CHALMERS

Total Site Analysis (TSA) Stenungsund

Research Project Report

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Cover:
Satellite view of the chemical cluster in Stenungsund, Sweden

Summary

This project was carried out in cooperation between the Division of Heat and Power Technology at Chalmers University of Technology, CIT Industriell Energianalys AB, AGA Gas AB, Akzo Nobel Sverige AB, Borealis AB, INEOS Sverige AB and Perstorp Oxo AB.

A Total Site Analysis (TSA) was performed in this study which can be used as a basis for future implementations of energy system integration at the chemical cluster in Stenungsund.

At first stream data (T_{start}, T_{target}, Q) and data on overall utility consumption of all the processes in the cluster was collected. The analysis is based on data collected on process streams heated or cooled with utility exceeding a heat load of 300 kW. Additionally steam from by-product incineration which cannot be utilised in another way is considered as process heat.

With this data the current energy system was analysed by determining steam excess and deficit at each steam level and company.

After that, the data was represented in curves, the so called total site profiles (TSP) and the total site composite curves (TSC). The curves were used to determine the site pinch (the limiting factor for further integration) and to identify measures to increase heat recovery.

The measures found by TSA were assessed qualitatively with respect to feasibility to determine the most attractive measures.

Finally the site wide potential for cogeneration and measures for reduction of external cooling demand below ambient temperature was analysed.

<u>Main findings are presented in the following:</u>

From the stream data collected is can be seen that the <u>total demand</u> of hot and cold utility of the cluster is 442 MW and 953 MW respectively.

By-products, which have to be incinerated on-site provide 40 MW of steam. To cover the <u>external heat demand</u> additional 122 MW of heat is supplied by steam/hot oil from boilers or directly by flue gas from added fuels purchased or available on site.

The TSP and TSC curves show a <u>site pinch</u> at the 2 bar(g) steam system (132 °C). The site pinch limits the potential for heat integration. To increase energy savings by heat integration it is necessary to change the position of the site pinch. It was shown that theoretically by introducing a site-wide hot water circuit, increased recovery of 2 bar(g) steam and adjustment steam levels in several heat exchangers the pinch point can be moved so that hot utility savings of 122 MW plus excess of 7 MW steam at 85 bar(g) can be realised.

Only introducing a <u>hot water circuit</u> can save 51 MW of steam from added fuels, which corresponds to estimated savings of 122 MSEK/year. It is possible to replace more steam by hot water, but the demand for 2 bar(g) steam is limited. Therefore a demand for low pressure steam must be created by adjusting steam levels in order to utilise more waste heat in a hot water circuit. The present delivery of heat to the district heating system is not affected by a site wide hot water circuit.

There is potential for increased recovery of 33 MW of 2 bar(g) steam from process heat. This would replace the production of the same amount of steam in the boilers, worth 79 MSEK/year.

A qualitative assessment on the implementation of a hot water circuit shows estimated steam savings of 55.2 MW (132 MSEK/year) with moderate changes (83.5 MW including more complex changes, 200 MSEK/year). Technically the introduction of a hot water circuit includes hot water pipes between several plants, as most of the consumers of heat are situated at the cracker site and at Perstorp but the sources are spread out across the cluster. Also piping is necessary to transfer the 2 bar(g) steam replaced by hot water to other plants with steam deficit.

The practical potential for increased 2 bar(g) steam recovery is estimated to 4.2 MW (10 MSEK/year) with moderate changes and 26.6 MW including more complex changes (64 MSEK/year). Increased 2 bar(g) recovery implies the construction of steam pipes from Borealis to Perstorp and INEOS, as most of the potential steam sources are located at Borealis but Perstorp and INEOS have a demand for 2 bar(g) steam

The theoretical cogeneration potential in the cluster is 19 MW_{el} in addition to the 10 MW_{el} generated today (additional revenue is 40 MSEK/year) assuming that steam demand at all pressure levels remains the same but the steam systems are connected with each other. A practical option to increase cogeneration with the existing equipment is to supply steam below 8.8 bar(g) produced at Borealis to INEOS, Akzo and Perstorp. This would result in additional 8.6 MW_{el} by cogeneration in Borealis turbo-alternator (estimated revenue: 18 MSEK/year).

Some process streams below ambient temperature are heated with steam. It has been shown that 6.5 MW steam is used for heating stream well below ambient temperature. This steam can be saved and the cooling energy can be recovered. This decreases the energy usage in the cooling system and also saves heating steam. Savings up to 48 MSEK/year were estimated.

It has been shown that by site wide collaboration it is possible to increase heat recovery, cogeneration and utilisation of waste heat. The results from this study are the bases to identify concrete projects which contribute to cost and CO_2 emissions savings. The study also shows the advantages of TSA in order to find solutions for process integration by the utility system on a site wide level.

Keywords: Total Site Analysis, Pinch Technology, Chemical Clusters, Area wide process integration, Utility System, Cogeneration

Sammanfattning

Projektet är ett samarbete mellan Värmeteknik och maskinlära på Chalmers, CIT Industriell Energianalys AB , AGA Gas AB, Akzo Nobel Sverige AB, Borealis AB, INEOS Sverige AB och Perstorp Oxo AB.

TSA-analysen (Total Site Analysis) används som en grund för att identifiera åtgärder för att integrera energisystemen vid det kemiska klustret i Stenungsund med syfte att effektivisera energianvändningen.

Analysen började med insamling av data för procesströmmar (T_{start}, T_{target}, Q) och data för totala ånganvändningen för alla processer i klustret. Analysen är baserad på data som samlats in för de procesströmmar som värms eller kyls med värmande och kylande media och har en värmeöverföring som är större än 300 kW. Ånga som produceras med biprodukter som måste eldas på anläggningen räknas som processvärme.

Det nuvarande energisystemet analyserades för att bestämma ångöverskott och ångunderskott vid de olika anläggningarna.

Efter det användes de insamlade värdena för att konstruera kurvor, TSA (Total Site Profiles) och TSC (Total Site Composite curve). Kurvorna användes för att bestämma pinchen (den punkt som hindrar integration) och för att identifiera åtgärder som gör det möjligt att öka integrationen.

En bedömning av de åtgärder som framkom i TSA-analysen gjordes för att avgöra hur de är möjliga att genomföra i praktiken.

Till slut gjordes en bedömning av potentialen för tillverkning av mottrycksel och en analys av åtgärder för att minska det externa kylbehovet för strömmar under omgivningens temperatur.

<u>Sammanfattning av resultatet:</u>

De insamlade värdena visar att det <u>totala behovet</u> av värme och kyla för hela Stenungsundsindustrin är 442 MW respektive 953 MW.

De biprodukter som måste förbrännas lokalt ger ett tillskott på 40 MW ånga. För att täcka det <u>externa värmebehovet</u> så tillförs 122 MW i form av ånga/hetolja från pannor eller direkt som värme från avgaser vid direkt förbränning av bränsle som finns att tillgå i Stenungsund eller bränsle som köps utifrån.

Från TSP- och TSC-kurvorna kan man avläsa att <u>pinchen för siten</u> är vid 2 bar(g)-ånga (132^{o}C). Pinchen begränsar möjligheterna för att integrera energisystemen. För att minska energianvändningen genom integration är det nödvändigt att förflytta pinch-punkten. Genom att introducera en hetvattenkrets, öka genereringen av 2 bar (g)-ånga och anpassa ångnivåerna i ett flertal värmeväxlare så kan pinchen flyttas så att den teoretiska besparingen av värmemedia blir 122 MW plus att det blir ett överskott av 7 MW ånga vid 85 bar(g).

Om man bara installerar ett <u>hetvattensystem</u> så kan man spara 51 MW ånga, vilket motsvarar en beräknad besparing på 122 MSEK per år. Det är möjligt att ersätta mer ånga med hetvatten, men det resulterar i ett överskott av 2 bar(g)-ånga. Därför måste behovet för lågtrycksånga ökas genom att anpassa ångnivåer för andra förbrukare om

mer värme ska kunna nyttjas i ett hetvattenssytem. Dagens leverans av fjärrvärme påverkas inte av att ett hetvattensystem införs.

Det finns en potential för att tillverka ytterligare 33 MW 2 bar(g)-ånga vid kylning av processen. Detta skulle kunna ersätta ånga som produceras i ångpannor och kan värderas till 79 MSEK per år.

Värdering av den praktiska genomförbarheten av ett hetvattensystem visar att man med inte allt för stora ombyggnader kan ersätta 55.2 MW ånga (132 MSEK per år) och med större ombyggnader 83.5 MW ånga (200 MSEK). Tekniskt innebär introduktionen av ett hetvattensystem att hetvattenledningar byggs mellan många av anläggningarna eftersom efterfrågan på hetvatten är störst på Borealis krackeranläggning och Perstorp medan källorna till hetvattensystemet finns på alla anläggningar. Det innebär också att man behöver bygga ångledningar för 2 bar(g)-ånga för att kunna transportera den ånga som sparas till de anläggningar som har ett behov av lågtrycksånga.

Den praktiska genomförbarheten när det gäller mer generering av 2 bar(g) ånga från processvärme är 4.2 MW (10 MSEK per år) för de mindre omfattande åtgärderna och 26.6 MW (64 MSEK per år) om man inkluderar mer omfattande åtgärder. Om mer 2 bar(g) ånga generas i processen så innebär det att det krävs ångledningar från Borealis till Perstorp och INEOS, eftersom den mesta ångan kan genereras på Borealis medan Perstorp och INEOS har behov av 2 bar(g) ånga.

Den teoretiska potentialen för att producea mottrycksel vid Stenungsundsindustrierna är 19 MW_{el} i tillägg till de 10 MW_{el} som genereras idag (vilket skulle innebära 40 MSEK per år) förutsatt att behovet av ånga på olika trycknivåer är detsamma som idag och att ångsystemen är integrerade. Ett praktiskt alternativ för att öka produktionen av mottryck är att hela ångbehovet under 8.8 bar(g), som finns hos INEOS, Akzo och Perstorp, försörjs med ånga från Borealis som kan producera mottrycksel i turbo-alternatorn. Det skulle resultera i ytterligare 8.6 MW_{el} (18 MSEK per år).

Några procesströmmar som opererar under omgivningens temperatur värms med ånga. Det är 6.5 MW ånga som används för att värma strömmar som är långt under omgivningens temperatur. Denna ånga kan sparas och dessutom kan kylan användas för att täcka kylbehov i andra procesströmmar. Detta innebär besparingar i både energi till kylsystemet och ånga. Besparingarna uppskattas till 48 MSEK per år.

Studien har visat att samarbete mellan anläggningar kan öka värmeåtervinning, produktion av mottrycksel och användning av återvunnen värme. Resultatet från detta arbete kan ses som grunden för att identifiera konkreta projekt som bidrar till minskade kostnader och CO_2-utsläpp. Studien visar fördelarna med TSA-analys när det gäller att hitta lösningar för att utveckla gemensamma system för värmande och kylande medier över anläggningsgränser.

Nyckelord: Total Site Analysis, Pinchteknik, Kemikluster, Processintegration, Servicesystem, Mottryckskraft

Contents

Preface

This project was carried out in cooperation between the Division of Heat and Power Technology at Chalmers University of Technology, CIT Industriell Energianalys AB, AGA Gas AB, Akzo Nobel Sverige AB, Borealis AB, INEOS Sverige AB and Perstorp Oxo AB. Financing of the project was provided by the participating companies (60%) including their working contribution and by the Swedish Energy Agency's *Process Integration* programme (40%). The project was conducted between October 15th and May 15th 2010 with Simon Harvey (Professor of Industrial Energy Systems at Chalmers University of Technology) as project leader. The study includes a total site analysis of the chemical cluster in Stenungsund and further investigations on increased energy integration, common utility systems for the participating companies and the cogeneration potential on site.

The following people participated in the study. Jerker Arvidsson at AGA Gas, David Ekeroth and Erik Falkeman at Akzo Nobel, Reine Spetz at Borealis, Kent Olsson, Peter Andersson and Helèn Axelsson at INEOS, Milos Pollard and Lars Lind at Perstorp, Simon Harvey at the Department of Energy and Environment, Chalmers and Per-Åke Franck at CIT Industriell Energianalys.

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Notations

Abbreviations:

Ar	Argon
BA-10	Berolamine-10
CC	Composite Curves
CCS	Carbon Capture and Storage
DEA	Diethanolamine
EDC	Ethane dichloride
EMU	Emulgol
EO	Ethylene oxide
ETBE	Ethyl Tertiary Butyl Ether
GCC	Grand Composite Curve
$\mathbf{H_2}$	Hydrogen
HCl	Hydrogen chloride
HDPE	High density polyethylene
HP	High pressure
HPPE	High pressure polyethylene
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
LP	Low pressure
LPPE	Low pressure polyethylene
MEA	Monoethanolamine
MP	Medium pressure
NaOH	Sodium hydroxide
PE	Polyethylene
PVC	Polyvinylchloride
RME	Rapeseed oil methyl ester
SCN	Steam cracked naphtha
SSSP	Site Source Sink Profiles
STF	Speciality surfactants
TSA	Total Site Analysis
TSC	Total Site Composites
TSP	Total Site Profiles
VCM	Vinyl chloride
VHP	Very high pressure

Symbols:

$\mathbf{Q}$	Heat load
$\mathbf{Q_{cooling,min}}$	Minimum cooling demand
$\mathbf{Q_{cooling,total}}$	Overall cooling demand
$\mathbf{Q_{heating,min}}$	Minimum heating demand
$\mathbf{Q_{heating,total}}$	Overall heating demand
$\mathbf{Q_{rec}}$	Heat recovered
$\mathbf{T_{start}}$	Stream starting temperature
$\mathbf{T_{target}}$	Steam target temperature
$\mathbf{\Delta T_{min}}$	Minimum temperature difference

1 Introduction

The chemical cluster in Stenungsund is Sweden's largest agglomeration of its kind. The main companies involved are AGA Gas AB, Akzo Nobel Sverige AB, Borealis AB, INEOS Sverige AB and Perstorp Oxo AB. The heart of the cluster is a steam cracker plant run by Borealis. Figure 1 shows the material flows between the different companies and plants.

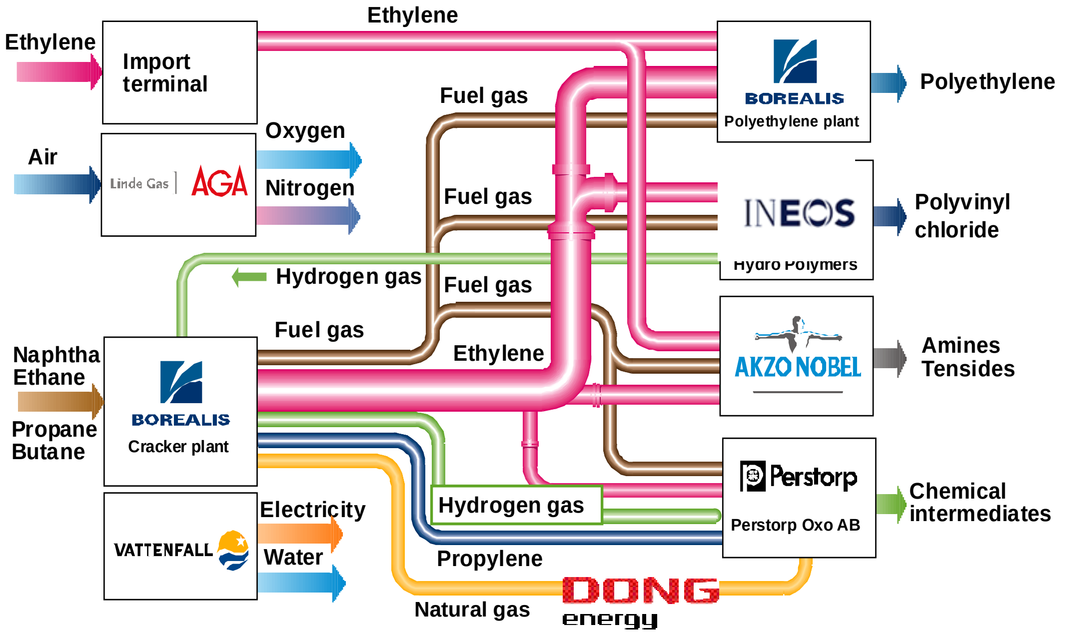

Figure 1 Major material and energy flows in the Stenungsund chemical cluster (Borealis AB 2009)

As can be seen in Figure 1 the companies already interact strongly with each other in terms of material exchange. This cooperation shall be complemented by energy integration throughout the chemical cluster in Stenungsund.

Chalmers has undertaken a number of studies conducted as M.Sc. thesis projects in the area of energy integration in collaboration with some of the participating companies. Such studies have quantified the potential for increased energy efficiency by process integration for some of the participating companies' production sites. Since these studies were mostly limited to single companies, the potential for energy saving by increased intercompany cooperation in terms of energy integration has not previously been addressed.

Site-wide process integration studies within industrial clusters often show large potential for energy savings, on average 20-25% compared to the current energy consumption of the total site (Linnhoff March 2000). Such studies provide the opportunity to analyze integration of additional energy processes making use of the site infrastructure, thereby contributing to an increased overall efficiency of the site. In order to achieve these goals, total site analysis (TSA) can be used as a tool to analyse the energy situation in an industrial cluster. TSA produces targets for the amount of utility used and produced through energy recovery by the different processes. The method enables investigation of opportunities to deliver waste heat from one process to another using a common utility system. It also enables redesign of the utility system for increased efficiency, e.g. adjusting steam levels to fit the site requirements.

2 Objective

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 chemical cluster in Stenungsund. The method is based on identifying process streams that are heated or cooled with utility in order to find possibilities for increased integration between utility systems of the plants.

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 chemical cluster, which can be used as basis for further studies, such as integration of energy-intensive climate-friendly processes such as advanced biorefinery concepts or Carbon Capture and Storage (CCS) for the cluster.

3 Processes and utility systems descriptions

At the first site visit at each company we received a brief presentation of the processes and the utility systems. Below is a short presentation of the included companies. We also defined the process stream data that had to be provided by the companies in order to enable us to perform the total site analysis.

Before initiating the collection of data we decided to limit the number of heat exchangers by only including heat exchangers with a heat load above 300 kW. This was done in order to handle the project within the given timeframe.

To be able to construct the composite curves consisting of process streams and the utility curves the following data was requested from the companies for each heat exchanger with a heat load > 300 kW :

- Name or identification of heat exchanger
- Start temperature of process stream
- Exit temperature of process stream
- Heat exchanger heat load (or data necessary to calculate the heat load)
- Utility used for heating or cooling

Data was requested to be representative for a normal operation situation.

After analysing the collected data we had another meeting at the sites to evaluate the possibility to implement the modifications identified as interesting in order to increase heat recovery from the process and reduce the added fuel demand.

3.1 AGA Gas

3.1.1 Products and processes

AGA Gas is a manufacturer of industrial gases and operates a cryogenic air separation plant in Stenungsund. The plant produces oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2) and argon (Ar) for the local companies and for sale on the market.

In a first stage the air is compressed and then purified by a molecular sieve to remove water and CO_2. Then the incoming feed air is heat exchanged with the outgoing product gases and waste streams in order to recover refrigeration from the leaving streams. After heat exchanging the air has a temperature of app. -175°C before it enters the cryogenic distillation column. Here N_2 leaves as top product while O_2 leaves the column at the bottom. To produce high purity O_2, an Ar rich side stream is removed from the low pressure column. The Ar rich stream can be vented or purified by oxidising hydrogen to water and removing this in a molecular sieve drier. The product streams are routed back to the front end heat exchanger to cool the incoming air and are thereby warmed to near ambient temperature. The liquid products can also be sent to storage tanks, from where liquefied N_2 and O_2 can be loaded on trucks or stored as back-up in case of varying demand at other plants in Stenungsund (UIGI 2009). Industrial CO_2 is produced from a CO_2-rich stream at Akzo Nobel's plant which is purified by AGA.

3.1.2 Utility System

Aga gas has a very low steam consumption and imports 28 bar(g) steam from Akzo Nobel. The steam is reduced and used at a low pressure. Cooling water and an ammonia system is used as external cooling utility. The largest energy consumption is electricity with app. 23 MW for compression of air and product gases.

3.2 Akzo Nobel

3.2.1 Products and processes

Akzo Nobel's site in Stenungsund consists of three plants. The heart of the site is the ethylene-oxide (EO) plant. EO is used as a raw material in the production of among others ethyloxylates, cellulose derivatives, ethanol- and ethylene amines. It is produced by partial oxidation of ethylene. Thereby EO, carbon dioxide (CO_2) and water are formed. The reaction is strongly exothermic. Steam is produced when cooling the reactor. After reaction the EO is dried, purified and sent to storage. Part of the EO is further reacted with water in a glycol reactor to form mono-ethylene glycol as the main product, which is used e.g. as in antifreeze or solvents. The CO_2 is converted into carbonic acid or directly sold to customers.

In the surfactants plant surface agents are produced, which are used in e.g. disinfectants, textile softeners and detergents. Two units, the emulgol (EMU) and speciality surfactants (STF) unit, manufacture over 300 different end-products. The EMU unit converts EO (or propylene oxide) together with fatty amides, amines, alcohols and acids into end-products. The STF unit applies a large variety of reactions generating different groups of surfactants.

The amine plant consists of two main processes. In one process ethanol amines are produced by a reaction between EO and ammonia. After the reaction the products are separated into diethanolamine (DEA), monoethanolamine (MEA) and Berolamine-10 (BA-10). MEA is further converted with ammonia and hydrogen in a catalytic reaction under high pressure and high temperature into ethylene amines in the ethylene amine process. A number of products are leaving the reactor and are purified in several separation units (Akzo Nobel 2004).

3.2.2 Utility system

The steam pressure levels at Akzo are 40, 28, 20 and 6 bar(g). Steam at 40 bar(g) is generated in a boiler fired with fuel gas, imported from Borealis and in a waste incinerator where by- products are fired. There is another boiler that delivers steam to the 28 bar(g) system. 20 bar(g) steam is generated from heat recovery from cooling of exothermic reactors.

Akzo recovers heat in an internal hot water system that operates between 65-85˚C. Sea water is used to cool the processes and cooling compressors are used to cool ethylenoxid storage below ambient temperature. In 2011 the cooling compressor system will be replaced by internal cooling energy from Akzo's ammonia terminal where ammonia is vaporised.

3.3 Borealis

3.3.1 Products and processes

Borealis is a supplier of plastic material for wires and cables, pipes, automotive and advanced packaging. In Stenungsund two Borealis sites are in operation. A cracker plant produces olefins and three polyethylene (PE) plants produce different qualities of PE used primarily for pipes, wires and cables. The cracker plant provides the feedstock to the Borealis PE plant, and to other companies present in the Stenungsund chemical cluster.

The nine cracking furnaces in the cracker plant convert a feedstock of naphtha, ethane, propane and others into unsaturated hydrocarbons, hydrogen, fuel-gas, cracked gasoline and heavier products. The different products from the cracking processes are separated downstream mainly by distillation, cooling, compression and further reactions before being stored in tanks or directly delivered to customers. ETBE is produced from a share of butylene/butadiene leaving the cracking furnaces in another plant. Table 1 shows the inputs and outputs from the cracker plant for the year 2008.

Table 1 Feedstock consumption and production of the cracker in 2008 (Borealis AB 2009)

Feedstock	[ktonnes/year]	Product	[ktonnes/year]
Naphtha	298	**Ethylene**	565
Ethane	321	**Propylene**	174
Propane	286	**Other (incl. fuel gas)**	424
Butane	268	**ETBE**	16
Ethanol	7		
Off-gas	3		

The PE area consists of three low pressure units (LPPE) based on a catalytic polymerization in gas phase and loop reactors to manufacture High Density PE (HDPE) and Linear Low Density PE (LLDPE) and a high pressure process (HPPE) producing low density PE (LDPE). In the low pressure units the incoming raw materials are cleaned before entering a circulating gas reactor. The reaction is exothermic. Circulating gas is cooled in water or air coolers respectively. One of the units works with the PE3 Borstar process which produces bimodal[1] HDPE (Spetz et al. 2006). The PE3 Borstar plant additionally contains two loop reactors (pre-polymerisation and main loop) and gas recovery facilities where unreacted raw material are purified and fed back to the process.

The current high pressure process will soon be phased out and replaced by another high pressure plant which will start operation in 2010. In the 5-stage primary and 2-stage hyper compressor the ethylene together with moderators is compressed up to 3200 bar. Recovered ethylene from the process is recompressed in the first two stages of the primary compressor and the mixed with fresh ethylene and additives. Process gas is pre-heated to 150-180°C. Polymerisation takes place at max. 350°C. After the reactor the product is cooled and separated from unreacted ethylene in a high and low

[1] *A multimodal polymer includes more than one molecular weight fraction. Properties can be better adjusted to specific applications (Whiteley 2000)*

pressure separator and the degassing silos. High pressure ethylene is cooled and separated from waxes before entering again the hyper-compressor. The low pressure ethylene is separated from waxes, cooled and fed to the primary compressor. The separated PE goes to the extruder line where it is further processed into pellets and sent to storage (Meyers 2004, chap.14).

Table 2 shows the inputs and outputs from the PE units for the year 2008.

Table 2 Feedstock consumption and PE production in the PE units in 2008 (Borealis AB 2009)

Feedstock	[ktonnes/year]	PE production per unit	[ktonnes/year]
Ethylene	444	**High Pressure PE (LDPE), to be phased out in 2010**	150
Propylene	0.132	**Low Pressure PE (HDPE)**	93
Co monomer	8.57	**PE3 Borstar, (HDPE)**	206
Additives	4.3	**New HPPE plant (LDPE), future production**	350[2]
Master batch	17.3		

3.3.2 Utility system

Fuel gas is used to heat the cracker furnaces, the steam boilers, the pilot gas system to the flares and the hot oil furnace. The fuel gas used consists of by-products from the cracking process, the ETBE production and if necessary natural gas, ethane and propane.

The steam pressure levels at the cracker plant are 85, 8.8, 2.7 and 1.8 bar(g). Steam at 85 bar(g) is generated by cooling the cracking products and in steam boilers. By expanding 85 bar(g) steam to 8.8 bar(g) several turbines are driven. The 8.8 bar(g) steam is mainly used as direct steam to the cracking furnaces, for heating purposes and as driving steam for turbines in the cracker plant. The back pressure of the turbines is 1.8 bar(g). This steam is used to supply heat to the cracker and in the deaerator of the boiler feed water system. In a 2.7 bar(g) steam system heat is recovered from the quench oil coolers after the cracking furnaces and delivered to several reboilers. Hot oil is heated in a furnace to 277°C and supplied to the SCN unit (Hedström & Johansson 2008).

The steam levels at the PE plant are 40, 11, 4 and 3 bar(g). 40 bar(g) steam imported from the cracker and produced in a boiler by incinerating by-products. 11 bar(g) and 4 bar(g) steam is recovered from the new HPPE and used at the PE plant. Excess steam can be exported as 4 bar(g) steam to the cracker plant. 3 bar(g) steam covers most of the heating demand of the LPPE units.

Sea water and air are used for external cooling at the cracker plant. As the products from the cracker process have to be cooled significantly below atmospheric temperature two refrigeration systems (ethylene and propylene) are operated each generating three different temperature levels. The propylene system operates at 9°C, -21°C and -40°C. The ethylene system used for even further cooing works at -62°C, -84°C and -100°C (Hedström & Johansson 2008). Cold utilities at the PE plant are fresh water from cooling towers and air.

[2] Annual capacity

3.4 INEOS

3.4.1 Products and Processes

INEOS ChlorVinyls in Stenungsund produces chlorine, sodium hydroxide (NaOH), hydrochloric acid (HCl), hydrogen, ethane dichloride (EDC), vinyl chloride (VCM) and polyvinylchloride (PVC) in three different plants. Table 3 shows the production of the different products in 2008.

Table 3 Production of INEOS products in Stenungsund 2008 (Josefsson 2009)

Product	[tonnes/year]
Chlorine	112 363
NaOH	125 832
HCl	24 602
Hydrogen (sold)	295
VCM	130 933
EDC	37 365
S-PVC (hard products)	130 565
P-PVC (soft products)	68 916

A chlorine plant converts sodium chlorine into chlorine, hydrogen and sodium hydroxide in an electrolytic amalgam-process. NaOH is mostly used in paper pulp manufacturing. Most of the hydrogen is combusted to produce steam, but some is sold to other companies.

The chlorine is used as feed together with ethylene in a vinyl chloride plant to produce EDC and VCM. EDC is produced in two ways. One part comes from the reaction of chlorine and ethylene to EDC. Another process uses ethylene and HCl as feed. After both processes EDC is separated and sent to a cracking furnace where a thermal conversion to VCM takes place. After cracking the VCM is purified and sent to storage.

VCM is the monomer of PVC. The polymerisation takes place in batch reactors. The reactors are charged and then heated to 45-75°C (Allsopp W. & Vianello 2009). After the polymerisation (exothermic) started the vessels are cooled to maintain a constant temperature of 40-60°C. In the next step the solid PVC is separated from unreacted VCM, which is reused in one of the reactors. PVC is then dried by different processes and sent to storage (Josefsson 2009).

3.4.2 Utility system

The steam pressure levels at INEOS are 28, 20, 10, 6 and 1 bar(g). 28 bar(g) steam is generated in a boiler that can be fuelled with gas or oil. A boiler at 20 bar(g) is fired with by-products from the process. Steam at 10 bar(g) and 1 bar(g) is generated with process heat. There is also a 6 bar(g) steam system.

Direct firing of fuel gas is used for cracking and drying processes.

Cold utility is cooling water (sea water), cooled cooling water and a propylene cooling system. The cold cooling water is operated at 4-7°C and the propylene cooling system at -40°C.

3.5 Perstorp Oxo

3.5.1 Products and processes

Perstorp Oxo AB is a manufacturer of speciality chemicals with production sites in Nol and Stenungsund. A large part of the production is iso- and n-butylaldehyde, which is an intermediate in the production of polyols applied in water based colours and coatings, security glass and softeners in vinyl products. Waste heat from the site in Stenungsund is delivered to the local district heating system which distributes heat to apartments, houses and community buildings.

Synthesis gas is an important building block in processes at Perstorp Oxo. It consists of 50 % CO and 50 % H_2. In a synthesis gas generator methane is partly oxidised at 1400°C and 40 bars. After the reactor the synthesis gas is cooled in several steps. Major part of the heat is used to produce 40 bar(g) steam which is used to heat other processes. Some of the H_2 is separated from the synthesis gas and used in other hydration processes.

In two reactors aldehydes are catalytically produced from synthesis gas, H_2, ethylene and propylene. In three distillation columns the products are separated after the reaction before they are sent to storage. Some of the aldehydes are sold directly while others are processed further to e.g. softeners, colours and coatings.

Among other products, like octanoic acid (component in plastic films) and propionic acid (preservative agent) Perstorp manufactures rapeseed oil methyl ester (RME), which is used as vehicle fuel and glycerol an additive in food production in its' RME plant (Pollard 2010).

3.5.2 Utility system

The steam pressure levels at Perstorp are 41, 20, 14, 7 and 2 bar(g). Steam at 41 bar(g) and 14 bar(g) is generated in boilers fired with fuel gas and by-products from the process. Steam to the 41 bar(g) system is also supplied from a waste heat boiler, where heat from the process is recovered. 2 bar(g) steam is generated from process waste heat.

Perstorp recovers heat from the processes in a hot water system that operates between 40-120^{o}C. The heat is supplied to other parts of the processes and up to 15 MW are delivered to the district heating system of Stenungsund.

Fresh water from cooling towers and air coolers are used as cold utility.

4 Methodology

4.1 Pinch Analysis

4.1.1 General

Streams in industrial processes often have to be either heated or cooled in order to fulfil the process requirements. Therefore energy is added or removed respectively. This is achieved by heat exchange with hot and cold utility streams or by transferring heat between hot process streams, which have to be cooled and cold process streams which have to be heated. In order to do this in an energy-efficient way, pinch technology can be applied to design a heat exchanger network. This tool among others consists of tools and methods to quantify the minimum heating and cooling requirements of a process, define the optimal utility levels, design heat exchanger networks, estimate the cogeneration potential or heat and power integration and gives guidance for the thermal integration of equipments like e.g. distillation columns. The method is used both in grass-root and retrofit projects.

The basic principle of pinch analysis is that heat withdrawn from a process or stream operating at high temperature can be used to heat another stream with a heat demand at a lower temperature. A temperature, the so called pinch-temperature is defined as the temperature above the process has an energy deficit. Below the pinch temperature the process shows a surplus of energy. From this definition the 3 “golden” pinch rules can be derived.

- Don’t transfer heat through the pinch
- Don’t withdraw heat above the pinch
- Don’t add heat below the pinch

If these rules are broken, one commits a so-called pinch rule violation, which leads to an increased energy use compared to the minimum demand.

Pinch analysis is used to determine:

- The minimum heating and cooling demands for the process
- The maximum possible internal heat recovery
- Temperature level of the pinch point which provides useful information for designing a cost-effective optimised heat exchanger network
- Guidance for selection of appropriate process hot and cold utility
- Guidance for the integration of energy-intensive unit operations, e.g. distillation columns
- Identification of possible uses of low grade waste heat (Kreith & Goswami 2007, chap.15)
- Guidance for integration between different processes or sub-processes

For a retrofit case the following steps are performed during a pinch analysis:

- Definition of the stream system
- Gathering stream data from appropriate sources (T_{start}/T_{target}, heating/cooling loads)
- Definition of the minimum temperature difference for heat exchange ΔT_{min}

- Perform pinch calculations using appropriate software (e.g. Pro-Pi[3])
- Determine minimum hot and cold utility demand and potential for maximum internal heat exchange: Composite Curves (CC) and Grand Composite Curve (GCC) are constructed
- Determine the present heating and cooling demand from available process data
- Suggest new solutions for heat exchangers networks to eliminate pinch violations.
- Calculation of investment costs of suggested changes and analysis of economic performance of different options (Franck 1997)

4.1.2 Composite curves

When performing a pinch analysis one combines the temperature characteristics of all cold streams in order to construct a single composite curve. The same is done for all hot streams. Both composite curves are plotted together in one diagram, which shows the temperature versus the heat flow (T-Q-diagram). The region where the two curves overlap shows the potential heat recovery from the process. The diagram also shows the minimum heating and cooling demand ($Q_{H,min}$ and $Q_{C,min}$) of the system for ΔT_{min}. This is shown by the non overlapping areas in the diagram in Figure 2. The point where the distance of the curves on the temperature axis is ΔT_{min} is the pinch point. If the two curves intersect, the cold composite curve has to be shifted to the right, to maintain ΔT_{min}. This decreases the potential internal heat exchange and leads to higher utility consumption.

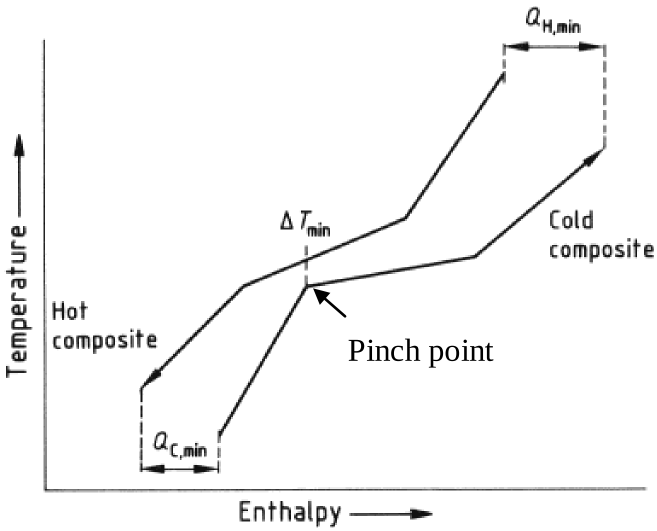

Figure 2 Composite curves showing the Pinch point and the energy targets (Linhoff & Sahdev 2002)

4.1.3 Grand Composite Curve

Another diagram derived from the stream data and used in pinch technology is the GCC. The whole process is divided in temperature intervals. The diagram shows the heat supply and demand in each of these temperature intervals. A positive slope

[3] Software developed by CIT Industriell Energianalys AB. $T_{start,}$ T_{target}, flowrate, cp and Q of all the streams are fed into an Excel sheet and the program calculates minimum heating/cooling demand, pinch temperature and constructs among others CC and GCC curves (Hedström, et al., 2008).

indicates a heat demand, a negative a heat surplus. This surplus can be transferred downwards the cascade to streams with heat deficit. It is amongst others used for e.g.

- Determining the utility levels and demands of e.g. exhaust gases, steam and cooling water
- Determining the potential for steam production, district heating and other energy recovery measures
- Integration of energy intensive unit operations, e.g. distillation columns
- Integration of heat pumps

Figure 3 shows an example of a typical GCC with suggestions for utility levels, internal heat exchange (pockets) and steam production (Smith 2005, p.373).

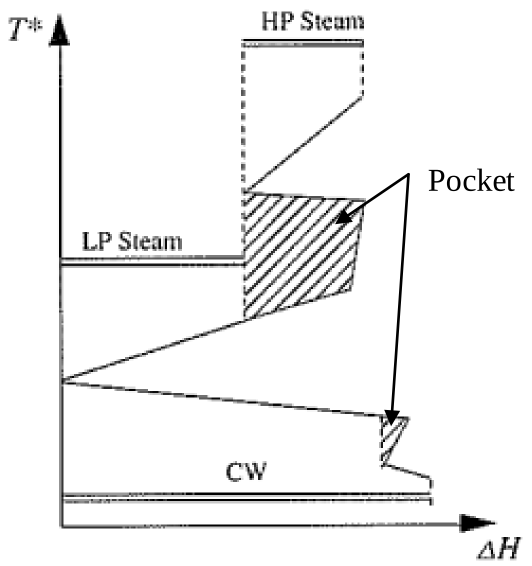

Figure 3 Grand Composite Curve (GCC) with hot/cold utility levels and internal heat exchange

The final goal of a pinch study is to maximize the energy efficiency, reduce the costs and enhance the overall environmental performance of a single or a whole set of industrial processes.

In this study pinch technology is used to identify the minimum heating and cooling demand of each plant to give an overview of the potential energy savings. Later GCC is e.g. used to determine the minimum added steam demand in a common system at the total site.

4.2 Total Site Analysis (TSA)

4.2.1 Choosing level of detail of the total site analysis

TSA is used 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) (Bagajewicz & Rodera 2001) and then passed to processes with a heat deficit by the common utility system. With the tool 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 cogeneration potential can be determined. (Simon Perry et al. 2008).

The process data collected can be divided into three different groups according to the level of detail of the analysis and the availability of process data.

- Black box approach:

  Unlike in regular Pinch Analysis, where process streams are characterized by their starting temperature T_{start}, target temperature T_{target} and heating/cooling loads, in the black boxes approach the process is represented by its utility demand only. E.g. if a process consumes 2000 kW of 3 bar(a) steam it is represented by this heat load at the corresponding steam temperature. Other uses of steam such as steam tracing or tank heating can be represented as black boxes. Steam consumers not included in stream data collected in this study were handled by this approach.

- Grey box approach:

  This approach considers the process-utility interface and ignores process-process heat exchange. This means, that process streams which are heated/cooled by utilities are considered in the analysis by their starting temperature T_{start}, target temperature T_{target} and heating/cooling loads. This implies that the current level of integration within the single units is not changed, but enables to identify changes in the utility system, e.g. producing hot utility instead of cooling a sufficiently hot process stream with CW, or changing utility levels to match the total site profiles. This approach is used for the analysis described in 4.2.3 to 4.2.7.

- White box approach or Detailed Pinch

  According to this method a detailed pinch analysis of the plant is carried out, including the process-process heat exchangers. In this analysis the conventional Composite Curves (CC) and the Grand Composite Curve (GCC) are constructed. Thereby the optimum hot and cold utility demand can be determined for each plant. The profile of the GCC above the pinch point represents the heat sink, below the pinch point the sources of heat are represented for each of individual process (Brown 1999).

4.2.2 Graphical representation of the current steam systems

Currently the steam systems of the different plants are not connected, it is suggested to first investigate possibilities to find ways to integrate the plants steam systems. As most of the steam headers are not connected thus site wide integration is not possible. Therefore the potential exchange of steam across the total site' steam systems is investigated.

Amounts of steam generated and consumed at each steam level are therefore taken from the process stream tables. Only steam generated in the processes is taken into account to determine the minimum amount of steam necessary to be produced in the boilers if optimal distribution of steam across the total site is applied. Steam produced is balanced with steam consumed at each plant and pressure level. This gives the amount of heat excess/deficit at each utility level for each plant and enables to find utility exchange possibilities at the total site. Excess and deficit are represented graphically as shown below in Figure 4.

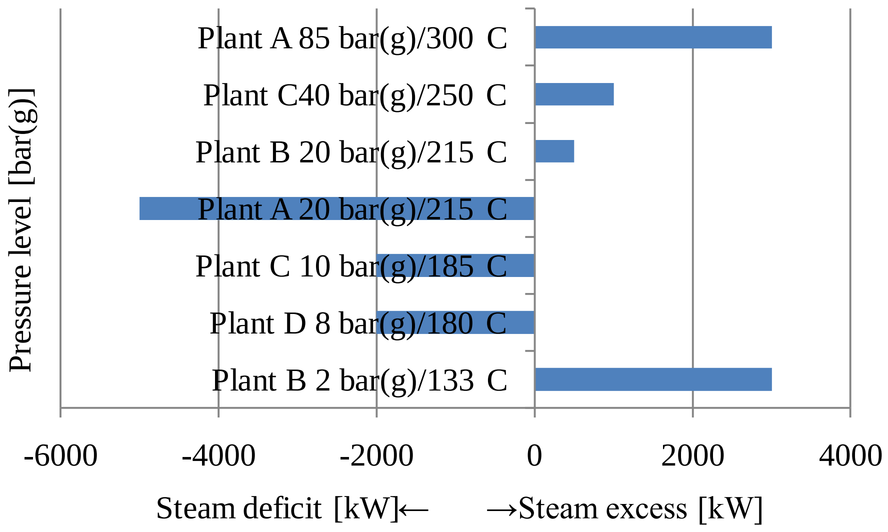

Figure 4 Graphical representation of steam excess and deficit at each plant and pressure level

It is hereby suggested to use pinch analysis to determine the heating and cooling demand (see GCC in Figure 5) in the steam system, where excess of steam at one pressure level is considered as hot stream and deficit of steam as cold stream. $Q_{heating}$ is the demand of steam that has to be added from the boilers to cover the total steam demand. The GCC also shows the steam levels at which the deficit and excess exists (illustrated in Figure 5) and can be used as guidance for optimal distribution of steam across the total site. Excess of steam can be sent to other plants or used for future expansions of the site.

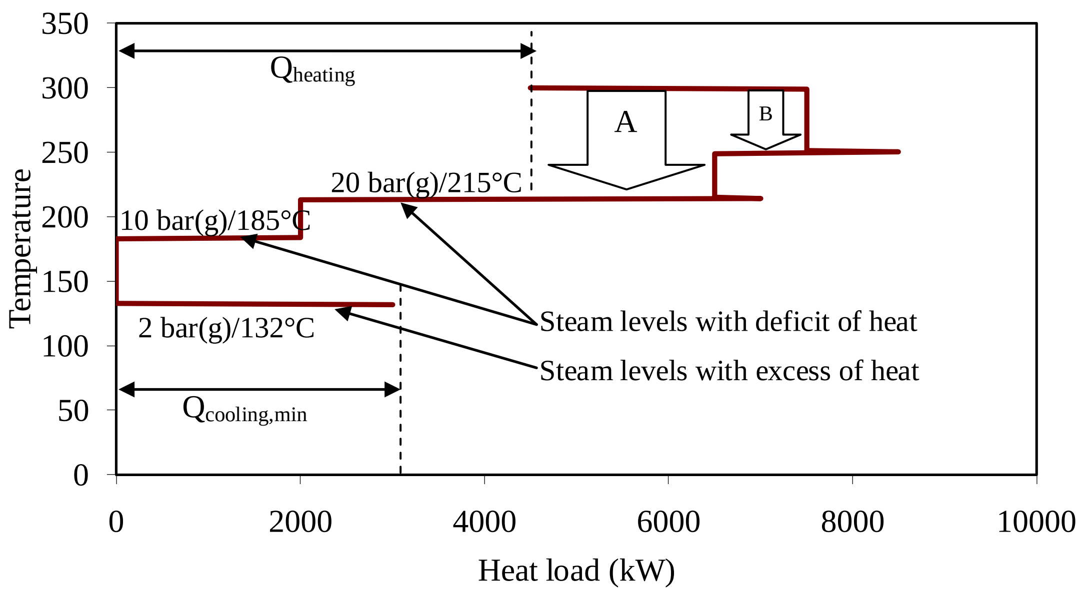

Figure 5 GCC of the steam system to determine the minimum added fuel demand in the boilers

To reach this minimum steam demand a steam distribution network is developed, which enables maximum steam utilisation. Options for transferring steam between the companies and pressure levels in order to increase energy savings are developed with help of diagrams like Figure 4 and Figure 5.

The arrows, A and B, show how steam recovered from the process can be transferred between steam levels. Steam expansion can also be done in turbines for cogeneration. Steam added to the system from the boilers ($Q_{heating}$) can be produced at a defined pressure and then expanded to the steam levels with deficits (10 an 20 bar(g) in the example). This expansion can also be performed in a steam turbine and generate electricity.

4.2.3 Representing the process streams with site source sink profiles (SSSP)

To identify more significant improvements the "grey box"-approach is applied, complemented by additional steam consumption not gathered in the stream data. This demand is represented in the curves as the amount of utility consumed with process temperatures corresponding to the utility temperature ("black box"-approach). Increased process integration will only be possible by changes in the utility system. In order to complement the study with steam demand that is not covered by the stream data gathered in this study the "black box"-approach is used.

The plants analysed produce a considerable amount of by-products, which have to be incinerated. Thereby steam is produced. Since this steam is indirectly generated by the process the flue gases from the incineration is included in the curves as a hot stream, cooled with boiler feed water.

Figure 6 shows an example of a SSSP, where the red line represents the sources of heat (streams that have to be cooled) and the blue line represents the heat sinks (streams that have to be heated).

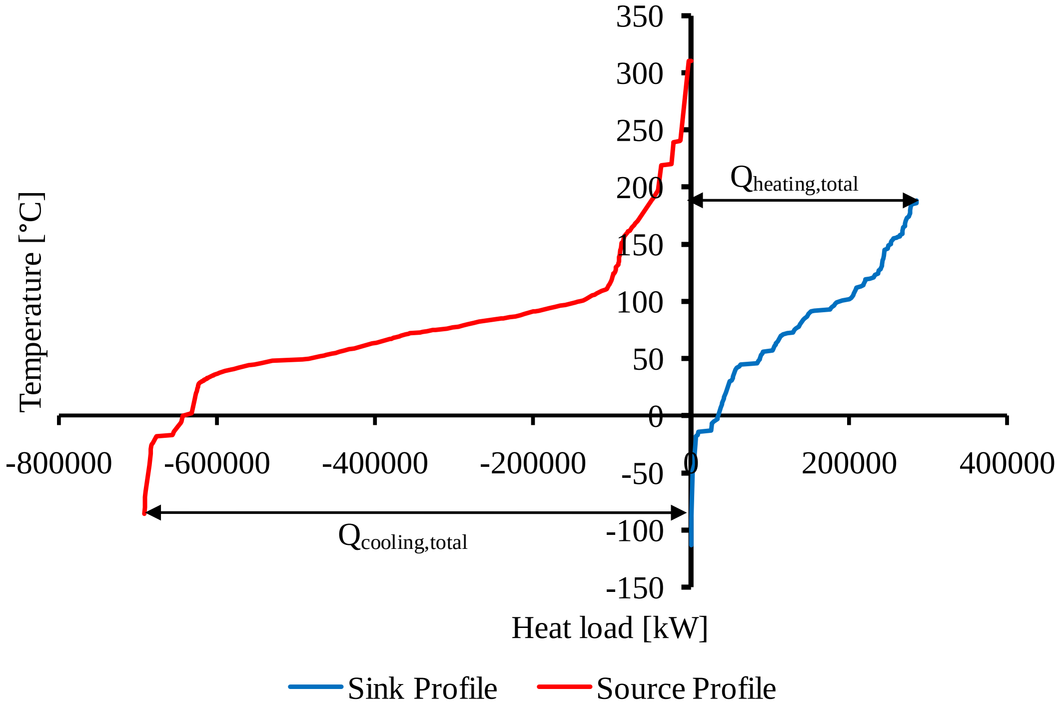

Figure 6 Example of a SSSP

Here the total heating and cooling demand of the total site can be determined.

4.2.4 Analysing utility use with total site profiles (TSP)

In addition to the process source/sink profiles the utility profiles can be plotted in the SSSP diagram. This enables to analyse how heat is supplied to and discharged from the processes and makes it possible to develop improved solutions for energy recovery and cogeneration. By combining the SSSP and the site utility profiles the so called total site profiles (TSP) are obtained shown in Figure 7 to the left. The source profile, the cold utility curve, the hot utility and sink profile are shown. The utility profiles represent the amount heat supplied to or discharged from the process at the different utility temperature levels. They are developed from process stream lists by allocating the utilities used to cool/heat each process stream.

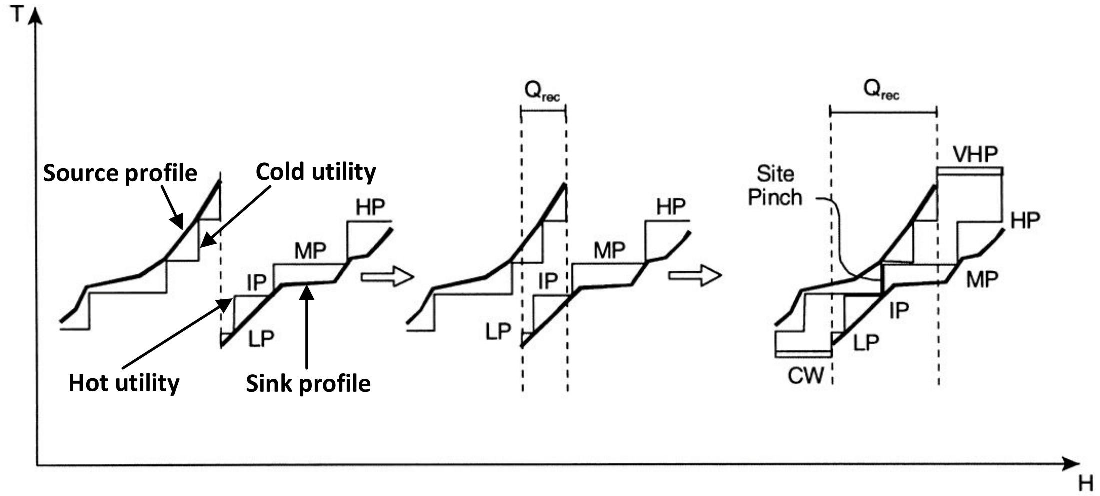

Figure 7 Total Site Profiles (TSP) and Total Site Composites (TSC) (Zhu & Vaideeswaran 2000)

These profiles represent the interaction of the process heat sources and sinks with the site utilities. It also shows the total sites' heating and cooling requirements and the utilities used to satisfy those requirements.

4.2.5 Determine heat demand with total site composites (TSC)

In order to find the maximum amount of heat recovery for the total site by the utility system the total site profiles are moved towards each other until the hot and the cold utility curve intersect in one point, see Figure 7 to the right. This point is the so called site pinch which limits the heat that can be recovered by the utility system (Zhu & Vaideeswaran 2000). These curves can be used to optimise the total site heat integration through the utility system by changing the utility levels to match better the process requirements and thereby increasing the overlap between the curves.

The remaining minimum heating demand ($Q_{heating}$) shown as very high pressure steam (VHP) in Figure 7 has to be added externally as hot utility. $Q_{heating}$ therefore directly relates to the fuel requirement. The cooling demand, shown as cooling water (CW) represents the amount of heat that has to be discharged from the processes to the atmosphere. Here excess heat is removed from the process by cooling media. The TSC can be used to determine the minimum necessary amount of steam produced in the boilers, potential heat recovery and cogeneration (J. Klemes et al. 1997).

4.2.6 Identifying improvements to the utility systems

After investigating the potential for energy savings by integrating the current utility levels, improvements by changing utility levels and introducing new ones are investigated. The profiles determined by TSA are used to investigate options to optimise the utility system. In order to increase energy recovery (save fuel) the site pinch has to be shifted. This is done by shifting utility loads as shown in Figure 8 where a new steam mains is introduced which distributes recovered steam to consumers. Changes and their effects on the overall energy situation at the total site are described. Examples for changes in the utility system are:

- Replacing steam by introducing a hot water circuit (Bagajewicz & Rodera 2001)
- Introduction of new steam mains
- Steam generation at higher levels
- Steam use at lower levels (Raissi 1994, chap.9)

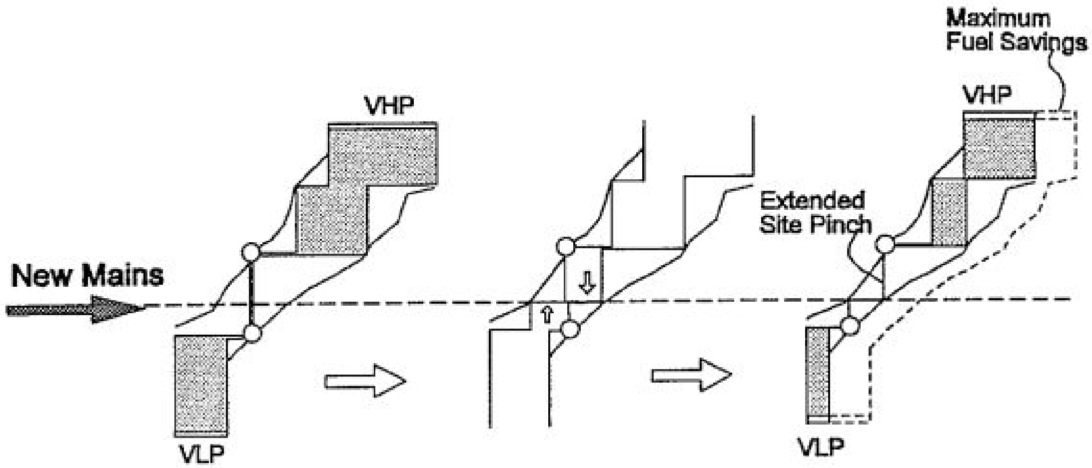

Figure 8 TSC illustrating increased energy savings by modifications to the utility system, here e.g. introduction of new steam mains (Raissi 1994, chap.7)

The grey shaded boxes indicate cogeneration potential. Figure 8 shows how energy savings resulting in lower steam demand will reduce the cogeneration potential.

4.2.7 Assessment of potential energy savings accounting for practical constraints

After identification of possible changes to the utility system the practical potential for energy savings by changes in the utility system is assessed by discussions with process engineers at the respective site. The modifications options identified using the TSA analysis are qualitatively assessed using a grading system with three stages is applied:

A. possible: no practical constraints, moderate investment costs are expected
B. possible, with constraints: several or more complex changes are necessary, higher investment costs are expected
C. impossible: process constraints make changes impossible

The categories do not include any quantification of cost and the resulting practical potential has to be investigated further to find the economic potential.

By applying this grading system, a more practical potential for energy savings by changing the utility system is presented.

4.2.8 Quantifying impact of energy efficiency measures on cogeneration potential.

Steam is produced in boilers at a high pressure. The steam can be delivered at a lower pressure either by expanding the steam through a throttle valve or via a turbine.

If the steam is throttled there is no enthalpy loss and the steam at the lower level will be superheated. Since saturated steam should be used for heat transfer processes the steam should be desuperheated. The steam is desuperheated by adding boiler feed water that will evaporate and extra steam will be generated.

If the steam pressure is reduced via a turbine, electricity can be cogenerated, which is an energy efficient way to produce electricity if a heat demand is at place.

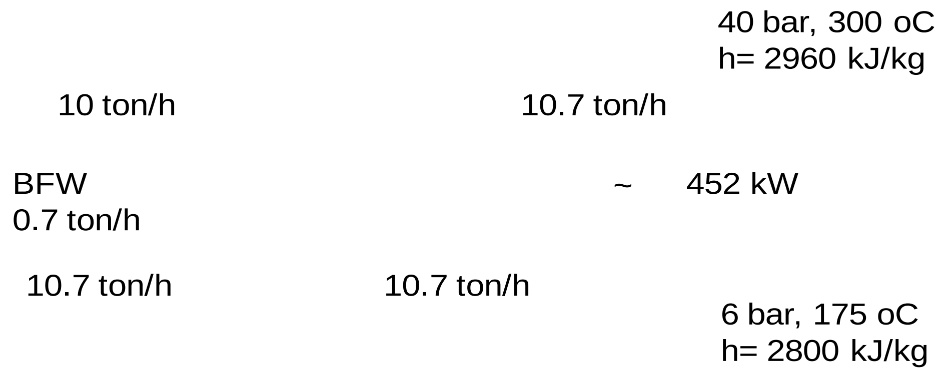

Figure 9 Example of how different ways of expanding steam between two pressure levels in the utility system either can generate more steam when the steam is expanded through a valve or generate electricity if the steam instead is expanded through a turbine.

Figure 9 shows the difference when steam is changed from one state to another along two different routes. In the first case, superheated boiler steam is throttled to utility pressure. Boiler feedwater must be mixed with the throttled steam in order to achieve "desuperheating", resulting in a higher steam flow. In order to end up with the same amount of utility steam to cover the process demand, more steam has to be produced in the boiler in the second case where steam is expanded through the turbine. This extra steam is converted to electricity with high efficiency.

The cogeneration potential is calculated with the following assumptions:

- High pressure steam properties: 85 bar(g) and 460 ^{o}C
- Steam from internally generated steam at 40 bar(g) is assumed to be superheated to 350 ^{o}C
- Steam in headers is superheated by 20 ^{o}C .
- When electricity is produced in a condensing turbine, the back pressure is 0.1 bar(a).
- Isentropic efficiency: η_{is} =0.8
- Electrical and mechanical efficiency in the generator : $\eta_{gen=}$0.95

5 Results

This section starts with a description of the current utility system.

To identify improvement to the utility sytem, the total site is analysed using two different approaches.

In the first case, presented in 5.2.1 the current steam system is analysed with the methodology shown in 4.2.2. The following assumptions are taken:

- Steam systems with current pressure levels and consumptions
- No changes of heat exchanger operation.
- Loads and utility levels are unchanged.
- Exchange of steam between plants is considered as a possible option.

In the second case, presented in 5.2.2, total site curves are developed using the grey box approach. The data for the heat exchangers with > 300 kW duty is represented with the gathered process data and additional steam consumption is represented in the TSA curves as the amount of utility consumed. The stream temperatures correspond to the utility temperature of the additional steam consumed ("black box"-approach). This analysis has the goal to identify:

- Modified utility system
- Changes of heat exchanger operation to recover maximum amount of heat.
- Introduction of new utilities and/or shifting of loads between utility levels.

In 5.3-5.5 the identified changes are discussed in terms of practical potential, cogeneration potential and finally a discussion about process streams below ambient temperature.

5.1 The current utility system

Heat to the processes is provided by steam, fuel gas, hot oil and hot water. Most of the heat is provided by steam and thus the analysis in 5.1.1 focuses on the steam system.

5.1.1 Steam production

An overview of steam production and use is given in Table 4. 73 % of the steam is generated from process heat and by incinerating by-products that must be incinerated on site. The rest has to be produced in boilers. All plants except AGA have boilers. Steam production is divided into three different groups:

Steam from excess process heat – Steam produced when cooling process streams with boiler feed water. The calculation is based on collected heat exchange data or available steam data.

Steam from by-product incineration – Some by-products have to be incinerated on site and are used for steam production. The fuels in this category cannot be sold or exported as fuel. Calculations are based on data from site visits.

Steam from added fuel –Added fuel is fuel produced on site Stenungsund (excluding the by-products above) or external fuel imported to Stenungsund. This steam production is calculated as the difference between the total steam production and the production from process heat + by-product incineration.

Total steam production – The sum of all steam production.

The steam production at different plants is presented in Table 4.

Steam used in steam turbines has to be calculated separately to exclude the energy that is transformed into shaft power in the turbine. When steam turbines are used *to drive process equipment*, the available amount of steam is calculated as the steam exiting the turbine and being available for heating purposes. Thus the energy converted into mechanical energy is excluded. However, *steam used in turbines for electricity cogeneration is not excluded* and is considered available for other uses.

5.1.2 Steam use

The consumers of heat included in stream data (heat load >300 kW) uses 80 % of the steam produced. The exclusion of smaller steam demands has been necessary in order to handle the project within the given timeframe. Most of the heat demands are calculated from heat exchangers, but direct steam injection is also included.

The fact that steam used for turbines which drive process equipment is excluded, limits the analysis since the current use of steam to turbines is accepted.

For steam consumers <300 kW the steam demand is included in the analysis as described in 5.1.3.

The data for the different plants at the site are listed in Table 4.

Use in heat exchangers >300 kW - Taken from the collected data for users >300 kW. To estimate the steam use, the duty in the heat exchangers is used. Thus the exit pressure and temperature of the condensate is not known.

Other use of steam – Calculated as the difference of total steam production and steam consumed in heat exchangers collected in this study (>300 kW). In this case the steam condensate is assumed to be cooled to 120 ^{o}C for higher pressure steam (>2 bar(g) and 100 ^{o}C for low pressure steam ($\leq$ 2 bar(g)).

Table 4 Total steam production, fuel demand and steam demand based on stream data and steam balances for the chemical cluster in Stenungsund

	Steam production [MW]					Steam use [MW]	
Site	**Excess process heat**	**Steam from by-product incineration**	**Steam from added fuel**	**Total steam production**	**Steam from added fuel**	**Use in heat exchangers >300 kW**	**Other use of steam**
AGA			0	0		0	
Akzo Nobel	26	6.4	25	57	42 %	44	14
Borealis Cracker	141		32	173	18 %	154	19
Borealis PE	35	4.0	2	41	4 %	11	29
INEOS	14	2.6	22	39	57 %	24	15
Perstorp	25	27	27	79	34 %	76	4
Sum	241	40	108	389	27 %	309	80

5.1.3 Handling of other steam users

Other users of steam – steam not accounted for in the stream data gathered – is calculated as the difference of total steam production and the steam use in heat exchangers >300 kW, as shown in Figure 10.

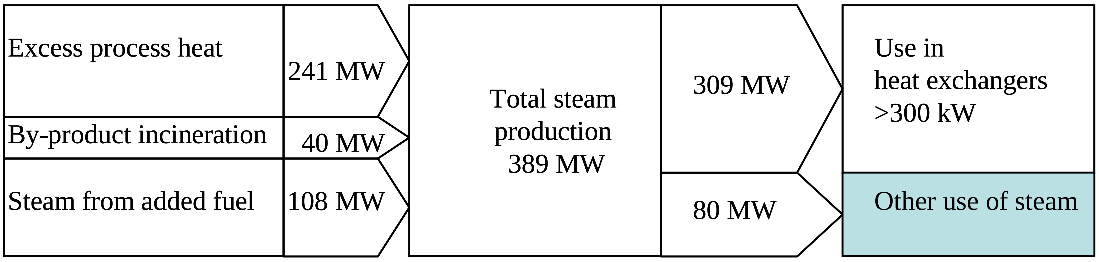

Figure 10 Representation of the amount of steam from process and boilers, the total steam production and the amount of steam covered by stream data collected for this study.

It is important to include this steam consumption in the study. The temperatures of the process streams corresponding to the steam use are unknown. Hence, the process streams are represented at the temperature level of the steam used. This means that the utility level for these users is fixed and cannot be modified in the analysis.

The use of steam for these small users is divided into use at different pressures according to steam balances of the different plants.

The fraction of steam included in process stream data gathered in this study compared to the total steam production is 80 %. This is considered acceptable with the uncertainties involved in the data collection listed below. This indicates that a relevant heat load limit for including heat exchanger was chosen.

Uncertainties in data collection:

- The exclusion of small heaters and other steam uses (tracing, heating, flares)
- Overall steam production and heat exchanger data are given at different times or for different operation circumstances
- Uncertainties in the heat exchanger stream data
- Uncertainties in steam measurement
- Work is extracted from the system as electricity and shaft power
- Steam excess that is not used for heating

5.2 Identifying improvements to the utility systems

5.2.1 Increased energy efficiency by integrating the existing steam systems

Since the steam system is a major part of the energy system the total sites' steam systems are investigated more in detail. Steam considered in this section is only steam used to heat the processes and steam recovered from process cooling and by-product incineration. Steam that is produced in boilers by added fuel is not included. Figure 11 shows the particular excess or deficit of steam at each plant and pressure level. Steam consumed is subtracted from steam produced at each level. The numbers give the excess/deficit of steam at each pressure level.

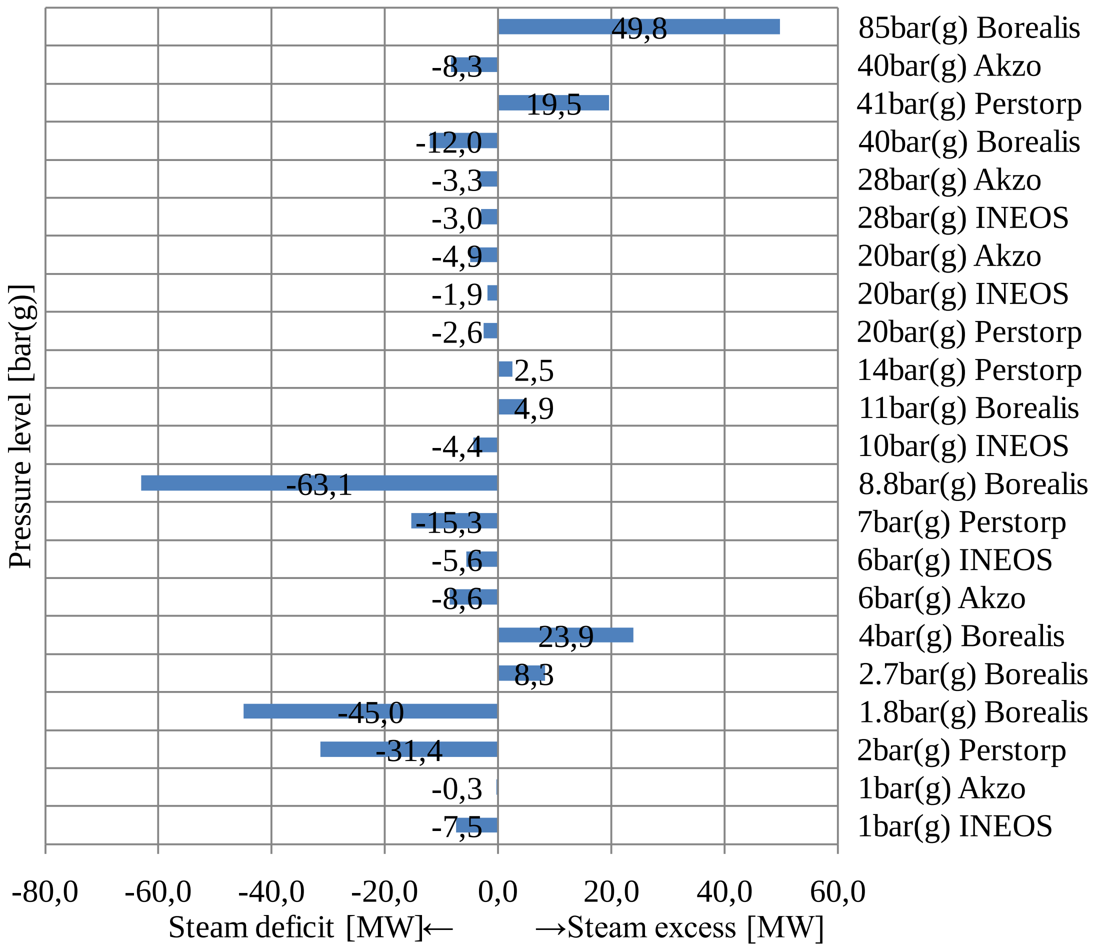

Figure 11 Representation of the steam excess/deficit at the total sites‘ pressure levels at the different plants (Steam produced in boilers by added fuel is not included)

The right side of the diagram shows excess of steam (in MW) at specific steam levels. The left side represents a deficit of steam at specific steam levels. This diagram enables to determine possible matches between steam levels with excess and deficit (excess of steam at a higher level can be transferred to a steam level with deficit). Therefore it gives guidance for determining exchange of steam across the total site.

To find the ideal distribution of steam across the site, pinch analysis is used in form of a GCC. The GCC of a combined steam system (see Figure 12) shows a heating demand of 108.3 MW. The whole steam system is divided in temperature intervals. A surplus of steam at one can be transferred downwards the cascade to steam levels with heat deficit. Distribution of steam as suggested in the GCC gives a maximum utilisation of steam, a remaining steam deficit at the lowest possible steam levels and the highest cogeneration potential (shown in 5.3.3)

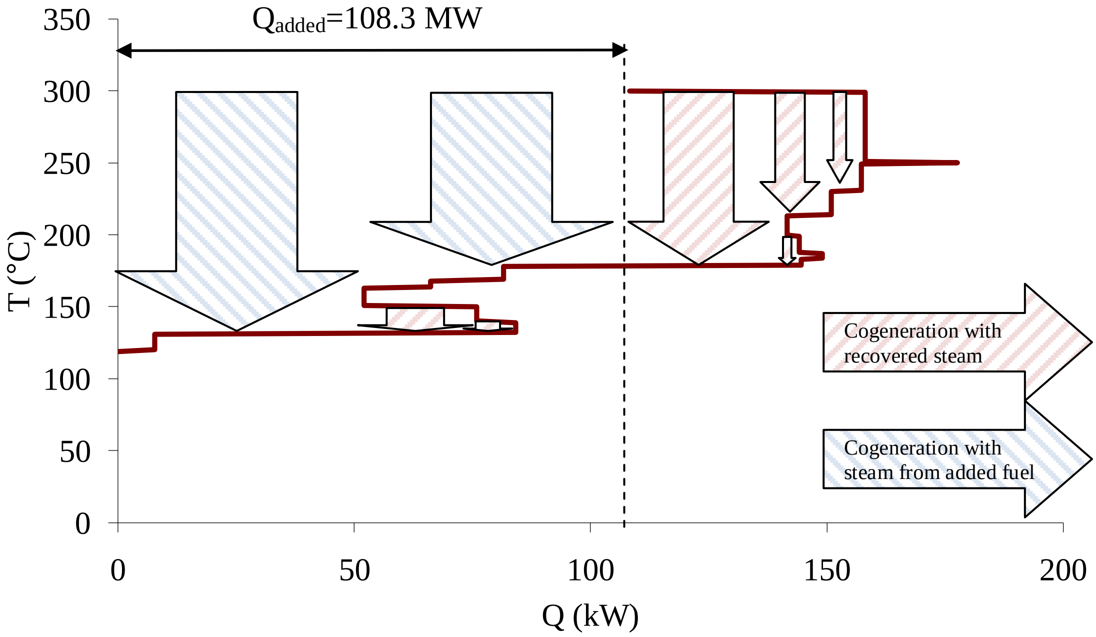

Figure 12 GCC of the steam system with minimum heating demand and „pockets“, showing potential for internal heat exchange

In order to realise the steam distribution as shown in the GCC eleven new steam headers have to be constructed. This leads to an ideal distribution of steam with deficits at the steam levels shown in Table 5.

Table 5 Steam levels and heat deficit at the total site with integrated steam systems

Steam level [bar(g)]	**Deficit [MW]**
8.8	26.8
7	15.3
6	14.2
2	44.2
1	7.8
Sum	108.3

The current steam systems are only partly connected, which means steam cannot be freely transferred between the companies as indicated in Figure 12. The current steam systems are described in chapter 7. The steam exchange between plants today:

- AGA receives 28 bar(g) steam from Akzo.
- Borealis PE receives 40 bar(g) steam from Borealis Cracker.
- Borealis Cracker will receive LP steam from Borealis PE.

Steam deficit at each plant can be determined with data from Figure 11. With the current steam system there is a deficit of steam at the steam levels listed in Table 6. This steam has to be produced by added fuel in the boilers.

Table 6 Steam levels with deficit if only current possibilities for steam exchange are considered

Remaining deficits	Level bar(g)	Load [MW]
Akzo	40	8.3
Akzo	28	3.3
INEOS	28	3.0
Akzo	20	4.9
INEOS	20	1.9
Borealis	8.8	25.3
INEOS	10	4.4
Borealis	1.8	7.9
Akzo	6	8.6
INEOS	6	5.6
Perstorp	2	27.3
Akzo	1	0.3
INEOS	1	7.5
Sum		108.3

The calculations for Table 6 are shown in Appendix 2. When comparing Table 5 and Table 6 it can be seen that the total steam demand doesn't change when combining the steam systems. This is due to the fact that the companies are in balance with their steam systems (none of the companies generates an excess of steam).

The steam levels with a deficit in a combined system are lower, see Table 5. This gives a **higher potential for cogeneration** (29 MW instead of 10 MW) in a common steam system, as steam produced in the boilers at high pressure can be expanded to a lower steam level where it is needed.

A common steam system **also increase the potential and incentive for further energy recovery measures**, e.g. steam recovered at one site which has no demand of steam at the recovered temperature can be transferred to another company if there is a demand.

A common steam system for all steam levels would require an investment in 11 new steam headers between the plants. There are different specifications for boiler feed water at the plants, depending on the pressure in the boilers. Thus, an integrated steam system will also require investments in condensate treatment.

5.2.2 Using total site profiles to improve energy efficiency

5.2.2.1 Maximum theoretical potential for heat recovery

In order to find the **maximum theoretical potential for heat recovery** from the processes the composite curves of the total site are plotted as shown in Figure 13. In this case it is assumed that heat exchange hypothetically occurs directly between the process streams. A temperature difference of 20 K is chosen. It can be seen that the "ideal" amount of heat recovery is 442 MW, which is all the heating demand of the processes. Additionally an excess of heat of 14 MW at high temperature levels can be generated. Direct heat exchange across the total site is very unrealistic. Therefore these values are only theoretical. Because of this other methods are developed, which make it possible to represent the processes and their interaction with the utility systems. This enables to target for process integration using the utility system.

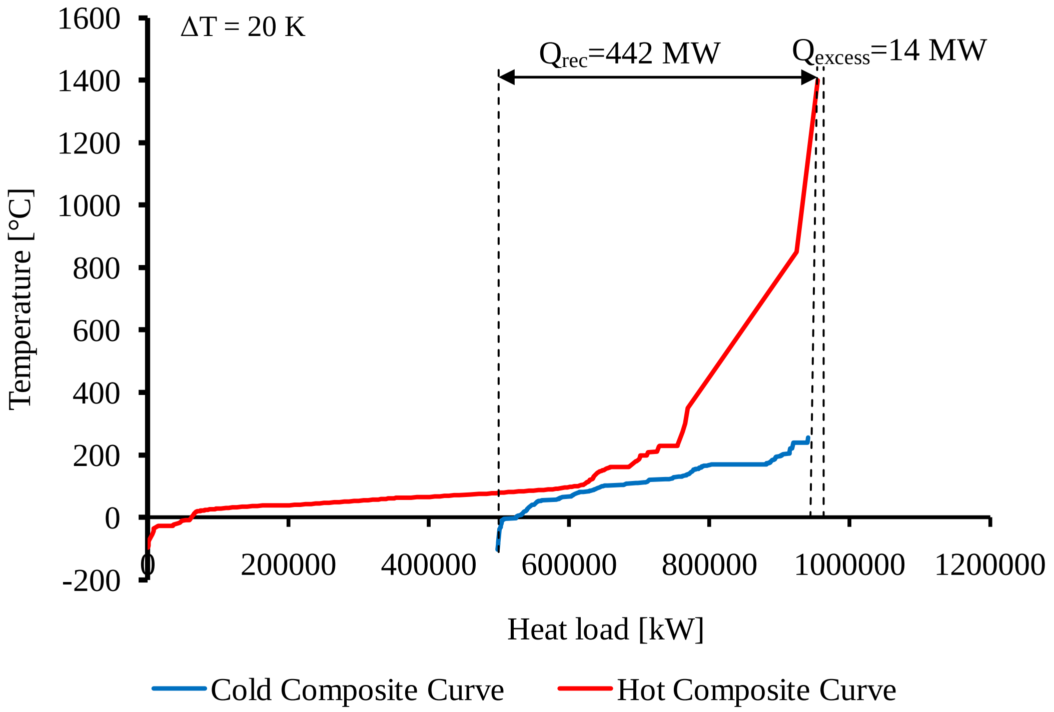

Figure 13 Composite curves of the total site in Stenungsund, representing the "ideal" potential for heat recovery by direct (process-process) heat integration

The method used is total site analysis (TSA) described in 4.2. First, curves are developed which represent the heat integration if no changes to the current heat exchangers are considered. This means the utility loads and levels are left untouched and only the utility systems of the different companies are assumed to be connected. The heating and cooling demand and the heat recovered are found in this way. The potential for cogeneration can be determined.

In the next step the curves are used to identify ways to increase heat integration by changes to the heat exchangers. Changing the utility in certain heat exchangers in order to recover and use heat from the process in a better way. With help of the total site curves improvements to the utility system are identified which enable to approach the theoretical heat recovery shown in Figure 13. Site wide utility levels are set and new utilities are suggested.

Several measures to recover energy are already implemented at the different plants. Heat is recovered directly (process-process heat exchange) and indirectly (heat recovery by the utility system). This study follows the "grey box"-approach (see 4.2.1) and therefore focuses on the process-utility interface for heat integration.

Additional steam demand which is not covered by the streams gathered in this study is considered as "black box". This is done as follows:

- The steam demand is included in the TSA curves with the amount of steam used for heating.
- It is included in the hot utility curve at the respective steam saturation temperature.

– In the sink profile with a temperature 10 K below the steam temperature.

5.2.2.2 Total site profiles (TSP)

Figure 14 shows the TSP of the Stenungsund chemical cluster. The diagram represents cold and hot process streams (blue and red curve), and cold and hot utility curves (green and orange curve). **Process cooling** is shown at the left side of the graph. In order to withdraw heat from the hot process streams it is transferred to the cold utility curve. **Process heating** is shown at the right side. Hot utility is used to deliver heat to the cold process streams. Total cooling and heating demand, the amount of heat discharged to the atmosphere (to cooling water and air) and the heat recovered from the processes and supplied to the processes by different utilities can be determined.

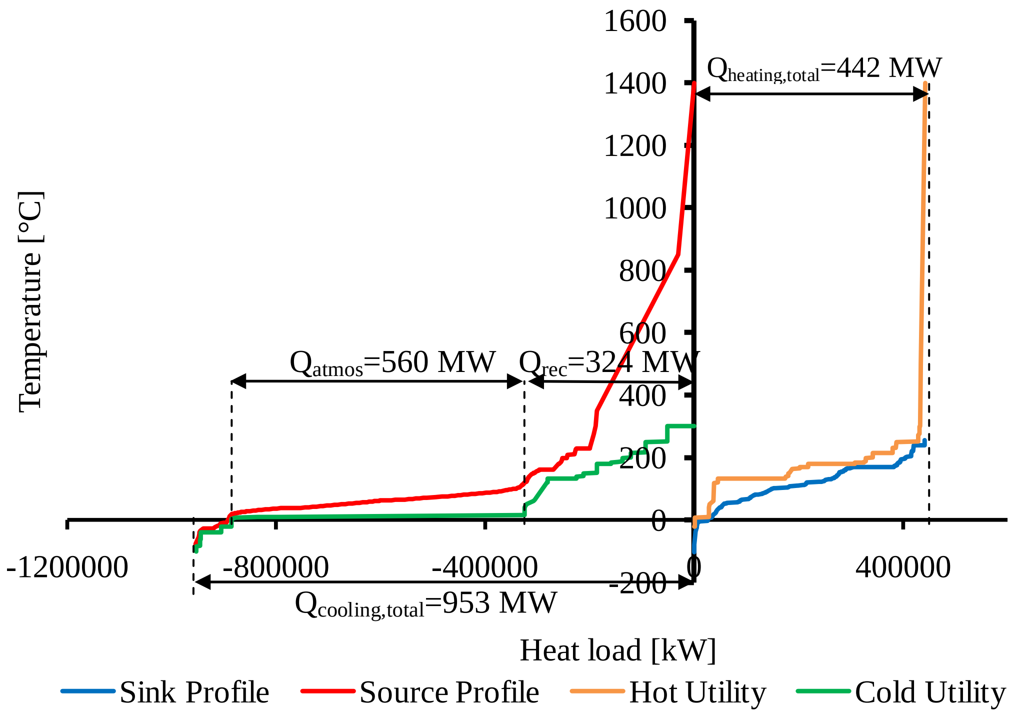

Figure 14 TSP representing the process-utility interface of the Stenungsund chemical cluster

The total cooling demand of the processes is 953 MW. This cooling demand is covered by a number of utilities. Some of them are recovering heat from the processes as e.g. steam or hot water. Heat is also discharged to cooling water or to air. Processes that need to be cooled below ambient temperature utilise cooling media such as ethylene, propylene, cooled cooling water or ammonia.

324 MW heat is recovered of which 281 MW[4] is recovered as steam. The total amount of process heat discharged to the environment by CW and air is 560 MW. The rest of the cooling (77 MW) is done by cooling media.

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[4] Includes 40 MW of steam which is generated when by-products are incinerated. This incineration is necessary to reduce the environmental impact of the by-products or utilisation otherwise is not possible.

The total heating demand is 442 MW of which 389 MW is covered by steam at different pressure levels, while 55 MW is covered by hot water/oil, flue gases, refrigerant and steam condensate. Heating processes with refrigerant (29 MW) is done to recover cooling energy and thereby decrease the energy consumption of the refrigeration systems.

5.2.2.3 Total site composites (TSC)

In order to determine the maximum heat integration at the total site with the current utility system the TSP are moved towards each other until the hot and cold utility curve intersect. This intersection point is the so called site pinch. It limits further heat integration by the utility system. This means that no further overlap of the curves is possible (Zhu & Vaideeswaran 2000). The overlap of the source and the sink profiles represents the amount of heat recovery by the utility system. The resulting graph can be seen in Figure 15.

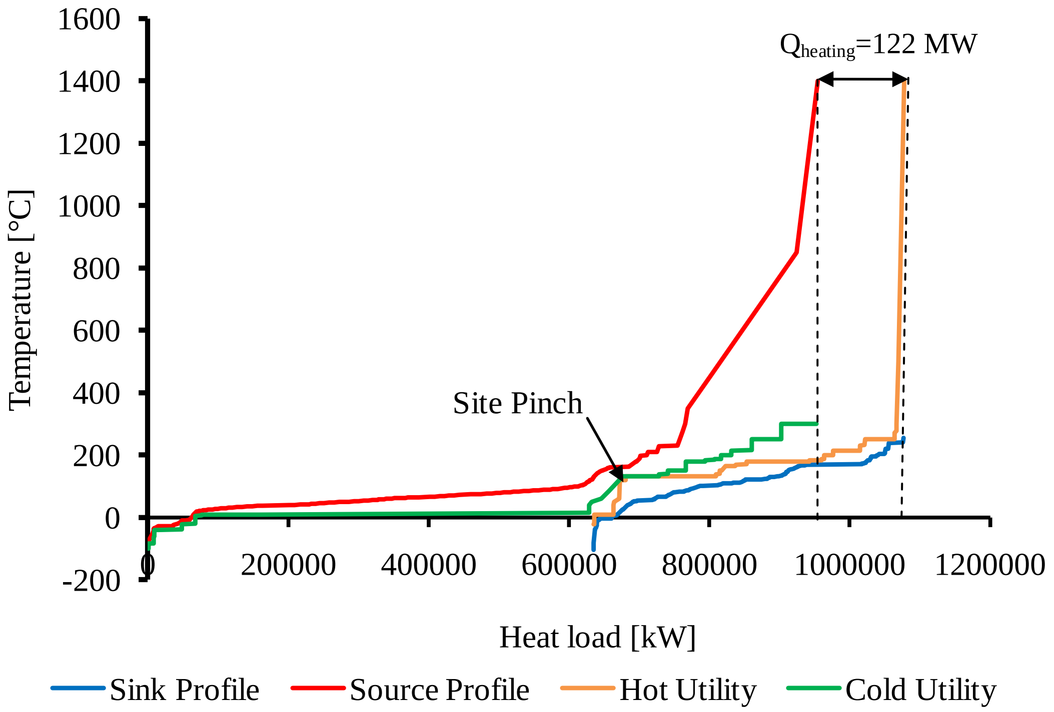

Figure 15 TSC showing the maximum heat integration in the Stenungsund chemical cluster

The total site composites (TSC) show that with the utility system the heating demand of the total site is 122 MW.

The theoretical savings potential if "ideal" process integration, as shown in Figure 13, is applied is:

Excess of steam with "ideal" system + Current heating demand = Savings

14 MW (from Figure 13) + 122 MW (from Figure 15) = 136 MW

Another finding from Figure 15 is that not all the heat recovered from the hot process streams is used to heat cold streams. This can be explained by:

- Some process streams deliver heat to the local district heating system, which is outside the system boundaries

- Some circulating water systems don't utilise all the heat recovered and are therefore discharged to the cooling water system

The total amount of heat recovered in hot water systems at the different plants is 43 MW of which 9 MW are utilised. The difference of 34 MW can be explained by the factors mentioned above.

The site pinch, which limits further integration within the utility system is at the 2 bar(g) steam level (132°C). Elimination of this pinch point by changes in the utility system leads to additional energy recovery. The profiles shown in Figure 14 and Figure 15 are used to determine improvements to the utility systems.

5.2.2.4 Improvements to the utility system

Introduction of a hot water circuit:

One option to increase energy efficiency at the total site is to eliminate the site pinch by the introduction of a hot water circuit between 50 and 100°C. Heat from hot process streams can be recovered in a circulating hot water system and delivered to cold process streams. This option is interesting because in the cluster a lot of excess heat is available in the temperature range chosen, which can be used to replace steam in several heat exchangers.

By introducing such a hot water circuit steam is substituted with hot water. The demand of 2 bar(g) steam decreases which moves the pinch point so that the curves' overlap can be increased. This can be seen in the enlarged section of Figure 16. The dotted line shows the current utility system. The green and the orange line represent the utility system after introduction of the hot water circuit. Introducing a hot water circuit results in:

- Recovery and utilisation of 60 MW of hot water between 50 and 100°C
- Savings of 51 MW[5] steam at 2 bar(g) and below

[5] Not all the 60 MW recovered in the hot water circuit are used to save low pressure steam. 9 MW of heat are already recovered and utilitsed in hot water systems. Therefore the hot water circuit saves 51 MW of steam at 2 bar(g) and below.

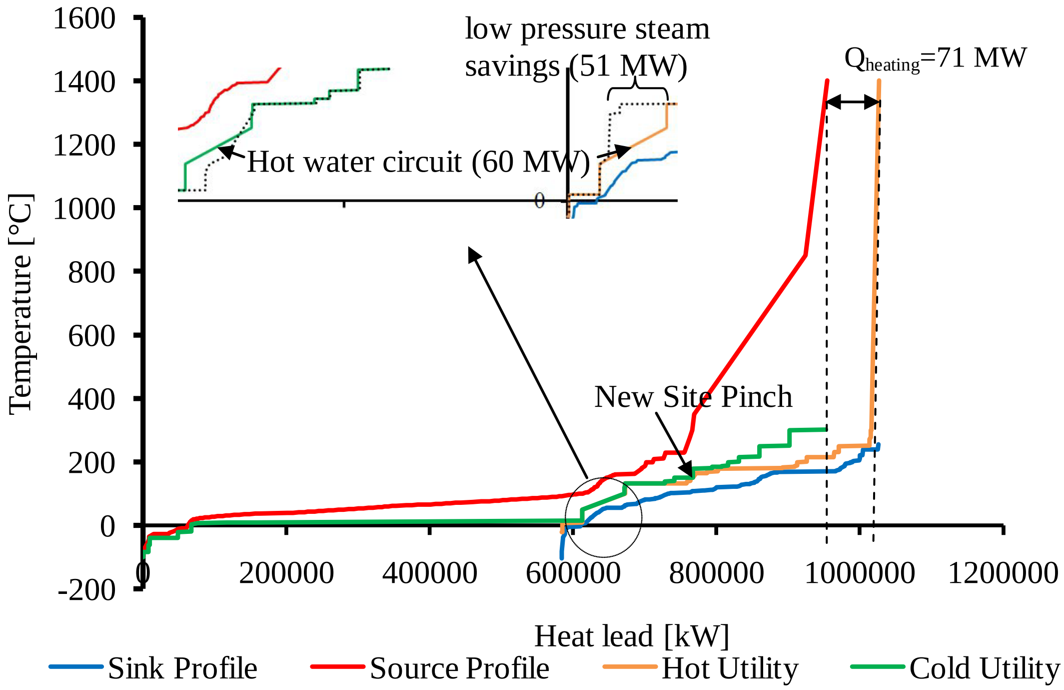

Figure 16 TSC after introduction of a hot water circuit between 50 and 100°C

With integration of the hot water circuit the heating demand at the total site becomes 71 MW. The potential steam savings are 51 MW.

An economic evaluation of the savings indicates annual steam savings of 122.4 MSEK/year[6].

When introducing the hot water circuit a new site pinch is created at 151°C. In order to further integrate the plants (up to 96 MW by transferring more heat in a hot water circuit) the site pinch has to be eliminated. This can be done by:

- Decreasing the heating steam levels to below 151°C where it is possible or
- Increasing the level of recovered steam to above 151°C if possible.

Utilise the potential for increased 2 bar(g) steam recovery:

Another option to increase process integration with the utility system is to increase the recovery of 2 bar(g) steam. The total site profiles show that there is potential for recovery and use of 33 MW of 2 bar(g) steam. This can be seen in Figure 17. The enlarged section in the figure shows the potential for steam recovery. Comparing the current cold utility profile (dotted line) with the cold utility profile after increased 2 bar(g) steam recovery gives the amount of steam which can be additionally generated from process heat. Figure 13 also shows the effect of this measure on the total heating demand. Increased recovery of 2 bar(g) steam lowers the heating demand by added fuels to 89 MW, which corresponds to potential steam savings of 33 MW steam from added fuel.

[6] Background to economic evaluation see Appendix 4.

An economic evaluation of this potential shows annual steam cost savings of 79.2 MSEK/year[6].

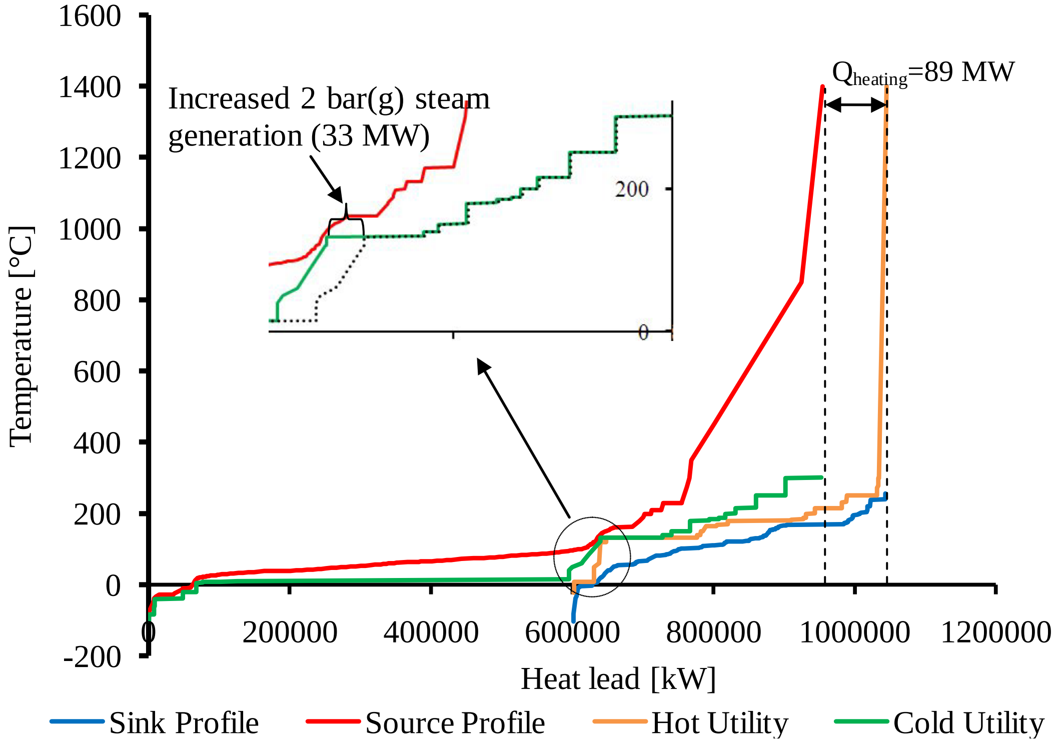

Figure 17 TSC with increased 2 bar(g) steam recovery

It can be seen in Table 6 that almost all the current deficit of steam at 2 bar(g) and below (35.1 MW) can be covered by this measure. Most of the 2 bar(g) steam that could be generated from process heat comes from Borealis. At the Borealis site there is currently no deficit of steam at this pressure level. The steam generated at Borealis could be used to satisfy the demand at Perstorp, INEOS and Akzo Nobel (see Table 6).

51 MW of 2 bar(g) steam can be saved before an excess of 2 bar(g) is generated. **Further utility savings** can be reached by shifting loads in heat exchangers to lower levels or by recovering steam from the processes at higher levels.

Further process integration with the utility system

In order be able to utilise all heat recovered that can be recovered in a hot water system and the increased amount of 2 bar(g) steam it is necessary to do further adjustments to the utility system. When moving the total site profiles towards each other, new pinch points are created. They can be eliminated by adjusting utility levels (shifting loads between utilities by e.g. increasing temperature of steam recovery and/or lower temperature of steam used for heating). Figure 18 shows the TSP after several suggested changes to the utility system.

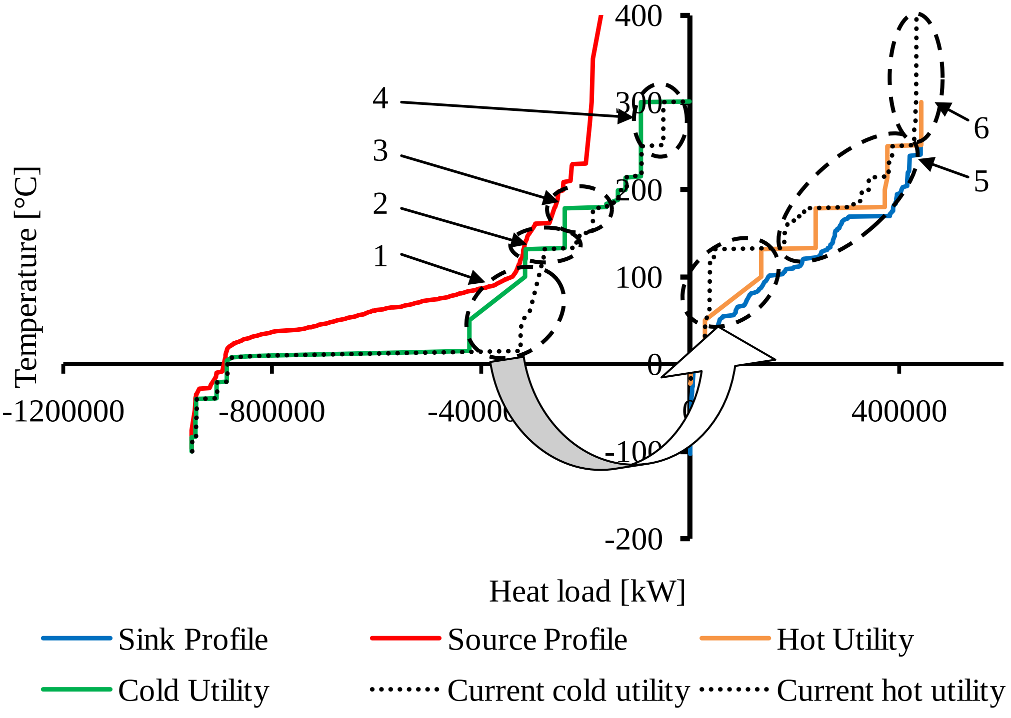

Figure 18 TSP showing measures to reach maximised energy recovery by the utility system

Changes in both the process heating and cooling have to be applied to further improve the process integration at the total site. E.g. if the process is cooled by steam generation there also has to be a demand for the steam in the process. Otherwise the steam cannot be utilised and has to be discharged. Adjustments to the process heat exchangers have to be done to make the steam generated in the process available to them. Table 7 summarises the measures shown in Figure 18 and their effects on the heating/cooling demand.

Table 7 Measures and effects of changes to the utility system shown in Figure 18. NB Measures 3-6 is not described in text above.

No.	Measure	Advantages
1	Introducing a circulating hot water system between 50 and 100°C	Saves 96 MW[7] of LP steam and cooling demand
2	Increase LP steam recovery	Increase in LP steam by 33 MW covers LP steam demand
3	Increased 8.8 bar(g) steam recovery by 50 MW	Necessary for further integration (to cover 8.8 bar(g) demand)
4	Increased steam recovery at 85 bar(g) by 44 MW	Necessary for further integration
5	Lower steam level for process heating by 129 MW	Necessary for further integration (utilisation of recovered steam)
6	Replace flue gas by steam by 10 MW	Necessary for further integration

[7] 96 MW is the potential for heating process streams with hot water in a range between 50 and 100 °C

Assuming that all the suggested changes are applied the potential for increased heat recovery with the suggested measures is 129 MW. This includes steam savings of 122 MW of the plants added fuel demand and additional surplus of 7 MW of steam at a pressure of 85 bar(g). With the adjustments described in Table 7 the utility curves overlap as shown in Figure 19.

7 MW excess steam realised by the changes suggested should be compared to the theoretical steam excess of 14 MW shown in Figure 13. It can be seen that with the suggested adjustments to the utility system it is possible to almost reach the efficiency of the ideal system.

The surplus of steams can be used for e.g. electricity production or to supply new processes with heat. The TSC representing this utility system to maximise energy recovery is presented in Figure 19. The utility levels for an optimised utility system can be found in the TSC. Here it is suggested:

- Circulating hot water between 50 and 100°C
- 2 bar(g) steam
- 8.8 bar(g) steam
- 40 bar(g) steam
- 85 bar(g) steam

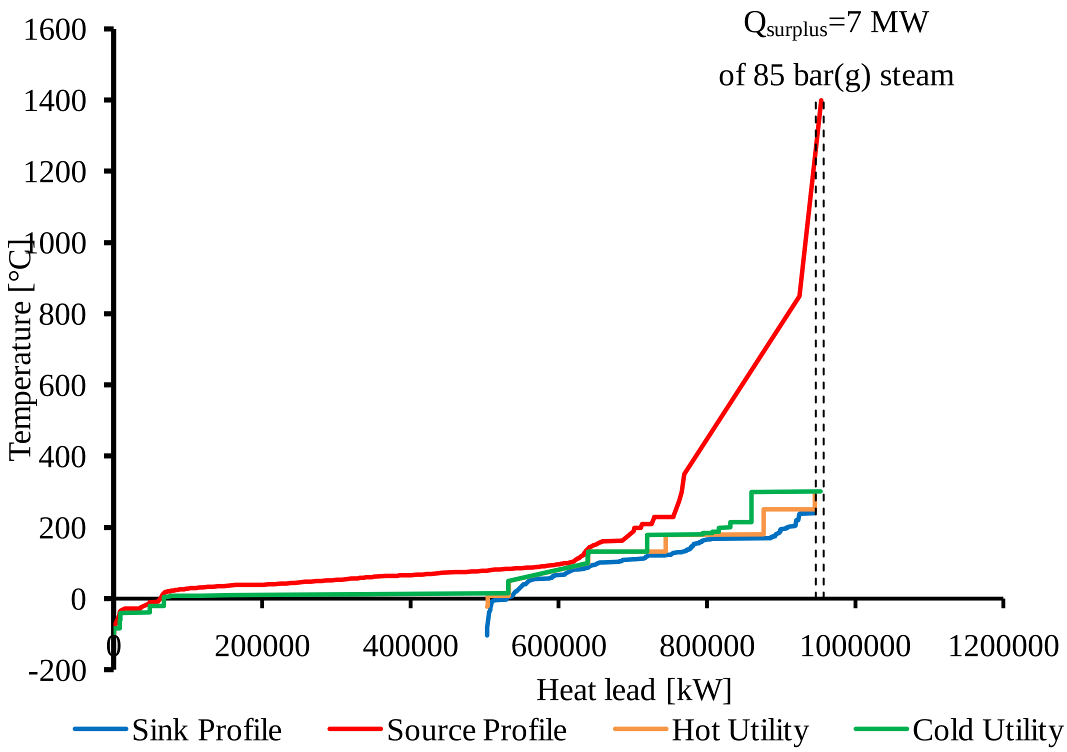

Figure 19 TSC for utility system modifications that maximise heat recovery

A table with loads and pressure levels of the utility system shown in Figure 19 is given in Appendix 3.

Effects on cooling water demand

If heat from the process is recovered and used instead of being discharged the cooling demand is decreased. This is especially important for plants using fresh water, as the cooling water use is restricted for them. But it also lowers the pump work in the cooling water pumps and therefore saves electricity.

5.3 Qualitative evaluation of potential solutions

The practical potential to implement the modifications suggested in 5.2 is evaluated qualitatively. This is done by a qualitative assessment of utility changes in each heat exchanger that are included in the suggested changes. The qualitative feasibility analysis is performed according to 4.2.7. In discussions with process engineers at the site complexity of utility changes is assessed and heat exchangers where it is impossible to use another utility are identified.

The following grading system is applied:

A. possible: no process constraints, moderate investment costs are expected
B. possible, with constraints: several or more complex changes are necessary, higher investment costs are expected
C. impossible: process constraints make changes impossible

The results are shown in:

- Figure 20, for the suggested hot water circuit classified in category A
- Figure 21, for the suggested hot water circuit classified in category A and B
- Figure 22, for increase 2 bar(g) steam generation from process heat classified in category A and B

This estimation was done in a screening session and does not involve any technical or economical calculations. But the results give an indication of how realistic the theoretical potential is. The following figures visualise the practical potential for implementing utility systems as suggested in 5.2.2.

5.3.1 Hot water circuit

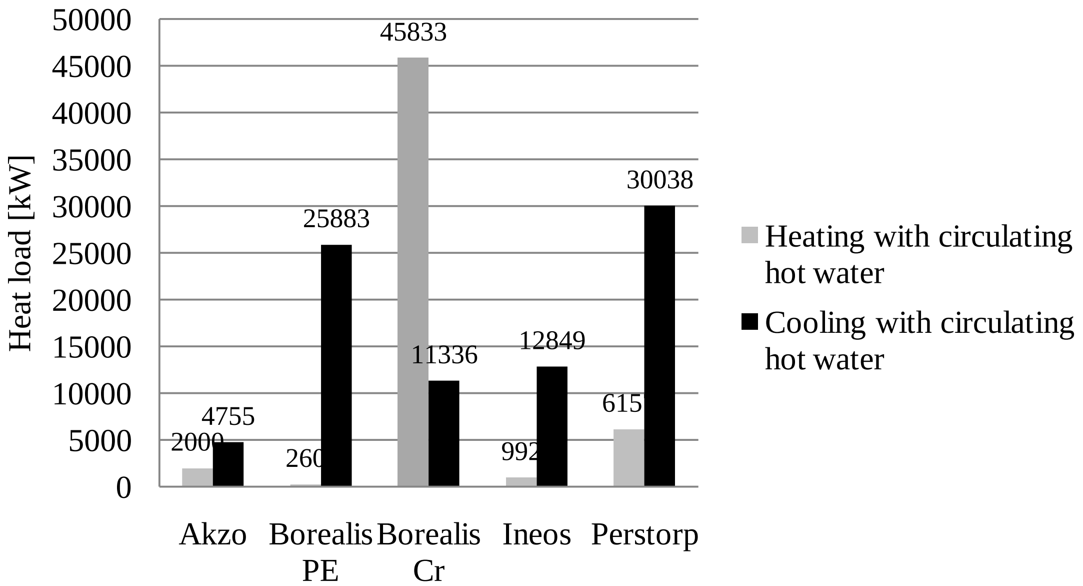

Figure 20 Practical potential for implementing a hot water circuit considering changes classified as A

Figure 20 shows the practical potential for implementing a hot water circuit. Only heat sources and sinks in category A are included. It can be seen that all the plants have a high potential to deliver heat to a common hot water circuit. The highest demand for heat from such a circuit is found at Borealis' cracker plant, Perstorp and Akzo.

- Total heat delivered to hot water circuit in category A: 85 MW
- Total heat withdrawn from hot water circuit in category A: 55.2 MW

Utilising the potential of a hot water circuit in category A, steam savings of 132.5 MSEK/year[6] can be realised.

Figure 21 shows the practical potential for implementing a hot water circuit for category A and B. All plants could deliver a large amount of heat to the hot water circuit. By far the highest heat sink for a hot water circuit is the cracker plant but also the other plants have considerable heating demand between 50 and 100°C.

- Total heat delivered to hot water circuit in category A + B: 255 MW
- Total heat withdrawn from hot water circuit in category A + B: 83.5 MW

Utilising the potential of a hot water circuit in category A and B, steam savings of 200.4 MSEK/year[6] can be realised.

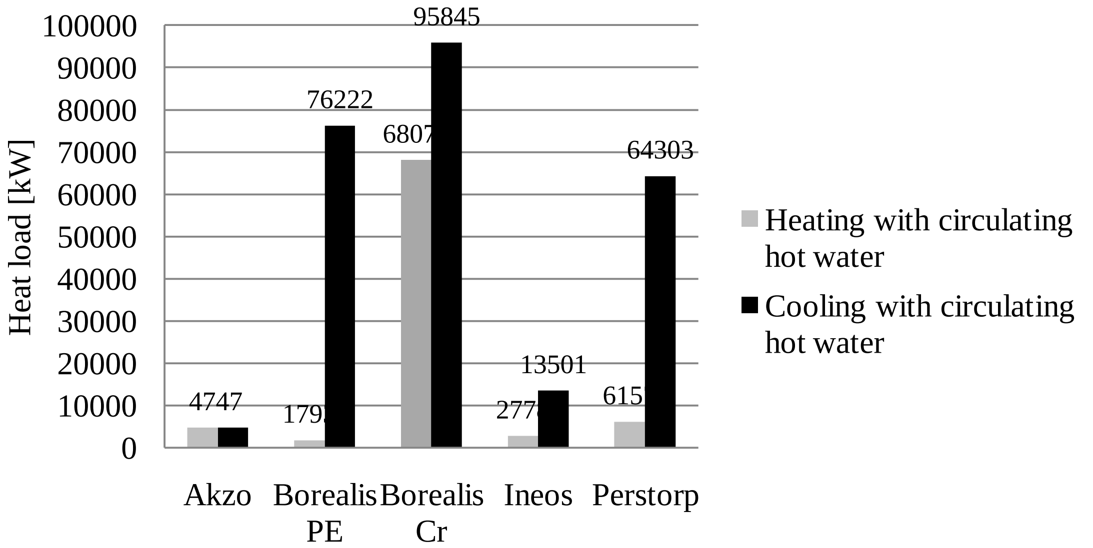

Figure 21 Practical potential for implementing a hot water circuit considering changes classified as A and B

<u>Practical consequences of the introduction of a hot water circuit:</u>

The introduction of a hot water circuit implies that process coolers have to be redesigned to use hot water instead of cooling water or air. Process heaters have to be redesigned for hot water instead of steam heating. Hot water pipes between several plants have to be constructed, as most of the consumers of heat are situated at the cracker site and at Perstorp but the sources are spread out across the cluster.

<u>Difficulties when integrating several plants with a hot water circuit:</u>

- Different operating times
- Long distance between the plants
- Larger area in the new heat exchangers → expensive in congested areas

- Many heat sources and sinks → temperature regulation difficult
- Utilisation of saved steam can involve further investments[8]

<u>Potential for supplying hot water to the district heating system:</u>

Borealis and Perstorp deliver heat to the district heating system of Stenungsund but the demand for district heat in Stenungsund is limited. It has been discussed to extend the Gothenburg district heating system to Stenungsund. This gives the opportunity for the cluster to deliver more heat to the system. Not all the potential for heat recovered can be utilised in the cluster and also in some cases it might be more profitable to deliver waste heat to the district heating system instead of using it to replace steam. This is especially the case when more complex retrofits are necessary to replace steam with hot water in the processes.

5.3.2 Increased steam recovery

Figure 22 shows the potential for increased 2 bar(g) steam generation. A large amount of steam can be produced at the cracker plant. This steam could be generated by further cooling the flue gases of the older cracking furnaces. Other potential sources of low pressure steam are available at Borealis' PE plant and at INEOS.

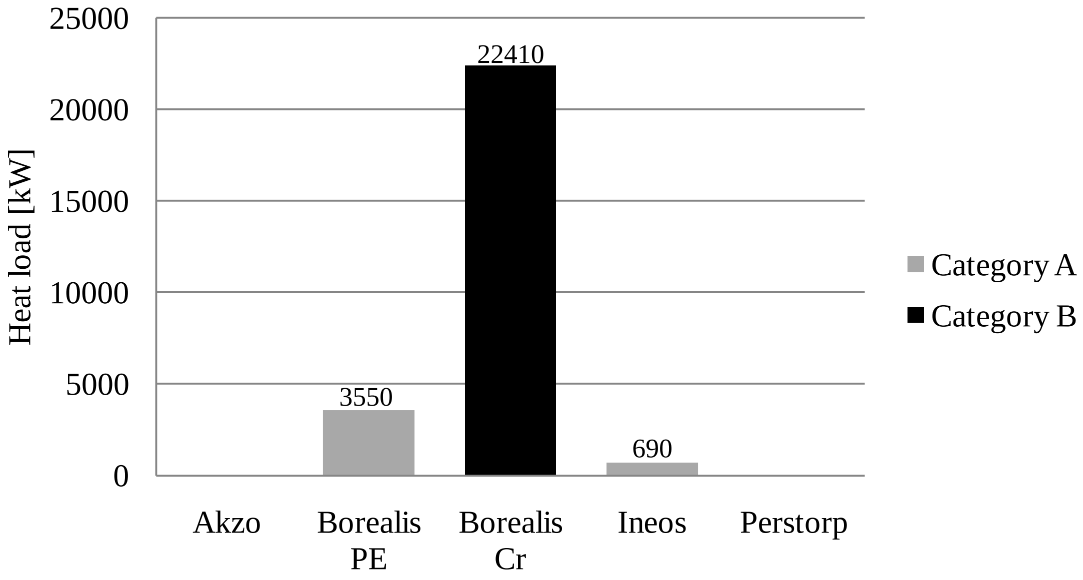

Figure 22 Practical potential for increased generation of 2 bar(g) steam generation

The total practical potential for 2 bar(g) steam generation in category A and B is 26.6 MW, compared to the theoretical value of 33 MW.

An economic evaluation shows potential savings of 10 MSEK/year for category A measures and 64 MSEK/year[6] if both A and B measures are implemented.

Increased 2 bar(g) recovery demands the installation of steam generators and the construction of steam pipes from Borealis to Perstorp and INEOS, as most of the

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[8] If steam savings apply at a company that currently has no demand at the this level, further investments to utilise the steam are necessary. E.g. heat exchangers that work on the sam steam level or piping to transfer the steam to another plant.

potential steam sources are located at Borealis but Perstorp and INEOS have a demand for 2 bar(g) steam

5.3.3 Further changes to the utility system to increase savings

To avoid an excess of low pressure steam, the low pressure steam demand must be increased. According to the total site profiles (see Figure 14) and the stream data gathered it is possible to decrease the steam pressure in several heat exchangers. Besides increased heat integration, using steam at lower pressure increases the potential for cogeneration. The potential to use steam at lower pressure to heat processes is 26.2 MW with moderate 34.8 MW including more complex changes.

5.4 Cogeneration potential

Four cases of electricity generation are estimated.

- ⇒ Theoretical cogeneration potential with the current utility levels and current steam demand and excess in an integrated steam system
- ⇒ All steam is produced at Borealis and distributed to plants with a deficit of steam below 8.8 bar(g).
- ⇒ Cogeneration potential with a totally integrated steam system and a new, common boiler
- ⇒ Cogeneration to produce steam at 14 bar(g) and 2 bar(g) at Perstorp

5.4.1 Theoretical cogeneration potential with the current utility levels and current steam demand and excess in an integrated steam system

The cogeneration potential for an entirely connected steam system is shown in Figure 12. The red arrows represent the cogeneration potential with steam recovered from the process. The blue arrows show steam produced from added fuel in the boilers.

For the theoretical case it is assumed that steam from the process can be expanded in turbine from the pressure at which it is produced down to the pressure level at which it is used. Steam from the boilers can be expanded from generation pressure (here 85 bar(g) is assumed) to its' utilisation pressure to produce electricity.

The theoretical cogeneration potential is 29 MW if steam is expanded as shown in Figure 12. Today 10 MW electricity is produced. The additional 19 MW corresponds to 40 MSEK/year[6].

5.4.2 All steam is produced at Borealis and distributed to plants with a deficit of steam below 8.8 bar(g).

The data for the following analysis is extracted from Table 6. An option for increased cogeneration with the existing cogeneration equipment and utility system is described more in detail.

Borealis has the possibility for cogeneration when producing 85 bar(g) steam and expanding it to 8.8 bar(g). Therefore it can be advantageous to cover the deficits of steam at levels below 8.8 bar (g) at other sites by steam from Borealis. The deficits of steam at other sites are shown in Table 8. These deficits could be covered by steam from Borealis and thereby electricity is produced.

Table 8 Companies with deficit at steam levels below 8.8 bar(g) which could be additionally supplied with cogeneration steam from the cracker plant

Plant	Level [bar(g)]	Load [MW]
Akzo	6	8.6
Akzo	1	0.3
Perstorp	2	27.3
INEOS	6	5.6
INEOS	1	7.5
Sum		**49.3**

Necessary measures:

- Borealis to INEOS: 13.1 MW to cover deficit of 6 and 1 bar(g) steam
- Borealis to Akzo: 8.9 MW to cover deficit of 6 and 1 bar(g) steam
- Borealis to Perstorp: 27.3 MW to cover deficit of 2 bar(g) steam
- Improved condensate treatment

Effects:

- Covers INEOS', Akzo's and Perstorp's demand of steam below 8.8 bar(g).
- Additional 49.3 MW of 8.8 bar(g) steam must be produced by cogeneration at Borealis.
- Production of additional 8.6 MW electricity when expanding steam from 85 to 8.8 bar(g).
- Additional 59 MW 85 bar(g) steam must be produced at Borealis.

An economic evaluation of the suggested measure indicates a revenue increase of 18 MSEK/year.

5.4.3 Cogeneration potential with a totally integrated steam system and a new, common boiler

Integration of the total site utility system aims at reducing energy use at the total site. The results of the TSA analysis show that no steam will have to be produced with added (purchased) fuel if all suggested measures are implemented. However, a more realistic result of a modification is that there will still be a demand for steam production.

Here, the cogeneration potential in a new separate, common boiler with a back-pressure steam turbine is assessed. The boiler is assumed to produce steam at 140 bar and 540 ^{o}C. Depending on what measures are carried out in the processes the remaining steam demand will be at different steam pressures, thus evaluation is carried out for two different back-pressure levels.

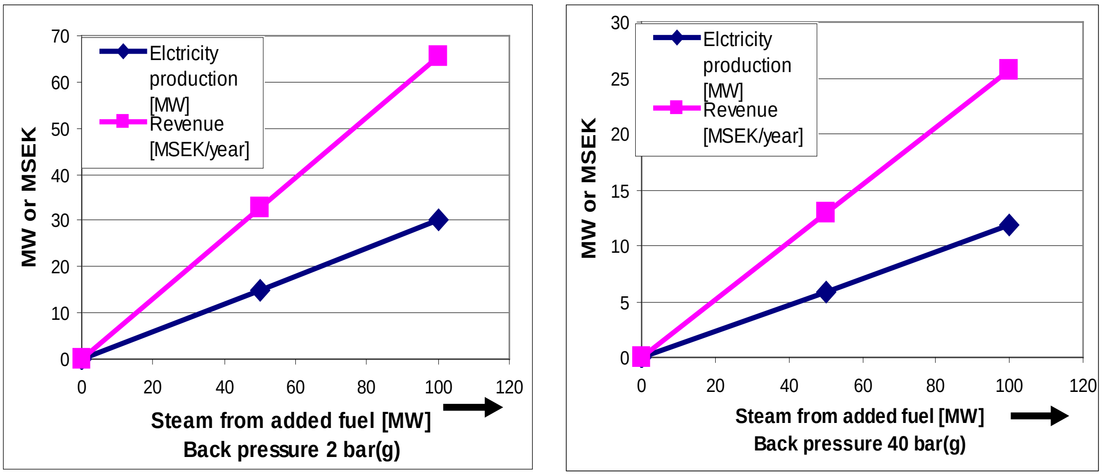

Figure 23 Electricity production and revenue (electricity sold - extra fuel) for backpressure 2 bar(g) and 40 bar(g).

It can be seen in Figure 23 that with increased energy efficiency (= lower steam demand), the cogeneration potential becomes less. This is due to the fact that less steam has to be produced in the boilers at high pressure which takes away the opportunity to expand this steam in a turbine to lower levels where it is applied in the process. Figure 23 also show that the cogeneration potential increases if the remaining steam demand is at a low pressure.

5.4.4 Cogeneration at Perstorp

Perstorp has a high steam demand at low pressure and generates steam at 40 bar(g). A steam turbine with backpressures at 14 bar(g) and 2 bar(g) could generate 8.5 MW electricity (corresponding to a revenue of 16 MSEK/year[6]).

5.5 Heat exchangers operating below ambient temperature

All plants except Perstorp are operating cooling systems to provide cooling below the temperature that the cooling water system can provide. At the AGA air separation process the process streams are to a great extent integrated and utility is not used with a few exceptions. Most cooling utility is used at the Borealis Cracker plant, and an analysis of the system is included in a Master Thesis (Hedström and Johansson, 2008).

Cooling below ambient is expensive and the cost increases sharply with lower temperature (Kemp 2007). Reduction in cooling demand by increased process integration will save energy, electricity or steam depending on how the compressors are driven.

Since cooling is expensive, the cooling utility levels are carefully chosen to fit the temperature level. However, heating of cold streams below ambient temperature is in some cases applied with utility far above the necessary temperature level. Except for saving high temperature utility, such as steam, a more careful design could use the cooling capacity of the sub-ambient stream that has to be heated to reduce the energy use in cooling systems. To transfer cooling energy from streams below ambient temperature to streams that have to be cooled to low temperatures, so called low temperature heat transfer media can be used. Depending on the temperature this can be e.g.:

- Sodium chloride brine: down to -21 ^oC
- Calcium chloride brine: down to –40 ^oC
- Ammonia
- Liquid ethylene or propylene: even lower temperatures (Heaton 1996, p.244)

Table 9 Streams heated by steam at low temperatures

Steam description	Load [MW]	Tstart [°C]	Ttarget [°C]
Ethylene vaporizers at the EFAB tank[9]:	2	-103	40
Oxygen and nitrogen vaporizers at AGA (intermittent)	1	-135	20
Vaporizers at Borealis operating below 0 C	3.5		

Potential low temperature sources are shown in Table 9. It shows streams below ambient temperature that are currently heated with steam. Utilising them to recover cooling energy can save both steam and power used to drive the cooling systems.

The gathered stream data indicates that 29 MW of heat is transferred from the refrigerant to cold streams in order to recover some of the energy invested in cooling. Some of that energy is recovered at higher temperatures and not included in the figure above.

If the cold streams currently heated by steam instead are heated with process streams that have to be cooled, cooling demand at low temperatures can be reduced which will result in substantial energy savings. The energy requirement in a refrigeration system depends on the temperature:

Table 10 Power demand of cooling energy depending on the refrigeration temperature (Kemp 2007)

Refrigeration temperature [°C]	Power use [$MW_{el}/MW_{cooling}$]
-40	0.6
-100	1.6

Table 10 shows the power demand of cooling energy depending on the refrigeration temperature. The shaft work for the compressor is either generated with electricity or steam. By utilising the cooling energy at EFAB and AGA (3 MW, see Table 9) refrigerant at -100 ^oC can be replaced. This can save 4.8 MW_{el}, and 3 MW steam, corresponding to 30 MSEK/year.

If the vaporizers at Borealis can replace refrigerant at -40 ^oC (3.5 MW, see Table 9), 2.1 MW_{el} and 3.5 MW steam corresponding to 18 MSEK/year can be saved.

The steam savings above are included in the savings discussed in 5.3.

Further integration of the cooling systems of the different plants might have benefits other than energy savings, such as cost reduction for operation and maintenance of cooling system equipment.

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[9] Evaporation of ethylene from the EFAB tank is expected to increase.

6 Conclusions

Total site analysis (TSA) is based on analysis of current use of utilities for heating and cooling and the focus is on finding energy saving potential by integration of the utility systems for the included plants.

First stream data was collected for the most significant process streams and completed by data on utility consumption for other uses. Thereby all the utility demand was accounted for in the study.

Starting with the analysis of the current steam system, potential improvements were identified. After that additional options for increased energy savings were developed by also allowing changes in heat exchanger operation. The results of the study reflect the current heat energy situation at the total site and give suggestions on how fuel and cooling capacity savings as well as the potential for cogeneration can be utilised. In order to assess the feasibility of the heat integration measures their practical potential was estimated.

Present energy system

Total heating demand for the total site today is 442 MW. Most of the heating demand is covered with heat recovered from the processes. 122 MW heat has to be supplied as added fuel, directly or as steam/hot oil. Assuming a boiler efficiency of 80 %, 150 MW fuel is required. This corresponds to operating costs of approximately 288 MSEK/year. Most of this fuel is produced as a by-product from the cracker plant, but approximately 25 MW fuel has to be imported to Stenungsund.

Theoretical potential for reduced fuel usage

The TSA analysis shows that with an optimal utility system all heating demand supplied with added fuel can be saved and there will be a heat surplus of 14 MW. The total savings are then 122 MW + 14 MW = 136 MW.

Measures required to achieve theoretical potential

Introduction of a hot water belt that recovers heat at 50-100 ^{0}C and replaces steam in heat exchangers that operate below 90 ^{0}C. This can save 51 MW of steam. More steam savings can be achieved when changing heat exchanger operations so that steam replaced by hot water can be utilised to heat other processes. In this case the theoretical potential for steam utility savings is 96 MW.

Increased low pressure steam generation from process streams that are today cooled by cooling water or air can increase LP steam generation by 33 MW.

If all these measures could be implemented the energy savings would be 129 MW.

Practical potential of increased steam recovery and introduction of a hot water circuit

Implementation of a hot water circuit shows practical potential steam savings of 55.2 MW (132 MSEK/year) with moderate changes (83.5 MW including more complex changes, 200 MSEK/year).

Technically the introduction of a hot water circuit includes hot water pipes between several plants, as most of the consumers of heat are situated at the cracker site and at Perstorp but the sources are spread out across the cluster.

The practical potential for increased 2 bar(g) steam recovery is estimated to 4.2 MW (10 MSEK/year) with moderate changes and 26.6 MW including more complex changes (64 MSEK/year).

Increased 2 bar(g) recovery implies the construction of steam pipes from Borealis to Perstorp and INEOS, as most of the potential steam sources are located at Borealis but Perstorp and INEOS have a demand for 2 bar(g) steam.

Cogeneration

The potential for cogeneration will decrease when the steam demand is reduced.

If all steam demand below 8.8 bar(g) is produced at Borealis at 85 bar(g)it is possible to cogenerate 8.6 MW electricity which corresponds to a revenue increase of 18 MSEK/year. This measure requires new steam headers from Borealis cracker to Akzo, INEOS and Perstorp plus additional condensate treatment.

Complete integration of all the steam systems of the 5 companies and no changes to the heat exchangers utility supply, results in an increased cogeneration potential of 19 MW (app. revenue is 40 MSEK/year).

An option with a new, common boiler connected to a back-pressure steam turbine was evaluated. The cogeneration potential depends on the pressure level on the exiting steam and on the steam demand and is estimated to between 0-40 MW (0-82 MSEK/year).

Cooling below ambient

Some process flows below ambient are heated with steam. If they instead were heated with process flows that require cooling media, both electricity and steam would be saved.

7 Future Work

The work presented gives a base for future energy efficiency projects in the chemical cluster in Stenungsund.

Further technical and economical analysis on the integration possibilities by a circulating hot water circuit should be investigated. Therefore the qualitative analysis performed in 5.3 can be used to identify the most interesting options and evaluate them according their technical and economical potential.

Process integration of streams below ambient temperature should be analysed more in detail. Savings in cooling loads can be of high economical interest as cooling below ambient temperature is very energy demanding.

The work accomplished in this study has also underlined a need for further development of the TSA methodology so as to enable better analysis of complex sites where steam is exchanged between plants and different pressure levels and used as reactant, utility, mechanical shaft work driver, and cogeneration. Further complications arise from the fact that steam drivers are used to drive high pressure compressors for sub-ambient refrigeration systems, thus creating a physical link between the heating and cooling utility systems. Further development of the methodology is one of the major components of suggested future work.

Another suggestion for future work is to use the results from this study to investigate opportunities to integrate energy-intensive climate-friendly processes such as advanced biorefinery concepts or carbon capture and storage in the chemical cluster in Stenungsund.

8 References

Akzo Nobel, 2004. A site with a view - Site Stenungsund. Available at: www.ethyleneamines.com/NR/rdonlyres/A7FAF030-9E84-417A-AA10-CBE70AC3444B/0/Akzo_eng_LR.pdf [Accessed February 18, 2010].

Allsopp W., M. & Vianello, G., 2009. Poly(Vinyl Chloride) : Ullmann's Encyclopedia of Industrial Chemistry. In Ullmann's Encyclopedia of Industrial Chemistry. Weinheim: Wiley & Sons. Available at: mrw.interscience.wiley.com/emrw/9783527306732/ueic/article/a21_717/current/html?hd=All,pvc&hd=All,process [Accessed September 30, 2009].

Bagajewicz, Miguel, and Hernàn Rodera. 2001. On the use of heat belts for energy integration across many plants in the total site. The Canadian Journal of Chemical Engineering 79, no. 4: 633-642. doi:10.1002/cjce.5450790424.

Borealis AB, 2009. Borealis Miljörapport 2008, Borealis AB. Available at: www.borealisgroup.com/pdf/stenungsund/Borealis_Miljorapport_2008_1.pdf [Accessed September 22, 2009].

Brown, S.M. 1999. The drive for refinery energy efficiency. Petroleum Technology Quaterly (Autumn)

Franck, Per-Åke. 1997. Lecutre notes: Pinch technology in practice. Chalmers Industriteknik Energiteknisk Analys.

Hackl, Roman, and Stephanie Perret. 2009. Power production with Organic Rankine Cycle technology utilizing waste heat from a cracker and three polyethylene units. Master Thesis. Göteborg: Chalmers University of Technology. http://publications.lib.chalmers.se/cpl/record/index.xsql?pubid=94982.

Heaton, C.A., 1996. An Introduction to industrial chemistry, Springer.

Hedström, Hanna, and Daniella Johansson. 2008. A Pinch targeting study of the Borealis Cracker plant in Stenungsund. Chalmers university of technology. Master Thesis. Göteborg: Chalmers University of Technology. http://publications.lib.chalmers.se/cpl/record/index.xsql?pubid=68102

Josefsson, Lars. 2009. INEOS Extern miljöredovisning EMAS 2008. INEOS ChlorVinyls, May 12. http://www.emas.se/redovisningar/emas146-2008se.pdf.

Kemp, Ian C. 2007. Pinch analysis and process integration. Butterworth-Heinemann.

Klemes, J., V. R. Dhole, K. Raissi, S. J. Perry, and L. Puigjaner. 1997. Targeting and design methodology for reduction of fuel, power and CO2 on total sites. Applied Thermal Engineering 17, no. 8-10 (August): 993-1003. doi:10.1016/S1359-4311(96)00087-7.

Kreith, Frank, and D. Yogi Goswami. 2007. Handbook of energy efficiency and renewable energy. CRC Press.

Linhoff, Bodo, and Vimal Sahdev. 2002. Ullmanns Encyclopedia of Industrial Chemistry: Pinch Technology. In Ullmanns Encyclopedia of Industrial Chemistry. Weinheim: Wiley VHC.

Linnhoff March. 2000. The Methodology and Benefits of Total Site Pinch Analysis. TotalSiteMethodology. www.linnhoffmarch.com/pdfs/TotalSiteMethodology.pdf.

Meyers, Robert. 2004. Handbook of Petrochemicals Production Processes. 1st ed. McGraw-Hill Professional, April 15.

Perry, S., Klemes, J. & Bulatov, I., 2008. Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. Energy, 33(10), 1489-1497.

Pollard, MilosLetter. 2010. Allmänt om Site Stenungsund. February 26.

Raissi, K. 1994. Total site integration. PhD Thesis, University of Manchester Institute of Science and Technology.

Smith, R., 2005. Chemical process design and integration, Chichester West Sussex England ;Hoboken NJ: Wiley.

Spetz, R. et al., 2006. Energy survey: Borealis PE-site 2004.

UIGI. 2009. Universal Industrial Gases, Inc.Cryogenic Air Separation and Liquefier Systems. www.uigi.com/cryodist.html.

Whiteley, S. 2000. Polyolefins : Ullmann's Encyclopedia of Industrial Chemistry : Wiley InterScience. In Ullmann's Encyclopedia of Industrial Chemistry. 7th ed. Weinheim: Wiley VHC, June 15. mrw.interscience.wiley.com/emrw/9783527306732/ueic/article/a21_487/current/abstract.

Zhu, Frank X. X., and Lakshmi Vaideeswaran. 2000. Recent research development of process integration in analysis and optimisation of energy systems. Applied Thermal Engineering 20, no. 15-16 (October 1): 1381-1392. doi:10.1016/S1359-4311(00)00013-2.

9 Appendix

9.1 Appendix 1

Process flowsheets

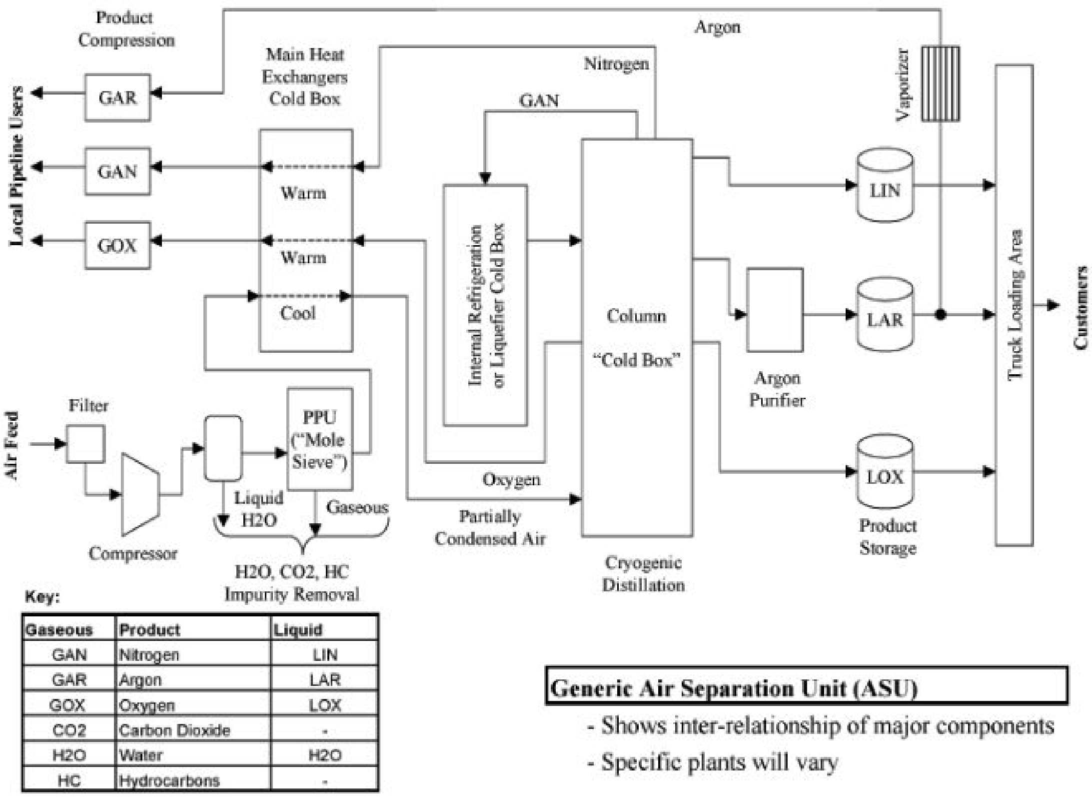

Figure 24 Process flowsheet of an air separation unit (UIGI 2009)

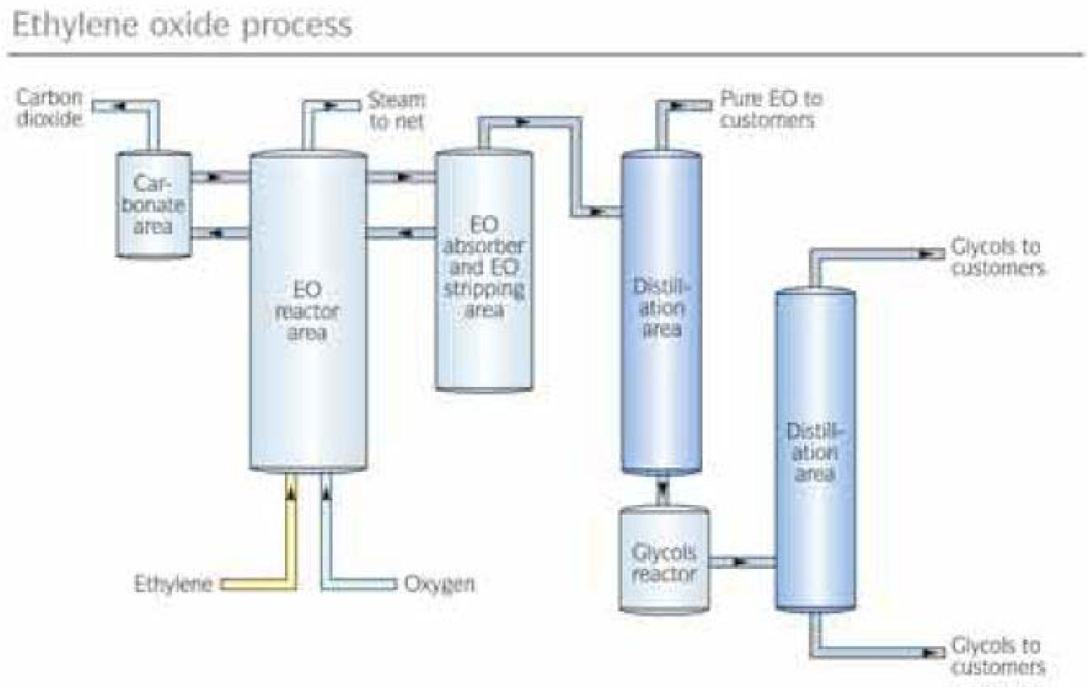

Figure 25 The Ethylene oxide process at Akzo Nobel (Akzo Nobel 2004)

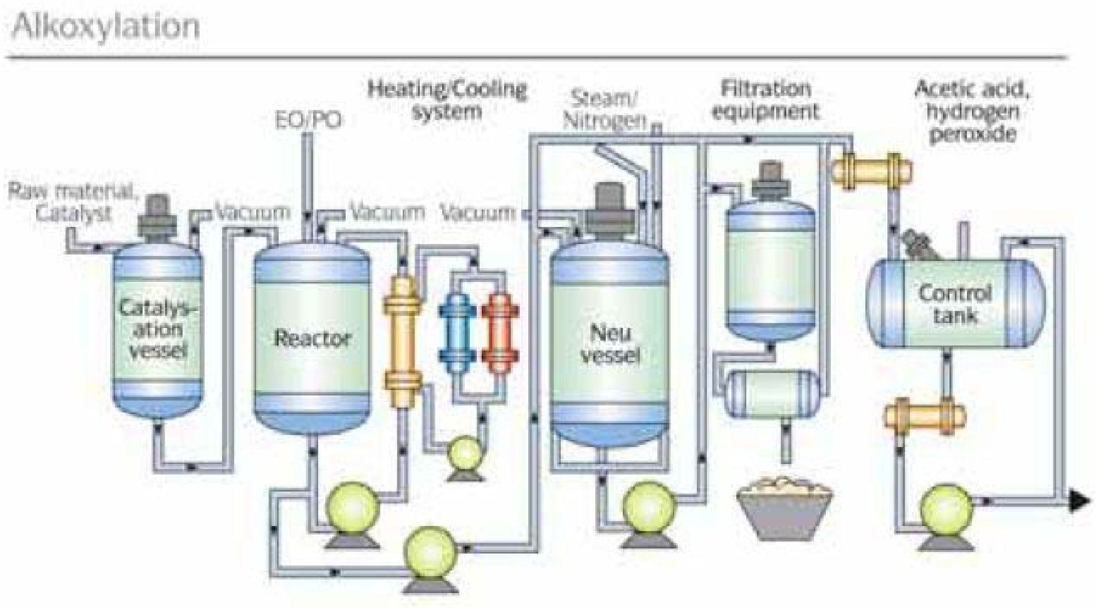

Figure 26 The Alkoxylation process at Akzo Nobel (Akzo Nobel 2004)

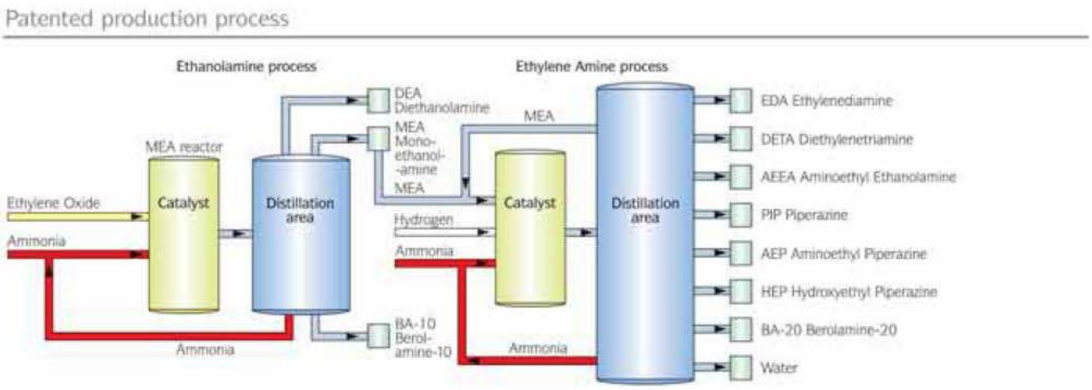

Figure 27 The amines process at Akzo Nobel (Akzo Nobel 2004)

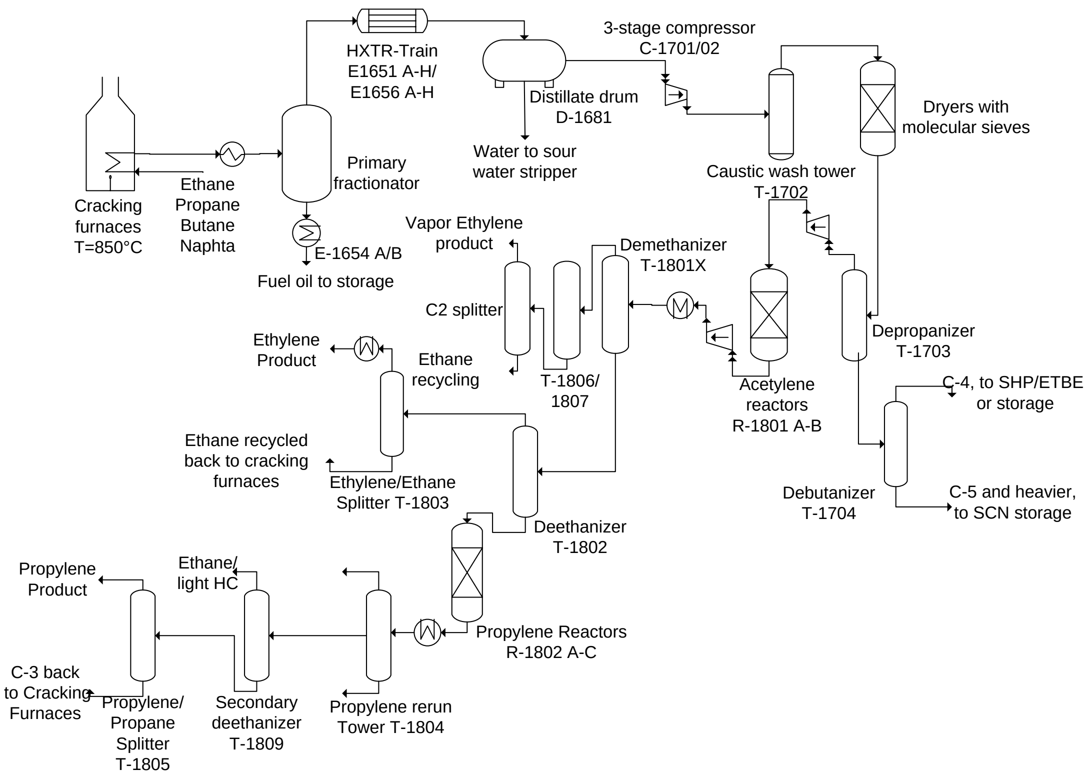

Figure 28 The cracker process at Borealis (Hackl & Perret 2009)

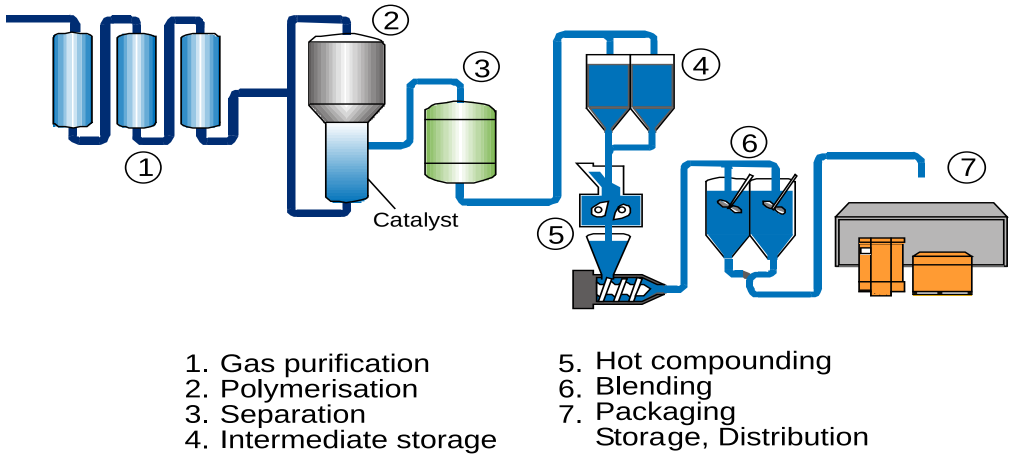

Figure 29 The low pressure PE process at Borealis (Borealis AB 2009)

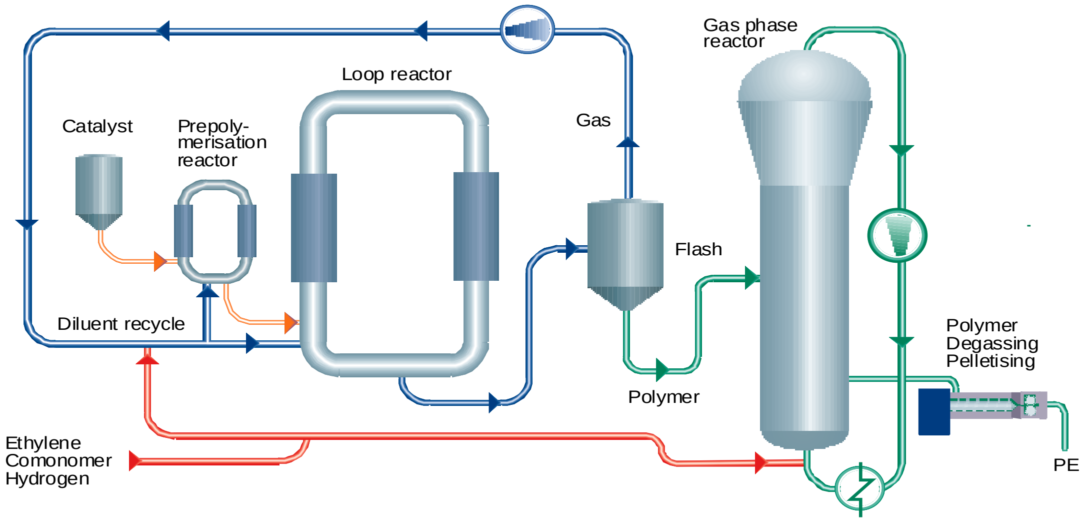

Figure 30 The PE3 Borstar process at Borealis (Borealis AB 2009)

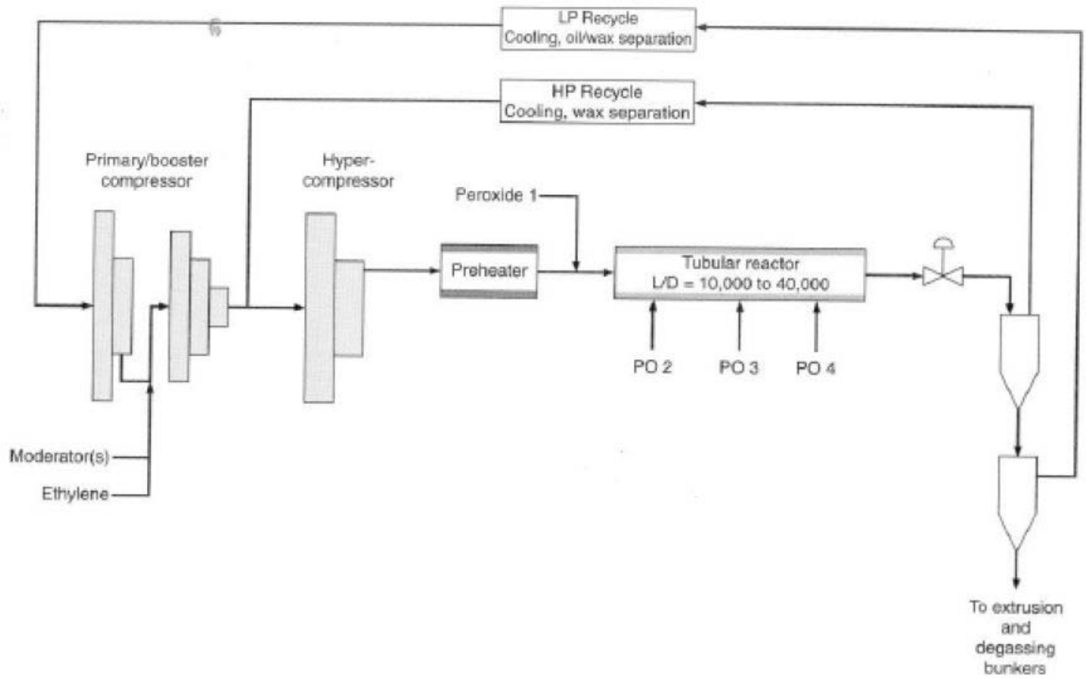

Figure 31 The new high pressure PE process at Borealis (Meyers 2004)

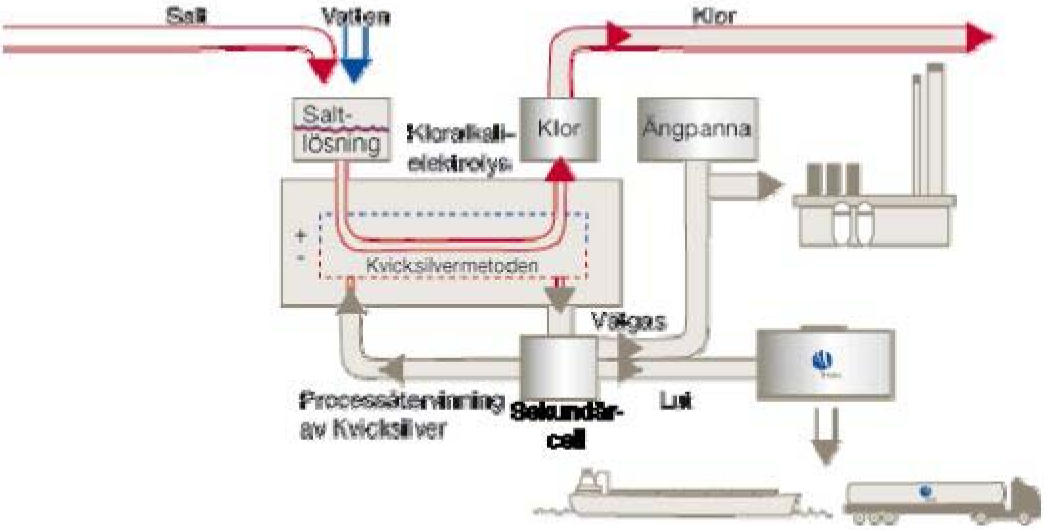

Figure 32 The chlorine process at INEOS (Josefsson 2009)

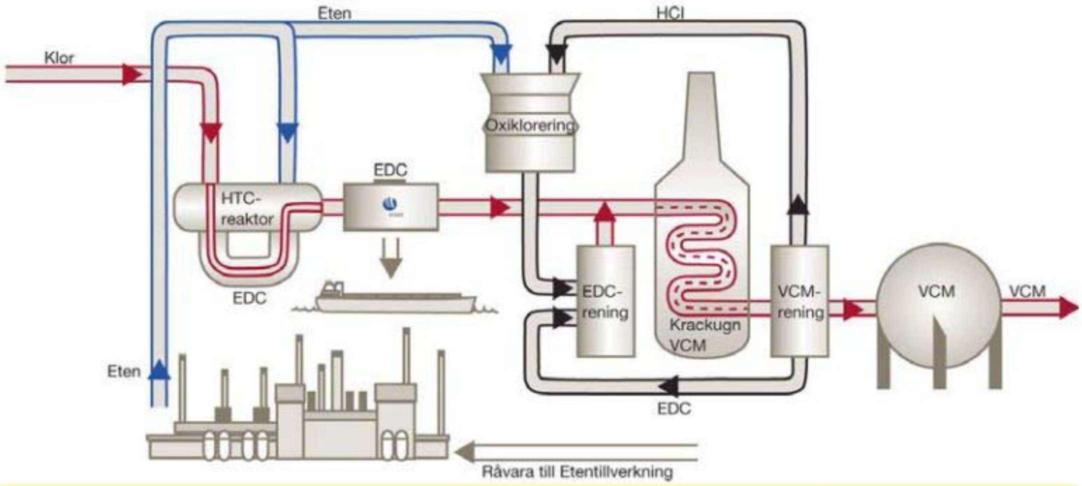

Figure 33The VCM process at INEOS (Josefsson 2009)

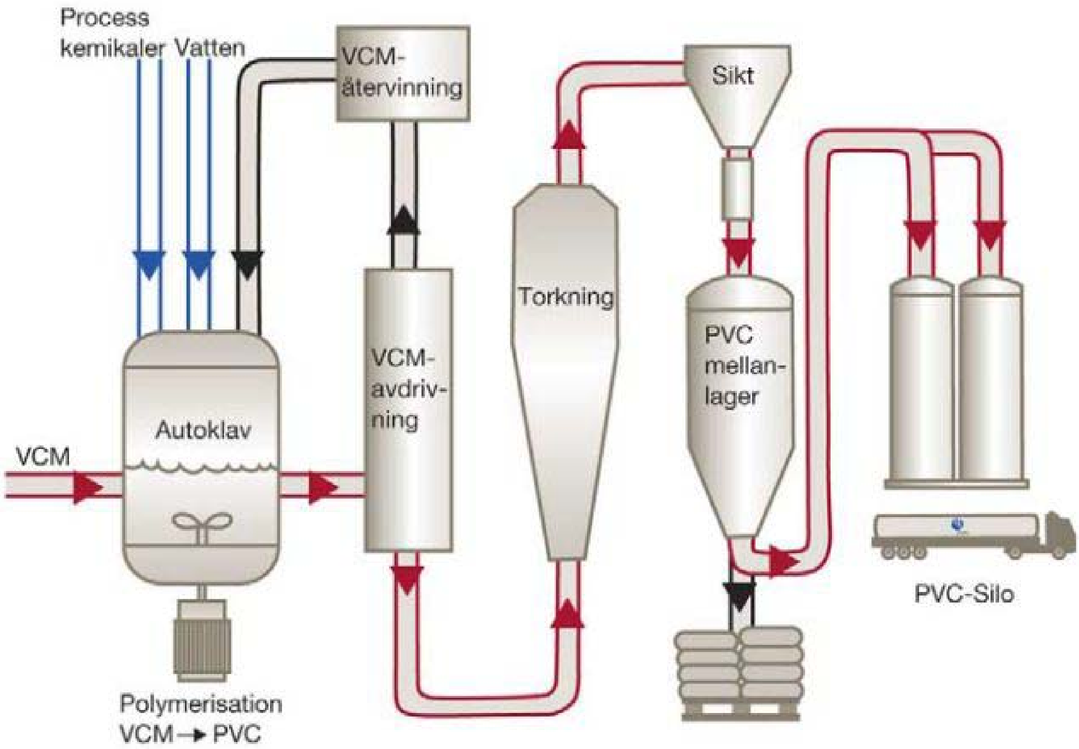

Figure 34 The PVC process at INEOS (Josefsson 2009)

9.2 Appendix 2

Table 11 shows how the excess or deficit of steam at certain steam levels in the current utility systems was calculated. Excess of steam at a higher steam level can be used to cover a deficit at a lower level.

Table 11 Calculation of steam levels with deficit

Steam level	Excess/Deficit [MW]	Deficit after let down [MW]
85bar(g) Borealis	49,8	
40bar(g) Borealis	-12,0	
8.8bar(g) Borealis	-63,1	-25.3
4bar(g) Borealis	28,8	
2.7bar(g) Borealis	8,3	
1.8bar(g) Borealis	-45,0	-7.9
Sum		-33.2
40bar(g) Akzo	-8,3	-8.3
28bar(g) Akzo	-3,3	-3.3
20bar(g) Akzo	-4,9	-4.9
6bar(g) Akzo	-8,6	-8.6
1bar(g) Akzo	-0,3	-0.3
Sum		-22.5
41bar(g) Perstorp	19,5	
20bar(g) Perstorp	-2,6	
14bar(g) Perstorp	2,5	
7bar(g) Perstorp	-15,3	
2bar(g) Perstorp	-31,4	-27.3
Sum		-27.3

28bar(g) INEOS	-3,0	-3.0
20bar(g) INEOS	-1,9	-1.9
10bar(g) INEOS	-4,4	-4.4
6bar(g) INEOS	-5,6	-5.6
1bar(g) INEOS	-7,5	-7.5
Sum		-22.3

9.3 Appendix 3

Table 12 Loads and pressure levels of the utility system for maximised total site integration; including generation and consumption of steam in the improved system

Steam level [bar(g)]	Generation [MW]	Consumption [MW]	Difference [MW]
85 bar(g)	51	1	50
40 bar(g)	42	69	-27
20 bar(g)	29		29
14 bar(g)	15		15
11 bar(g)	9		9
10 bar(g)	13		13
8.8 bar(g)	53	132	-79
2.7 bar(g)	21		21
2 bar(g)	80	105	-25
1 bar(g)	1		1
HotW	107	107	0
Sum	421	414	7

9.4 Appendix 4

Table 13 Prices for steam, electricity and fuel assumed for economical evaluation of energy efficiency measures

Assumed prices:	SEK/MWh
Saved steam	300
Electricity	600
Additional Fuel for steam production	240

Table 14 Economical evaluation ofenergy efficiency measures suggested in the report with an assumed running time of 8000 h/year

Cases	Steam savings [MW]	Electricity produced/ saved [MW]	Addition al fuel [MW]	Value [SEK/h]	Incomes [MSEK/y]
Cogeneration by sending steam from Borealis to INEOS,Akzo,Pertorp, see 5.3.3		8,6	13,6	1890,3	15,1
Introducing only hotW, see 5.2.2	51			15300,0	122,4
Increased steam recovery, see 5.2.2	33			9900,0	79,2
Maximised heat recovery (hotW, LP-steam and steam level adjustments), see 5.2.2	122	2,3		37980,0	303,8
hotW category A, see 5.3	55,2			16560,0	132,5
hotW category A + B, see 5.3	83,5			25050,0	200,4
Steam category A, see 5.3	4,24			1272,0	10,2
Steam category A + B, see 5.3	26,6			7980,0	63,8
Common steam system, see 5.3.3		19,0	26,8	4959,0	39,7
Electricity from 7 MW excess steam		2,3		1380,0	11,0
Cogeneration at Perstorp (see 5.4.4)		8,5	11,9	2040,0	16,3
Utilising cooling energy at EFAB and AGA (see 5.5)		4,8		2880,0	23,0
Utilising low-T evaporators at Borealis (see 5.5)		2,1		1260,0	10,1