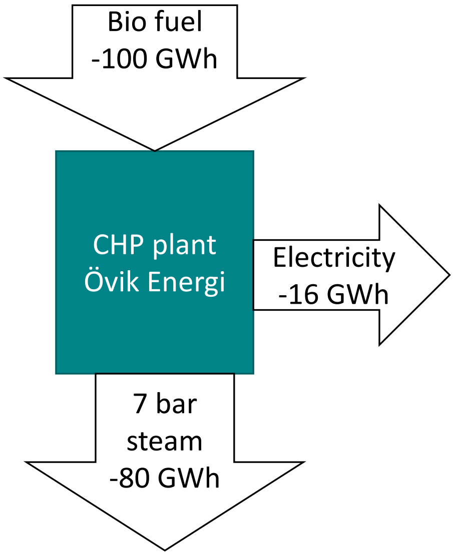

Figure 23 HEAT RECOVERY WITHIN THE BIOREFINERY CLUSTER SITE. Schematic of how the decreased demand of 7 bar steam reduces biofuel usage and electricity generation in the CHP plant of Övik Energi.

5.2 Heat recovery within Domsjö Fabriker (10 MW)

Regarding the alternative with heat integration measures at the single site of Domsjö Fabriker, the energy savings potential is calculated to be 10 MW. The energy savings of 7 bar steam is assumed to come from Övik Energi:s CHP plant for 85 % of the hours of the year. This results in reduced purchase of biofuel and decreased electricity production in the CHP plant at Övik Energi. Figure 25 illustrates how the reduced demand of 7 bar steam affects the bio fuel demand and the electricity generation.

The fuel reduction is estimated to 84 GWh/year, which correspond to a cost reduction of about 15 million SEK. The reduced electricity generation is about 14 GWh/year which corresponds to a loss of income of about 6 million SEK.

The investment cost is estimated to 46 million SEK, which includes replacing or upgrading 18 heat exchangers as well as new piping. In Table 13 in Appendix A, the heat sources and heat sinks which are affected are listed. The payback period for this alternative is estimated to be 5 years.

As in the case with heat recovery within the total site, the potential for CO_2 emission reduction is double-sided. The reduced demand of solid biofuels enables biofuels to replace fossil fuels elsewhere, which reduces carbon dioxide emissions. On the other hand, renewable electricity production will decrease which may lead to increased use of fossil electricity as a consequence which increases carbon dioxide emissions.

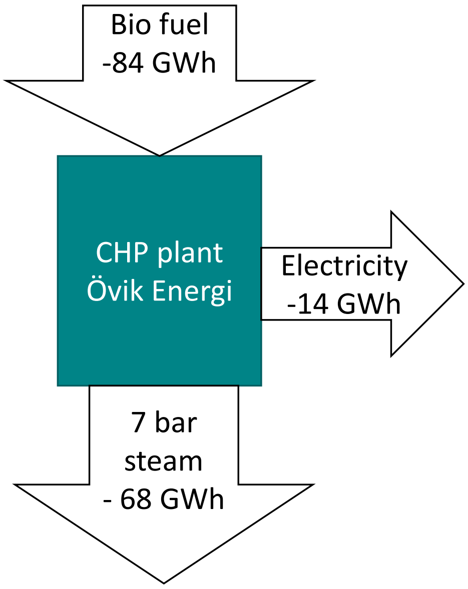

Figure 24 HEAT RECOVERY WITHIN DOMSJÖ FABRIKER ONLY. Schematic of how the decreased demand of 7 bar steam reduces bio fuel usage and electricity generation at the CHP plant of Övik Energi.

5.3 Replace 7 MW use of 7 bar steam with district heating

Replacement of 7 bar utility steam by district heating increases the opportunity for electricity generation at the CHP plant at Övik Energi by about 7 GWh/year. This corresponds to an increased income of about 3 million SEK. Figure 26 shows how the conversion from 7 bar steam to district heating affects the bio fuel demand and electricity generation at the CHP plant at Övik Energi.

The investment cost is estimated to 16 million SEK, which includes replacing or upgrading 14 heat exchangers as well as new piping. In Table 13 in Appendix A the heat sources and heat sinks which are affected are listed. The payback period for this alternative is estimated to 3 years.

Note that the potential for replacing 7 bar steam with district heating has been estimated conservatively; assuming that the low summer temperature of district heating supply occurs the year round. In reality, higher temperatures would be used during other seasons, which makes the actual potential higher. Furthermore, it would be possible to consider to use a higher hot water temperature around the year for delivery to the Domsjö biorefinery cluster. For example, if 150 °C was delivered, the vast part of the steam demand could be replaced.

The potential to reduce CO_2 emissions in this case is positive. The demand for solid biofuels does not change but the renewable electricity production is increased which may lead to decreased use of fossil electricity as a consequence which decreases carbon dioxide emissions.

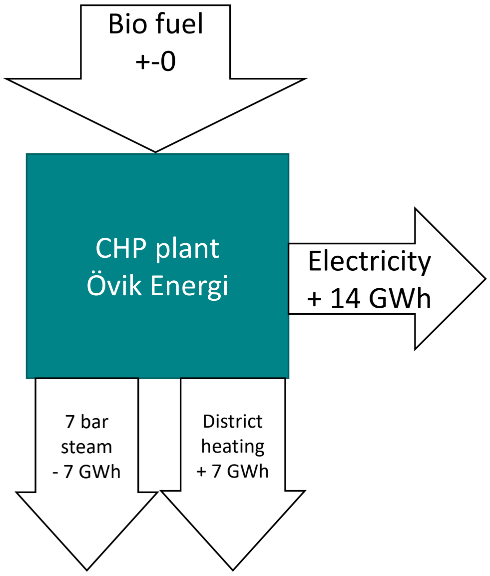

Figure 25 REPLACE 7 BAR STEAM BY DISTRICT HEATING. Schematic of how the conversion of 7 bar steam to district heating affect the demand to buy bio fuels and increases the electricity generation in the CHP plant of Övik Energi.

5.4 Comparison of the energy measures

The three different energy measures were evaluated in terms of economic performance and potential of CO_2 emission reduction on a generic level. The economic payback period (PBP) was estimated based on the decreased cost for fuel purchase, reduced or increased electricity production and the investment cost. Figure 27 shows the comparison of the three alternatives. The results are also shown in Table 9.

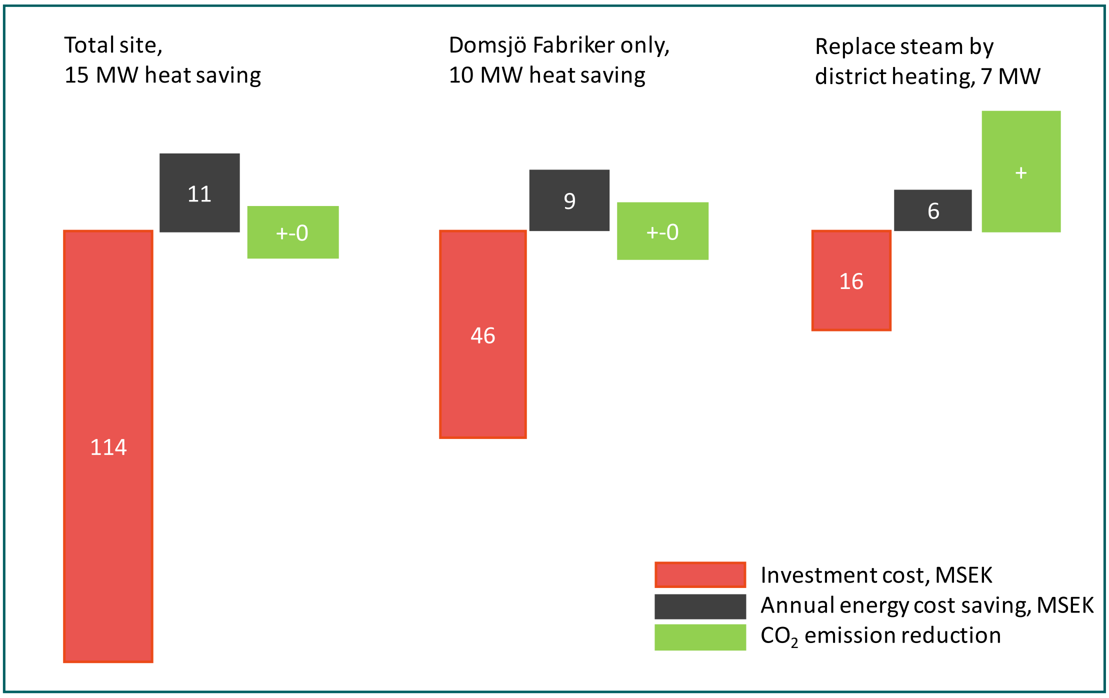

Figure 26 Illustration of the economic performance and CO_2 emission reduction of the analysed energy measures.

Table 8 Comparison of estimated economic performance and CO_2 emission reduction of the analysed energy measures

Suggested solution	**Economic performance**				**CO_2 emission reduction (+/-)**
	Fuel savings [MSEK/year]	**Impact on electricity production [MSEK/year]**	**Investment cost [MSEK]**	**PBP [year]**	
Heat integration of the total bio refinery cluster	18	-7	114	**10**	(+) Enable solid biofuels (-) Decreased renewable electricity production
Heat integration at Domsjö Fabriker (Aditya Birla) only	15	-6	46	**5**	(+) Enable solid biofuels (-) Decreased renewable electricity production

Replacing 7 bar steam with district heating	+-0	6	16	3	(+) Increased renewable electricity production

6 Discussion and conclusions

The general conclusion regarding energy use within the Domsjö biorefinery cluster is that there is a significant potential for energy savings and energy cost savings. The utility temperatures are in many cases unnecessarily high. However, due to the current energy system configuration, particularly the turbine design, there is little incentive to reduce these temperature levels. Since turbine modifications were outside the scope of this study, only the alternatives with positive economic performance within the current system were retained for further investigation. It is recommended for the concerned companies to continue with a complete overview of hot utility temperature levels in combination with turbine modifications. The results of this work indicate that the option of substituting 22 bar steam with 7 bar steam and 7 bar steam with 3 bar steam should be investigated further, since these measures have the potential to increase the electricity generation.

Two main alternatives for heat integration were analysed in this work, I) heat integration of each of the separate plants within the Domsjö site without allowing for inter-company heat exchange and II) site-wide heat integration, where process heat from hot process streams is transferred to common utilities and used to cover the combined heat deficit of all sites. In both cases, indirect heat exchange was allowed with an assumed minimum temperature difference of 20 K between process and utility streams.

The result of heat integration of each of the separate plant sum up to a total heat recovery potential of 11 MW. Of this, 10 MW is located within Domsjö Fabriker.

The potential for site-wide heat recovery was estimated to 15 MW. Hence, the heat integration potential is larger and thus the minimum heating and cooling demand lower if heat integration between the plants is allowed. The heat recovery potential accounts to approximately 10 % of the total steam use at the site.

According to generic economic estimations, the heat integration within Domsjö Fabriker has a shorter payback period than the heat integration of the total site, 5 years and 10 years respectively. The reason for this is that a large number of new heat exchangers are required to implement the total site alternative. Selective reduction of the number of heat exchangers could significantly reduce the costs without reducing the heat recovery potential too much. It is expected that this could lead to heat recovery configurations with a significantly better economic performance.

Regarding potential of CO_2 emission reduction, the heat integration alternatives are two-sided. They achieve a reduced use of bio fuels and thereby enable more bio fuels to replace fossil fuels elsewhere, but the renewable electricity generation is decreased.

The third energy alternative which was chosen for analysis was to replace 7 bar utility steam by district heating. The potential for this is at least 7 MW and creates the opportunity for more generation of renewable electricity without increased fuel usage. However, this measure cannot be combined with heat integration since most of the affected heating points are the same.

To summarise, all the three energy alternatives which have been analysed have good economic performance. The highest potential for CO_2 emission reduction is found for the alternative to convert 7 bars steam use to district heating use.

In addition to the direct consequences on the energy system, such as reduced fuel demand or changes in electricity production, all cases mean that new opportunities arise. One opportunity is to use the steam capacity which is released to either increase the current production or add new production processes without investments in new boilers. Another opportunity could be to produce more lignin for sale instead of burning the sulfate liquor in the recovery boilers. To use the released steam capacity to a new process plant is further elaborated in the next phase of this study.

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Appendix A Lists of utilities, heat sources and heat sinks

Table 9 Utilities at the Domsjö biorefinery cluster

Site Utilities	**Abbreviation**	**Company**	**T_{in} [°C]**	**T_{out} [°C]**
Hot utilities (used for heating)				
Low pressure (LP) steam	3 bar	Domsjö Fabriker	144	143
Medium pressure (MP) steam, 7 bar	7 bar	Domsjö Fabriker, Nouryon, SEKAB	170	169
High pressure (HP) steam 22 bar	22 bar	Nouryon	220	219
Cold utilities (used for cooling)				
River water (*råvatten*)	RV	Domsjö Fabriker, Nouryon	3	15
Cold water SEKAB	CW	SEKAB	3	15

Table 10 Heat sources at the biorefinery cluster

Heat sources	**Company**	**Fluid/Material**	**T-start [˚C]**	**T-target [˚C]**	**Heat flow rate [kW]**	**Utility**	**A**	**B**	**C**
E-9301/02	Nouryon	Reactor content	85	50	200	RV	x		
E-9303/04	Nouryon	Reactor content	85	50	280	RV	x		
Kondensorer, R5, kyler reaktorinnehållet	Nouryon	Reactor content	85	50	180	RV	x		
K6-K8	Domsjö Fabriker	Gas mix (steam and SO_2)	142	10	1400	RV	x		

K9	Domsjö Fabriker	Gas mix (steam and SO_2)	139	95	2000	RV	x		
K10	Domsjö Fabriker	Gas mix (steam and SO_2)	134	95	3800	RV	x		
K11	Domsjö Fabriker	Gas mix (steam and SO_2)	140	70	2000	RV	x		
IND7	Domsjö Fabriker	Ethanol (some water)	80	50	500	RV	x		
SP5-SP7	Domsjö Fabriker	Methanol (in gas phase in the first step)	78	77	1300	RV	x		
E-5815-23	SEKAB	Acetaldehyde (g)	200	30	694	CW	x		
Condensor 5825	SEKAB	Acetaldehyde	50	49	2665	CW	x		
Underkylning	SEKAB	Acetaldehyde	49	20	219	CW	x		
Condensor 6126	SEKAB	Ethyl acetate/ water	70	69	3300	CW	x		
Underkylning	SEKAB	Ethyl acetate/ water	69	20	459	CW	x		
Condensor 6109	SEKAB	Acetaldehyde/ ethanol	55	54	469	CW	x		
Underkylning	SEKAB	Acetaldehyde/ ethanol	54	20	41	CW	x		
Condensor 6121	SEKAB	Ethyl acetate/water/ ethanol	70	69	2507	CW	x		
Underkylning	SEKAB	Ethyl acetate/water/ ethanol	69	20	348	CW	x		
Condensor 6129	SEKAB	Ethyl acetate/water	69	68	685	CW	x		

Underkylning	SEKAB	Ethyl acetate/water	68	20	93	CW	x		
Condensor 6161	SEKAB	Ethyl acetate	72	71	459	CW	x		
Underkylning	SEKAB	Ethyl acetate	71	20	66	CW	x		

Table 11 Heat sinks at the biorefinery cluster

Heat sinks	**Company**	**Fluid/ Material**	**T-start [°C]**	**T-target [°C]**	**Heat flow rate [kW]**	**Utility**	**Potential district heating < 82°C (kW)**	**Potential district heating < 72°C (kW)**	**A**	**B**	**C**
E-8443	Nouryon	PAI (Process air)	17	145	270	22 bar		116	x		
D-8401	Nouryon	Water	75	100	270	22 bar			x		
E-8437	Nouryon	PAI (Process air)	17	145	270	22 bar		116	x		
D-8402	Nouryon	Water	75	100	240	22 bar			x		
E-8440	Nouryon	PAI (Process air)	17	150	350	22 bar		145	x		
D-8403	Nouryon	Water	75	100	240	22 bar			x		
E-8413	Nouryon	PAI (Process air)	25	145	280	7 bar		110	x		
E-9403	Nouryon	PAI (Process air)	30	150	900	22 bar		315	x		

E-9903	Nouryon	PAI (Process air)	35	180	600	22 bar		153		x	
E-8342	Nouryon	PLE	120	140	570	7 bar			x		
R3	Domsjö Fabriker	Water	25	65	3000	7 bar	3000	3000	x		
K1	Domsjö Fabriker	Feed lye	150	155	100	7 bar					x
K2	Domsjö Fabriker	Feed lye	143	1557	7800	7 bar					x
K3	Domsjö Fabriker	Feed lye	133	155	7500	10 bar					x
B1	Domsjö Fabriker	Water	74	90	1000	7 bar			x		
B2	Domsjö Fabriker	Water	70	88	1000	7 bar			x		
B3	Domsjö Fabriker	Water/resin	70	96	100	3 bar			x		
T1	Domsjö Fabriker	Water	78	90	300	7 bar			x		
T2	Domsjö Fabriker	Air	0	18	1000	7 bar	1000	1000	x		
T3	Domsjö Fabriker	Air	0	18	500	7 bar	500	500	x		
T4	Domsjö Fabriker	Air	0	18	1200	7 bar	1200	1200	x		
T5	Domsjö Fabriker	Air	0	18	400	7 bar	400	400	x		
T6	Domsjö Fabriker	Water (vaporize from cellulose)	55	100	500	3 bar	189				x

T7	Domsjö Fabriker	Water (vaporize from cellulose)	55	100	1900	3 bar	718				x
T8	Domsjö Fabriker	Water (vaporize from cellulose)	55	100	4300	3 bar	1624				x
T9	Domsjö Fabriker	Air	75	115	2200	7 bar			x		
T10	Domsjö Fabriker	Air	73	115	3300	7 bar			x		
T11	Domsjö Fabriker	Air	90	136	7600	7 bar				x	
IND1	Domsjö Fabriker	Lye	90	98	8900	7 bar			x		
IND8	Domsjö Fabriker	Water-Ethanol	106	108	7700	7 bar			x		
IND16-IND18	Domsjö Fabriker	Lye	132	134	15000	7 bar					x
L1	Domsjö Fabriker	Air	33	132	2200	7 bar	867				x
L2	Domsjö Fabriker	Air	33	132	2200	7 bar	867				x
L3	Domsjö Fabriker	Lye	98	101	300	7bar			x		
L4	Domsjö Fabriker	Lye	91	92	500	7 bar			x		
L5	Domsjö Fabriker	Lye	91	92	500	7 bar			x		
SP2	Domsjö Fabriker	Ethanol / methanol	84	85	2000	7 bar			x		

FQ5813 Ånga D-5803 kg/d	SEKAB	Water	105	106	513	7 bar			x		
FQ5804 , Ånga D-5804 , kg/d	SEKAB	Ethanol	70	71	505	7 bar			x		
FQ5843, ånga E-5812, kg/d	SEKAB	Ethanol /air	120	121	362	7 bar					x
FQ5841 ånga E-5825 kg/d	SEKAB	Ethanol / water	110	111	2961	7 bar			x		
FQ6121 ånga D6113 kg/d	SEKAB	Acetic Acid / Ethyle acetate	105	106	1392	7 bar					x
FQ6122 ånga D6104 kg/d	SEKAB	Acetic Acid / Ethyle acetate	105	106	2275	7 bar			x		
FQ6123 ånga 7bar D-6106 kg/d	SEKAB	Ethanol	80	81	475	7 bar					x
FQ6137 ånga D6111 kg/d	SEKAB	Water	105	106	2785	7 bar			x		

FQ6151 ånga D6105 kg/d	SEKAB	Ethyle acetate	90	91	762	7 bar			x		
FQ6149 ånga D-6161 kg/d	SEKAB	Ethyle acetate	90	91	510	7 bar			x		

Table 12 Heat sources and heat sinks which are affected by the three studies cases respectively

HXTR-No.	Description	T-start [˚C]	T-target [˚C]	Heat flow rate [kW]	Heat source /sink	TSA New utility	TSA District heating	Domsjö Fabriker New utility
Domsjö Fabriker								
R3	Spritsvattenvärmare	25	65	3 000	Heat sink	x	x	x
K6-K8	GK 8	142	10	1 400	Heat source	x		x
K9	6 tums kylare	139	95	2 000	Heat source	x		x
K10	8 -tums kylare	134	95	3 800	Heat source	x		x
K11	Gaskylare kar 2	140	70	2 000	Heat source	x		x
B1	VVX filtrat	74	90	1 000	Heat sink	x		x
B2	VVX filtrat	70	88	1 000	Heat sink	x	x	x
B3	VVX vatten/harts	70	96	100	Heat sink	x	x	x
T1	Spritsvattenvärmare	78	90	300	Heat sink	x		x
T2	Luftbatteri	0	18	1 000	Heat sink	x	x	x
T3	Luftbatteri	0	18	500	Heat sink	x	x	x
T4	Luftbatteri	0	18	1 200	Heat sink	x	x	x
T5	Luftbatteri	0	18	400	Heat sink	x	x	x
T9	Fläkttork TM1	75	115	2 200	Heat sink	x		x
T10	Fläkttork TM2	73	115	3 300	Heat sink	x		x
IND7	Spritkondensor 3	80	50	500	Heat source	x		x
SP2	Färskångväxlare avmetanolisering	84	85	2 000	Heat sink	x		x
SP5-SP7	Kondensor avmetanoliseringskolonn	78	77	1300	Heat source	x		x
Nouryon								
E-8443	Ångbatteri förtork 1, CD 12	17	145	270	Heat sink	x	x	
D-8401	Förtork 1, CD80	75	100	270	Heat sink	x		
E-8437	Ångbatteri förtork 2, CD 12	17	145	270	Heat sink	x	x	
D-8402	Förtork 2, CD80	75	100	240	Heat sink	x		
E-8440	Ångbatteri förtork 3, CD 12	17	150	350	Heat sink	x	x	
D-8403	Förtork 3, CD80	75	100	240	Heat sink	x		
E-8413	Luftvärmebatteri Sluttork	25	145	280	Heat sink	x	x	
E-9403	Ångbatteri Ringtork	30	150	900	Heat sink	x	x	
E-9903	Ångbatteri Kvarntork	35	180	600	Heat sink	x	x	
E-9301/02	Kondensorer R3, kyler reaktorinnehåll	85	50	200	Heat source	x		
E-9303/04	Kondensorer R4, kyler reaktorinnehåll	85	50	280	Heat source	x		

	Kondensorer R5, kyler reaktorinnehåll	85	50	180	Heat source	x		
SEKAB								
	FQ5804 , Ånga D-5804	70	71	505	Heat sink	x	x	
	E-5815-23	200	30	694	Heat source	x		
	Condensor 6126	70	20	3 759	Heat source	x		
	Condensor 6121	70	20	2 855	Heat source	x		
	Condensor 6161	72	20	526	Heat source	x		

Appendix B Estimation of investment costs for heat recovery measures

The investment costs for heat recovery measures were estimated according to the method described in Hackl and Harvey (2013, 2015). The method is based upon the concept of heat exchanger area targeting described in Kemp (2007). The estimated area cost is then used to calculate the equipment cost based on the procedure described in Smith (2016). The procedure is summarized below and illustrated for the site composite curves for the Domsjö biorefinery site (Category A and B utility exchanges, cost-optimal utility loads assuming an available utility mix consisting of district heating, 3-bar steam, 7-bar steam and 22-bar steam).

1. Heat exchanger area targeting

The first step in the procedure is to establish the composite curves of process streams to be heated or cooled, as well as the composite curves of the utility streams assumed to be used to provide heating or cooling, as described in detail in the main section of this report. Thereafter, enthalpy intervals can be defined, such that the composite curve temperature profile is strictly linear for both the utility stream and the process stream in the interval. Figure A-1 illustrates this and indicates enthalpy intervals *i-1*, *I*, and *i+1* for the hot utility and corresponding heating composite.

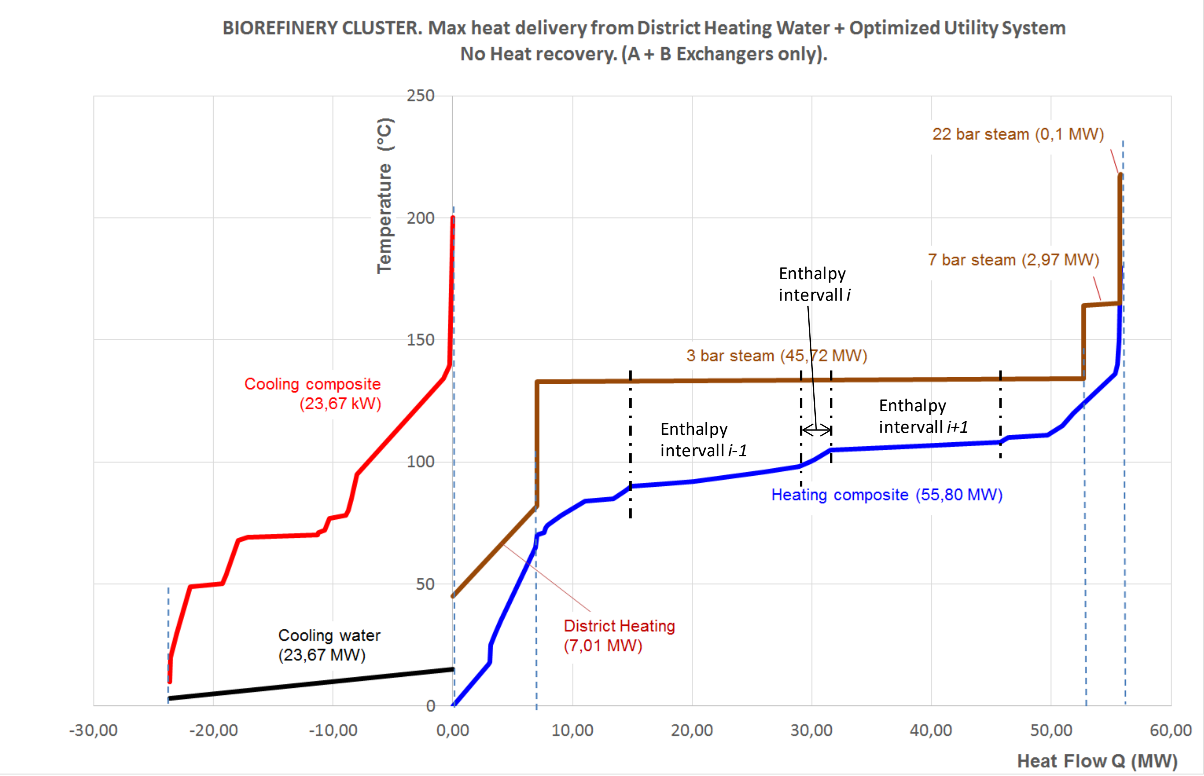

Figure A-27 Definition of enthalpy intervals for heat exchanger area estimation

For each enthalpy interval *i*, the required heat exchanger area A_i for vertical heat exchanging between the utility stream and the process stream(s) can be estimated from eq (A.1)

$$A_i = (\Delta Q_i / U_i) / \Delta T_{LMi} \qquad \text{(A.1)}$$

Where ΔT_{LMi} is the logarithmic mean temperature difference based on the hot and cold stream temperatures that define the interval; ΔQ_i is the enthalpy (heat) flow being transferred within the interval, and U_i is the overall heat transfer coefficient characterizing the streams in the interval. In this study, and average representative value of U=0.5 kW/m^2/K was used for all heat exchange intervals.

Thereafter, the total heat exchanger area required can be determined by summing the areas obtained for all enthalpy intervals, see eq (A.2)

$$A_{tot} = \Sigma_i A_i \qquad \text{(A.2)}$$

2. Heat exchanger cost estimation.

The basic equipment cost for a standard shell-and-tube heat exchanger manufactured using carbon steel (CS) material and operating at moderate pressure and temperature conditions was estimated according to the procedure outlined in Smith (2016).

First, the equipment cost was estimated using eq. (A.3):

$$C_E = C_B \cdot \left(\frac{K}{K_B}\right)^M \cdot CEPCI_{HX} \cdot SEK / US\$ \qquad \text{(A.3)}$$

Where:

- C_E = basic equipment cost for new carbon steel heat exchanger with capacity K [m2] operating at moderate p and T [SEK, 2017 money value]
- C_B = Known base cost [US$]
- K_B = Base capacity [m2] corresponding to C_B
- M = cost scaling factor dependent on equipment type

According to (Smith 2016) for shell-and-tube heat exchangers: C_B = 32800 US$ for K_B = 80 m2; and M = 0.68; for year 2000.

Furthermore, the maximum allowable area per heat exchanger is 4000 m2, if larger area is required an additional heat exchanger must be erected.

The CEPCI index for heat exchangers was used to update costs from 2000 (Index=370.6) to 2017 (Index=591), i.e. $CEPCI_{HX}$ = 591/370.6 = 1.594).

Finally, an indicative exchange rate of 9.1 SEK/US$ was used to convert costs to SEK.

The basic equipment cost C_E can then be adjusted using cost factors to correct for materials of construction, design pressure and design temperature, as well as standard installation cost factors, according to eq (A.4).

$$\begin{aligned} C_{INV} = {} & [f_M \cdot f_P \cdot f_T \cdot (1 + f_{PIP})] \cdot C_E + \\ & (f_{ER} + f_{INST} + f_{ELEC} + f_{UTIL} + f_{OS} + f_{BUILD} + f_{SP} + f_{DEC} + f_{CONT} + f_{WC}) \cdot C_E \end{aligned} \qquad \text{(A.4)}$$

The cost factor values are summarized in the tables below. Note that the table includes a standard cost factor for piping, i.e. more detailed estimated based on physical flows and piping distances were not performed.

Cost factor	Value	Comment
Material f_M	1	Carbon steel
Pressure f_P	1	0.5 – 7 bar(a)
Temperature f_P	1 / 1.6	0 - 100°C / 100 - 300°C
Piping f_{PIP}	0.7	
Equipment erection f_{ER}	0.4	
Instrumentation f_{INST}	0.2	
Electrical installation f_{ELEC}	0	Not relevant for HX network retrofit

Cost factor	Value	Comment
Utilities f_{UTIL}	0	Not relevant
Off-sites f_{OS}	0	Not relevant
Buildings f_{BUILD}	0	Not relevant
Site preparation f_{SP}	0	Not relevant
Design and engineering f_{DEC}	1	
Contingency f_{CONT}	0.4	
Working capital f_{WC}	0	Not relevant

3. Heat recovery network cost estimation

The composite curves used to define the enthalpy intervals in Figure A-1 do not contain information about the number of heat exchangers and how the total heat exchanger area is distributed between these units. The number of exchangers N was determined by analyzing the corresponding stream data. It was assumed, as discussed in Kemp (2007) that the total heat exchanger area A_{tot} is divided equally between the N exchangers. Furthermore, each exchanger's area was increased by 25%, according to standard practice. The cost estimation procedure described above was then applied to all exchangers in order to obtain the cost estimation for the given heat recovery system.

IVL Swedish Environmental Research Institute Ltd.
P.O. Box 210 60 // S-100 31 Stockholm // Sweden
Phone +46-(0)10-7886500 // www.ivl.se