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Applying exergy and Total Site Analysis for targeting refrigeration shaft power in industrial clusters

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Abstract

Process cooling below ambient temperature is an energy demanding part of many chemical production processes. Compression refrigeration systems operating at very low temperatures consume a lot of high quality utility such as electricity or high pressure steam to drive the compressor units. In industrial process clusters with several processes operating at low temperatures, it is important to investigate opportunities for exchange of low-temperature energy between processes. This paper demonstrates how Total Site Analysis and exergy analysis can be applied to target for shaft power and related hot utility savings for processes and utility systems operating below ambient temperature. Shaft power targeting by optimizing refrigerant use is conducted. In addition the methodology is extended for shaft power targeting in connection with site-wide heat recovery from cold process streams to generate sub-ambient utility. The methodology is illustrated through application to a case study of a chemical cluster. One chemical plant within the cluster operates two compression refrigeration systems at its steam cracker plant.

The results of the case study indicate potential savings of 1.5 MW of shaft power by optimizing the use of refrigerant from the compression refrigeration system and additional 2.5 MW of shaft power by recovering refrigeration from two other sites located outside the cracker plant. In total this corresponds to 15 % of the total shaft power consumption of the refrigeration systems. Economic evaluation of the proposed measures indicates a pay-back period of approximately 4 years.

Key words: Process integration, Pinch analysis, Exergy analysis, Total Site Analysis, Industrial refrigeration systems

NOMENCLATURE

Abbreviations

C2	Refrigerant ethylene
C3	Refrigerant propylene
CC	Composite Curves
CW	Cooling Water
GCC	Grand Composite Curve
HP	High Pressure (steam)
LP	Low Pressure (steam)
MP	Medium Pressure (steam)
TSA	Total Site Analysis
TSP	Total Site Profiles

Symbols

A	Heat exchanger area [m^2]
η_{ex}	Exergetic efficiency [-]
ΔEx_{p}	Exergy flow rate difference in the process [W]
ΔEx_{r}	Exergy flow rate difference in the refrigeration system [W]
$\Delta Ex_{\mathrm{r,mod}}$	Exergy flow rate difference in the modified refrigeration system [W]
ΔEx_{u}	Exergy flow rate difference in the utility system [W]
P	Actual shaft power [W]
Φ	Heat flow rate [W]
T	Temperature [°C]
T_{ref}	Reference Temperature [°C]
T_{start}	Starting Temperature of a process stream [°C]

T_{target}	Target Temperature of a process stream [°C]

1. Introduction

1.1 Background

According to the International Energy Agency's latest Energy Technology Perspectives 2012 report [1], energy related global CO_2 emissions must be cut to half of current levels by 2050 and continue to decrease afterwards in order to curb the global temperature increase to 2 °C. Increased end-use efficiency of fuel and electricity is seen as one of the most important strategies to reach the 2 °C goal. Energy intensive industries consume large amounts of utility (e.g. fuel, steam, Cooling Water (CW), refrigerant and electricity) in order to operate their processes. High efficiency in industrial production processes is of utter importance to stay competitive and achieve sustainability.

Industrial clusters have good prerequisites to decrease their overall resource consumption by site-wide energy and materials integration. This paper shows how Process Integration methods can be used to target for increased energy efficiency by identifying measures for decreasing the shaft power consumption of industrial refrigeration systems, both on a single plant and a site-wide scale. A targeting procedure dealing with single plant and site-wide energy efficiency measures is presented. Targeting shaft work savings by for site-wide recovery of cooling capacity below ambient was not dealt with in literature. The targeting procedure is presented and applied in a case study to a chemical cluster.

1.2 Related work

This work is based on previous work by the authors in which opportunities for site-wide heat integration throughout the chemical cluster in Stenungsund were investigated, with a focus on heat integration opportunities above ambient temperature [2]. Hackl et al. published the methodology applied in the study and the main results obtained by investigating site-wide heat integration opportunities in the Stenungsund chemical cluster [3].

Pinch Analysis is a widely used approach for process heat integration. It was developed by Bodo Linnhoff at the University of Leeds in the end of the 70-ties [4] and has been developed further at among others the University of Manchester Institute of Science and Technology (UMIST). An updated version of the user guide on Pinch Analysis was published by Kemp (2007) [5]. Studies have shown that energy savings of up to 20 % to 40 % can be achieved by Pinch Analysis [6]. Total Site Analysis (TSA) is an extension of Pinch Analysis that can be used to investigate site-wide heat integration opportunities. TSA is used to integrate the individual heating and cooling demands of different processes within a total site. Excess heat or cooling capacity from one process plant is transferred to a common utility (e.g. steam, hot water, refrigerant) and then delivered to processes with a heat or cooling deficit by the utility system. The concept of TSA was introduced by Dhole and Linnhoff [7] with the purpose of extending Pinch technology from analysis of integration opportunities in single processes to site-wide integration. Further development of the methodology was performed by Raissi [8], Hu and Ahmad [9] and Klemes et al. [10]. A thorough description of the methodology is presented by Klemes et al. in reference [11].

Umeda [12] and Linnhoff and Dhole [13] developed a methodology which extends Pinch Analysis for the design of low temperature processes. It combines Pinch Analysis with exergy concepts. The main goal of the method is to achieve increased understanding of how to design a refrigeration system and the heat exchanger network. Dhole and Linnhoff [14] proposed a methodology for overall design and analysis of low temperature processes. Fritzon and Berntsson [15] and Panjeshahi et al. [16] applied the method to target for energy efficiency measures in single plant industrial case studies. Maréchal and Favrat [17] used the exergy concept combined with the pinch based approach for studying the optimal integration of energy conversion systems. Hirata [18] describes how Process Integration methods can be used for investigating low temperature heat integration measures in an ethylene production process. Hirata and Kakiuchi [19] studied the integration of excess heat driven adsorption heat pumps to replace cooling capacity in the refrigeration system of an ethylene production process. Fabrega et al. [20] performed an exergetic analysis of the refrigeration system in a steam cracker plant. In their study the equipment with the highest rates of exergy destruction were identified and measures reducing exergy destruction by approximately 13 % were suggested. Ataei [21] presented a case study on the combined use of pinch and exergy analysis in order to decrease the power consumption of an olefin plant. Ghorbani and Salehi [22] applied a combination of pinch and exergy analysis in the design of the refrigeration cycle of a natural gas liquids process. Aspelund et al. extended Pinch Analysis and exergy principles to the design of sub-ambient temperature processes [23]. Marmolejo-Correa and Gundersen identified challenges related to using exergy efficiency as a performance indicator for low temperature process design. They propose new design approaches in reference [24] and proposed a new graphical approach to apply exergy to low temperature process design [25] as well as processes operating both above and below ambient temperature [26].

Application of the combined exergy/Pinch Analysis approach on a total site scale was introduced by Dhole and Linnhoff [7]. The site-wide recovery of cooling from cold process streams below ambient temperature was not considered in their work. In the literature the combined exergy/Pinch Analysis approach on a total site level mainly focuses on investigating heat recovery measures via common steam or other hot utility systems. The site-wide recovery of cooling capacity via common cold utility systems using refrigerants across different plants and companies and resulting shaft power savings is not dealt with in detail.

1.3 Aim

The aim of this work is to establish a methodology to target for cooling capacity and resulting shaft power savings based on Total Site Profiles (TSP) and exergy analysis. The methodology is then applied to a chemical cluster case study in order to determine practical ways to decrease the utility usage by creating an improved and interconnected utility system. First, the target for decreasing the shaft power consumption within the current refrigeration systems is established by optimizing the use of refrigerant at given temperatures. Thereafter the target for site-wide recovery of cooling capacity via a common cold utility system is estimated and the corresponding shaft power savings are determined. The later has not been dealt with in detail in the literature. The challenges are to identify suitable cold process streams which enable recovery of cooling capacity, determine the resulting shaft power targets and utilize the targets for identifying specific measures for achieving the targets. The targeting procedure is presented and applied to a case study in a petrochemical cluster. In the case study improvements to the cooling systems in terms of how cold utility is utilized within the processes are investigated and measures for decreasing the heat and power consumption of the chemical cluster by increased recovery of cold utility across the total site are suggested. Based on the targeting results specific energy efficiency measures are suggested and evaluated with respect to economic performance.

1.4 The chemical cluster

The chemical cluster investigated in this paper is located in Stenungsund on the West Coast of Sweden, and is Sweden’s largest agglomeration of its kind. The companies located within the cluster are AGA Gas AB producing industrial gases, Akzo Nobel Sverige AB producing amines and surfactants, Borealis AB producing ethylene and polyethylene, INEOS Sverige AB producing polyvinyl chloride and Perstorp Oxo AB producing speciality chemicals. The heart of the cluster is a steam cracker plant run by Borealis, which delivers both feedstock and fuel gas to the surrounding plants. The process consumes a lot of low temperature cooling at temperature levels down to –100 °C. Some of the surrounding companies also operate low temperature processes, e.g. an Air Separation Unit and an ethylene import terminal. Figure 1 illustrates the material and energy flows across the chemical cluster. The companies already interact strongly with each other in terms of material exchange. As shown in Figure 1 ethylene and other products are distributed among companies across the site. Collaboration in terms of heat is very limited. Steam is only exchanged between the steam cracker and the polyethylene plant and to a minor extent the ASU is supplied by steam from Akzo Nobel’s boilers.

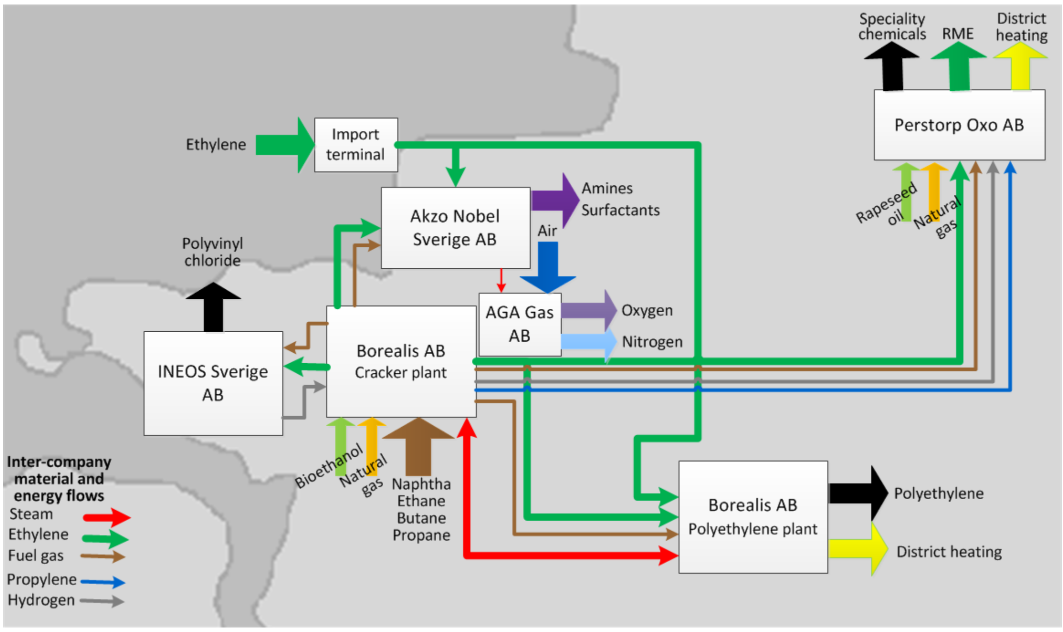

Figure 1 Material and energy flows across the chemical cluster in Stenungsund [27].

Exploiting evaporation of feedstocks from low temperature storage within the cluster to provide low-temperature cooling at other locations is one way to decrease the cluster’s overall electricity and heat consumption.

1.5 Steam and refrigeration systems

Most of the refrigeration at the cracker plant is performed by two interconnected vapour-compression refrigeration systems; a propylene (C3) and an ethylene (C2) compression refrigeration system (see Figure 2). The propylene system’s four stage compressor is driven by a steam turbine (steam expansion from a gauge pressure of 85 to 8.8 bar) and delivers cooling at three levels (9 °C, –21 °C, –40 °C). Depending on the production capacity of the cracker plant the compressor power of the propylene refrigeration system is normally between 18 MW and 24 MW.

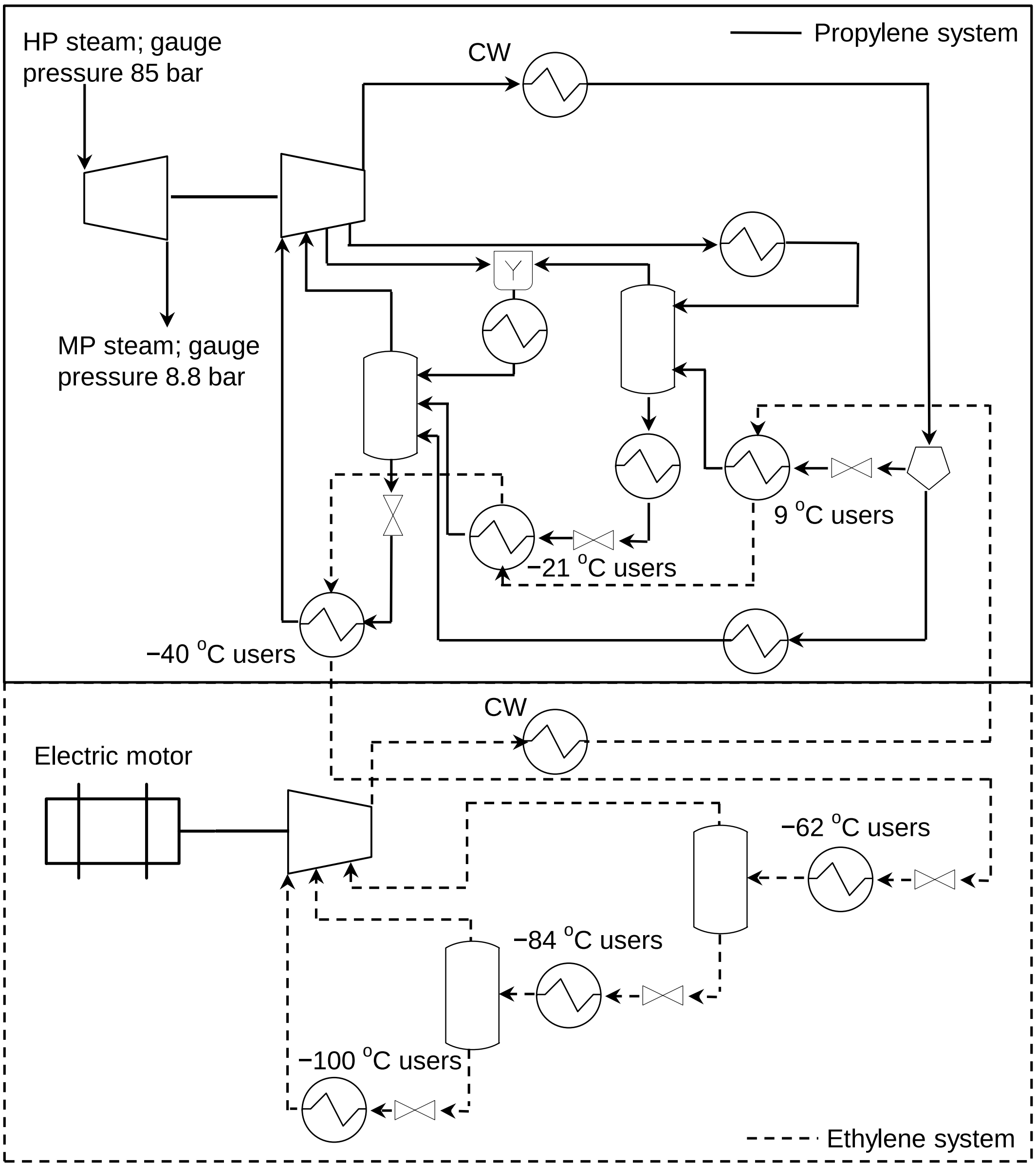

Figure 2 PFD of the propylene and ethylene refrigeration systems at the cracker plant.

The compressor of the ethylene refrigeration system is driven by an electrical motor. The electric power requirement system typically varies between 4 MW and 4.5 MW, approximately 10 % of the total electricity consumption of the cracker plant. Cooling is delivered to the process at three levels (–62 °C, –84 °C, –100 °C). The two systems are interconnected where part of the propylene systems' cooling capacity is used to cool the ethylene system.

The propylene refrigeration system is strongly integrated with the steam system of the site. Figure 3 shows the steam system. High pressure (HP) (gauge pressure of 85 bar) steam is generated in the steam boilers as well as by recovering heat from the product gases of the cracking furnaces. Some of the steam is partly expanded to a gauge pressure of 40 bar and exported to another site. The rest is expanded to medium pressure (MP) (gauge pressure of 8.8 bar) level via a turbine driving the compressor of the propylene refrigeration system, a turbine driving an electricity generator or a let-down station. Most of the MP steam is injected directly into the cracking furnaces, but some is also used for process heating and to drive other turbines. Low pressure (LP) (gauge pressure 1.8 bar) steam is used for process heating and in the deaerator.

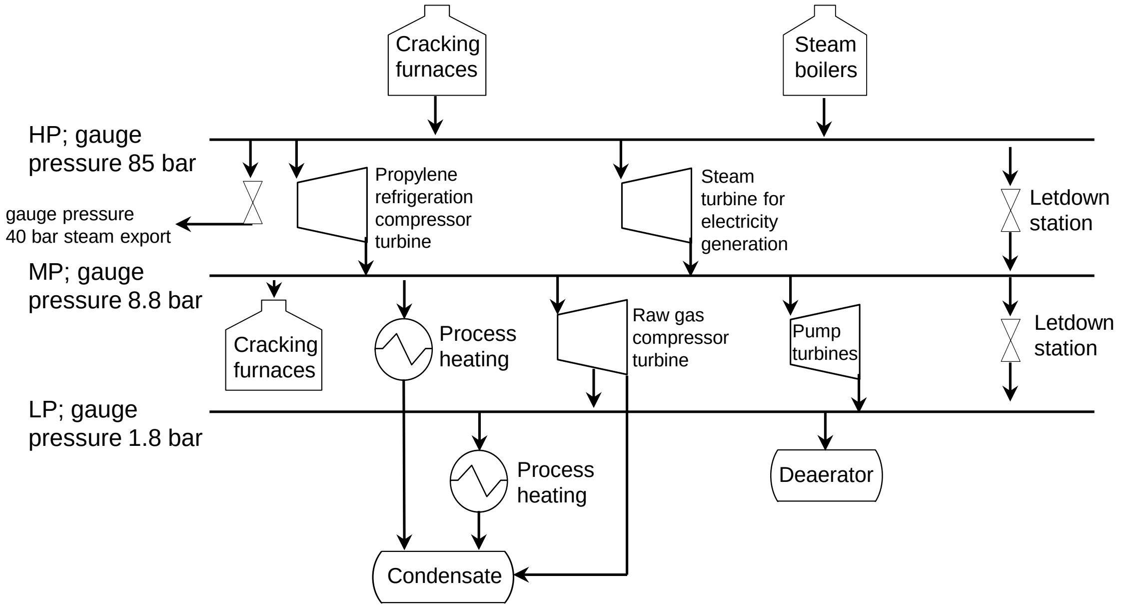

Figure 3 Steam system of the cracker plant.

In the steam network shown in Figure 3 it can be seen that shaft power generated by expanding HP steam is used both for refrigeration and electricity generation. If the shaft power consumption of the propylene refrigeration system decreases, the HP steam can either be used for increased electricity production in the existing steam turbine or less HP steam is produced in the steam boilers, thus saving fuel.

2. Methodology

2.1 Targeting for decreasing exergy losses

Pinch Analysis mainly focuses on targeting for heat integration potential and related fuel savings. Primary energy savings achieved by heat integration measures saving cooling capacity in refrigeration systems (as investigated in this study) cannot be directly evaluated using regular Pinch Analysis. Therefore the exergy concept using Carnot efficiency based curves is applied in combination with Pinch Analysis which enables targeting for shaft power savings in low temperature processes.

Exergy is defined as the maximum theoretical useful work (shaft work or electrical work) obtainable as two systems interact to equilibrium or the minimum theoretical useful work required to bring matter to a specified state [28]. The main difference to conventional and combined exergy Pinch Analysis is that the *y*-axis of the Composite Curves (CC) and Grand Composite Curve (GCC) show Carnot efficiency corrected temperature instead of temperature. Carnot efficiency is defined by $\eta_c = 1 - T_{ref} / T$ (T_{ref} = reference temperature). An example of such a curve is shown in Figure 4. Using Carnot efficiency corrected temperature instead of temperature has the advantage that sources of exergy flow rate losses can be easily identified graphically and quantified by integrating the areas between the curves, without the need for time consuming process simulation of the given case. In this study the curves are applied to target for decreasing exergy flow rate losses by optimizing refrigerant use and decreasing exergy flow rate losses by site-wide recovery of refrigeration.

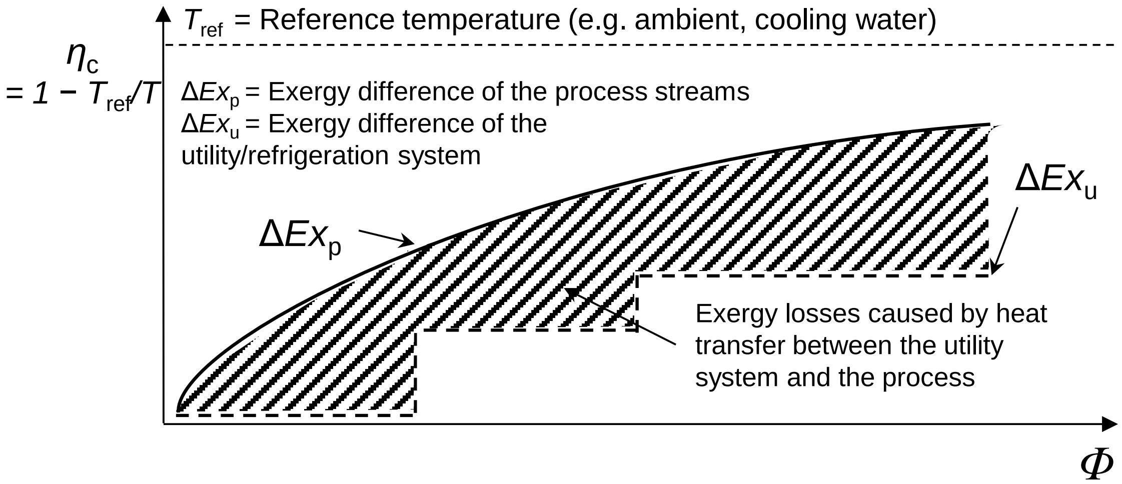

Figure 4 A schematic example of a exergy CC showing the composite curve of the process (full line), composite curve of the utility system (dashed line), the resulting exergy flow rate difference of the process streams and the utility system and the exergy flow rate losses caused by heat transfer between the utility system and the process [13].

In order to construct the profiles shown in Figure 4 the following procedure is applied:

- Collection of relevant stream data (T_{start}, T_{target}, Φ, type of utility).
- The process stream profile can be plotted using T_{start}, T_{target} and Φ for each stream according to the description by Kemp [5].
- The utility profile is plotted in the same way using T and Φ of the utilities used for heating/cooling the plotted process streams.
- A suitable T_{ref}, e.g. CW temperature is defined.
- The process stream and utility profiles are plotted in the exergy η_c-Φ-CC diagram.

The area between the respective curve and the reference temperature line in the exergy CC represents the exergy flow rate that must be supplied in order to achieve the desired target temperature. The area between the upper full line and the reference temperature line represents the exergy flow rate difference of the process streams, ΔEx_p. This is the minimum exergy input necessary to cool the process streams to their target temperature. A utility system able to reach this minimum exergy input needs an infinite number of utility levels and an infinitely small minimum temperature difference. The area between the lower dashed line and the reference temperature line represents the exergy input to a real utility system designed for cooling the given process. The area between the process (full) line and the utility system (dashed) line can be considered as exergy flow rate losses caused by the utility systems' design (cooling temperature levels, temperature difference, etc.). The presented curves can be used to target for reduction of the exergy flow rate losses by identifying changes to the design of the utility system resulting in a decrease of exergy flow rate losses. This is done by modifying the curves in order to decrease the area between the utility and process curve. In most cases process streams have strict demands on T_{start}, T_{target} and Φ, which is why often the process profiles cannot be changed. If the process stream profile cannot be changed to only measures to decrease the area between the curves is to move the utility profile closer towards the process stream profile. Looking at Figure 4 the following changes to the utility profile are identified:

- Utilizing each utility level as much as possible (until a utility pinch point is activated).
- Adjust the utility temperature levels to better fit the process stream profile.
- Increasing the number of utility levels to better fit the process stream profile.

The areas shown in the Carnot efficiency based curves only represent exergy flow rate differences.

The method and the same type of graph can also be applied to target for shaft power savings at total sites, by applying the exergy concept to TSPs as demonstrated by Dhole and Linnhoff (1993) [7]. They used exergy TSPs to target for fuel, co-generation, emissions and cooling.

In this paper the methodology is extended and applied to estimate the target for site-wide recovery of cooling capacity and associated consequences for shaft power consumption of the plant's refrigeration systems.
The following procedure is applied:

- Stream data collection for cold process streams below ambient temperature from the different plants (companies) (T_{start}, T_{target}, Φ, type of hot utility)
- The process stream and current hot utility profile are plotted as exergy CC diagram as described above.

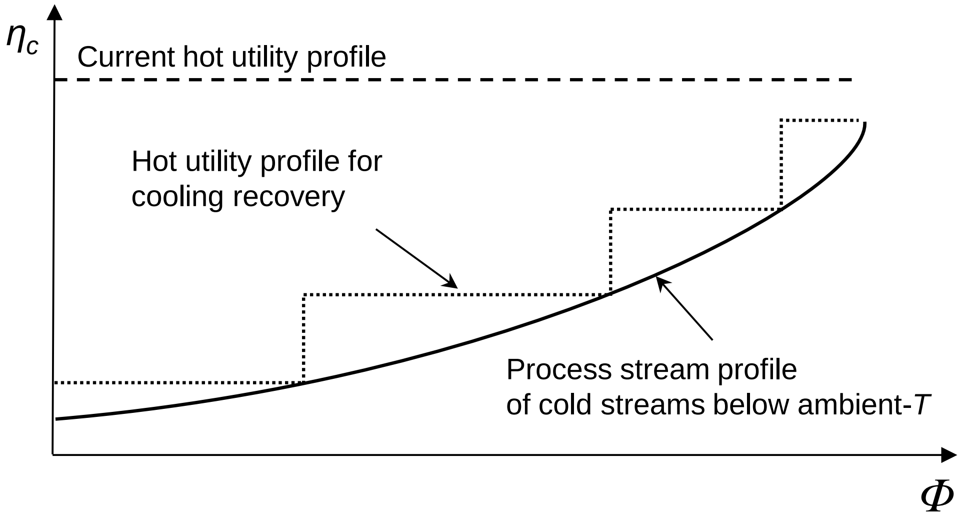

Figure 5 Illustration of the targeting procedure for site-wide recovery of cooling capacity from cold process streams (full line) below ambient temperature; current hot utility (dashed line), utility system recovering cooling capacity (dotted line).

Figure 5 illustrates the process of how the potential for recovering cooling capacity is estimated. The graphs are explained in the following and the procedure for targeting recovery of cooling capacity is described:

- The area between the current hot utility profile (dashed line) and the process stream profile (full line) represents the exergy flow rate losses caused by the current utility system.
- As only streams below ambient temperature are included in the process stream profile it is possible to recover cooling capacity.
- The temperature levels of the current refrigeration utility system are retained, see dotted lines in Figure 5.
- An improved utility system is designed and its potential for recovering cold utility is determined by activating a utility pinch against the cold process profile at each utility level.
  →The target for recovery of cooling capacity can thus be determined.
- The recovered cooling capacity replaces refrigerant from the refrigeration systems.
- The corresponding decrease of exergy flow rate losses can be calculated as it corresponds to the exergy necessary to generate the recovered cooling capacity.

2.2 Estimating shaft power target based on exergy savings targets

In the previous section the methodology for targeting decreased exergy flow rate losses was described. In order to establish the value of achieving these targets it is necessary to translate the exergy savings into shaft power savings using an appropriate value of the exergetic efficiency η_{ex} of the utility/refrigeration cycle. The exergetic efficiency is defined as shown in Eq. (1):

$$\eta_{ex} = {}^{\Delta Ex_u}\!\big/_{P} \tag{1}$$

where P represents the actual shaft power for the investigated process at a certain operating point. The actual shaft power is obtained by measurements or process simulation if measurements are not available. ΔEx_u is the exergy flow rate difference of the utility/refrigeration system. It is obtained from exergy Pinch curves of the real refrigeration system operating at the same conditions as used to determine P. Once determined for the investigated system, η_{ex} can be used to estimate consequences on the shaft power demand of changes to the process, heat exchanger network and refrigeration systems. η_{ex} accounts for friction and other losses in the refrigeration system.

In a case study Linnhoff and Dhole [13] determined a value of $\eta_{ex} = 0.59$. The study investigated the same type of system as in this paper, a refrigeration system in an ethylene production plant. The method has been shown to be very accurate giving a deviation of only 1.9 % compared to process simulation results for the same unit.

The exergetic efficiency for the system investigated in this paper was determined to $\eta_{ex} = 0.66$ by using measured shaft power data obtained for the targeted refrigeration systems.

2.3 Identification of specific measures and economic evaluation

The shaft power targets estimated by using the combined Pinch Analysis/exergy approach presented above can be used as guidelines for identifying specific process improvements. This paper discusses how specific measures can be identified and evaluated with respect to economic performance.

The procedure for identifying specific improvements is as follows:

- Utility systems changes with large savings potential are identified in the exergy Pinch curves.
- Necessary changes to heat exchangers are determined.
- Stream tables (given in Table 2 and Table 4) are used to identify the streams (or parts of streams) which could be heated or cooled by another utility which enables for decreasing exergy flow rate losses caused by heat transfer.
- The specific changes to the heat exchangers currently treating the streams are identified, e.g. new T_{target} and Φ.

Once the changes are identified the resulting exergy flow rate and shaft power savings can be calculated and their economic value (e.g. economic value of electricity which generates the shaft power, see Table 1) is estimated. Then the costs of the suggested measures are estimated.

In this paper an example of such an analysis is presented on selected measures for the given case study. The heat exchanger area of the new heat exchangers necessary to obtain the estimated savings is calculated. The data and equations used are shown in Table 1. Based on the heat exchanger area costs of heat exchangers are calculated using cost functions according to Sinnott and Towler [29]. The following Table 1 contains the necessary assumptions and data gathered for conducting the economic analysis. Pay-back time is used as a feasibility indicator.

Table 1 Assumptions and data for heat exchanger area estimation and economic evaluation [30].

Description	*Value*	*Unit*	*Comment*
Area calculation	$A = \Phi/(U \cdot \Delta T_m)$	m^2	
U-value	700	$W/m^2 \cdot K$	*
Heat exchanger type	U-tube shell and tube		
Material	Carbon steel		
Cost function	$24\,000 \cdot 46 \cdot A^{1.2}$	A in m^2	
$\mathrm{CEPCI}_{\mathrm{HXTR}}$	1.14		**
Currency conversion	0.7525	$/€	***
Location factor	1.13		****
Installation factor	3.5		*****
Design and Engineering	0.3		
Contingency	0.1		
Electricity price	60	€/(MW·h)	

Chapter 1 *Typical value given by Sinnott & Towler for heat transfer between organics
Chapter 2 **Chemical engineering plant cost index (CEPCI) for heat exchangers 2011/2007
Chapter 3 ***01-22-2013
Chapter 4 ****Sweden not available; average for certain European countries assumed
Chapter 5 *****Typical installation factor for heat transfer equipment

3. Case Study Results and Discussion

3.1 Improvements to the current refrigeration system

First an investigation of the current design of the refrigeration systems is conducted in order to improve the way cold utility is used in the process and to thereby increase energy efficiency. Process stream data and utility data from a previous TSA study are used to construct the exergy CC for process and utility streams below ambient temperature. Table 2 shows the process stream data and current utility used for process cooling, and Table 3 presents the current cold utility usage at the different levels. Figure 6 shows the hot process streams and the cold utility profile of the steam crackers' streams below ambient temperature.

Table 2 Hot process stream/heat exchanger data and current utility used for process cooling.

No.	T_{start}/˚C	T_{target}/˚C	Φ/kW	Current cold utility
1	24	14	530	C3/9 °C
2	27	16	1 190	C3/9 °C
3	27	11	2 600	C3/9 °C
4	27	16	433	C3/9 °C
5	−8	−10	10 820	C3/ −21 °C
6	10	−16	4 280	C3/ −21 °C
7	14	−15	1 600	C3/ −21 °C
8	15	−16	1 490	C3/ −21 °C
9	32	−9	790	C3/ −21 °C
10	−8	−16	270	C3/ −21 °C
11	−27	−28	19 590	C3/ −40 °C
12	−26	−36	4 480	C3/ −40 °C
13	−24	−35	2 080	C3/ −40 °C
14	−19	−35	2 340	C3/ −40 °C
15	−15	−24	9 000	C3/ −40 °C*
16	10	−34	850	C3/ −40 °C*
17	−34	−39	610	C2/ −62 °C
18	−27	−96	320	C2/ −62 °C
19	−53	−81	1 250	C2/ −84 °C**
20	−43	−76	6 070	C2/ −84 °C**
21	−90	−97	645	C2/ −100 °C
22	−90	−97	245	C2/ −100 °C
23	−57	−96	170	C2/ −100 °C

* can be partly replaced by C3/ −21 °C

** can be partly replaced by C2/ −62 °C

Table 3 Current cold utility demand and the change in demands when implementing the suggested changes to the utility system.

Cold utility level	Current cold utility demand Φ/kW	Demand change $\Delta\Phi$/kW	Demand change %
C3/9 °C	4 753	884	18.6
C3/ −21 °C	19 250	2 537	13.2
C3/ −40 °C	38 340	−2 738	−7.1
C2/ −62 °C	930	2 106	227
C2/ −84°C	7 320	−2 755	−37.6
C2/ −100 °C	1 060	−35	−3.3

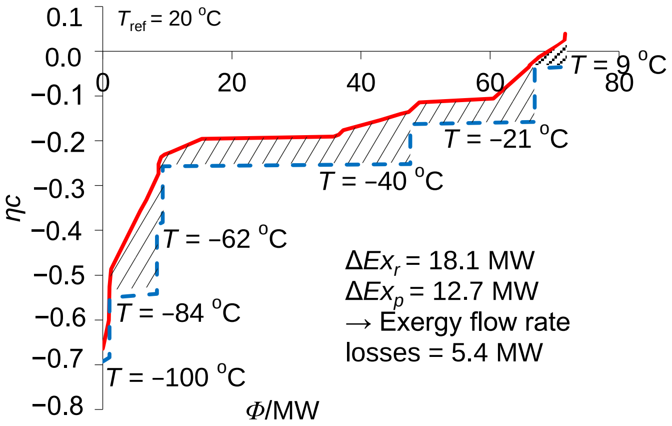

Figure 6 Exergy CC showing process streams at the steam cracker plant cooled by refrigerants (full line) and the corresponding cold utility profile (dashed line).

The area between the two curves corresponds to 5.4 MW, which represents the exergy flow rate being lost due to the way heat is transferred from the process streams to the cold utility system. From the shape of the curves it can be seen that there is a large gap between the utility profile and the hot process stream profile. If the existing utility levels are retained, the only way to decrease the area between the curves is to maximize cold utility use at as high temperature as possible. For example, the use of refrigeration at –40 °C should be decreased and the use of refrigeration at –21 °C increased so as to activate a utility pinch for the –21 °C system. The same can be done for the –84 °C and the –62 °C systems. As a result of these changes in utility use the area between the curves can be decreased. In this case a minimum temperature difference of 3 K was assumed. Using these constraints (minimum temperature difference of 3 K and retained utility levels) the utility system demands were thus revised so as to maximize the use of refrigerant at as high temperature as possible and thereby minimize exergy flow rate losses.

The resulting curve is shown in Figure 7 (dotted line). The current cooling levels are retained, but instead cold utility is used at as high temperature as possible. Table 3 shows the resulting net demand changes at the different cold utility levels. The area between the utility and process curve is decreased and so are the exergy flow rate losses (ΔEx_{r} of current refrigeration system = 18.1 MW; $\Delta Ex_{\mathrm{r,\ mod}}$ of the suggested refrigeration system = 17.1 MW). The area between the two curves now corresponds to 4.4 MW of exergy flow rate losses, which means that by redesigning the cold utility system in the suggested manner exergy flow rate losses of approximately 1 MW can be avoided (see Figure 7). Taking into account η_{ex} (= 0.66) shaft power savings of approximately 1.5 MW can be achieved by the suggested changes to the utility system. This corresponds to about 5.4 % of the total shaft power consumed in the refrigeration systems.

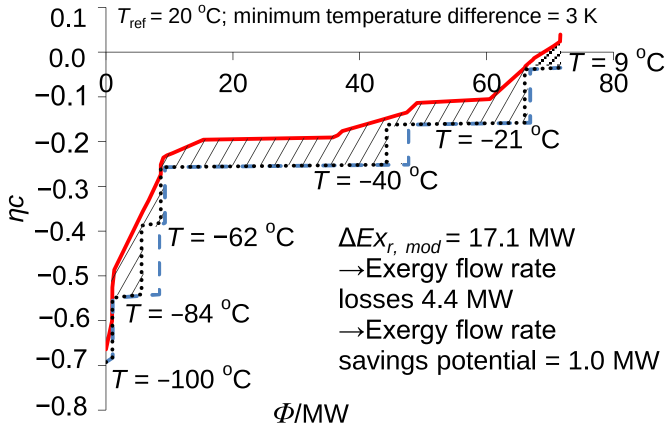

Figure 7 Exergy CC showing streams at the steam cracker plant cooled by refrigerants (full line), the improved utility profile (dotted line) at the current cold utility levels; current utility profile (dashed line).

The area between the exergy CCs and thereby the exergy flow rate losses can be further decreased by changing the refrigeration cooling levels. For example, the introduction of an additional cooling level between the current –21 °C and –40 °C levels and between 9 °C and –21 °C would largely decrease the exergy flow rate losses caused by heat transfer between the utility system and the process streams. This is considered to be an unlikely measure as it involves changes to the compressors themselves and to a large number of heat exchangers which have to be redesigned for new utility temperature levels. Therefore the current utility system levels are accepted and only cooling demand changes considered further in this work.

3.2 Increased recovery of sub-ambient temperature utility

An additional way to decrease the shaft power consumption of the refrigeration systems is to increase the recovery of cold utility from cold process streams. Very cold process streams within the cluster (down to –148 °C) are currently heated with unnecessarily hot utility (e.g. steam). Cold process streams below ambient temperature were identified across the total site and are shown in Table 4. By replacing the hot utility with refrigerant at one of the current utility levels it is possible to recover cooling capacity. In this way the demand for refrigerant from the compression refrigeration systems is decreased resulting in less shaft power consumption.

Table 4 Cold process stream/heat exchanger data and current utility used for process heating of cold process streams below ambient temperature across the total site.

No.	T_{start} /°C	T_{target}/°C	Φ/kW	Current hot utility
24	−101	−16	780	20bar steam
25	−16	−15	901	20bar steam
26	−15	27	301	20bar steam
27	−101	−16	1 634	CW
28	−16	−15	1 877	CW
29	−15	27	628	CW
30	4	73	2 377	MP
31	−85	−15	272	LP
32	−15	−14	656	LP
33	−14	20	116	LP
34	−40	3	667	LP
35	−30	9	1 031	LP
36	−10	4	688	LP
37	−98	−14	50	LP
38	−14	−13	104	LP
39	−13	20	20	LP
40	−148	−147	719	28bar steam
41	−130	−129	300	28bar steam
42	−27	2	710	C3/9 °C
43	−8	−7	2 160	C3/9 °C
44	−4	−3	16 600	C3/9 °C
45	2	7	114	C3/9 °C
46	4	7	5 936	C3/9 °C
47	7	8	464	C3/9 °C
48	−25	−19	1 790	C3/9 °C
49	−81	−25	1 235	C3/ −21 °C

Figure 8 shows the exergy TSP for process streams below ambient temperature and the corresponding hot utility curve, required in order to determine site-wide targets for recovering cooling capacity and estimate the resulting shaft power savings. The left side of Figure 8 shows hot process streams (full line) and the cold utility profile (dashed line). The right side shows cold process streams (full line) and the current hot utility (dashed line) used for process heating. The area between the curves (striped) represents the exergy flow rate losses caused by heat transfer between the utility system and the process streams. It can be seen in the right side of Figure 8 that there is a large gap between the hot utility profile and the cold process streams, thus indicating large exergy flow rate losses due to heat transfer from the hot utility to the cold process streams. Heating of the cold process streams can be performed by utility at a lower temperature. As the process streams are below ambient temperature it is even possible to recover cooling capacity.

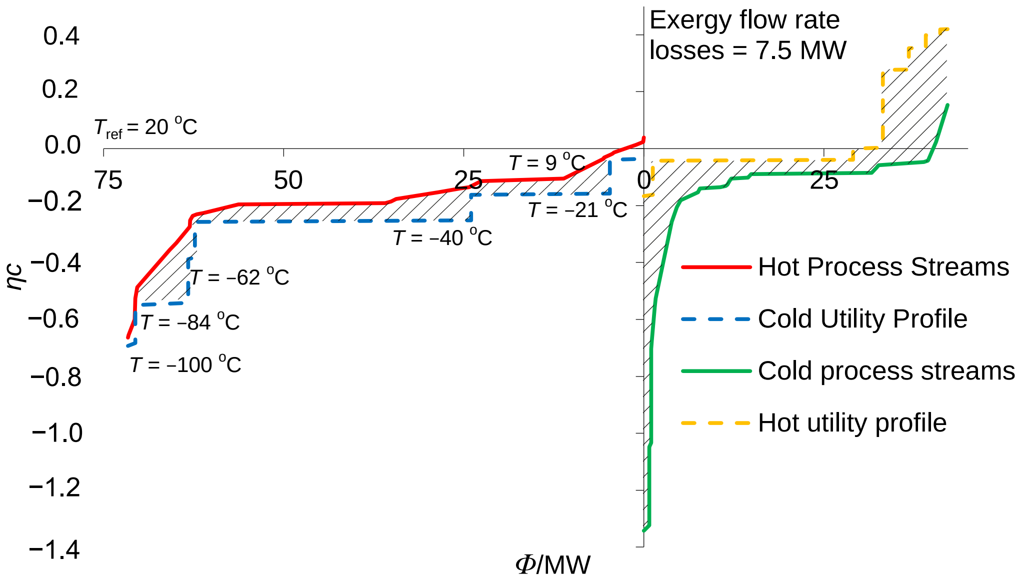

Figure 8 Exergy TSP showing process streams at the steam cracker plant cooled by refrigerants and the cold utility profile (left), the total sites cold streams below ambient-T and the respective hot utility profile (right).

Assuming a minimum temperature difference of 3 K a utility system utilizing optimal cooling (retaining the cluster's existing cold utility levels) was designed. The utility system was designed so that a pinch point is activated at each utility level of the hot utility curve with the cold process stream profile. The resulting curve represents the utility system with the lowest possible area (corresponding to the lowest possible exergy flow rate losses) between the hot utility curve and the cold process stream profile, see Figure 9. Cold process streams are heated by utility at the same temperature as the current refrigerant levels. Thereby the area between the curves is decreased so that the sum of exergy flow rate losses is decreased from 7.5 MW to 3.5 MW. The decrease in exergy flow rate losses is achieved by replacing hot utility (e.g. steam) and instead recovering cooling capacity from process streams below ambient temperature.

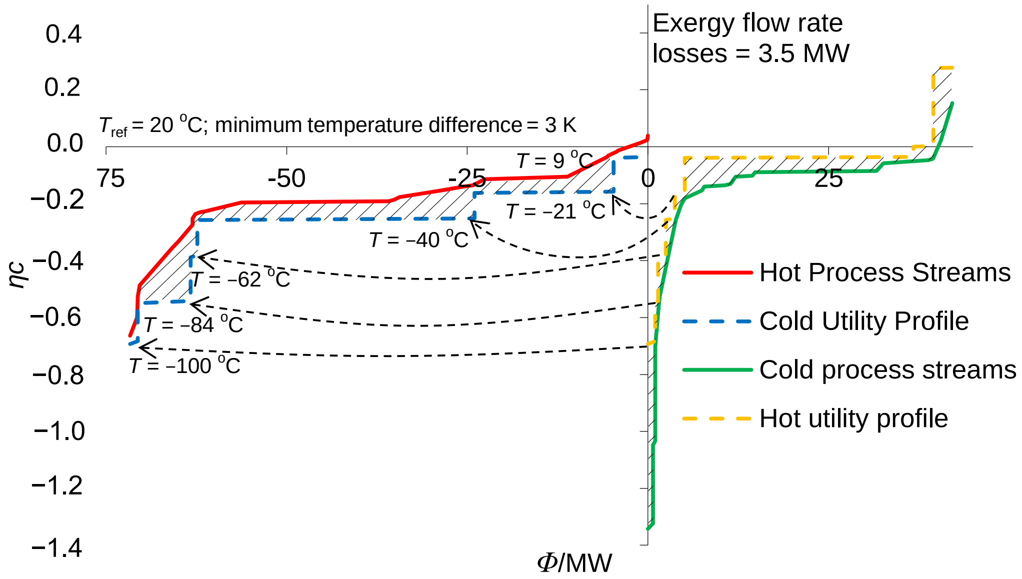

Figure 9 Exergy SSSP showing process streams at the steam cracker plant cooled by refrigerants and the cold utility profile (left), the total sites cold streams below ambient-T and a suggested improved hot utility profile (right).

The targets for increased recovery of cold utility and the resulting avoided exergy flow rate losses are summarized in Table 5. These results indicate that by changing the utility system in order to recover more cooling capacity from cold process streams, while retaining the current utility levels, it is possible to decrease the exergy flow rate losses in the cooling system by 1.63 MW. Taking into account η_{ex} (= 0.66) this corresponds to shaft power savings of 2.5 MW. This is approximately 10 % of the total shaft power consumption of the refrigeration systems. In the suggested improved hot utility system for several heat exchangers, utility steam is replaced by a refrigerant to recover cooling capacity. In addition to relieving the refrigeration systems, this measure could also save approximately 6.3 MW of utility steam at gauge pressure levels between 1.8 bar and 28 bar. The steam can in return be used for process heating and ultimately save fuel in the cluster’s boilers.

Table 5 Summary of the process cooling demand, the potential for cooling recovery from cold process streams and the resulting avoided exergy flow rate losses considering the current cold utility levels.

Cold utility level	Current cold utility demand Φ/MW	Potential additional recovery of cold utility from cold process streams Φ_{rec}/MW	Avoided exergy losses [MW]
C3/9 °C	4.8	0	0
C3/ −21 °C	19.3	0.2	0.03
C3/ −40 °C	38.3	1.3	0.3
C2/ −62 °C	0.9	0.9	0.4
C2/ −84 °C	7.3	0.4	0.2
C2/ −100 °C	1.1	1.0	0.7
Sum	71.7	3.8	1.63

3.3 Identification of specific measures and economic evaluation

Four promising measures to decrease the shaft power consumption by improving the use of refrigerant were identified and evaluated. The measures suggested involve replacing the current refrigerant used for process cooling by a refrigerant at higher temperature, thereby decreasing the shaft power consumption of the compression refrigeration systems. The streams subject to modifications in this example are marked in Table 2. The current utility used heat exchangers no. 15 and 16 (process stream heaters) can be partly replaced by utility at a higher temperature. The same can be done for heat exchangers no. 19 and 20. This is presented in Table 6. The changes presented imply that four new heat exchangers are installed in order to enable utilizing utility at a higher temperature for process cooling. The T_{start}, T_{target}, Φ and the new utility used for process cooling in the heat exchangers is given.

Table 6 Summary of suggested changes to heat exchangers and resulting exergy flow rate and shaft power savings.

No.	T_{start}/°C	$T_{target,new}$/°C	Φ/kW	New cold utility
15	−15	−18	3 000	C3/ −21 °C
16	10	−18	541	C3/ −21 °C
19	−53	−57	179	C2/ −62 °C
20	−43	−57	2 575	C2/ −62 °C

By applying these measures exergy flow rate losses can be decreased by approximately 780 kW, corresponding to shaft power savings of approximately 1200 kW. It is assumed that the economic value of the saved shaft power corresponds to the value of electricity. Assuming an electricity price as given in Table 1 an annual cash flow of 565 000 €/a can be expected. The total project cost of installing four heat exchangers was estimated to approximately 2.3 M€, thus resulting in a pay-back period for the project of approximately 4 years.

3.4 Sources of error and uncertainty

Process stream data used to construct the exergy CC and exergy TSP are based on average, steady state operation of the processes within the cluster. Heat/Cooling demand fluctuations and temperatures changes might occur depending on e.g. the production rate or product type. It is also assumed that all the processes are running simultaneously. It should be noted that the TSP curve considered in this work included certain streams from an ethylene import terminal and O_2/N_2 storage tanks which are not always in operation. These streams are at very low temperatures (down to −147 °C), meaning recovery of cooling capacity implies large shaft power savings. Therefore the streams are considered in this pre-study. These issues have to be considered when designing the suggested energy efficiency measures in detail.

The economic evaluation was conducted based on literature data for preliminary cost estimates with a typical accuracy of ±30 % [29].

4. Discussion and Limitations

With the methodology presented it is not directly possible to allocate the actual shaft power savings between the ethylene and propylene refrigeration cycles, as these two systems are interconnected. The ethylene system is powered by an electric motor while the propylene system is driven by an HP steam turbine. Therefore shaft power savings determined in the case study cannot be directly converted into fuel or electricity savings, as they are determined for the combined systems. If it is assumed that HP steam is produced regardless of the consumption of the propylene refrigeration system (e.g. steam from excess process heat) this steam can be expanded in another turbine, producing electricity instead (see Figure 3). This is the case in the given cluster. The steam boilers are at minimum capacity, meaning that HP steam is produced regardless of the shaft power consumption of the propylene refrigeration system. In this case the shaft power savings targets correspond to electricity savings, considering turbine, electric motor and generator efficiencies. This situation can change in the future and also in other plants. For sites where there is no turbine for electricity generation available the actual savings by the suggested measures are less. In cases where HP steam production in boilers can be decreased, the shaft power savings identified result in both electricity and fuel savings. Therefore evaluation of the actual steam and electricity savings potential has to be performed from case to case and cannot be generalized.

The steam savings potential due to avoided cold process steam heating identified in this study is mainly at LP level. LP steam in petrochemical plants is often in excess. It has to be further evaluated if this steam savings in reality result in fuel savings in the clusters boilers, before it can be considered as an efficiency gain. If the LP steam savings result in an excess of steam from the cluster, meaning that there is no other use for the steam within the cluster, alternative applications for excess heat should be investigated. Using excess heat for absorption cooling is one way to use excess heat and at the same time reduce the shaft power demand of the compression refrigeration systems. Other uses for excess heat are district heating or low temperature electricity generation by organic rankine cycle technology.

Changing the consumption of utility at different levels might make other changes to the refrigeration systems necessary, e.g. the temperatures in the refrigeration system could change when changing usage at different temperature levels. This might not be an issue for minor changes, as is the case for most of the cases shown in Table 3. However, the changes suggested to the –84 °C and –62 °C utility levels represent a large relative increase/decrease in cooling utility usage. This might make additional changes to the refrigeration systems necessary and has not been considered in this study. More detailed analysis including process simulation of the refrigeration systems and investigation of the design capacity of the existing refrigeration systems can be used to approach this issue.

The results of this analysis can be used as input to a more thorough, practical investigation of the suggested energy efficiency measures. Here the actual effects of the suggested changes on the current refrigeration systems should be investigated and the expected steam and electricity savings should be determined.

5. Conclusions

Traditionally Heat Integration tools are used for targeting energy efficiency by improving recovery of process heat and improving the use of hot/cold utility. Combining exergy and Pinch Analysis it is possible to target for decreased exergy flow rate losses. On a site-wide scale this was only done considering recovery of hot utility. In this paper Heat integration tools, namely TSP and exergy analysis were used to target for energy savings potential in refrigeration operations within a chemical cluster utilising excess process cooling to decrease shaft power consumption. The methodology was shown to be very useful in an industrial case study. Increased recovery of cooling capacity together with an improved use of refrigerant for process cooling could result in potential shaft power savings of approximately

4 MW. This corresponds to approximately 15 % of the total shaft power consumption of the cooling systems investigated. In addition, utility steam savings due to avoided process stream heating of approximately 6.3 MW can be achieved as a side-effect of recovering cooling capacity from cold process streams.

Using Exergy CC was shown to be useful for rapid identification and evaluation of the consequences of local measures for decreasing shaft power in a compression refrigeration system. The methodology can be applied to determine optimal utility levels and evaluate the effects of demand changes between different utility levels on the refrigeration shaft power consumption.

Combining TSP and exergy analysis was shown to be a useful way to determine targets for recovery of cooling capacity at a site-wide level and at the same time evaluate the refrigeration shaft power savings potential of these measures. The methodology can be applied to all industries that operate refrigeration systems for targeting for shaft power savings by recovery of cooling capacity from cold process streams, e.g. cryogenic distillation reboilers, storage tanks etc.

The methodology presented in this paper was shown to enable for efficient identification of specific changes to the heat exchanger network in order to increase energy efficiency. Economic evaluation of the identified measures was demonstrated. An example for promising energy efficiency measures applied to the given case study was shown to have a pay-back time of approximately 4 years.

Another important insight of this work is the importance of involving all companies within the cluster in studies such as the one presented in this paper. Thereby the companies become more aware of their opportunities for achieving common energy saving measures. This enables for increased inter-company collaboration, identification of other common energy efficiency projects and ultimately to a more resource efficient and competitive production.

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