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Energy Analysis of Evaporator System in Fertilizer Production

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MASTER THESIS

for

student Vegard Ingebrigtsen

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Energy analysis of evaporator system in Fertilizer production

Energianalyse av inndampingssystem ved produksjon av gjødsel

Background and objective

Yara Glomfjord has a general lack of steam, and today steam at 16bar is produced by an electro boiler approximately 75% of the operational time to cover the required steam consumption in the evaporation equipments in the fertilizer factory. The factory has a large amount of excess heat, but this exists as polluted steam (process steam) or hot condensate/discharge water. It is considered to re-design the evaporators for KS, where the vapor is the cleanest and multiple effects and recompression can be evaluated.

Production of KS is a by-product of the NPK-production. There are two evaporators in the production line. In the case of low N/P-ratios both evaporators are in use. In the opposite case only one. This makes the energy balance different for the whole product range. Energy balance for both low- and high N/P-ratios is therefore necessary in order to do detailed energy analysis. This will be the first objective.

The two evaporators for KS are of old design. The second objective is to evaluate how this equipment would look if designed today, and how much energy that can be saved. Benchmark calculations are to be carried out, comparing results to exiting solutions and with solutions at Yara Porsgrunn, where some energy conserving work have already been done.

The overall objective of the work is to evaluate the different alternatives and make recommendations for improvements in the process.

The master thesis should be written in English and follow Yara International standard for documentation.

The following tasks are to be considered:

1. Literature reviw of energy system for NPK faktory.
2. Evaluation of two different energy flows with high and low N/P relation
3. Evaluate potential for energy reduction in the system by doing a pinch analyses of the energy flows

4. Benchmarking of the of the existing evaporation system with the system at the factory in Porsgrunn
5. Design a new energy efficient evaporation system integrated in the process
6. Make a draft paper (10-15 pages) from the result of the work
7. Suggestion for further work

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM (http://daim.idi.ntnu.no/). An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. The final report, with summery and all other material and documents have to be given to the supervisor in digital format on a CD.

Department of Energy and Process Engineering, 16. January 2012

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Preface

This master thesis has been written at the Norwegian University of Science and Technology, at the Department of Energy and Process Engineering, in collaboration with Yara Glomfjord, Yara Porsgrunn and Epcon Evaporation Technology AS. In light of what has been accomplished in this thesis, a few names needs to be mentioned:

First of all I want thank Yara Glomfjord and Morten Høvset for the opportunity to work with a very interesting and practical project. Throughout the project thesis preparing for this text and the work in this master thesis I can truly state that this has been a supreme learning experience for me.

To Morten Høvset personally I also owe huge thanks due to the work he has put in to this project. We have worked very well together and the results we have obtained are based on outstanding communication and equal dedication to the project. By remembering that the starting point of this project was almost nothing, it is a striking fact how well everything turned out in sense of usefulness for Yara and learning for me.

Next up I also want to give a special thanks to my supervisor at NTNU prof. Trygve Magne Eikevik, who I want to thank for valuable feedback and discussion, but also for supporting my decisions in this project. After all, this project was built from scratch and some of the most important factors of reaching the goal where our communication and the support that was offered me.

I also owe my gratitude to Epcon Evaporation Technology and Kjetil Evenmo, for seemingly putting unlimited resources up for this project, and a great interest for the energy integration tasks at Yara Glomfjord.

Thanks are also given to the engineering staff at Yara Porsgrunn who took great interest in our project an offered advice and information on the operation of evaporator equipment.

Department of Energy and Process Engineering, 01.06.2012

Vegard Byre Ingebrigtsen

Contents

Nomenclature

A	Area
A_{ext}	External area
A_i	Internal cross section area
C_f	Friction factor
c_p	Specific heat capacity
$c_{p_{liq}}$	Specific heat capacity in liquor
$c_{p,L}$	Specific heat capacity in liquid
COP	Coefficient of performance
D	Diameter
D_i	Inner diameter
D_o	Outer diameter
E	Enhancement factor
$\boldsymbol{E}$	Total energy use
E_{el}	Electrical energy use
E_{st}	Steam energy use
e_{el}	Specific electrical energy use
e_{st}	Specific steam energy use
F	Counter flow correction factor
h	Heat transfer coefficient
h_c	Convective heat transfer coefficient
h_i	Internal heat transfer coefficient
h_{nb}	Heat transfer coefficient from nucleate boiling
h_o	External heat transfer coefficient
$\overline{h_L}$	Average heat transfer coefficient
h_{fg}	Latent heat of vaporization
$h_{fg_{16bar}}$	Latent heat of vaporization for 16bar steam
h_{fg_v}	Latent heat of vaporization in vapor
h'_{fg}	Corrected latent heat of vaporization
k	Conduction coefficient
k_l	Liquid conduction coefficient
k_w	Material conduction coefficient
L	Length
$\dot{m}$	Mass flow
$\dot{m}_{CN}$	Mass flow of Calcium Nitrate
$\dot{m_{liq}}$	Mass flow if liquor
$\dot{m}_v$	Mass flow of vapor
$\dot{m}_w$	Mass flow of water
$\dot{m}_{saved}$	Saved steam
$\dot{m}_{steam}$	Mass flow of steam
$\dot{m}_s$	Steam use
n	Number of tubes
Nu	Nusselt number
Nu_D	Nusselt number in tube

p	Pressure
p_{cr}	Critical pressure
Pr	Prandtl number
$\dot{Q}$	Heat transfer
$\dot{Q}_C$	Heat out of system
$\dot{Q}_H$	Heat into system
$\dot{q}''$	Heat transfer per area
R	Heat resistance due to pollutants on tube surface
Re	Reynolds number
Re_D	Reynolds number in tubes
Re_δ	Reynolds number in condensing film
S	Suppression factor
s	Specific steam use
T	Temperature
T_C	Temperature cold reservoir
$T_{condensing}$	Saturation temperature – temperature of condensing
T_f	Film temperature
T_H	Temperature hot reservoir
T_i	Inlet temperature
T_o	Outlet temperature
T_s	Surface temperature
T_{sat}	Saturation temperature
ΔT	Change in temperature
ΔT_{liq}	Change in temperature in liquor
ΔT_{lm}	Logarithmic mean temperature difference
U	Overall heat transfer coefficient
U_{req}	Required overall heat transfer coefficient
$\bar{V}$	Mean velocity
W_c	Compressor work
x	Weight percent CN in liquor
μ	Viscosity
μ_L	Liquid viscosity
ρ	Density
ρ_L	Liquid density
η	Efficiency

Abbreviations

B	Element: Boron.
Cold side	The liquid being heated. ML side of all problems.
COP	Coefficient of performance.
EGA Boilers	Electrical boilers for steam production.
FFE	Falling film evaporator.
Hot side	The liquid used as heating medium. Steam or hot water for the purpose of this text.
K	Element: Potassium.
CN	Calcium nitrate. By product of NPK-production.
Liquor	Liquid that's being processed into compound fertilizer at an early phase.
Mg	Element: Magnesium.
MVR	Mechanical vapor recompression.
ML	Mother Liquor. Liquor before neutralization.
N	Element: Nitrogen.
NP-liquor	Liquor after neutralization.
N/P-ratio	Classification of product. Defined as the ratio between NO3-N and Phosphorus (P) in the liquor.
NPK	Compound fertilizer mainly composed of N, P and K.
N-P-K	Identification of the content of the individual compounds in compound fertilizer.
P	Element: phosphorus.
S	Element: Sulfur.
SSA	Nitric acid production line A.
SSB	Nitric acid production line B.
TVR	Thermal vapor recompression
Wt%	Weight percent

Figures

Tables

Summary

Yara Glomfjord is the north most production facility of compound fertilizer in the world and produces annually about 500 000 tons NPK and 200 000 tons CN. The general energy system of the process plant utilizes steam as the main energy carrier for the entire production site. Yara Glomfjord has today a general lack of steam, and steam is produced in EGA boilers approximately 75% of operational time to cover all heating tasks. The main objective of this Master thesis is to analyze energy flow in in the factory to identify energy saving potential, and later to suggest improvements for the CN-evaporator system in order to retire the use of EGA boilers and supply excess heat for other heating tasks in the factory.

First off analysis was made on general energy flows in the factory. This was done in order to reveal potential for energy savings and to clarify which paths to choose for further heat integration. The result of the analysis shows that *latent heat flows* are of far greater importance than *sensible heat flows* to the general steam balance at Yara Glomfjord. It was also identified that the large potential for latent heat recovery lies within the evaporator equipment.

Next up this text suggests investment in evaporator equipment in order to integrate latent heat, so that the overall steam consumption goes down. Three different suggestions were presented and analyzed in detail in the document: CN-Evaporator System Design. The most proving suggestions are *new equipment coupled in cascade with old evaporators* or a *new independent MVR evaporator* in front of old solution. Both suggestions are found to retire EGA boilers completely and also supply excess heat for other heating tasks. This text recommends one of these two suggestions.

To suggest new improvements in the CN-evaporator system Epcon Evaporation Technology AS were involved. Testing at Epcon's facilities in Trondheim indicate a new possibility. For the suggested retrofit cascade evaporation system, submergence of boiling pressure is possible. These findings supports the recommendations from this text to invest in a new evaporator coupled in cascade with the old solution with submergence of boiling pressure. In this way the energy savings in question can be implemented with only a small investment and almost no energy cost in a vacuum pump.

As a huge potential for energy savings was found possible at reasonable cost and at a manageable technical level, the findings of this Master thesis hopefully settles the steam issues of the Yara Glomfjord compound fertilizer plant once and for all.

In light of the late findings of this project, with the possibility of submergence of boiling pressure a hint is also sent to Yara Porsgrunn. As a great role model for Yara Glomfjord they utilize latent heat, but at the cost of expensive compressor work and not with submergence of boiling pressure which this text clearly states to be the superior technology.

Sammendrag

Yara Glomfjord er verdens nordligste fullgjødslefabrikk og produserer årlig 500 000 tonn NPK og 200 000 tonn KS. Det generelle energisystemet baserer seg på damp som energibærer til hele produksjonsområdet. Yara Glomfjord har i dag et underskudd på damp og må produsere ekstra damp i EGA kjeler i om lag 75% av driftstiden for å dekke alle varmebehov. Hovedmålsettingen med denne masteroppgaven er å analysere energistrømmer i fabrikken for å avdekke energibesparingspotensiale og foreslå forbedringer i KS-inndampningsanlegget, slik at EGA kjelene kan tas ut av drift og damp kan frigis til andre varmeoppgaver.

Det første som ble gjort var en analyse av energistrømmene i fabrikken. Dette ble gjort for å avdekke potensiale for energibesparelser og for å kartlegge gode energiintegrasjons muligheter. Resultatet fra analysen viser at latent varmestrøm er av mye større betydning enn følbar varme for dampbalansen hos Yara Glomfjord. Det ble også avklart at det største potensialet for energibesparelser i latent varme ligger i KS-inndampningsanlegget.

Det neste som ble gjort var å foreslå investeringer i nytt inndampningsutstyr som integrerer latent varme, slik at dampforbruket går ned. Tre forslag ble presentert og analysert i detalj i dokumentet: CN-Evaporator System Design. De to mest lovende forslagene er *ny inndamper koblet i kaskade med regjerende løsning* og *selvstendig ny inndamper med dampkompresjon foran gammel løsning.* Begge forslag sparer nok damp til å ta EGA kjelene ut av drift og frigir damp til andre varmeoppgaver. Denne teksten anbefaler en av disse løsningene.

Epcon Evaporation Technology AS ble også involvert for å foreslå nye løsninger. Tester ved Epcon sitt testanlegg i Trondheim var med på å avdekke nye muligheter. I tilfellet med ny kaskade-inndamper er det mulig å kjøre kokeprosessen på underatmosfærisk koketrykk. Dette støtter opp om anbefalingen i denne teksten om å investere i ny kaskade-inndamper. På denne måten kan energibesparelsene gjøres uten å tilføre nevneverdig energi og til en relativ lav innkjøpskostnad.

Siden et stort energibesparelsespotensiale er avdekket med lav kostnad og en overkommelig teknisk kompleksitet, håper denne masteroppgaven å sette punktum for dampproblematikken ved Yara Glomfjord en gang for alle.

I lys av de seneste oppdagelsene i denne masteroppgaven, der undertrykkskoking ble funnet mulig, sendes også et hint til Yara Porsgrunn. Som rollemodell for Yara Glomfjord har de allerede varmeintegrert KS-inndampningsanlegget sitt ved hjelp av komprimert avdamp, men denne teksten konkluderer med at dette kan gjøres enda smartere med underatmosfærisk koking.

1 Introduction

1.1 Background

Yara Glomfjord is the north most Compound Fertilizer production facility in the world and it is located at Glomfjord, approximately two hours outside Bodø.

The accessibility of large amounts of electric power was the background for Norsk Hydro (Later Yara) to found an ammonia production site in the late 1940s. Ammonia at first where shipped to Hydro's NPK-production in Porsgrunn, but in 1955 NPK-production facilities in Glomfjord where established. The ammonia production was terminated in 1993, and today Yara Glomfjord consists of NPK-production, CN-production, Nitric acid production facilities and shipping.

In 2006 the power production in Glomfjord funded by Norsk Hydro fell under the Norwegian Reversion Act. This Act state that non-governmentally initiated hydro power licenses are to be overtaken by the state after 60 years[1]. Since Yara do not produce electricity anymore, it has to be bought of the market.

Yara Glomfjord has today a general lack of steam for large parts of operational time. However, the factory also has large amounts of excess heat, mainly present as process steam and hot condensate. Due to the steam issues and the rise of electric power cost, Yara Glomfjord administration wants to look into heat integration options for the plant.

The task of energy recovery at Yara Glomfjord has therefore been taken on in a few projects lately. The work that needs to be mentioned is an internal energy report by factory engineers (Torgersen, 2003), Enova energy projects (Høvset, 2011) and the preliminary work leading up to this thesis (Ingebrigtsen, 2011). The latter (Ingebrigtsen, 2011) states a few important tasks for the future, which is the starting point for this thesis.

1.2 Historical Energy use of Norwegian Industry

Norwegian industry is very energy intensive compared with industry in other countries. Norwegian land based industry have been among the most energy intensive since the early 1970s. The large power demanders; aluminum production, ferro-alloy production, chemical production, and paper production represents 80% of the total energy consumption of Norwegian industry (Enova, 2009).

[1] http://www.eu-norge.org/Aktuelt/Nyhetsartikler/fakta_om_hjemfall/

Norwegian natural resources have been a requirement for the blooming of Norwegian power demanding industry. Especially the access to relatively cheap hydro power has been important to the industry growth.

In the period 1990 to 2005 the industry have managed to reduce the energy intensity with 1% per year, this have compensated for the growth and kept the total energy consumption stable. The improvement in energy efficiency can be explained by the new economical factor that became introduced with higher electrical prices.

Enova have in 2009 pointed out that Norwegian land based industry have a technical potential of reducing energy consumption with 27 TWh compared to the reference level of 2020[2], whereof 13,3 TWh is related to the utilization of low temperature production excess heat (Enova, 2009). Before taking on the tasks of this thesis it is therefore noted a *general potential* of heat recovery related to low temperature excess heat.

1.3 The Writing of this Thesis

This Master thesis addresses the analytical foundation and calculations needed to initiate expensive projects of heat integration in the CN-Evaporator System at Yara Glomfjord.

The fundamental understanding needed to solve this task has been made through on-site work at the Yara Glomfjord production plant throughout the gathering of data and the writing of this Master thesis. To learn the basic production operations, time was spent with the process operators and engineers in the factory. The first part of the project and this thesis was therefore practical in the manner of learning the production process.

This master thesis is written with the theoretical and analytical fundament of energy recovery and analysis of energy flow up front. The thought here is to make clear which possibilities that lies ahead concerning energy recovery, and which are the smart paths to choose. But this is also done in order to communicate the fundamentals, and what is learned from the practical experiences in the factory.

Thereafter this thesis presents the analytical arguments for specific technical solutions to enhance the energy performance of the CN-evaporator system. This way it is argued, with root in the fundamental energy recovery potential, which technical solution to choose in order to solve the greater objective of steam issue at Yara Glomfjord.

Important to note is the confidentiality agreement that lies behind the writing of this thesis. The details of CN evaporation technology is a manufacturing secret and the process of

[2] Reference Level of 2020 is the energy level in 2020 with today's energy utilization. This is also referred to as the frozen technology scenario.

making CN as a byproduct of NPK is a production-model only utilized by Yara in Porsgrunn and Glomfjord. This information have therefor been restricted to one chapter and taken out of the main text. However, to get the right argumentative structure it fits in between chapter 5 and 6 of the main text. With the CN-Evaporator System Design chapter this Master thesis is structured like this:

- *Description of the process in general* at Yara Glomfjord.
- Presentation of *The Energy System* and mapping of *the energy flows in the factory*.
- Identification of *The Energy Savings Potential* based on analytical arguments.
- Description of *Evaporator Design* and *heat integration options* for such.
- Detailed analytical work on retrofit and new-design of *The CN-Evaporator System*[3].
- *Suggested Improvements* concerning investment in evaporator equipment.
- *General Discussion and Conclusion* based on all thesis work.
- Suggested *Further Work*.

Appendix A: CN-Evaporator System Design is Yara Glomfjord property and supplied for interested parties only.

1.4 Collaboration Partners

This thesis has been written in collaboration with Yara Glomfjord, under the supervision of maintenance manager Morten Høvset. Advanced technical input is also given by Epcon Evaporation Technology AS, led by senior engineer Kjetil Evenmo. Main supervisor for this Master thesis is prof. Trygve M. Eikevik at the Department of Energy and Process Engineering, NTNU.

1.5 Safety Management

When spending time in an industrial production site safety precautions must be made. At Yara Glomfjord and Yara Porsgrunn safety is very important, and all personnel that gains access to the factory goes through a safety course. In addition, at all times safety equipment must be worn i.e., helmet, hard shoes, and goggles. Yara's ambition is to set industry standard regarding safety and environmental precautions. The practical work that lies behind this thesis has followed Yara safety standards at all points.

[3] This part is held confidential and supplied for interested parties only.

2 Process Description

2.1 Introduction

The production process of Compound Fertilizer and Calcium Nitrate is a complex chemical process that is very energy intensive, both in the form of excess heat and energy demand. In following paragraphs a description is made to highlight the energy demand and use in production. The focus here will therefore be on the energy flow and not so much on the chemistry. Also excluded here will be some details concerning the dry end of fertilizer-production.

2.2 Production of Compound Fertilizer and Calcium Nitrate

At Yara Glomfjord both compound fertilizer (NPK) and Calcium nitrate (CN) are produced. Compound fertilizer contains a lot of plant nutrition compounds, especially Nitrogen (N), Phosphorus (P) and Potassium (K). In addition some other high value compounds are added like Magnesium (Mg), Sulfur (S) and Boron (B). Yara produces a number of different combinations of NPK, identified by their NPK-rating (or N-P-K identifying the content of the individual compounds, e.g. 14-14-21). Calcium nitrate is produced as a byproduct of the NPK-production and contains mainly of Calcium nitrate ($Ca(NO_3)_2$) and water. The process utilized at Yara Glomfjord is developed by Erling B. Johnsen in the city of Odda, referred to as the "Nitro Phosphate Process" or the "Odda-Process". Besides Yara Glomfjord, Yara Porsgrunn is the only one in the world to utilize this dual production of compound fertilizer and Calcium nitrate (Jordal, 2005) (Steen, et al., 1987).

Phosphorus is extracted from phosphorus minerals (apatite), which also contains Calcium. Apatite is dissolved in Nitric acid (HNO_3). The solution is cooled by crystallization equipment, and at this low temperature most of the Calcium is precipitated as Calcium nitrate ($Ca(NO_3)_2$). Calcium nitrate crystals are precipitated from what is called the "Mother Liquor", and then separated by filtration. "Mother Liquor" or ML is the basis for NPK-production. The filtrate (ML) is neutralized with NH_3 and nitrogen content is corrected with HNO_3. These chemical procedures are exothermic and produce heat. After the neutralization section the liquor is evaporated, with 16bar steam, to a water content of 2-3 %. Thereafter salts and Magnesium is added and the mixture is granulated to grains. The product is dried in rotating driers, sieved and cooled. For better storing properties oil and powdery substance is added (Jordal, 2005). The NPK-part of production is sketched on the left hand side of Figure 2-1.

The precipitated Calcium nitrate is refined parallel to the main NPK-process. CN is separated from the NPK-process by filtration in a crystallized form, and continues to a melting tank. The melted CN is then neutralized with NH_3-gas and added water before it is cleansed. Cleansed CN-liquor is driven in a buffer system for evaporation. Depending on the product type (N-P-K), CN-liquor is evaporated in one or two parallel evaporators, utilizing 16bar steam to obtain low water content. The product is dried in a similar way as the product in the NPK-process, but pelletized not granulated (Jordal, 2005). The CN-part of production is sketched on the right hand side of Figure 2-1.

The production is divided into a wet- and dry- subdivision. In the wet division all liquids ("liquors") are produced, and in the dry division the liquor is mixed with dry substances and refined to finished products. Total production rate is annually approximately 500 000 tons NPK and 200 000 tons CN (2002). 60% of all fertilizer produced is sold in the Norwegian market (Jordal, 2005).

2.3 Different product types

NPK is produced in a number of different combinations, resulting in different running conditions at the plant. In general production types are identified by their combination of N-P-K, but it is often referred to the N/P-ratio, the ratio between NO_3-N and Phosphorus (P) in the liquor. Before the neutralization phase the "mother liquor" has an N/P ~ 0.8, but this is corrected with HNO_3 to get the desired N/P-ratio in the finished product. The N/P-ratio varies from 0.9 – over 6 (Steen, et al., 1987).

According to the desired N/P-ratio the by production of precipitated Calcium nitrate also varies. At lower N/P-ratios the production of Calcium nitrate is higher. At the production facility in Glomfjord there are two evaporators for CN available and at low N/P-ratio they are both in use, and energy demand for the plant is at its peak. Yara Glomfjord produces a lot of low N/P rated product. For this project steam is set to be an issue for 75 % of operational time.

For high N/P-ratios on the other hand the energy consumption is lower. With e.g. High N/P product type N-P-K: 18-3-15, only one evaporator for CN is active in production and hence energy demand is also much lower. To ease calculation high N/P is assumed operational conditions for the remaining 25% of operational time.

2.4 Process Flow

The production process as described in previous paragraphs is presented in Figure 2-1, with a principal sketch of process flow in NPK and CN production at Yara Glomfjord (Jordal, 2005):

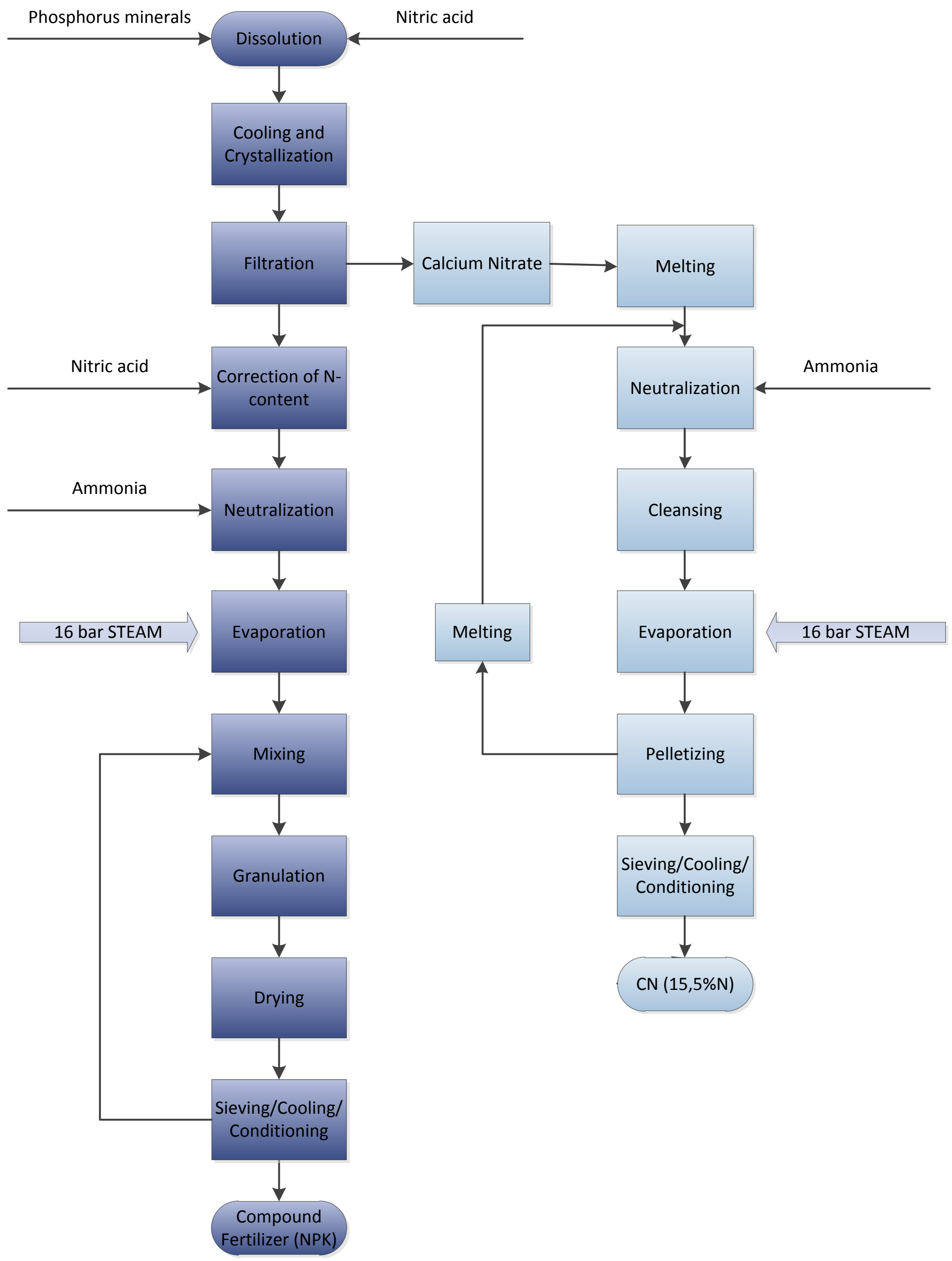


Figure 2-1: Principal sketch of process flow in NPK and CN production **(Jordal, 2005)**.

3 The Energy System

3.1 Introduction

The energy system of the Yara Glomfjord production plant is designed with steam as the main energy carrier. Steam is generated as excess heat in the factory and from primary energy sources to cover process heating tasks. The heating tasks vary with product type, but have its extremities at high- and low N/P-ratio. Descriptions of the energy system and its discovered potential for improvement are given in an internal energy report (Torgersen, 2003). Some other texts of interest are; literature on energy management at Yara (Sollesnes, et al., 2001); and the project thesis in preparation for this text (Ingebrigtsen, 2011).

In the following paragraphs general descriptions of the Yara Glomfjord energy balance, with emphasis on steam, will be given. Magnitude of numerical trends will be discussed here, and calculation of such will follow methodology of earlier work (Torgersen, 2003). A general source of data is Yara process data (Yara, 2011) and guesswork from factory engineers (Høvset, 2012).

3.2 Energy Sources

The total energy need of the Yara Glomfjord production site is covered by three sources, i.e. oil, electrical power and *ammonia*. Besides being an important component in the product (Nitrogen-source), ammonia is also the most important source of energy to the process at Yara Glomfjord (Torgersen, 2003).

3.2.1 Ammonia

The production site consists not only of the compound fertilizer production plant, but also of a Nitric acid production facility. Here ammonia is burned to produce nitric acid, but also large amount of excess heat as a byproduct. This heat is utilized to generate steam, which is refined to the factory standard of 16bar and slightly above 205°C. The steam is produced in two parallel production lines SSA and SSB, and the acid production maintains about ~ 46tons/h of 16bar steam total (Yara, 2011). In addition to the excess heat, there are two steam EGA boilers capable of approximately 10MW each that can be put into production to maintain plant operation stability. Today these boilers are in use 75% of operational time (Yara, 2011). Together these steam sources presently cover the energy need of most heating tasks in the factory at Yara Glomfjord.

Ammonia is also the energy carrier in the neutralization section of NPK-production. “Mother liquor” is neutralized with NH_3 and the nitrogen content is then corrected with HNO_3. The two reacts exothermically, and the heat of formation for ammonia and nitric acid is in the order of ~10MW (80GWh annually), as suggested in the internal energy report from 2003 (Torgersen, 2003). The report also correctly states that the energy flow takes two paths. The exothermic heat spreads and heats the liquid (ML) to about 125-130°C, but the water content is also reduced by evaporation from 34% in the uncorrected liquor, to about 13% out of the neutralization section. This considerable amount of energy is recognized by earlier work, but the energy following the evaporated vapor as latent heat has up to date not been given much attention. This text will take on the task to model energy flow, and take this latent energy into account in later chapters. See Appendix D for a small comment.

3.2.2 Oil and electrical power

As mentioned the other energy sources are electrical power and oil. Electrical power is, besides general tasks such as lights, mostly used in the acid factory and the largest consumer is the production of steam with EGA boilers. For the purpose of this text, electrical consumption of boilers is set to be 35GWh annually (Yara, 2011). If there are 342 production days annually, 98% regularity and 1,3tons/h steam from 1MW[4], the average steam production from the EGA boilers are about 5,66tons/h. Since the Boilers are in use only 75% of operational time, the average production on day of operation is 7,5tons/h.

Oil is used for heating air to the compound fertilizer drier, in the dry end of production. Considerable heat integration tasks have already been done concerning this energy source, saving 6,5GWh in oil consumption (Høvset, 2011). Based on the numbers from the energy report (Torgersen, 2003) and late savings, today's consumption is about ~18,5GWh annually. An important note is that this oil use is a heating task that could have been replaced with excess steam.

3.2.3 Total energy supply to process

All the energy contributors have been listed to sum the total energy supply to the process in Table 3-1:

Table 3-1: **Total energy supply to process.**

	High N/P Steam eqv. [tons/h]	Low N/P Steam eqv. [tons/h]	High N/P Power [GWh/year]	Low N/P Power [GWh/year]
Ammonia combustion	46	46	200	200
Reaction heat of Ammonia and Nitric acid	-	-	80	80
Electrical power EGA boilers	-	7,5	-	35
Oil	-	-	18,5	18,5
SUM	**46**	**53,5**	**298,5**	**333,5**
Operational time	25%	75%	25%	75%

[4] This calculation is also done in (Torgersen, 2003).

Average sum	**51,5[tons/h]**	**325[GWh/year]**

Regarding the steam equivalent, it is known that ammonia combustion generate 46tons/h of steam, which when condensed equals 200GWh/year of heat. This calculation is done with the latent heat of 16bar steam and 342 days of production. The boilers on the other hand, are known to consume an amount of energy, which with the preheating of the boiler gives 5,66tons/h of steam in average, as calculated earlier. Both calculations can be found in appendix C.

3.3 Energy Consumers

The large energy consumers in the production are mainly operated with steam as the energy carrier. The steam consumers are the evaporation equipment, NH_3-stripping, different smaller heating tasks, some vague consumers and losses. Other large energy consumers are heating of air for the NPK-driers with oil and the neutralization section where reaction heat is utilized.

3.3.1 Evaporation equipment

The largest energy consumer of the Yara Glomfjord production site is the evaporation equipment. For low N/P production conditions there are two evaporators for CN in use and one for the NPK production. These CN-evaporators are operated with 11tons/h of steam each and the NPK-evaporator with about 22tons/h. For high N/P conditions only one of the CN-evaporators are in use (Yara, 2011).

For high N/P the annual consumption of the NPK-evaporator is 96GWh/year and the one CN-evaporator is 48GWh/year. The consumption is calculated from the stated amount of condensing 16bar steam used in the units.

It must be noted that the steam energy, that is extra for low N/P-conditions, comes from EGA boilers. The extra energy consumption for low N/P is therefore not the condensing energy of the 16bar steam, but the actual electricity use of the boilers. The energy consumption in these boilers when measured in GWh/year must take into account the energy loss from electricity to steam. This text models the problem such that CN-evaporator 2 uses 15GWh/year of surplus steam and 51GWh/year of steam from boilers, taking into account the preheating in an electrical boiler. In steam use this refers to 3,5tons/h of surplus steam from ammonia combustion and 7,5tons/h of steam generated by boilers. This scenario applies for 75% of operational time as already stated for low N/P production.

3.3.2 NH_3-stripping

Next large consumer is NH_3-stripping. Ammonia is used in the neutralization section of the production of compound fertilizer. It exists as NH_4 in process water and needs to be taken to a higher temperature and pressure to retrieve clean water and ammonia NH_3 in gas phase. This is a relatively fixed consumer of steam, and is for the purpose of tis text set at an average of 4tons/h steam consumption for both high- and low N/P-ratio. Annually consumption is 17GWh/year (Høvset, 2012).

3.3.3 Vaporizer 3

At high N/P-ratio the ammonia vaporizer equipment contributes to steam consumption. NH_3 is imported to the factory to be consumed in the nitric acid plant, and exist in liquid phase in in a huge mountain storage facility. At high N/P-ratios the consumption of ammonia in the neutralization section is higher and additional ammonia needs to be added. This extra ammonia comes from vaporizer 3 in the vaporizer section of the general ammonia supply to the factory. This is presented in the process flow diagram for vaporization of NH_3 in Figure 3-1.

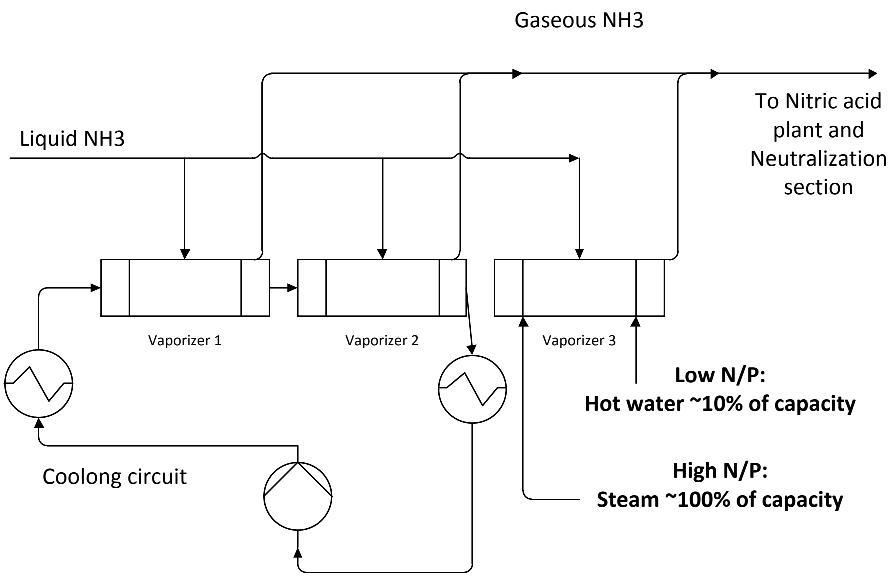


Figure 3-1: Schematics of Ammonia-vaporizer 3 at high- and low N/P **(Høvset, 2012)**.

As identified by Figure 3-1, steam is only used at high N/P. The consumption is about 2tons/h and 9GWh/year (Høvset, 2012).

3.3.4 Preheating of ML

As presented in preparation for this text (Ingebrigtsen, 2011), preheating of ML is initiated at Yara Glomfjord. This is done with steam and consumes 2tons/h or 9GWh/year at low N/P-ratio production.

3.3.5 PKL

Another small consumption is made by the Packing, Dock and Storage department (PKL), to clean equipment etc. This consumption is about 1tons/h or 4GWh/year for all N/P-ratios (Høvset, 2012).

3.3.6 Vague

The diffuse steam consumers are e.g., condensation in the pipe system (main pipe from Nitric acid factory is approximately 1km), heating of process streams both at 16bar and downgraded to 6bar, various building heating tasks, steam cleaning of equipment, lack of isolation, leakage, and dehumidification of air. The total consumption for this category is set to 2,5tons/h of steam, 11GWh/year (Høvset, 2012). This value might be a little on the low side but holds for the purpose of this text.

This text also recognizes some dumping of steam at high N/P when consumption is somewhat lower, and this amount is set to be 3,5tons/h of steam, 15GWh/year (Høvset, 2012).

3.3.7 Total energy supply to process

All the energy consumers have been listed to sum the total energy need in the process in Table 3-2:

Table 3-2: **Total energy need in process.**

	High N/P Steam eqv. [tons/h]	**Low N/P** Steam eqv. [tons/h]	**High N/P** Power [GWh/year]	**Low N/P** Power [GWh/year]
NPK-evaporator	22	22	96	96
CN-evaporator 1	11	11	48	48
CN-evaporator 2	-	3,5+7,5	-	15+51
NH_3-stripper	4	4	17	17
Vaporizer 3	2	-	9	-
Preheating of ML	-	2	-	9
Vague steam consumers	2,5	2,5	11	11
PKL	1	1	4	4
Dumping	3,5	-	15	-
Hot air for NPK-drying process	-	-	18,5	18,5
Neutralization section	-	-	80	80
SUM	**46**	**53,5**	**298,5**	**333,5**
Operational time	25%	75%	25%	75%
Average sum	**51,5[tons/h]**		**325[GWh/year]**	

3.4 Energy and Steam Balance

By identifying the individual consumers and sources of energy, it is identified that the energy balance of importance is the steam balance. This means that the consumption of other energy sources (electrical and oil) are independent of N/P-ratio, but the steam balance is not. It is therefore here emphasized on *the steam balance* for the factory at present conditions.

As already mentioned the steam balance varies with product type. However, the extremities are given at high- or low N/P-ratio. Thus by giving the steam balance for both high- and low N/P-ratio one can suggest the steam balance for the whole product assortment. An idea of the steam balance for the production is given in Figure 3-2, based on numbers produced in Table 3-1 and Table 3-2.

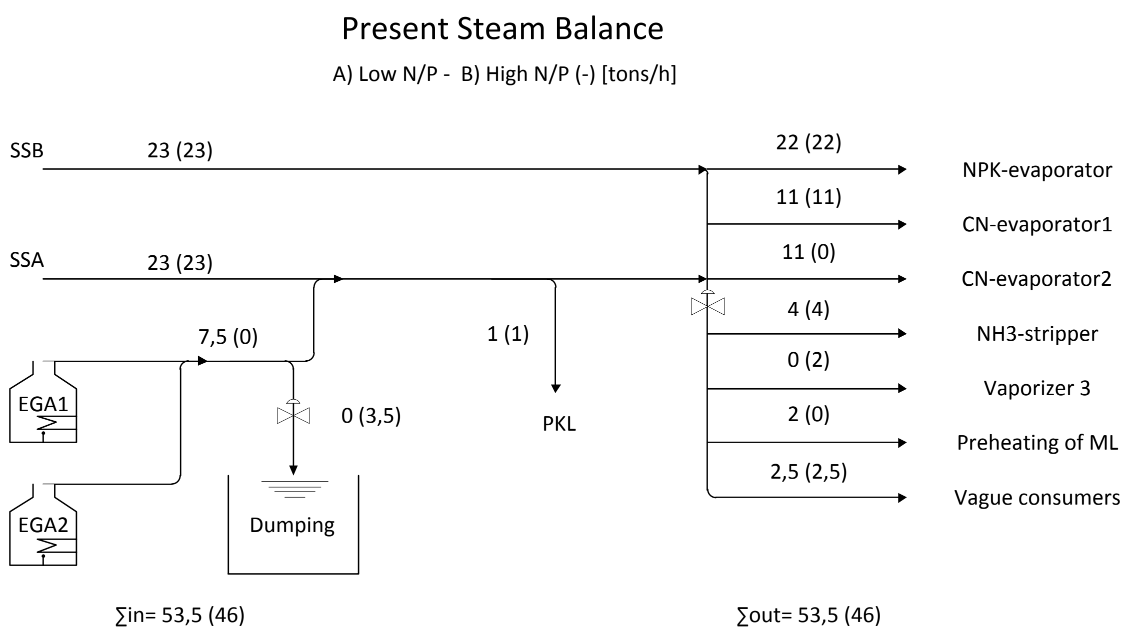


Figure 3-2: Flow chart of present steam balance.

From Figure 3-2 energy use of compound fertilizer production with both high and low N/P-ratio are compared. The main difference lies in use of both CN-evaporators at low N/P-ratio. Below in Figure 3-3 and Figure 3-4, the steam balance is shown independently for low N/P and for high N/P in sankey diagrams:

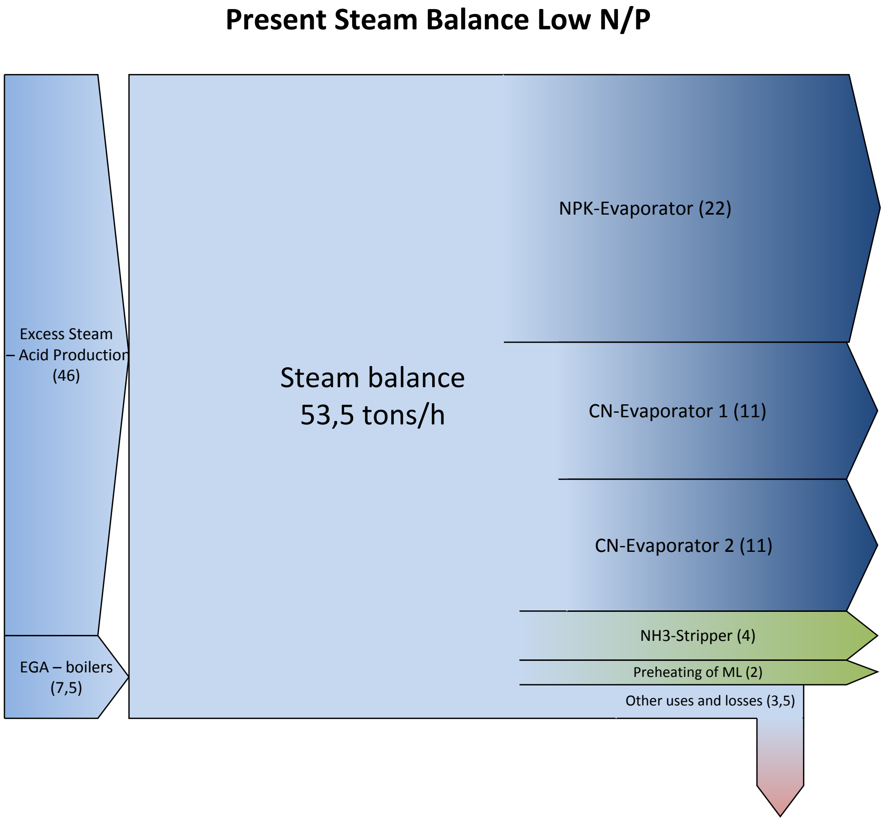


Figure 3-3: Steam balance low N/P.

Figure 3-3 shows the factory steam balance for low N/P and the figure illustrates how EGA boilers are necessary in order to cope with factory steam demands. It is also more than evident how the evaporator equipment is the large steam consumers. The evaporators demands ~80% of the available steam energy.

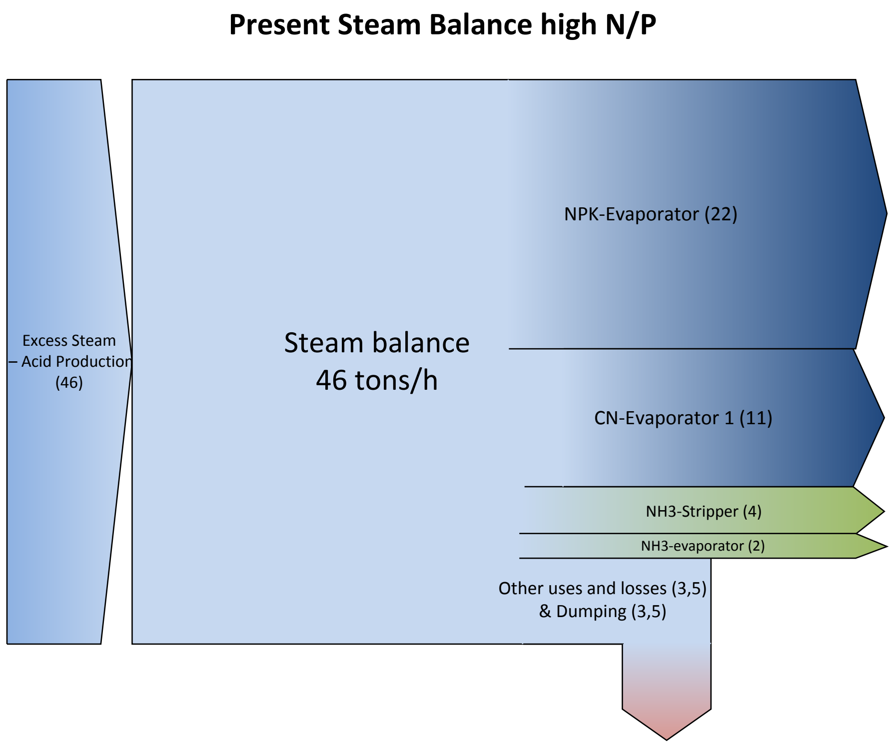


Figure 3-4: Steam balance high N/P.

For high N/P, as shown in Figure 3-4, it is evident that the factory runs on excess heat and the steam dumping is present at 3,5tons/h. High N/P is therefore not a problem scenario in factory economics.

4 Energy Savings Potential

4.1 Introduction

The energy tradition at Yara Glomfjord is highly dominated by two things. The first is the onsite production of Nitric acid that gives the plant an energy surplus for high N/P compositions. This again results in little interest in energy savings, when the energy consumed is free. The second influence is that of the electricity price. In Norway the development of the industry has followed in line with the growth of hydropower electricity production. For Yara Glomfjord who used to operate its own hydro power plant close to the production site, electricity has traditionally been cheap. However, savings today will directly reduce the boiler steam production for 75% of the operational time, and with the present electricity rates a considerable amount of money. The heating tasks presently done with oil are also possible to solve with live steam. Savings in steam beyond the retirement of the boilers therefore theoretically saves oil consumption. Because of these facts energy savings as an area of interest has become more interesting for Yara Glomfjord.

It is also worth mentioning that downtime costs are huge, and an economic favorable project does therefore need to be really good. However, in light of the present economic situation, with higher electrical prices the bar for a good project has been lowered. Some projects have already been initiated, e.g. preheating of air to be utilized in the drying process, preheating of the CN-liquor before entering the evaporators with process steam (Høvset, 2011), and preheating of ML (Ingebrigtsen, 2011). Despite improvements, the preliminary work for this thesis suggests energy savings potential to be of a far greater character (Ingebrigtsen, 2011).

To meet this problem with the right perspective the economic foundation needs to be drawn out. The power consumption of the boilers is known, and is recognized by this text to be 35GWh annually. With the present electrical price at about 0,5NOK/kWh this energy costs:

$$35 * 10^6 kWh * 0,5NOK/kWh = 17,5MNOK \qquad \text{Result 4-1}$$

Hence, steam savings of 5,66tons/h on average or 7,5tons/h in 75% of operational time, will permanently end the need of the EGA boilers and save the factory 17,5MNOK annually.

Regarding the oil consumption, assuming the equipment needed in order to do oil heating tasks with surplus steam are present, 18,5GWh of oil can be saved. Saving steam beyond 35GWh will therefore also save an estimate of 0,5NOK/kW of oil not used. Total retirement of oil consumption will save the factory an annual energy cost of:

$$18{,}5 * 10^6 kWh * O{,}5NOK/kWh = 9{,}25MNOK$$ **Result 4-2**

The economic potential is great and internal reports at Yara Glomfjord list a number of measures to reduce steam consumptions, among others the projects already initiated (Torgersen, 2003). But in order to choose the right path ahead, detailed analytical work will be needed to justify the good projects, and meet the issues in a rational and structured manner. In the preliminary work of this thesis (Ingebrigtsen, 2011), the following tasks for future energy conservation work was identified:

- *Factory energy flow analysis*: The first task is the pressing need for detailed information of hot and cold streams. In order to evaluate which heating mediums to apply, the complete set of available resources needs to be known. This analysis is very complex and time consuming, but will open for much more advanced heat integration operations and applying of heat integration tools like the *pinch analysis*.

- *Complex heat integration*: With the detailed energy flow of the factory in place, a *complex heat integration network of heat exchangers* can be designed, with a balance between operational cost, downtime and equipment cost. The heat exchangers that are found cost efficient will then do large savings on operational cost, and free steam off the grid to other demands.

- *The expensive projects*: There are several more costly options, than the ones already initiated, with a far greater energy recovery potential. Hereunder lays new design or retrofit design of evaporator equipment, with *multiple effects* and *thermal*- or *mechanical recompression* and *high temperature heat pumps*.

- *Steam and power production*: Since the factory is producing steam in the Nitric acid production lines, an attractive idea is to be on the constant surplus side. If Yara Glomfjord overcomes the issues of high steam consumption for 75% of operational time, they will become a steam producer and steam can be sold to other industry plants on site or as electricity. This should be an underlying goal of the energy work done in the future.

As the successor of the project thesis (Ingebrigtsen, 2011), this text will address some of these tasks. The overall goal is to suggest new solutions for CN-evaporators (new or retrofit), which is an *expensive project*, but in doing so this text first takes on the task: *the factory energy flow analysis.*

This chapter will in upcoming paragraphs discuss the underlying theory of process integration and pinch analysis, present data and map energy flows in the factory. The data will then be analyzed to give better understanding of the energy flow in the factory, such that the discussions on initiating expensive heat integration projects can be made.

4.2 Process Integration and Pinch analysis

Process integration is defined by the IEA as *"systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reducing environmental effects"* (Gundersen, 2002). *Pinch analysis* is perhaps the most recognized of these methods. Through its 30 year history Pinch analysis has proved to be a simple concept in a field generally known for its complex mathematics. It is a method of systematic approach, where necessary calculations can be carried out with a pocket calculator. Reports from the pinch analysis on industrial applications claim to achieve large energy savings as well as reduced capital investment cost due to optimal heat exchanger area design. Today pinch analysis and process integration have evolved past just energy, to include e.g. pressure drop optimization, water- and hydrogen management (Ebrahim, 1999).

4.2.1 Design and retrofit

While the application of pinch technology early on where related to new design, the majority of the applications in the industry today concerns existing plants. These are called *retrofit-projects* and are typically projects to improve energy utilization, improve operation, removal of bottlenecks and integration of new equipment. The term *retrofit* concerns energy utilization projects with factory economics as most important parameter. The goal here is to reduce operational cost through energy savings, that are so favorable that they are worth both downtime and investment cost. Hence, literature (Gundersen, 2002) claims that timing retrofit projects to periods of plant maintenance and projects including pure energy savings with more general plant modifications make the best projects.

4.2.2 Pinch analysis tools

As discussed above pinch analysis can be applied in a number of ways, and does therefore need to be restricted to the task at Yara Glomfjord. This text will therefore consider the following points of interest:

4.2.2.1 Data gathering and simplification

The most important task at this moment as identified by the preliminary work for this thesis (Ingebrigtsen, 2011), is the systematic overview of hot and cold streams. In order to get a good overview, simplifications needs to be done. But it is also of upmost importance to keep enough detail to give the following analysis value.

Literature (Gundersen, 2002) states that the most time consuming and critical phase of any retrofit project is the data extraction. All hot and cold mediums of importance need to be identified with the following characteristics, listed in Table 4-1:

Table 4-1: **Data needed for the Pinch analysis.**

Stream	Temperature in	Temperature out	Mass flow	Heat capacity	Latent heat	Enthalpy
Hot	T_i	T_o	$\dot{m}$	c_p	–	$\dot{m}c_p\Delta T$
Cold	T_i	T_o	$\dot{m}$	c_p	–	$\dot{m}c_p\Delta T$
Phase change	T	T	$\dot{m}$	–	h_{fg}	$\dot{m}h_{fg}$

For a phase changing medium latent heat will be needed, and for any hot or cold stream the heat capacity.

4.2.2.2 Pinch point analysis

The pinch-technique is, for a given project, to identify energy targets and their minimum driving forces across any use of heat exchangers (Ebrahim, 1999). The minimum driving forces is an entry parameter ΔT_{min} , set to balance operational stability with cost. Often this parameter is chosen by experience, and often larger for the retrofit case than for new design (Gundersen, 2002). The pinch point is the bottleneck of energy transfer in the process, and it is most easily displayed with *the composite curves*.

By adding the enthalpy changes for the hot and cold process streams separately and for each temperature interval in the process, the hot and cold composite curves can be drawn. This drawing completes the composite curves as shown in Figure 4-1 (Gundersen, 2002):

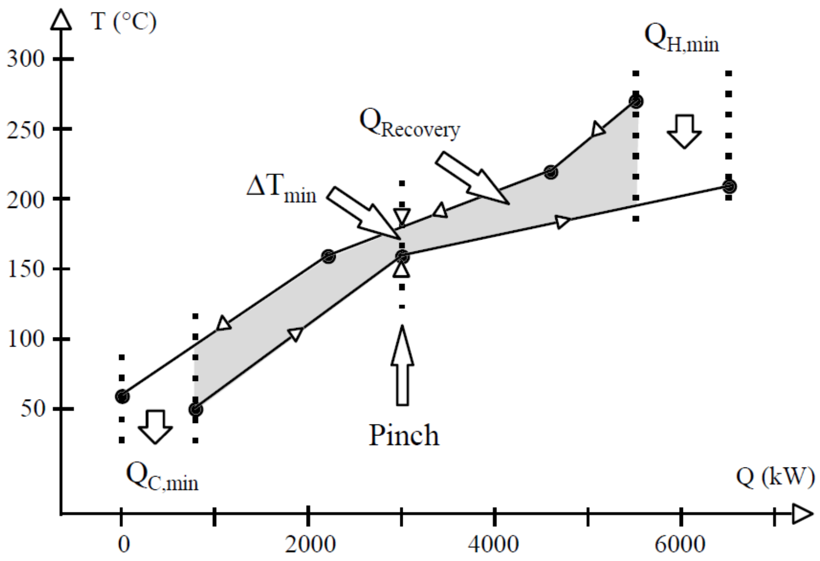


Figure 4-1: The Composite Curves.

Identified by the arrows are the ΔT_{min}, which happens to be *the pinch point* for a proper heat integrated process. The minimum amounts of needed utilities are identified as $Q_{C,min}$ and $Q_{H,min}$.The gray area in between the composite curves is the heat transfer of a perfect heat integrated process, with a large number of heat exchangers. It is an important note that this is the perfect integrated point, and a baseline for the actual process and retrofit project.

Establishing the composite curves is therefore a tool in which one can obtain the pinch point of a process. In practice, however, they are considered more of a learning tool and minimum energy consumption and heat recovery pinch are more often obtained by numerical procedures such as *the heat cascade*.

In the heat cascade, the supply and target temperatures of all process streams divide the temperature scale into temperature intervals, in the same way as the construction of the composite curves. On the left side of the diagram hot streams supply heat into various intervals according to a hot temperature scale. Similarly, on the right hand side cold streams extracts heat according to a cold temperature scale. The difference in temperature scale is the minimum driving forces ΔT_{min}. The objective is to allow heat to cascade down into the next interval, in order to maximize heat recovery. When transport of energy in between intervals is balanced with utilities, the pinch point is where no energy is transferred into the next interval. The heat cascade is shown in Figure 4-2 (Gundersen, 2002):

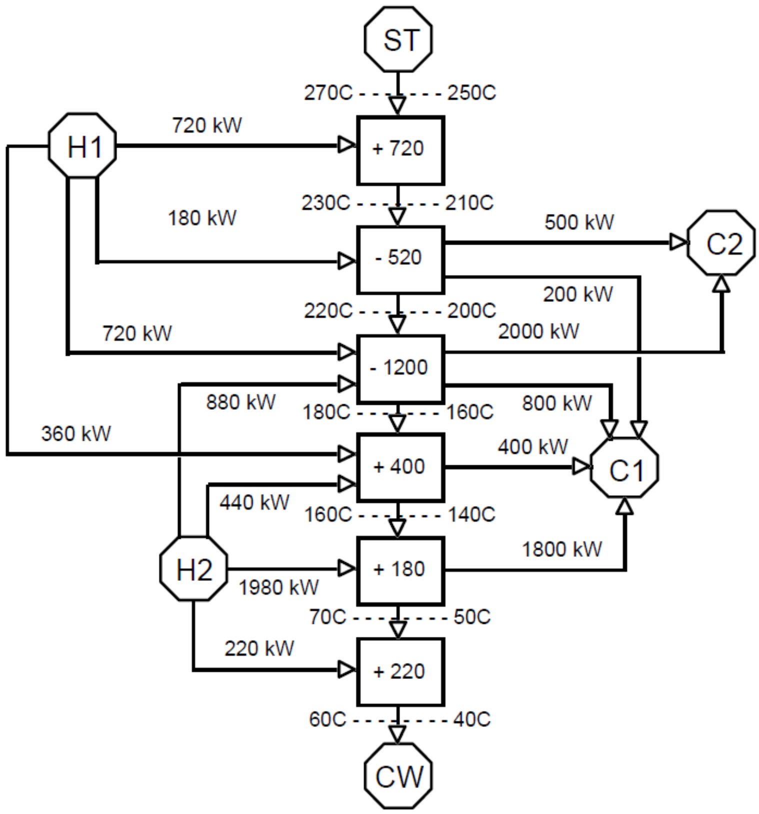


Figure 4-2: The Heat Cascade.

The arrows in between the temperature interval boxes identify energy transfer from one interval to the next. These cannot thermodynamically be less zero, but when the system is balanced with utilities (steam and cooling water), the one that is zero represents the pinch point.

4.2.2.3 The grand composite curve

The grand composite curve is one of the later developments within pinch technology. It is a curve based on the stream data that indicates best use of both hot and cold utility (Ebrahim, 1999). The curve is generated by plotting the temperature intervals from the heat cascade against corresponding flow of heat between intervals in the cascade (Gundersen, 2002). The grand composite curve from the heat cascade example presented in 4.2.2.2 is given in Figure 4-3:

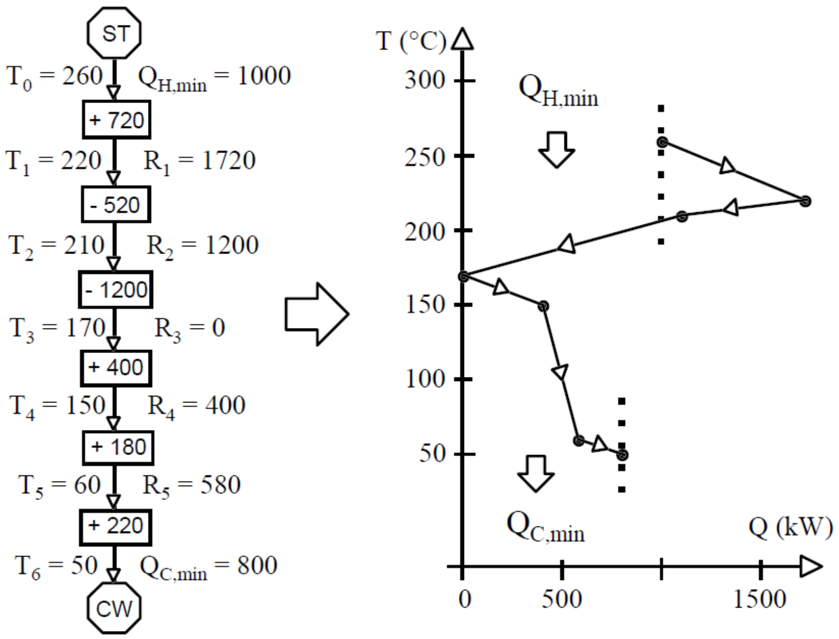


Figure 4-3: The Grand Composite Curve.

Some important notes on Figure 4-3 are, the pinch point where the graph meets the y-axis and minimum utility need marked with $Q_{C,min}$and $Q_{H,min}$.

Pinch analysis as described here have only included sensible heat, for non-phase-changing mediums. Therefore some additional analytical detail would here be needed since the heating tasks at Yara Glomfjord are to a large extent *latent* heat. Latent heat is modeled as straight lines in the grand composite curve. Literature (Gundersen, 2002) gives an example of a distillation column (with reboiler and condenser) in addition to the grand composite curve given in the previous example, shown in Figure 4-4:

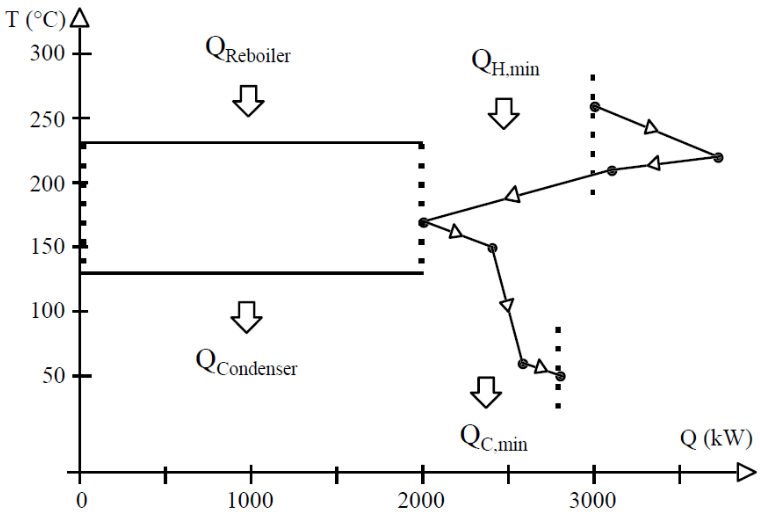


Figure 4-4: Latent heat in Grand Composite Curve diagram.

The latent heat modeled in Figure 4-4 is marked with straight lines. And it is notable how the process needs both vaporizing heat $Q_{Reboiler}$ and produces condensing heat $Q_{Condenser}$.

4.2.2.4 Existing process stream network

The pinch point divides the process into a heat deficit part above pinch and a heat surplus part below pinch. Heat transfer from deficit to surplus does not sound logical, but is in fact what commonly happens in process design without integration perspectives. This is why large savings can be done by doing a pinch analysis to make sure no heat is transferred across pinch.

With the pinch point established on can draw up the existing process stream network and identify heat that is being transferred across pinch and therefore identify *heat penalties*. Literature (Gundersen, 2002) defines three possible ways of heat transfer across pinch, given in Figure 4-5:

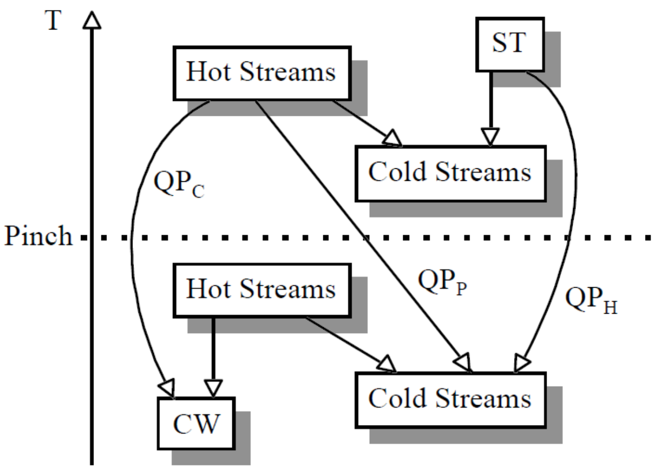


Figure 4-5: Cross Pinch penalty diagram.

The cross pinch penalties of Figure 4-5 are:

- Heat transfer from a hot stream above pinch to a cold stream below: QP_P
- Heating a cold stream below pinch with hot utility, such as steam: QP_H
- Cooling a hot stream above pinch with cold utility, such as cooling water: QP_C

For the energy integration task at hand, at the Yara Glomfjord production facility, these are important to note. Since the overall goal of this text is to suggest investments in evaporator equipment, these have to be done on with fundamental heat penalty savings in mind.

4.3 Analysis

As mentioned in the introduction of this chapter the task of *the factory energy flow analysis* will be address. This is an important task for the understanding of the fundamental energy situation at the factory, which is needed to initiate a discussion on investment in new equipment. This text has the overall goal of suggesting new solutions for the CN-evaporator system in mind, and therefore up first is the presentation of the data gathered at Yara Glomfjord, and thereafter the analysis of these.

4.3.1 Data

The gathering of data is a very critical phase of the process integration work. For a complex process like the one at Yara Glomfjord, it takes time and experience to make the right approximations regarding energy flow. Since this also is the first mapping of hot and cold streams at the factory, experienced guess work is done. The data gathered by this text is therefore produced in very tight collaboration with factory engineering staff in order to find the balance between describing detail and applicable approximations.

Next important point of interest in the process of gathering stream data is N/P-ratio. As this text have already explicitly stressed, the factory energy balance, hence hot and cold stream *vary* with N/P-ratio. It is therefore decided to do a mapping of the extremity of energy use in the factory, which is for high- or low N/P. The extremities together will give the range of energy consumption for all product types. The following approximation was made:

- High N/P means product type N-P-K: 18-3-15
- Low N/P means product types of N/P~1 (N-P-K: 14-14-14)

Following in Table 4-2 and Table 4-3 are the presentation of the stream data gathered for high and low N/P.

Table 4-2: **Stream data for high N/P.**

Hot Streams					
	[C]	[C]	[kW/K]	[kW]	
Id	T_i	T_o	mcp	dQ	**Description:**
H1	180	100	3.8	304.0	Vapor from NPK-evaporation
H2	100	40	7.6	456.0	Condensate from NPK
H3	170	110	3.3	198.0	Vapor from CN-evaporation
H4	110	40	6.6	462.0	Condensate from CN
H5	100	40	11.7	702.0	Condense from Neutralization
H6	200	40	*variable*	6160.0	Condensate from evaporators
S1	100	100	-	4065.0	Condensing vapor from NPK
S2	110	110	-	3488.0	Condensing vapor from CN
S3	100	100	-	12572.0	Condensing vapor from Neutralization
Cold Streams					
	[C]	[C]	[kW/K]	[kW]	
Id	T_i	T_o	mcp	dQ	**Description:**
C1	90	110	16.8	-336.0	Preheating of CN-liquor
C2	110	170	16.8	-1008.0	Sensible heat of CN-evaporation
C3	-	-	-	-	ML-preheating
C4	120	180	38.5	-2310.0	Sensible heat of NPK-evaporation
C5	5	75	16.8	-1176.0	CN-melting
C6	10	110	42.0	-4200.0	Air heating
V1	110	150	-	-2222.0	NH3 Stripping
V2	20	100	-	-1111.3	Ammonia vaporization (3)
V3	180	180	-	-4065.0	Vaporizing water from NPK
V4	170	170	-	-3488.0	Vaporizing water from CN

Table 4-2 shows the stream data gathered for high N/P with the simplifications agreed upon with factory engineers (Høvset, 2012). Columns present temperature in T_i, temperature out T_o, mass flow times heat capacity mc_p and enthalpy dQ. Streams identification: hot stream H; condensing stream S; cold stream C; vaporizing stream V.

Table 4-3: **Stream data for low N/P.**

Hot Streams					
	[C]	[C]	[kW/K]	[kW]	
Id	T_i	T_o	mcp	dQ	**Description:**
H1	180	100	3.8	304.0	Vapor from NPK-evaporation
H2	100	40	7.6	456.0	Condensate from NPK
H3	170	110	6.6	396.0	Vapor from CN-evaporation
H4	110	40	13.1	917.0	Condensate from CN
H5	100	40	11.7	702.0	Condense from Neutralization
H6	200	40	*variable*	8224.0	Condensate from evaporators
S1	100	100	-	4065.0	Condensing vapor from NPK
S2	110	110	-	6976.0	Condensing vapor from CN
S3	100	100	-	12572.0	Condensing vapor from Neutralization
Cold Streams					
	[C]	[C]	[kW/K]	[kW]	
Id	T_i	T_o	mcp	dQ	**Description:**
C1	90	110	33.6	-672.0	Preheating of CN-liquor
C2	110	170	33.6	-2016.0	Sensible heat of CN-evaporation
C3	5	40	34.1	-1193.5	ML-preheating
C4	120	180	38.5	-2310.0	Sensible heat of NPK-evaporation
C5	5	75	33.6	-2352.0	CN-melting
C6	10	180	42.0	-7140.0	Air heating
V1	110	150	-	-2222.0	NH3 Stripping
V2	20	100	-	0.0	Ammonia vaporization (3)
V3	180	180	-	-4065.0	Vaporizing water from NPK
V4	170	170	-	-6976.0	Vaporizing water from CN

Table 4-3 shows the stream data gathered for low N/P with the simplifications agreed upon with factory engineers (Høvset, 2012). Columns present temperature in T_i, temperature out T_o, mass flow times heat capacity mc_p and enthalpy dQ. Streams identification: hot stream H; condensing stream S; cold stream C; vaporizing stream V.

4.3.2 Analysis of process and heat cascade

Following the strategy of the pinch technology presented in the previous paragraphs the first task is to established the heat cascade, for the given data of Table 4-2 and Table 4-3. This is done by dividing all heat transfer in temperature intervals as described in the paragraph describing heat cascade, 4.2.2.2.

One important note has to be taken. Hot stream labeled H6 is modeled with a variable mass flow. This is because it models the cooling of the condensate from the applied utility 16bar steam. The heat cascade will result in the values of minimum utility need, which again results in the mass flow of condensate. Hence this mass flow needs to be iterated with appropriate utility use, which is done in excel and can be found in detail in appendix E.

The finished iteration of the process heat cascade is given in Figure 4-6 and Figure 4-7:

Heat Cascade High N/P

	16bar		9247	kW	17.22152	t/h
	6bar		2118	kW	3.944542	t/h
R1		200	5182	180	21.16606	t/h
			-184			
R2		190	1510	170		
			-352			
R3		180	1158	160		
			-314			
R4		170	844	150		
			-843			
R5		140	0	120		
R5		140	2118	120		
			104			
R6		130	0	110		
			-296			
R7		110	3192	90		
			-115			
R8		100	18603	80		
			20			
R9		95	18623	75		
			-705			
R10		40	17918	20		
			-588			
R11		30	17330	10		
			-84			
R12		25	17246	5		
			17246	kW		
	h_fg16bar		1933	kJ/kg		
	cp_H6		4.2	kJ/kgK		
	mcp_H6		**20.09177**			

Figure 4-6: Heat Cascade High N/P.

Heat Cascade Low N/P

	16bar		12988	kW	24.18872	t/h
	6bar		2172	kW	4.045111	t/h
R1		200	8923	180	28.23383	t/h
			-103			
R2		190	1844	170		
			-439			
R3		180	1405	160		
			-401			
R4		170	1005	150		
			-1004			
R5		140	0	120		
R5		140	2172	120		
			50			
R6		130	0	110		
			-740			
R7		110	6237	90		
			31			
R8		100	22905	80		
			93			
R9		95	22998	75		
			-524			
R10		60	22474	40		
			-981.64			
R11		40	21492	20		
			-1097			
R12		30	20395	10		
			-339			
R13		25	20056	5		
			20056			
	h_fg16bar		1933	kJ/kg		
	cp_H6		4.2	kJ/kgK		
	mcp_H6		**28.22018**			

Figure 4-7: Heat Cascade low N/P.

In Figure 4-6 and Figure 4-7 green labels the residual, while red labels the heat transfer within a certain temperature interval. Temperature intervals are indicated alongside the cascade. The residuals are numbered R1 through R13. To get the appropriate utility use latent heat is included in the residuals. Also notable are the iterated value of $\dot{m}c_{p_{H6}}$ and the total steam consumption at 16bar and 6bar. Mark that when discussing the mass flow of H6 and the utility use it is based on maximum energy recovery as introduced in previous chapters, and a baseline for energy use in retrofit- or new-design projects. Total minimum steam use is found to be 21,2tons/h for high N/P and 28,2tons/h for low N/P.

4.3.3 Grand composite curves

With the heat cascade at hand the grand composite curve can be established from plotting the temperature intervals against heat transfer (red boxes in heat cascade). It was briefly mentioned in earlier paragraphs that latent heat and sensible heat is drawn separately. In Figure 4-8 and Figure 4-9 the sensible grand composite curve is blue and the latent grand composite curve is red.

The construction of the grand composite curves is done with the computer program PRO_PI2[5], by inserting the data from Table 4-2 and Table 4-3.

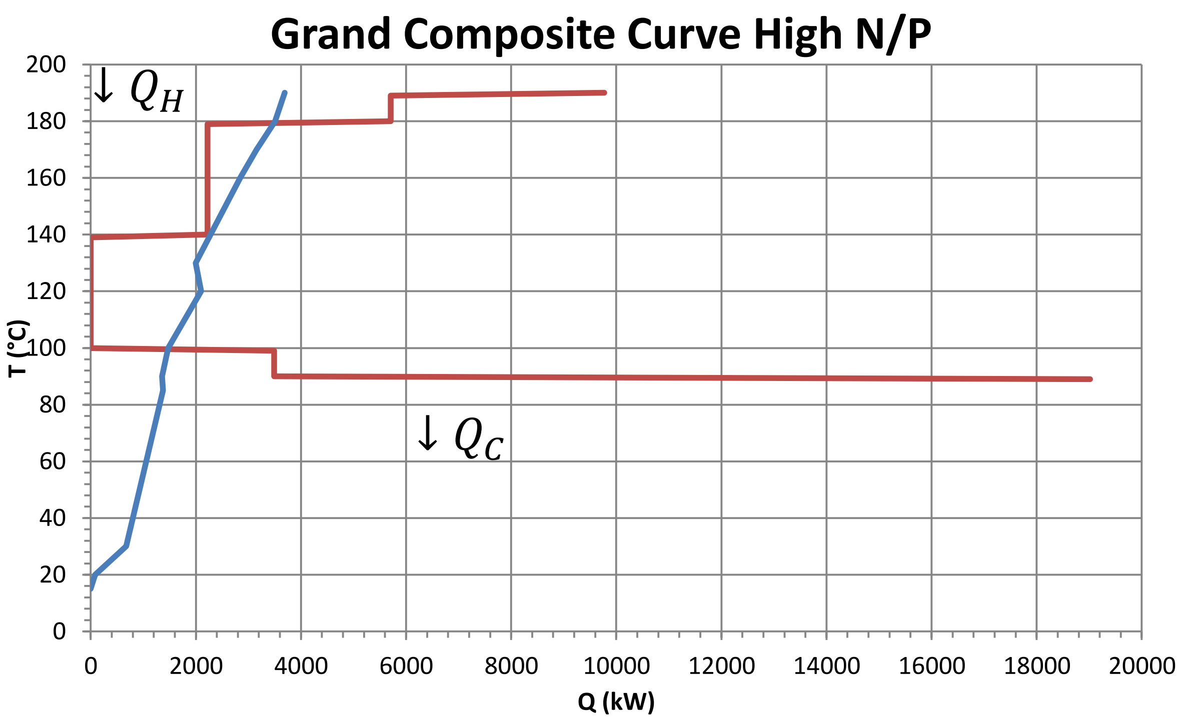


Figure 4-8: Grand Composite Curve High N/P.

[5] The software PRO_PI2 is developed at Chalmers University in Gothenburg.

Concerning the latent heat in Figure 4-8 and Figure 4-9, the energy marked at 100°C and down is surplus energy and the energy from 140°C and up is energy demand.

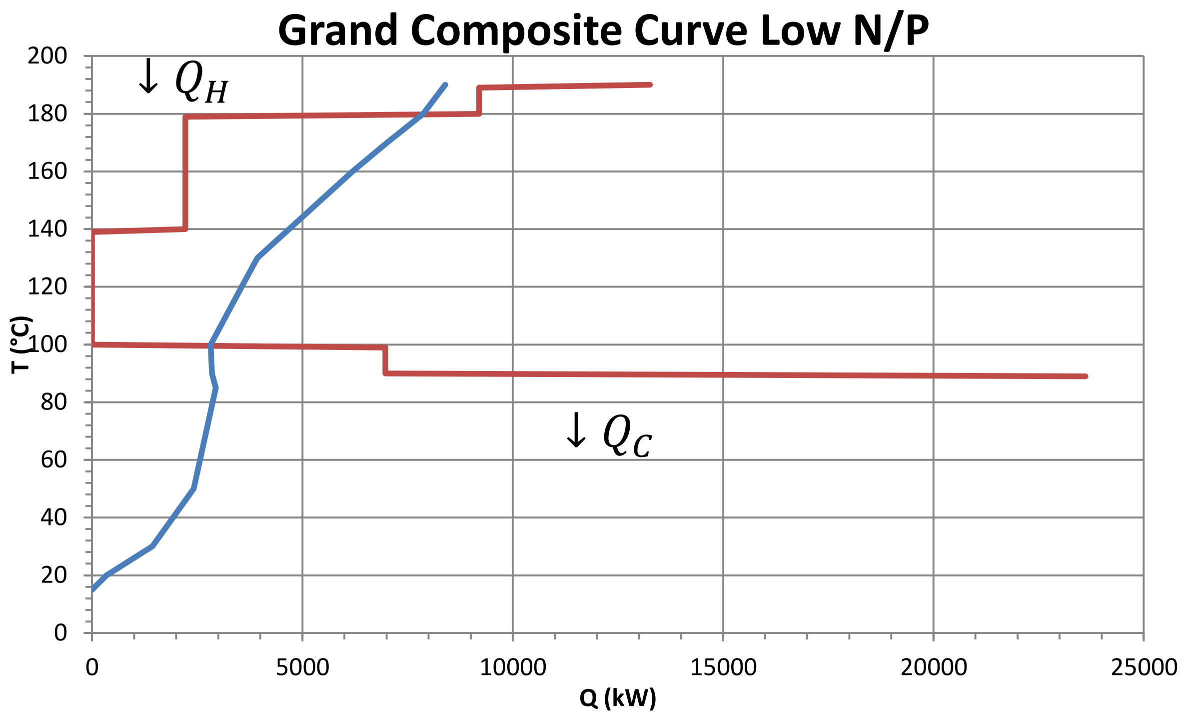


Figure 4-9: Grand Composite Curve Low N/P.

In Figure 4-9 it is notable that the energy amount of latent heat at 100°C and 180°C are twice as large as in Figure 4-8. This is due to the use of both CN-evaporators under low N/P conditions.

4.3.4 Heat pumps and vapor recompression

From the grand composite curves it is clear that the large amount of excess heat is latent at a relatively low temperature. It is not the intention to discuss the results just yet, but since the overall goal of this text is to suggest investments in evaporator equipment, a rough estimate will be done on mechanical recompression for the CN-evaporators.

Neither has *mechanical recompression* been properly introduced in this text, which will be the topic for upcoming chapters, but for the purpose of this estimate it is a type of heat pump. It is thought to move the surplus energy from low temperature to high temperature like it is presented in Figure 4-10:

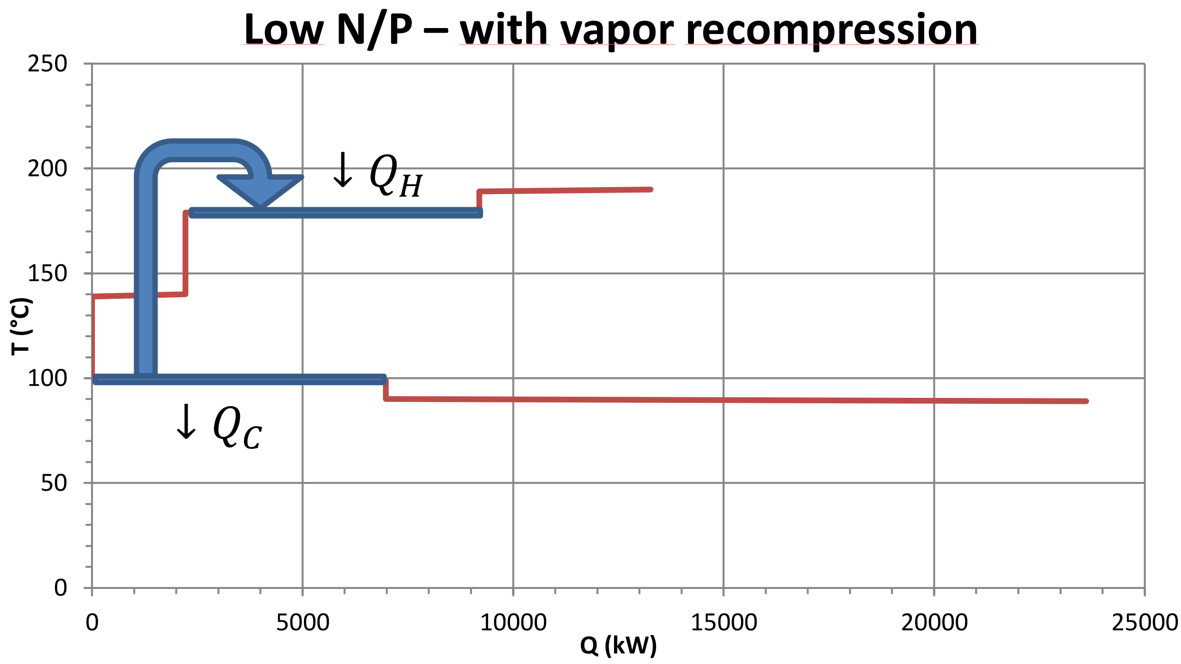


Figure 4-10: Vapor recompression of latent heat.

The rough estimate will here be made assuming the heat pump of interest to be ideal according to the Carnot equations. The coefficient of performance as expressed by the Carnot equations is given in literature (Moran, et al., 2004):

$$COP = \frac{Q_H}{W_c} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C} \qquad \text{Equation 4-1}$$

To do this simplified calculation it is also assumed that the vapor from the CN-liquor is gathered right after evaporation, as superheated steam at 170°C. Target temperature of 16bar steam is 205°C. This leaves this theoretical estimate for COP:

$$COP = \frac{478K}{478K - 443K} = 13{,}66 \qquad \text{Result 4-3}$$

This number states that the work input pays off 14 times, according to the assumptions above. A rough Carnot efficiency is η~50%, which leaves this estimate to COP~6,8.

4.4 Chapter Discussion

What is given in this chapter is the energy fundament of the factory operation, and therefore important numbers and figures to take into account for *the energy savings potential*.

One small comment up front is that the overall goal of this text is to suggest improvements in the evaporator system. The data presentation and argumentation of this chapter is therefor done somewhat to support the choice of vapor recompression.

4.4.1 Gathering of data

As mentioned in 4.2.2.1 data gathering it is truly a both difficult and critical part of an energy project. First of all the data gathering and the simplifications was done in collaboration with factory engineers, and therefore with support of the upmost expertise on the subject. However, it is still a balance between describing detail and practical approximations.

There are also some smaller heat consuming tasks no included in this analysis, but the heating tasks presented represents the large energy carriers of the process. One argument for this is the grand composite curve diagrams where both latent and sensible heat is presented. It is evident that the sensible heat flow of the factory is small compared to the latent heat. This again means that the modeling of latent vaporization and condensation is of more importance for the total energy balance of the factory than the sensible energy streams.

A more detailed comment on the data gathering, linked to the phase change in some heating tasks, is also needed. For cold streams of liquor to the evaporator equipment, they are modeled as heated streams up to the highest temperature, and then latent heat is added at the highest temperature. The hot streams from the evaporator equipment are modeled as superheated vapor being cooled, then condensing heat and then sub cooling at last. This is done to keep the analysis simple, but needs to be remembered for further calculations. E.g. for the COP of a heat pump it must be remembered that vapor recompression can be done on the superheated vapor and not at the condensing temperature, hence a higher COP is possible.

4.4.2 Heat cascade and grand composite curves

When the job of gathering data is done making the heat cascade is an easy job. However, in the case of the energy flow at Yara Glomfjord, iteration had to be done. This is because one of the hot streams is the condensate of 16bar steam used as utility. All iteration work is done in excel, and supplied in appendix E. Notable is that the iteration had to be done in advance of more detailed analytical work, e.g. the making of the grand composite curves.

The heat cascade gives minimum utility consumption. An important note is that this is with the optimum designed heat exchanger network with all necessary heat exchangers. Reaching this goal is a both costly and complex task as mentioned in the preliminary work for this thesis (Ingebrigtsen, 2011). This text's following strategy is therefore to do large savings at a reasonable return cost, with heat pump and vapor recompression in mind.

The software used for the construction of the grand composite curve is PRO_PI2, made by a professor at Calmar University of technology in Sweden. All stream data from Table 4-2 and Table 4-3 was entered to the software and grand composite curves were made. Separate curves were made for the two different N/P scenarios, but also separate curves for latent and sensible heat. The curves for the same N/P where plotted in the same diagram to underline differences in latent and sensible energy need.

4.4.3 Heat pump

Since it is the overall goal of this text to suggest retrofit design of CN-evaporator equipment, the rough estimate of COP was made, based on stream data from the analysis above. To be discussed is that this was a rough estimate, depending on existing equipment under optimal conditions. The COP was therefore adjusted after a Carnot efficiency of η~50%. Since this COP also is dependent on the existing equipment with a rather high temperature lift, the value might be a little on the low side.

This chapter leaves it as a discovered potential, but this text will address the topic of new solutions for CN-evaporators, in both new-design and retrofit, in as much more detail in upcoming chapters.

4.5 Chapter Conclusion

Based on stream data gathered at the Yara Glomfjord factory in collaboration with factory engineers, energy analysis was done for all process streams. Heat cascade and grand composite curves where made for both high- and low N/P-ratio. A huge potential for energy savings in latent low temperature heat was found.

Some key figures are the minimum consumption of steam, found to be 21,2tons/h for high N/P and 28,2tons/h for low N/P. This numbers are based on maximum heat recovery, without heat pumps or vapor recompression.

A realistic potential for vapor recompression has been found for CN-evaporators, and COP has been estimated to COP~6,8.

Generally it is noted that the factory energy flow is mostly preserved as *latent heat*, and integration of the *sensible heat* has little impact compared to heat pumping of latent heat.

5 Evaporator Design

5.1 Introduction

Evaporation is the separation of volatile components from heavier components based on the principal of vaporization. An evaporator is a device wherein liquid is evaporated from a low density feed material in order to produce a denser product (Chen, et al., 1997). However for process applications, evaporation as a term concerns separation of solid material and liquid. The solid is usually completely solved in the liquid, and by evaporation the concentration of solid is raised (Bolland, 1999). The removal of water from heavier components, when the heavy component is of interest, is usually done with evaporators. At Yara Glomfjord removal of water is the goal. Removal of water from a liquid through evaporation generally consumes less energy than removing the same amount of water from dried product (Jordal, 2005).

Evaporation differs from other separation methods like distillation because the vapor pressure of heavy component, which is a solid, is negligible compared to the vapor pressure of solvent (Bolland, 1999). Added heat will therefore vaporize solvent and concentrate amount of solid. Principally this is a very simple process, but because of a large specter of application and product types numerous evaporation systems and technologies are available. This chapter presents general technologies and heat integration options. But it is also here referred to literature like *Evaporation Technology* (Billet, 1989) where most evaporator types are presented.

5.2 Choice of Equipment

The most fundamental factors in choice of equipment, and design of such, are the properties of the feed stream and the desired capacity. For mixtures that does not involve risk of corrosion and scaling (fouling due to inverse solubility), problems of operation are seldom and simple equipment can be used. However, a number of scenarios with these issues are possible, and the design of such evaporators needs to take this into account (Bolland, 1999). Solubility is another issue, for high concentrations the liquid might get saturated and precipitation of solid occurs. Some principal sketches of the most commonly used principles are given in Figure 5-1 (Billet, 1989):

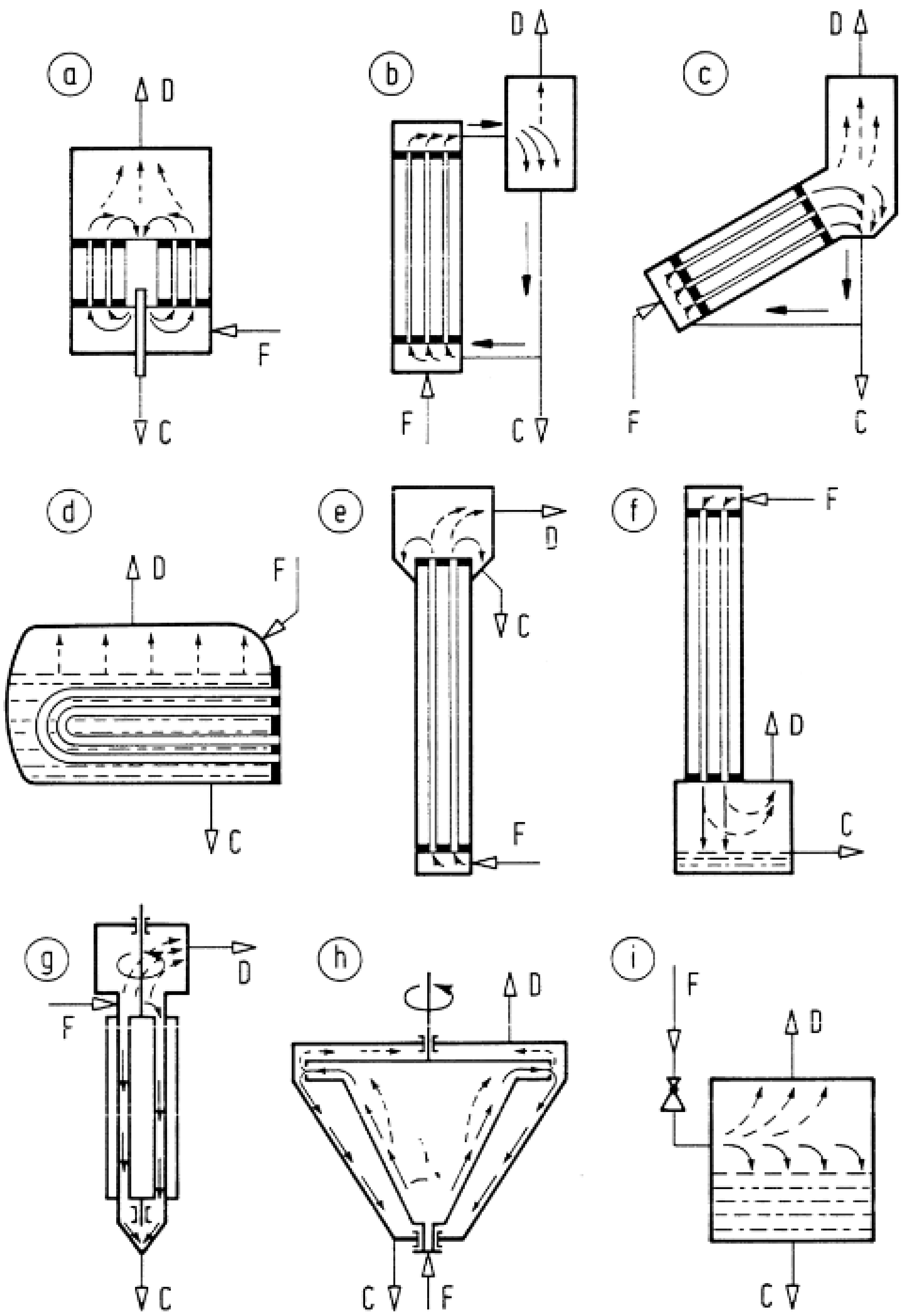


Figure 5-1: Principal sketches of evaporator designs **(Billet, 1989)**.

Figure 5-1 labels feed F, distilled vapor D and concentrate C. As mentioned the most important factors in choice of equipment are capacity and feed properties. The important feed properties are viscosity at the corresponding concentration, saturation point, residence time in evaporator, tendency of scaling and fouling, and *boiling point elevation*. Literature suggests these factors of equipment choice, as listed in Table 5-1 (Bolland, 1999):

Table 5-1: **Factors of evaporator equipment choice** (Bolland, 1999)**.**

Type	Viscosity μ[pa s]	Capacity	Tendency of Scaling	Residence time
Natural circulation: a, b, c, e	0.05	Small-Large	Large	Very long
Forced Circulation: b, c, e	1	Small-Large	Small	Very long
Climbing film: e	0.5	Small-Large	Large	Medium
Falling film: f, g	0.1	Small	Medium-Large	Short
Thin film: h	10-100	Medium-Large	Small	Short
Flash evaporation: i	0.001	Small-Medium	Small	Short-Long

The evaporator types in Table 5-1 are linked with the designs sketched in Figure 5-1 with the identification letter a through i.

5.2.1 Boiling point elevation

In choice of equipment based on feed properties, *the boiling point elevation* is of great importance. The boiling point elevation and freezing point depression are physical phenomena that occur in a fluid with a solute. They are categorized as colligative properties, such as *osmosis*.

When a substance is dissolved in a solvent the vapor pressure is lower than for the liquid in pure state. The consequences in a phase diagram are shown in Figure 5-2, substance in solvent noted T‘:

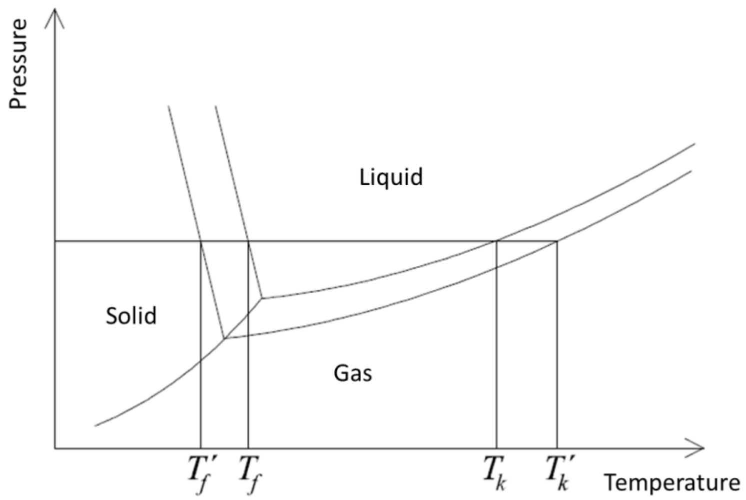


Figure 5-2: Boiling point elevation and freezing point depression **(Bolland, 1999)**.

In evaporation processes the boiling point rises. By changing the concentration of dissolved substance to a larger level, the significance of the boiling point elevation follows. Hence, the boiling point elevation rises with the concentration of the dissolved substance.

This text will stress this phenomenon as one of the most important design parameters after discussing the matter with commercial expertise on evaporation technology (Evenmo, 2012). Especially, this is found important for the case at Yara Glomfjord where concentration of salts in water reaches a very high weight percent[6].

5.2.2 Driving forces

The next point to make regarding design parameters is the available driving forces in the evaporator equipment. Based on what is already described under the paragraph boiling point elevation, the boiling point for reaching the desired concentration might be high. This again requires a high ΔT, which for low concentrations is bad energy economics. It is therefore stressed that multiple evaporators in series with fitting ΔT for each unit might be beneficial energy wise. However, the balance of investment cost and these savings have to be considered.

5.3 Energy Conservation and Vapor Recompression

Evaporators are heavy equipment that consumes a lot of energy. At Yara Glomfjord between 70% and 80% of the available steam is consumed in the evaporators at all N/P ratios, as it is shown in the steam balance Figure 3-3 and Figure 3-4. Heat integration in this equipment therefor represents a huge potential if possible.

The vapor exiting the evaporator contains significant heating value as latent heat of vaporization. This energy can be recovered by heat-recovery techniques, i.e., *multiple effect operation, reheating* between effects and by *recompression of vapor.* There are also other energy recovery methods of a simpler character such as *preheating of feed, heat integration of condensate, improved maintenance and insulation etc.* The typical energy savings by various methods are suggested by Anon in Table 5-2 (Chen, et al., 1997):

[6] Details are given in appendix A: CN-Evaporator System Design.

Table 5-2: **Energy savings by various methods.**

Typical Energy Savings by Various Methods

Method	Capital requirement	Achievable energy savings (%)
Venting and thermal insulation	Low	5
Improved maintenance	Low	5
Heat-recovery exchangers	Low	10
Condensate reuse	Low	5
Thermal recompression	Medium	45
Mechanical recompression	High	70–90
Additional effects	High	$\left[1-\left(\frac{N}{N+n}\right)\right]100\%$

Note: N = original number of effects; n = number of added effects.

Example: The savings for increasing a three-effect evaporator to four effects is equal to $\left[1-\left(\frac{3}{3+1}\right)\right]$ 100% = 25%, approximately.

From Anon. (1977).

The most important general heat integration techniques are presented in the upcoming paragraphs:

5.3.1 Preheating the feed by process heat

The feed of the evaporator is preheated with process heat, so that the evaporator needs less steam to evaporate the liquor. This method is preferred used when the feed is not on the boiling point, or under certain local conditions, e.g., an evaporation stage is to be integrated with the process or the vapor from the evaporator is not clean enough for recompression. Preheating might also be done with the vapor from the evaporator itself in cases where the local conditions allow it (Billet, 1989).

A general observation is that it is beneficial for the feed to be close to boiling point before entering evaporator equipment. This is to some extent utilized for both evaporator systems (NPK and CN) at Yara Glomfjord (Ingebrigtsen, 2011).

5.3.2 Multiple effect evaporation

Multiple effect, also known as *cascade,* evaporation refers to a number of effects connected in tandem, so that the vapor from a preceding stage acts as the medium for heating the subsequent stage (Billet, 1989). This gives a reduction in steam use, but also in cooling water since the only vapor that needs to be condensed is that out of the last effect. However multiple effect evaporators are very sensitive to change in operating conditions (Chen, et al., 1997).

The motivation for using multiple effects is energy savings. Multiple effects evaporations are an economically good design when the price of extra heating surface is lower than the price of additional energy for a single unit. There are three principles: *counter current*- and *co-current*- and *parallel* multiple effects (Bolland, 1999). From the same literature the flow diagram of counter current multiple effects (three effects) in Figure 5-3 are given:

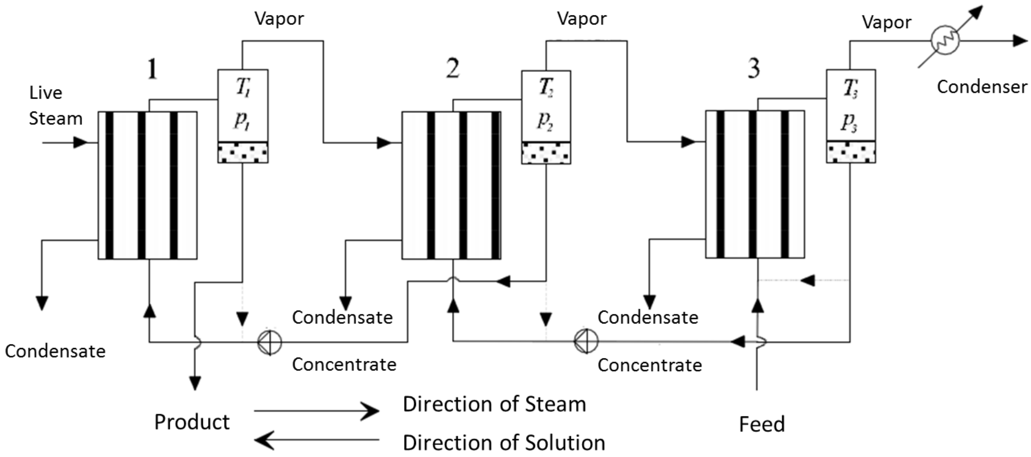


Figure 5-3: Principal sketch of multiple effect evaporation technology **(Bolland, 1999)**.

The principle course of the temperature profile is also presented by Bolland, and given in Figure 5-4:

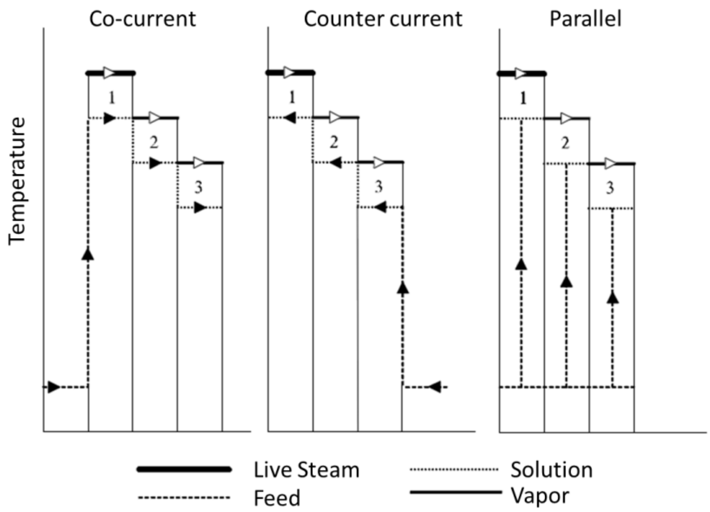


Figure 5-4: Temperature levels in multiple effect evaporation **(Bolland, 1999)**.

5.3.3 Mechanical recompression

In mechanical recompression the evaporation vapor is compressed to a higher pressure and saturation temperature so that it can be re-used in the evaporator heat exchanger. Under optimum conditions, the equivalent of up to 20 effects in energy savings can be done with mechanical recompression, and therefore this is the energy saving technique with highest potential (Chen, et al., 1997). Several options are available, including the use of mechanical recompression in single- or multiple effect systems, between effects. The compressor type and use may also vary, with one or more stages and size and type of compressor. However high energy recovery in these type of systems, it must be balanced against investment cost, maintenance and electrical energy cost for the chosen equipment. It must also be noted that with use of recompressed vapor in the evaporator, additional energy must be provided for heating in the start-up phase and to operate the compressor. A flow chart for evaporator with mechanical recompression is shown in Figure 5-5.

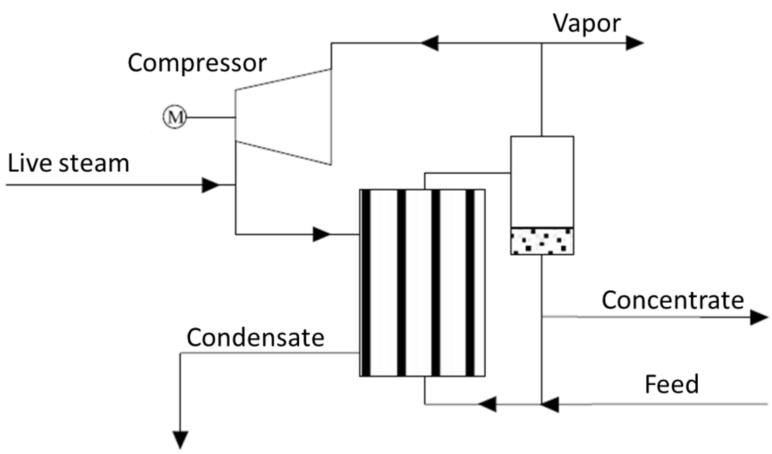
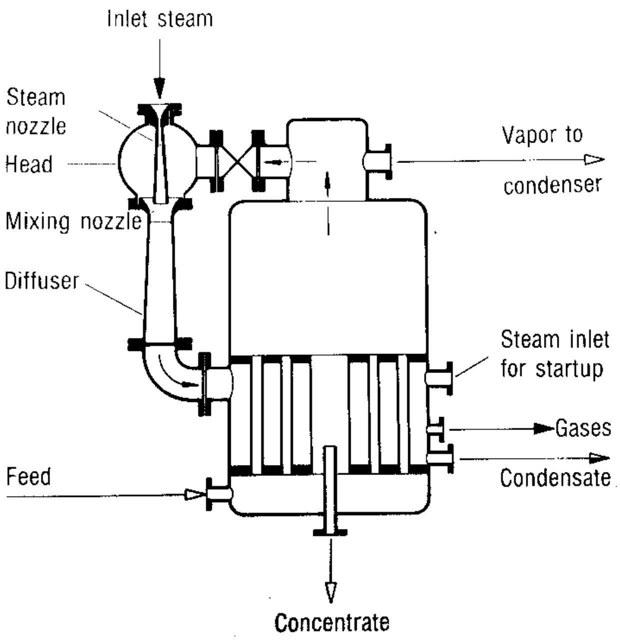


Figure 5-5: Flow chart for evaporator with mechanical recompression **(Bolland, 1999)**.

5.3.4 Thermal recompression

Thermal recompression serves the same mission as mechanical, but with different equipment and cost. Here, the vapor is compressed by a steam-jet ejector to the temperature and pressure of the steam supply. Ejectors have been widely accepted in industrial practice for this purpose on account of the advantages they offer. The assembly consists of a steam nozzle, suction chamber, a mixing nozzle and a diffuser. Because the device is design without moving parts it is both cheap and reliable. It can also be constructed in a wide range of materials (Billet, 1989). This makes thermal recompression favorable compared to the mechanical recompression in price, but with a lower energy recovery potential. Thermal recompression also demands a certain purity of the vapor. Principal sketch is presented in Figure 5-6:



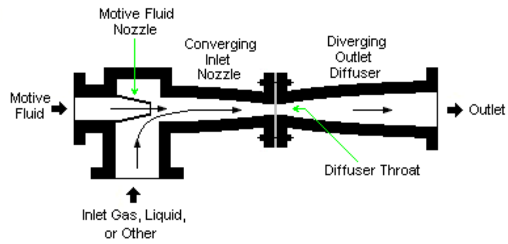


Figure 5-6: Flow chart for evaporator with steam-jet ejector for compressing vapor on left hand side **(Billet, 1989)**. On the right hand side is enlarged schematics of the steam nozzle.

5.3.5 Sub atmospheric boiling

Sub atmospheric boiling or submergence of the boiling pressure on the liquor side of the evaporator is in principal the same thing as vapor recompression. The idea is to gain a certain temperature difference by changing pressure in either the hot side or the cold side of the heat exchanger. By discussing the topic with experts on the subject, this text recognizes submergence of boiling pressure as superior to vapor recompression between effects in cascade evaporation (Evenmo, 2012).

What is important in choosing this option is how the liquor behaves at the given temperature and pressure. Liquor might for example be heated atmospherically without problems, but by lowering the pressure precipitation of the solved salt might occur. If this is not the case, submergence of boiling temperature is preferable.

5.4 Economic effect of Energy Savings

It is very important to have the complete economic perspective when dealing with energy savings. Both investment cost and operation cost needs to be accounted for to make a decision. Many existing systems are designed with minimal capital cost during a time with low energy cost. As a result of higher electric prices, considerable economic benefits can be made with retrofit design of evaporators. This means new investments can be made, and balanced with energy savings and todays energy prices. Literature (Chen, et al., 1997) gives these general subcategories of modifying existing evaporators with respect to cost:

1) **Fine tuning existing evaporators.** This category is considered low on capital requirement and also low energy savings potential. It consists of improvement of existing equipment i.e. venting and insulation, but also improved maintenance.
2) **Modifying auxiliary hardware.** This category is considered medium on capital investment and saving potential. It consists of heat exchanger for preheating of feed, heating between effects and reuse of condense.
3) **Major hardware modifications.** This category is considered high on capital requirement and also high energy savings potential, i.e. mechanical vapor recompression and additional effects.

It is noted that there is a general trend between investment and energy savings (see Table 5-2). Energy saving in this case can be read as reduction in operational cost, and needs to be balanced against investment cost and the cost of downtime.

6 Suggested Improvements

6.1 Introduction

The analytical part of this thesis concerning CN-evaporator design is held confidential, and supplied for interested parties as appendix A: CN-Evaporator System Design. However in order to give this text argumentative structure, results and discussion will be found in the main text. The results and benchmarking of these are given and discussed in upcoming paragraphs.

6.2 Results of Evaporator Design Analysis

6.2.1 Original solution

In the present solution at Yara Glomfjord the evaporation of CN is done mostly in one evaporation step. The feed is preheated but the total energy efficiency of the evaporator system is very low. A sketch of the present flow schematics is presented in Figure 6-1:

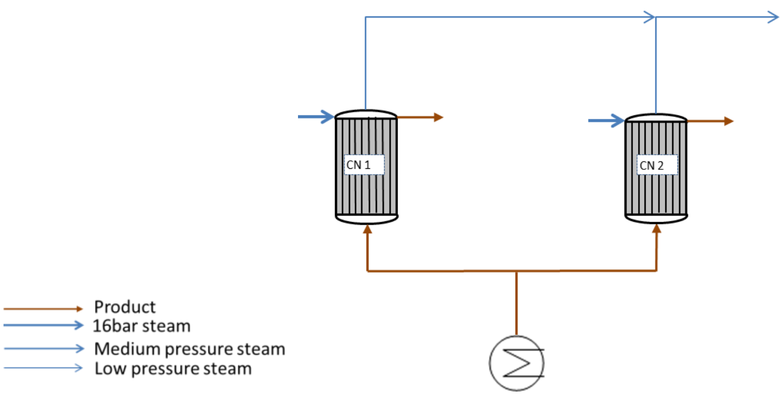


Figure 6-1: Original solution.

With the means from chapter Evaporator Design and the analytics of appendix A: CN-Evaporator System Design, three suggestions of improvement are given. The three suggestions of improvement and their performance are presented here:

6.2.2 New two effect cascade evaporator

The first suggestion is to design a new evaporator which is to be integrated in a cascade system with the existing equipment. In doing so the new unit should use vapor from the existing equipment with recompression as the energy source. This means that the technology *cascade* and *vapor recompression* between effects are both utilized. The schematics of this suggestion are given in Figure 6-2:

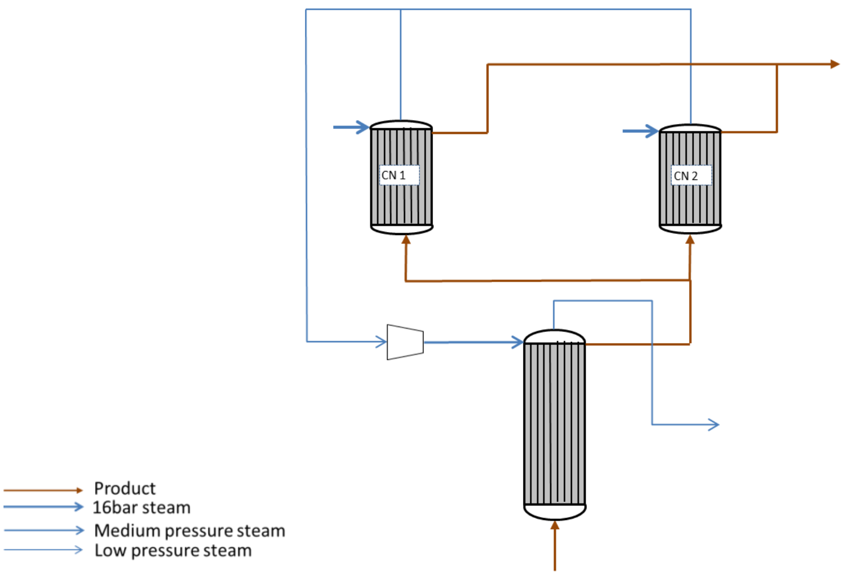


Figure 6-2: New two effect cascade evaporator with recompression.

This solution is rather simple and demands only a slight recompression of vapor, since the vapor comes from higher pressure evaporation in the second effect. The new equipment needed is a long tubed evaporator in advance of the existing equipment, compressor, piping and valves etc.

The large benefits of this solution are the energy savings possible, despite a rather simple solution with low recompression. If decoupled, the "old solution" can also still be used. This is a great advantage in a worst case scenario with problems in the startup of the new equipment. Because of the possibility to switch back when facing problems, downtime is avoided. Decoupling might also be an advantage in cleaning of the first effect, and also here avoid downtime.

On the other hand there are a few disadvantages as well. First up, this system is designed in such a way that the energy leaving the second effect is the energy supply of the first effect. Hence, this unit can only operate up to a certain level and produce a maximum concentration out of first effect. This again means that a certain level of energy is saved, and more is not possible. The vapor leaving the first effect is also not integrated and might be a good topic for further work.

The performance of this suggestion is based on analytical work in appendix A: CN-Evaporator System Design and given in Table 6-1:

Table 6-1: **Two-effect new design cascade evaporator performance.**

Total steam use	Electricity use	Evaporated mass	Steam savings	Energy savings in EGA boilers	Energy savings in Oil consumption	Total energy savings
$\left[\frac{tons}{h}\right]$	$[MW]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$[GWh]$	$[GWh]$	$[GWh]$
12	0,5	16	10	35	10	45

In Table 6-1 it is notable that all the energy need originated from the EGA boilers is saved, and also a huge portion of the oil consumption. The oil is saved because the heating task can be done with excess live steam after investment in this suggestion.

6.2.3 Two effects cascade evaporator using old equipment

The second suggestion is closely related to the previous. The idea is the same, but in solving this task it is suggested to re-build the two existing evaporators in cascade such that the last effect supplies the first with energy. The technology utilized is still *two-effect cascade* and *vapor recompression* between effects. The schematics are given in Figure 6-3:

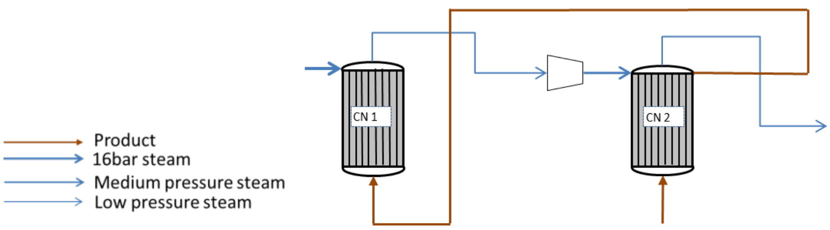


Figure 6-3: Two effects cascade evaporator using old equipment.

This solution is the simplest possibility with all original equipment and re-piping. Hence, the re-build also has a low cost, despite rather large savings.

The weakness however is the flexibility. Taking one unit out of production means downtime in the whole CN-production line. Also, compared to the previous solution, a new design two effect will perform better energy wise. The performance based on analytics from appendix A: CN-Evaporator System Design is given in Table 6-2:

Table 6-2: **Two-effect cascade using old equipment performance.**

Total steam use	Electricity use	Evaporated mass	Steam savings	Energy savings in EGA boilers	Energy savings in Oil consumption	Total energy savings
$\left[\frac{tons}{h}\right]$	$[MW]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$[GWh]$	$[GWh]$	$[GWh]$
14,2	0,5	16	7,8	35	1,2	36,2

In Table 6-2 it is made clear that also here EGA boilers are retired. However, this solution only saves a small portion of oil consumption which is almost negligible.

6.2.4 New MVR evaporator

The last suggestion is also related to the previous ones. The idea is to place a mechanical vapor recompression new-design evaporator in front of the existing equipment to remove enough water previous to the original process to retire boilers and use of oil. Existing equipment would maintain the boiling at the highest temperature. The MVR itself is self-sufficient with energy with only a small amount of live steam for startups and compressor work. This solution is related to previous ones with *vapor recompression* technology but this solution is not coupled in *cascade.* The schematics are given in Figure 6-4:

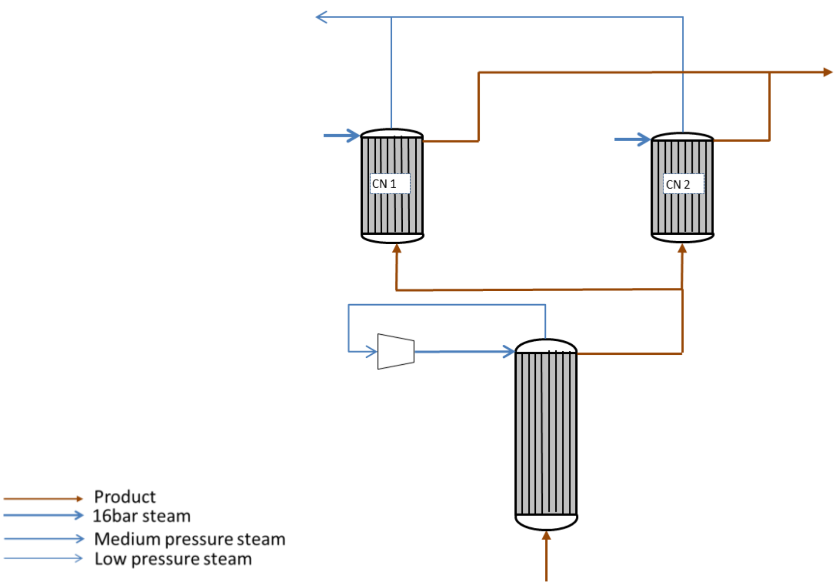


Figure 6-4: New MVR self-sufficient evaporator.

This is the most complex new design with a new unit separate to the existing system and the largest compressor. The new unit is also self-integrated with recompressed vapor and is therefore self-sufficient with energy.

The largest benefit is the design point witch can be chosen. In this text it is made to be precisely the energy savings that needs to be done in order to retire both oil use and electrical consumption in boilers. As option one this solution is robust in chance of downtime, with the ability to switch back to the old solution.

On the other hand this is the most expensive solution. Compressor, all extra piping and equipment to make this a self-sufficient unit is costly, but in the light of the savings possible with this solution they might as well be worth it. Table 6-3 shows the performance based on appendix A: CN-evaporator system design:

Table 6-3: **Independent new MVR evaporator.**

Total steam use	Electricity use	Evaporated mass	Steam savings	Energy savings in EGA boilers	Energy savings in Oil consumption	Total energy savings
$\left[\frac{tons}{h}\right]$	$[MW]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$[GWh]$	$[GWh]$	$[GWh]$
10	0,82	16	12	35	18,5	53,5

By designing a new independent MVR-evaporator, both EGA boilers and oil consumption can be retired. Table 6-3 shows savings of 53,5GWh, which is the amount of energy savings which is economically beneficial as discussed in chapter 4.1.

6.3 Benchmark

In order to do a proper benchmarking of the performance, data is gathered from the document: CN-Evaporator System Design. The performance parameters are also defined in the same document. To give this text proper context this part (6.3, originally A.8) is re-written here:

6.3.1 Performance Calculation

In order to do the best decision making the analytical data from the different suggestions needs to be evaluated and measured against cost. To benchmark the analytical work done in this chapter a few performance parameters, and the contributing numbers to these will be defined and calculated.

6.3.1.1 Definitions:

The values included in the performance parameters are the following:

Definitions

$$\dot{\boldsymbol{m}}_{\boldsymbol{s}} \sim steam\ use\ [tons/h]$$

$$\dot{\boldsymbol{m}}_{\boldsymbol{v}} \sim evaporated\ vapor\ [tons/h]$$

$$\boldsymbol{E}_{\boldsymbol{el}} \sim electricity\ use\ [MW]$$

$$\boldsymbol{E}_{\boldsymbol{st}} = \dot{m}_s * h_{fg_{16bar}}$$
$$\sim energy\ content\ of\ steam\ use\ [MW]$$

$$\boldsymbol{E} \sim total\ energy\ use\ [MW]$$

6.3.1.2 Steam use and performance

First up is how much steam a selected solution will save. This is given by the energy transfer in the unit, made possible by compressor work and *latent heat* from either the unit itself

(FFE-MVR) or the next effect. This energy is integrated in the system and need not be supplied by live steam. Hence the *steam savings* is given by the unit duty:

$$\dot{m}_{saved} = \frac{\dot{Q}_{unit}}{h_{fg_{16bar}}} [tons/h]$$ Equation 6-1

The total steam consumption is the consumption of the existing evaporator system minus the savings.

$$\dot{m}_s = (22 - \dot{m}_{saved})[tons/h]$$ Equation 6-2

The complete evaporator system for CN-evaporation is designed to evaporate a given amount of water, calculated earlier in this text, in order to maintain a certain concentration out of the system. The mass of evaporated vapor is known to be:

$$\dot{m}_v = 16tons/h$$ Equation 6-3

The energy that follows the steam use is identified by this text as E_{st}. Steam use is here defined as total mass flow of live steam to the whole CN-evaporation system identified m_s.

$$E_{st} = \dot{m}_s * h_{fg_{16bar}} \ [MW]$$ Equation 6-4

Specific steam energy use is a performance parameter defined to be the energy content of the steam use divided by mass flow of evaporated vapor. The specific steam energy use is given in kWh per ton evaporated vapor, and is identified e_{st}:

$$e_{st} = \frac{E_{st}}{\dot{m}_v} \left[\frac{kWh}{ton}\right]$$ Equation 6-5

Next performance parameter is the *specific steam use,* defined as the use of live steam divided by evaporated vapor mass in tons per ton:

$$s = \frac{\dot{m}_s}{\dot{m}_v} \left[\frac{tons}{ton}\right]$$ Equation 6-6

6.3.1.3 *Electricity use and energy performance*

The electrical input to the process equals the compressor work. The performance parameter is here called *specific electrical energy use* and is the net input of work on the compressor divided by evaporated mass:

$$e_{el} = \frac{E_{el}}{\dot{m}_v} = \frac{W_c}{\dot{m}_v} \left[\frac{kWh}{ton}\right]$$ Equation 6-7

To make a figure of the complete energy use of the system both steam and electrical energy is needed. The performance parameter *specific energy use* is defined by this text as the total energy input in form of steam E_{st} and compressor work W_c, divided by evaporated vapor mass. The specific energy use is in kWh per ton evaporated vapor, identified *e*:

$$e = \frac{E}{\dot{m}_v} = \frac{E_{st} + W_c}{\dot{m}_v} \left[\frac{kWh}{ton}\right]$$ Equation 6-8

$$e = e_{st} + e_{el} \left[\frac{kWh}{ton}\right]$$ Equation 6-9

6.3.2 Benchmark parameters

The benchmark parameters are gathered in Table 6-4. The table is also added some details concerning price, technology and additional comments. In this way Table 6-4 has distinctive value for the reader.

Performance of existing systems at Yara Glomfjord and Yara Porsgrunn are also added in order to benchmark new parameters against existing solutions.

Table 6-4: **The benchmark parameters.**

		Yara Glomfjord existing system	Yara Porsgrunn evaporation system (string-B)	Two-effect new design cascade	Two-effect cascade using old equipment	New design separate falling film MVR evaporator[7]
Technology	[–]	Short tube evaporator with	Multiple evaporators in two effect	Long tube evaporator in cascade	Short tube evaporators in cascade	Separate FFE with MVR

[7] Based on Epcon FFE-MVR solution, A.12.1

		preheating of feed	cascade with MVR	with MVR	with MVR	
Total steam use $\dot{m}_s$	$\left[\frac{tons}{h}\right]$	22	11,1	12	14,2	**10**
Total steam saved $\dot{m}_{saved}$	$\left[\frac{tons}{h}\right]$	-	-	10	7,8	**12**
Total evaporated vapor $\dot{m}_v$	$\left[\frac{tons}{h}\right]$	16	11,9	16	16	16
Electricity use E_{el}	$[MW]$	0	1,08	**0,5**	**0,5**	0,82
Steam energy use E_{st}	$[MW]$	11,8	6,0	6,4	7,6	**5,4**
Specific steam use s	$\left[\frac{tons}{ton}\right]$	1,38	0,93	0,75	0,89	**0,63**
Specific steam energy use e_{st}	$\left[\frac{kWh}{ton}\right]$	737,5	504,2	400,0	475,0	**337,5**
Specific electricity use e_{el}	$\left[\frac{kWh}{ton}\right]$	-	90,8	**31,3**	**31,3**	51,3
Specific total energy use e	$\left[\frac{kWh}{ton}\right]$	737,5	595,0	431,3	506,3	**388,8**
Energy savings in EGA boilers	$[GWh]$	0	-	**35**	**35**	**35**
Energy savings in oil consumption	$[GWh]$	0	-	10	1,2	**18,5**
Total energy savings	$[GWh]$	0	-	45	36,2	**53,5**
Cost	$[MNOK]$	-	-	4,5	**Low**	17
Savings	$\left[\frac{MNOK}{yr}\right]$	-	-	19,5	18,1	**26,75**
Repayment time	$[moths]$	-	-	3	**<1**	8
Comments	$[-]$	Least energy efficient. Large energy recovery potential.	Better solution than at Glomfjord energy wise. Depends on heavy machinery.	Simple yet effective solution. Old solution can still be used.	Not possible to recouple to old solution.	Most expensive and energy efficient. Old solution can be used.

In Table 6-4 the best performance value is highlighted with bold font.

6.4 Recommended Actions

First of all it is inevitable to avoid recommendation of the use of multiple effects or MVR heat integration in the CN-evaporator system. All suggested solutions serve the purpose of retiring the EGA boilers, and hence a large portion of the project goal is achieved. The question is therefore no longer whether heat integration should be used but how.

6.4.1 Benchmark points

To recommend any action all the parameters from the benchmarking needs to be taken into account. One easy way of doing this is to give the different solution points for performance in every benchmark category. Underneath the best performer is given the value 3, second best is 2 and the poorest performer is given the value 1. The values are then added together to make up *a performance score* for the individual solution in Table 6-5:

Table 6-5: **Benchmark points.**

	Two-effect new design cascade	Two-effect cascade using old equipment	New design separate falling film MVR evaporator
Total steam use $\dot{m}_s$	2	1	3
Total steam saved $\dot{m}_{saved}$	2	1	3
Total evaporated vapor $\dot{m}_v$	3	3	3
Electricity use E_{el}	3	3	1
Steam energy use E_{st}	2	1	3
Specific steam use s	2	1	3
Specific steam energy use e_{st}	2	1	3
Specific electricity use e_{el}	3	3	1
Specific total energy use e	2	1	3
Energy savings in EGA boilers	3	3	3

Energy savings in oil consumption	2	1	3
Total energy savings	2	1	3
Cost	2	3	1
Savings	2	1	3
Repayment time	2	3	1
SUM	**34**	**27**	**37**

From the figures in this table it is clear that the two solutions that demands new evaporator equipment outperforms the re-build. On the basis of this and on the basis of the two-effect with old equipment having operational condition issues, this text *recommends the investment in new equipment.*

6.4.2 Oil savings

The important factor of investing in new equipment is not really the details of the solution but the larger context in which the evaporator equipment will be put. The benchmarking have been done on background of oil savings as just as important factor as EGA boilers retirement. The investment of switching from oil to steam as heating medium for air heating is therefore one of the most stressed future work assignments. However, this text arguments on the basis that air heating medium will be switched. In this case this text *recommends aiming for energy savings in both EGA boilers and in oil consumption*.

6.4.3 Sub atmospheric pressure

The sub atmospheric solution instead of compressed vapor is more energy efficient in cascade evaporation. In fact the energy need is about ~5kW (Evenmo, 2012) of operating a vacuum pump and extra pumping in the process. This number compares to the compressor work of about ~500kW. The electrical price can still be assumed 0,5NOK/kWh, which gives this compressor an operational cost of ~2MNOK annually (based on 342 production days).

The issue however, is how the liquor at a certain concentration behaves under low pressure. In theory the boiling is possible, but one never knows what scaling and fouling effects that appears under a certain condition. If the liquor operates good under submerged boiling pressure this text *recommends the use of sub atmospheric boiling* based on energy concerns and because of compressors being heavy equipment that is both expensive and demanding in form of maintenance.

6.4.4 Final recommendation

As an end result this text will recommend investment in new equipment under the following requirements:

- If investment in evaporator equipment is done simultaneously with investments or investigation of steam as air heating medium; this text recommends the investment in a *new independent MVR-evaporator*, that retires both EGA boilers and oil consumption completely
- If investment in evaporator is done without investigation of steam as air heating medium; this text recommends the investment of a *new two-effect cascade evaporator with submergence of boiling pressure** that retires the use of EGA boilers completely and gives room for large improvements in oil consumption in the future.

*This text recommends the use of submergence of boiling pressure in choice of a *new two-effect cascade evaporator*, if good test results of liquor at boiling temperature and pressure in interest is provided.

For a *new independent MVR-evaporator*, this text recommends falling film evaporator with mechanical vapor recompression, as suggested by Epcon Evaporation Technology AS.

7 General Discussion

7.1 What have been investigated?

The goal of this Master thesis has been to investigate energy savings by heat integration in the Yara Glomfjord compound fertilizer production plant. First a general mapping of energy flow in the factory was made for both high-, and low N/P and thereafter argumentation was made for investing in new equipment in the CN-evaporator system. The overall objective of this last year's project have been to save steam, and in doing so retiring the use of EGA boilers and oil consumption in the factory.

7.2 Results from Analysis

7.2.1 Energy flow analysis

From the energy flow analysis in chapter 4.3, the conclusion was made that the large energy streams in the Yara Glomfjord process are preserved as *latent heat*. This was done on the background of a general pinch analysis that led up to the *grand composite curve.* The grand composite curve is shown in Figure 4-8 and Figure 4-9 for high and low N/P, and it is evident that latent heat is of far greater interest than sensible heat.

An assumption for heat pumping of latent heat was also made, and at this time in the project it was concluded that a potential for heat pumping or mechanical vapor recompression exists. A rough estimate was made and COP was found to be ~6,8. For the new two-effect design suggested by this thesis the savings equals the duty of the first effect and the COP can be calculated as savings divided by compressor work. The actual COP is found to be:

$$COP = \frac{\dot{Q}_{unit}}{W_c}$$

Equation 7-1

$$COP = 10{,}76$$

Result 7-1

COP is higher than first assumed because it is applied on the first effect and not on the whole unit as in the estimate. Hence, the temperature lift is lower and the COP is higher.

The data gathered in chapter 4.3.1 is the first real mapping of energy flow at the Yara Glomfjord production facility and is therefore of interest for the future, and of value for the factory.

7.2.2 CN-evaporator system design

The next analytical step of this text is the suggested designs improvements in the CN-evaporation system. The intention was here to address the largest potential for integration of latent heat, which was found to be the CN-evaporators.

It has been stated that heat integration of latent heat in the CN-evaporator system has a huge energy savings potential. Remembering Anon's effect formula, see Table 5-2, one extra effect will improve the total evaporator system efficiency with 50%:

$$Savings = \left[1 - \left(\frac{N}{N+n}\right)\right] 100\% \qquad \text{Equation 7-2}$$

$$N \sim effects$$
$$n \sim additional\ effects \qquad \text{Result 7-2}$$

$$Savings = 50\%$$

The two recommended solutions from chapter 6.4.4 save between 10-12tons/h steam out of a previous steam use of 22tons/h, Anon's suggestion therefore holds.

7.3 The New Steam Balance

In the suggestions given in this text the goal of retiring EGA boilers have been successful, and to some extent the retirement of oil, based on which suggestion to choose. The energy balance of the factory for low N/P was given in Figure 3-3. This text will here redo the figure for suggested improvements. By using 11tons/h of live steam savings, slightly more than *new two-effect* and slightly less than *new independent MVR*, the new steam balance is given in Figure 7-1:

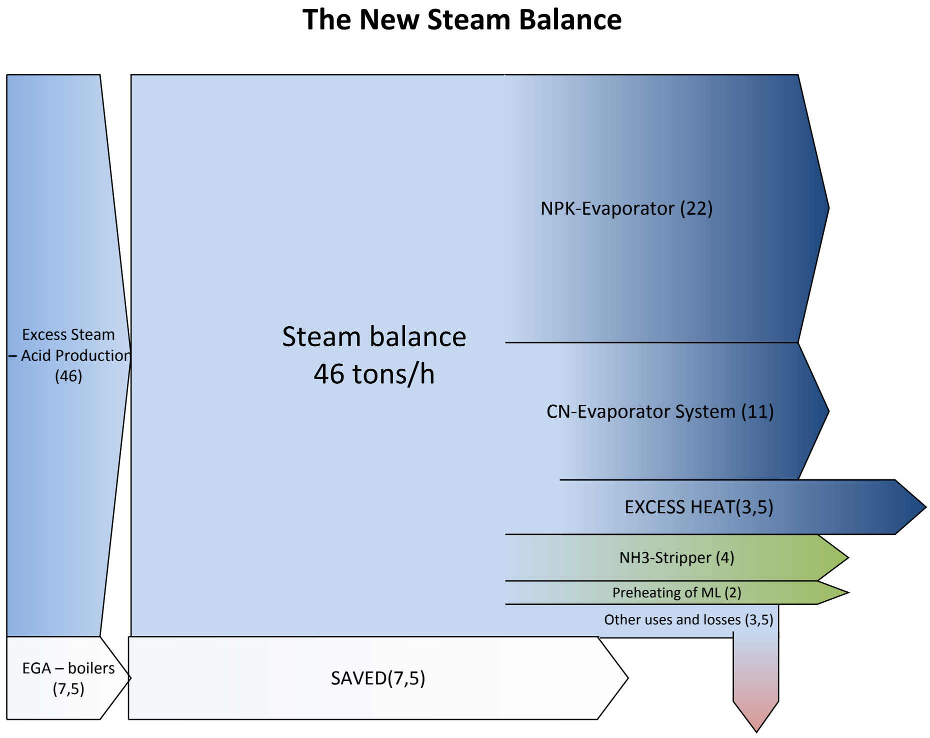


Figure 7-1: The Yara Glomfjord low N/P steam balance after modification.

In gray the figure shows the significance of the old EGA boiler use at low N/P. It is also notable that a new arrow marked excess heat has appeared. This heat is now free to use for other heating tasks in the factory e.g. retirement of oil consumption.

7.4 What have been done at Yara Glomfjord

It is an important fact that this thesis is written in collaboration with Yara Glomfjord. The engineering staff at the factory is working with the issues discussed here on a daily basis. While this thesis have been written, Yara Glomfjord have kept an ongoing dialog with Epcon Evaporation Technology AS, and a pilot test of new evaporator equipment was held in the Epcon testing facilities in Trondheim in May 2012.

The striking results are no scaling and fouling under submergence of boiling temperature for the relevant concentration in a simulated first effect evaporation step. *This strongly supports the recommendations of this master thesis and the way towards investment in a new two-effect evaporator at Yara Glomfjord.* The situation is presently a very good project for Yara that is up for evaluation for economic support, *and will very likely be initiated*.

8 General Conclusion

Historically Norwegian land based industry is one of the most energy intensive in the world, much because of the seemingly unlimited hydro power resources at low cost. But in later years, in the face of environmental issues and high electrical price, the industry is starting to adapt. With the presence of expensive energy, utilizing energy recovery and heat integration options becomes part of the agenda. Yara Glomfjord is part of this equation, and has worked specifically with energy savings through several Enova projects (Høvset, 2011) and others (Ingebrigtsen, 2011). Since 2001 the electric power consumption per ton product have declined by 35 % at Yara Glomfjord (Holst, 2008), but there is still a large potential for energy recovery, and the key might very well lie in the evaporation equipment. The bottom line conclusion of the *Energy Analysis of Evaporation System in Fertilizer Production* is at this point very simple:

From the energy flow analysis it is evident that the *latent heat* is of far greater importance than *sensible heat* in heat integration tasks at the Yara Glomfjord production site. This text therefore concludes that the best path ahead is to consider energy recovery of latent heat.

In addressing this task *the evaporator equipment for CN-evaporation* is found to have a huge potential, in magnitude 50% energy recovery potential of latent heat.

The technologies *mechanical vapor recompression* and *cascade evaporation with submergence of boiling pressure* are both found possible for the relevant concentration. For a cascade solution submergence of boiling pressure is preferred to avoid the need for a compressor. This text therefore recommends investment in new equipment.

All recommendation in this text is found to retire the EGA boilers completely. The economic savings drown up for the EGA boilers are found to be: *17,5MNOK annually*. In doing recommended improvements excess heat is also gained, which can be utilized to retire some or all of the oil consumption in the factory. These savings are found to be up to: *9,25MNOK annually*. All investments are found to have down payment time of less than one year.

This text finally concludes that with doing recommended investments huge energy savings can be achieved at reasonable cost and at a manageable technical level.

9 Further Work

9.1 Further Heat Integration

The most important task for future is the task of preheating the feed for the CN-evaporator, as it is presented in CN-Evaporator System Design, A.9.6. The way in which this is solved is somewhat irrelevant, but the issues needs to be addressed in order to apply the solutions recommended in this text. The first thing that comes to mind is the energy flows in the evaporator system which are still not integrated, e.g. the two solutions recommended by this text only heat integrate the latent heat leaving one effect. That means the vapor from the other effect is still available for heat integration and should be a task for future improvement.

9.2 Switching from Oil to Steam

The second most important task for the future found in this thesis is to do proper analytical work and investigations of the air heating. With all the free live steam from the current project it is possible to reduce the total oil consumption as well, but to do so more detailed investigations needs to be done. This text recognizes this task as the most economic beneficial work for the future.

9.3 Improvements at Yara Porsgrunn

Yara Porsgrunn utilizes a huge compressor at 4,3MW in order to recompress vapor in the evaporator system. The late findings of the collaboration between this Master thesis writing, Yara Glomfjord and Epcon Evaporation Technology AS states that the same process can be done with submergence of boiling pressure instead of vapor recompression. Hence both energy benefit from using vacuum pumps instead of a compressor and the benefit of not having large compressor equipment that demands maintenance can be achieved.

The Yara Porsgrunn process is also characterized by several small improvements over the years and would have great use of some simplification. The potential energy wise seems to be in the same magnitude as at Yara Glomfjord, but financially steam savings is not so important at Yara Porsgrunn due to a steam surplus fact and no EGA boilers. Retiring the compressor at the other hand, is large economical savings in the order of ~17,2MNOK annually, with an electrical price of 0,5NOK/kWh and 8000 operational hours a year.

10 References

Anon. 1977. *Upgrading Existing Evaporators to Reduce Energy Consumption.* s.l. : ERDA, U.S. Dept. of Commerce, 1977.

Billet, Reinhard. 1989. *Evaporation Technology.* Weinheim : VCH, 1989.

Bolland, Olav. 1999. *Inndampingsteknikk.* Trondheim : Institutt for termisk energi og vannkraft - NTNU, 1999.

Chen, Chin Shu and Hernandez, Ernesto. 1997. Design and Performance Evaluation of Evaporation. *Handbook of Food Engineering Practice.* 1997.

Ebrahim, Al-Kawari Mubarak. 1999. Pinch technology: an efficient tool for chemical-plant energy and capital-cost saving. *Applied Energy.* 1999.

Enova. 2009. *Potensial for energieffektivisering i norsk industri.* s.l. : Enova, 2009.

Evenmo, Kjetil. 2012. *Meeting and telphone conversations with Epcon Evaporation Technology AS.* Trondheim, March-June 2012.

Gundersen, Truls. 2002. *A Process Integration Primer.* Trondheim : International Energy Agency, SINTEF Energy Research, 2002.

Holst, Anders. 2008. Yara Porsgrunn med enormt potensiale. s.l. : Enova, 2008.

Høvset, Morten. 2012. *Guesswork on numbers in process at Yara Glomfjord.* 2012.

—. 2011. *Sluttrapport ENOVA avtale SID 07/228.* Glomfjord : Yara Glomfjord, 2011.

Ingebrigtsen, Vegard Byre. 2012. *Energy Analysis of Evaporator System in Fertilizer Production.* Trondheim : EPT, 2012.

—. 2011. *System Modeling and Energy Recovery in Fertilizer Production.* Depertment of Energy, Process and Fluids Engineering, NTNU. Trondheim : EPT, 2011.

Jordal, Arve. 2005. *Prosessbeskrivelse for fremstilling av Fullgjødsel og kalksalpeter.* Glomfjord : Yara Glomfjord, 2005.

Moran, Michael J. and Shapiro, Howard N. 2004. *Fundamentals of Engineering Thermodynamics 5th.edition.* s.l. : John Wiley Sons, Inc., 2004.

Sollesnes, Geir and Valjord, Ronny. 2001. *Energiledelse Fase 1, Hydro Agri Glomfjord.* s.l. : Norsk Energi, 2001.

Steen, J., Aasum, Erik H. and Heggeboe, Trygve. 1987. The Norsk Hydro Nitropohsphate Process. [ed.] Francis T. Nielsson. *Manual of Fertilizer Processing.* New York : Marcel Dekker, 1987, Vol. 5.

Torgersen, Bjarne. 2003. *Energi/Dampbalanse.* Glomfjord : Yara Glomfjord, 2003.

Yara. 2011. *Process Records.* Glomfjord : Yara Glomfjord , 2011.

Appendix A: CN-Evaporator System Design

This chapter is the property of Yara Glomfjord. The chapter is confidential and removed from the main document. Interested parties are supplied a copy.

Appendix B: Draft Paper

Energy Analysis of Evaporator System in Fertilizer Production

Draft Paper

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Department of Energy and Process, Norwegian University of Science and Technology, 2012

Abstract

The energy situation at Yara Glomfjord has been analyzed in order to prepare for decision making in equipment investment. Present situation is troubled energy wise at 75% of operational time, with a general lack of steam. This text suggests investment in evaporator equipment in order to integrate latent heat so that the overall steam consumption goes down and the general steam lack is retired. The most proving suggestions are new equipment coupled in cascade with old evaporators or a new independent MVR evaporator in front of old solution. Both suggestions are found to end steam problems. This paper is based on Master thesis: Energy Analysis of Evaporator System in Fertilizer Production (Ingebrigtsen, 2012).Introduction

Introduction

Yara Glomfjord is the north most compound fertilizer production facility in the world and is located at Glomfjord, approximately two hours outside Bodø. Total production rate is annually approximately 500 000 tons NPK and 200 000 tons CN (2002). 60% of all fertilizer produced is sold in the Norwegian market (Jordal, 2005).

In 2006 the power production in Glomfjord funded by Norsk Hydro fell under the Norwegian Reversion Act. This Act state that non-governmentally initiated hydro power licenses are to be overtaken by the state after 60 years[8]. Since Yara do not produce electricity anymore, it has to be bought of the market. The process is originally designed after the cheap electricity, and hence large heat integration tasks are possible.

Yara Glomfjord has today a general lack of steam 75% of operational time. However, the factory also has large amounts of excess heat, mainly present as process steam and hot condensate. Due to the steam issues and the rise of electric power cost, Yara Glomfjord administration wants to look into heat integration options for the plant.

[8] http://www.eu-norge.org/Aktuelt/Nyhetsartikler/fakta_om_hjemfall/

The task of energy recovery at Yara Glomfjord has therefore been taken on in a few projects lately. The work that needs to be mentioned is an internal energy report by factory engineers (Torgersen, 2003), Enova energy projects (Høvset, 2011) and system modeling and energy recovery (Ingebrigtsen, 2011) .The master thesis which is the basis of this paper takes on the task of energy analysis in order to do improvements in the CN-evaporator system (Ingebrigtsen, 2012).

Energy use and savings potential

Steam balance

The energy system of the Yara Glomfjord production is designed with steam as the main energy carrier. Steam is generated as excess heat in the factory, mainly from burning ammonia to make nitric acid for the process.

The heating tasks vary with product type, but have its extremity at 75% of operational time and extra steam is produced in EGA boilers. The steam balance for troubled operational condition is shown in Figure 2.

Descriptions of the energy system and its potential for improvement are given in an internal energy report (Torgersen, 2003) and in the master thesis that this paper is based on (Ingebrigtsen, 2012).

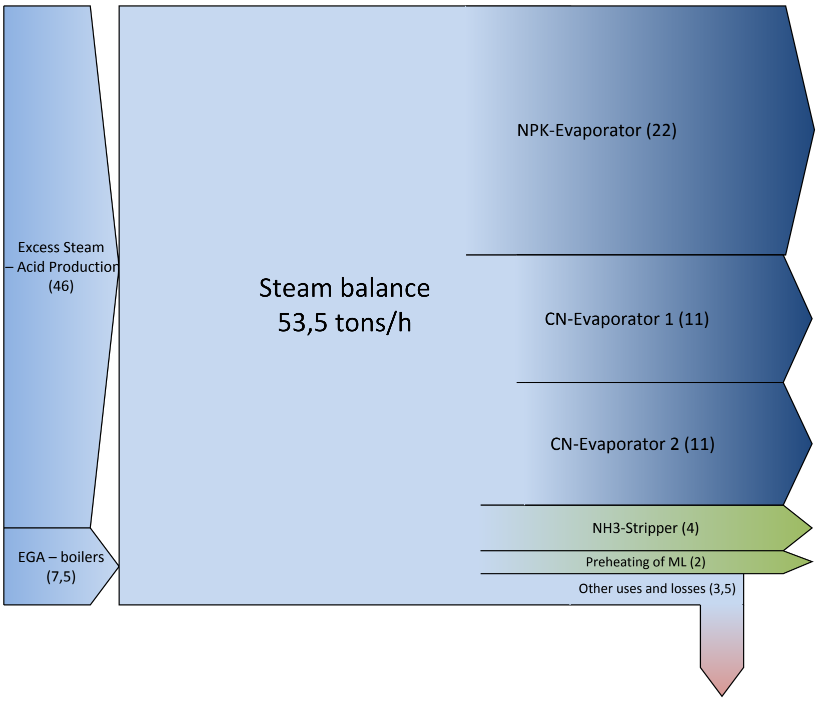

Figure 2: Steam balance for troubled operation scenarios at Yara Glomfjord **(Ingebrigtsen, 2012)**.

Figure 2 shows that the use of EGA boilers are necessary in order to cope with the factory steam needs at troubled conditions. At these conditions 7,5tons/h of live 16bar steam is produced in the EGA boilers. Also notable from the figure is that the evaporators are the largest steam consumers in the factory and both CN-evaporators at the factory are in use. At non troubled operation conditions only one is used.

Energy economics

The energy tradition at Yara Glomfjord is highly dominated by two things. The first is the onsite production of Nitric acid that gives the plant an energy surplus for some compositions. This again results in little interest in energy savings, when the energy consumed is free. The second influence is that of the electricity price. For Yara Glomfjord who used to own a hydro power plant, electricity has traditionally been cheap. However, savings today will directly reduce the EGA boilers steam production for 75% of the operational time, and with the present electricity rates a considerable amount of money. Because of these facts energy savings as an area of interest has become more interesting for Yara Glomfjord.

To meet this problem with the right perspective the economic foundation needs to be drawn out. The power consumption of the boilers is known, and is recognized by this text to be 35GWh annually. With the present electrical price at about 0,5NOK/kWh this energy costs is:

$$35GWh * 0,5NOK/kWh$$

$$= \mathbf{17,5}\boldsymbol{MNOK}$$

Hence, steam savings of 7,5tons/h in 75% of operational time, will permanently end the need of the EGA boilers and save the factory 17,5MNOK annually.

Factory energy flow

From doing an energy flow analysis of the factory it is clear that the large amount of excess heat is *latent* at a relatively low temperature (Ingebrigtsen, 2012). To see the potential for heat integration with vapor recompression a rough estimate is done on mechanical recompression for the CN-evaporators.

Mechanical vapor recompression is a type of heat pump. It is thought to move the surplus energy from low temperature to high temperature like it is presented in Figure 3:

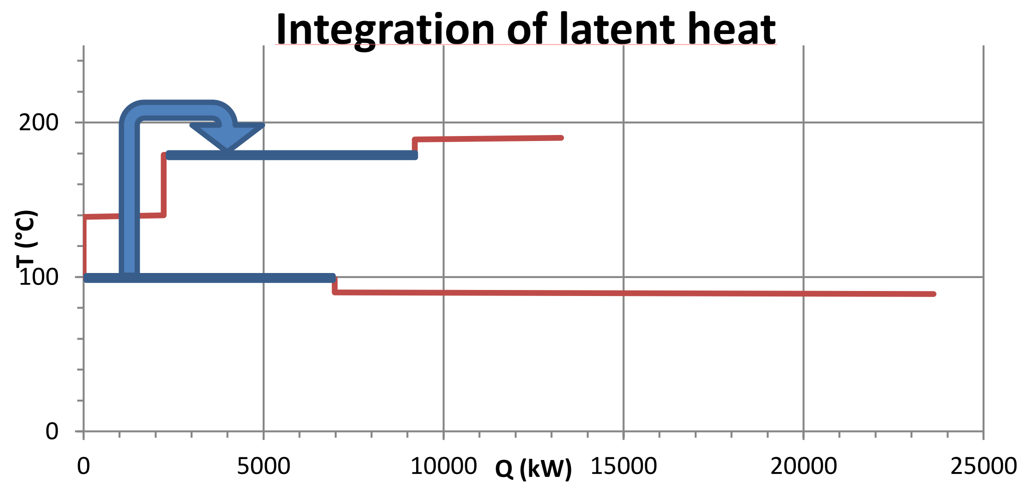

Figure 3: Vapor recompression of latent heat **(Ingebrigtsen, 2012)**.

Figure 3 is really the result of the energy flow analysis (*the grand composite curve*), and shows the latent heat flow of the factory (Ingebrigtsen, 2012).The rough estimate will here be made assuming the heat pump of interest to be ideal according to the Carnot equations. The effect factor as expressed by the Carnot equations is given in literature (Moran, et al., 2004):

$$COP = \frac{T_H}{T_H - T_C}$$

To do this simplified calculation it is also assumed that the vapor from the CN-liquor is gathered right after evaporation, as superheated steam at 170°C. Target temperature of live steam is at 16bar steam and 205°C. This leaves this estimate for COP:

$$COP = \frac{478}{478 - 443} = 13{,}66$$

A proper Carnot efficiency is η~50%, which leaves the COP~6,8. This number states that the work input pays off 6,8 times, according to the assumptions above.

Suggested improvements

Energy conservation and vapor recompression

Evaporators are heavy equipment that consumes a lot of energy. At Yara Glomfjord about ~80% of the available steam is consumed in the evaporators, as it is shown in the steam balance, Figure 2. And at these high levels of energy consumption, steam is being generated by EGA boilers. According to calculations 1,3 ton/h saved steam consumption corresponds to ~1MW in electricity savings (Torgersen, 2003). The steam used in boilers translates to 35GWh annually.

The vapor exiting the evaporators contains significant heating value as latent heat of vaporization. This energy can be recovered by heat-recovery techniques, i.e., *multiple effect operation, reheating* between effects and by *recompression of vapor.* There are also other methods of a simpler character such as *preheating of feed, heat integration of condensate, improved maintenance and insulation etc.*

The typical energy savings by various methods are suggested by Anon in Table 1 (Chen, et al., 1997):

Table 1: Energy savings by various methods in evaporation

Typical Energy Savings by Various Methods

Method	Capital requirement	Achievable energy savings (%)
Venting and thermal insulation	Low	5
Improved maintenance	Low	5
Heat-recovery exchangers	Low	10
Condensate reuse	Low	5
Thermal recompression	Medium	45
Mechanical recompression	High	70–90
Additional effects	High	$\left[1-\left(\frac{N}{N+n}\right)\right]100\%$

Note: N = original number of effects; n = number of added effects.

Example: The savings for increasing a three-effect evaporator to four effects is equal to $\left[1-\left(\frac{3}{3+1}\right)\right]$ 100% = 25%, approximately.

From Anon. (1977).

Economic effect of Energy Savings

It is very important to have the complete economic perspective when dealing with energy savings. Both investment cost and operation cost needs to be accounted for to make a decision. Many existing systems are designed with minimal capital cost during a time with low energy cost. As a result of higher electric prices, considerable economic benefits can be made with retrofit design of evaporators. This means new investments can be made, and balanced with energy savings and todays energy prices. Literature (Chen, et al., 1997) gives these general subcategories of modifying existing evaporators with respect to cost:

Fine tuning existing evaporators: This category is considered low on capital requirement and also low energy savings potential. It consists of improvement of existing equipment i.e. venting and insulation, but also improved maintenance.

Modifying auxiliary hardware: This category is considered medium on capital investment and saving potential. It consists of heat exchanger for preheating of feed, heating between effects and reuse of condense.

Major hardware modifications: This category is considered high on capital requirement and also high energy savings potential, i.e. mechanical vapor recompression and additional effects.

It is noted that there is a general trend between investment and energy savings (see

Table 1) Energy saving in this case can be read as reduction in operational cost, and needs to be balanced against investment cost and the cost of downtime.

Original solution

In the present solution at Yara Glomfjord the evaporation of CN is done mostly in one evaporation step. The feed is preheated but the total energy efficiency of the evaporator system is very low. A sketch of the present flow schematics is presented in Figure 4:

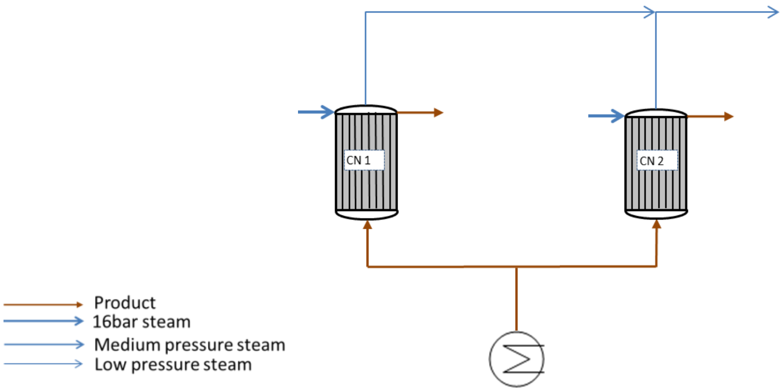

Figure 4: Original solution **(Ingebrigtsen, 2012)**.

Suggested new solutions

With the means from chapter Evaporator Design and the analytics of appendix: CN-Evaporator System Design, three suggestions of improvement are given (Ingebrigtsen, 2012). The three suggestions of improvement and their performance are presented here:

New two effect cascade evaporator

The first suggestion is to design a new evaporator which is to be integrated in a cascade system with the existing equipment. In doing so the new unit should use vapor from the existing equipment with recompression as the energy source. This means that the technology *cascade* and *vapor recompression* is both utilized. The schematics of this suggestion are given in Figure 5:

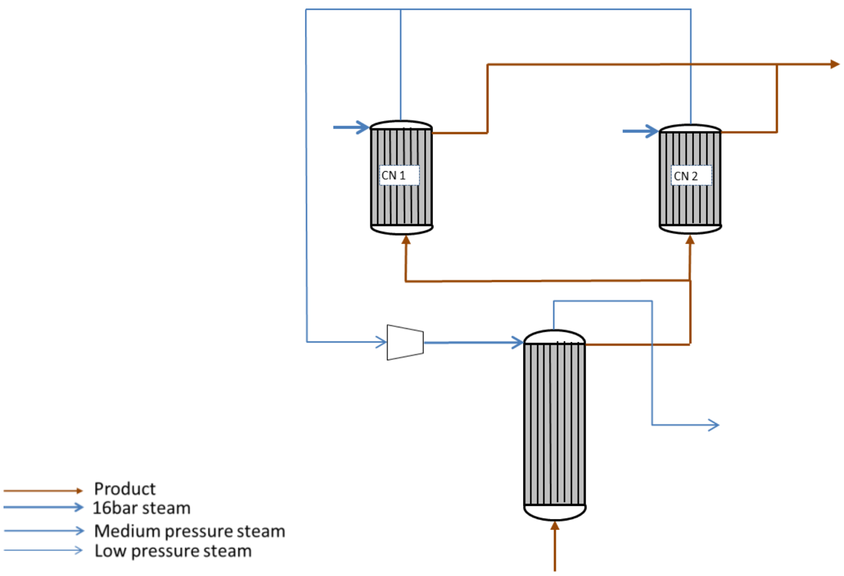

Figure 5: New two effect cascade evaporator with recompression **(Ingebrigtsen, 2012)**.

This solution is rather simple and demands only a slight recompression of vapor, since the vapor comes from higher pressure evaporation in the second effect. The new equipment needed is a long tubed evaporator in advance of the existing equipment, piping and valves etc.

The large benefits of this solution are the energy savings possible, despite a rather simple solution with low recompression. If decoupled, the "old solution" can also still be used. This is a great advantage in a worst case scenario with problems in the startup of the new equipment. Because of the possibility to switch back when facing problems, downtime is avoided. Decoupling might also be an advantage in cleaning of the first effect, and also here avoid downtime.

On the other hand there are a few disadvantages as well. First up, this system is designed in such a way that the energy leaving the second effect is the energy supply of the first effect. Hence, this unit can only operate up to a certain level and produce a maximum concentration out of first effect. This again means that a certain level of energy is saved, and more is not possible. The vapor leaving the first effect is also not integrated and might be a good topic for further work.

The performance of this suggestion is based on analytical work in master thesis (Ingebrigtsen, 2012) and given in Table 2:

Table 2: **Two-effect new design cascade evaporator performance** (Ingebrigtsen, 2012)**.**

Total steam use	Electricity use	Evaporated mass	Steam savings	Energy savings in EGA boilers	
$\left[\frac{tons}{h}\right]$	$[MW]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$[GWh]$
12	0,5	16	10	7,5	35

In Table 2 it is notable that all the energy need originated from the EGA boilers are saved, and also a large amount of excess heat is freed.

Two effects cascade evaporator using old equipment

The second suggestion is closely related to the previous. The idea is the same, but in solving this task it is suggested to re-build the two existing evaporators in cascade such that the last effect supplies the first with energy. The technology utilized is still *two-effect cascade* and *vapor recompression*. The schematics are given in Figure 6:

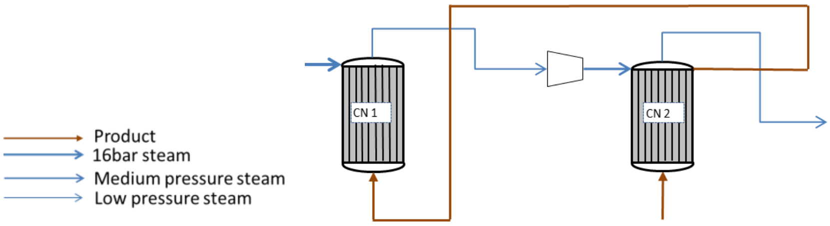

Figure 6: Two effects cascade evaporator using old equipment **(Ingebrigtsen, 2012)**.

This solution is the simplest possibility with all original equipment and re-piping. Hence, the re-build also has a low cost, despite rather large savings.

The weakness however is the flexibility. Taking one unit out of production means downtime in the whole CN-production line. Also, compared to the previous solution, a new design two effect will perform better energy wise. The performance based on analytics from appendix: CN-Evaporator System Design is given in Table 3:

Table 3: **Two-effect new design cascade evaporator performance** (Ingebrigtsen, 2012)**.**

Total steam use	Electricity use	Evaporated mass	Steam savings	Energy savings in EGA boilers	
$\left[\frac{tons}{h}\right]$	$[MW]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$[GWh]$
14,2	0,5	16	7,8	7,5	35

In Table 3 it is made clear that also here EGA boilers are retired. However, this solution only generates a small portion of excess heat which is almost negligible.

New MVR evaporator

The last suggestion is also related to the previous ones. The idea is to place a mechanical vapor recompression new-design evaporator in front of the existing equipment to remove enough water previous to the original process to retire boilers and use of oil. Existing equipment would maintain the boiling at the highest temperature. The MVR itself is self-sufficient with energy with only a small amount of live steam for startups and compressor work. This solution is related to previous ones with *vapor recompression* technology but this solution is not coupled in *cascade.* The schematics are given in Figure 7:

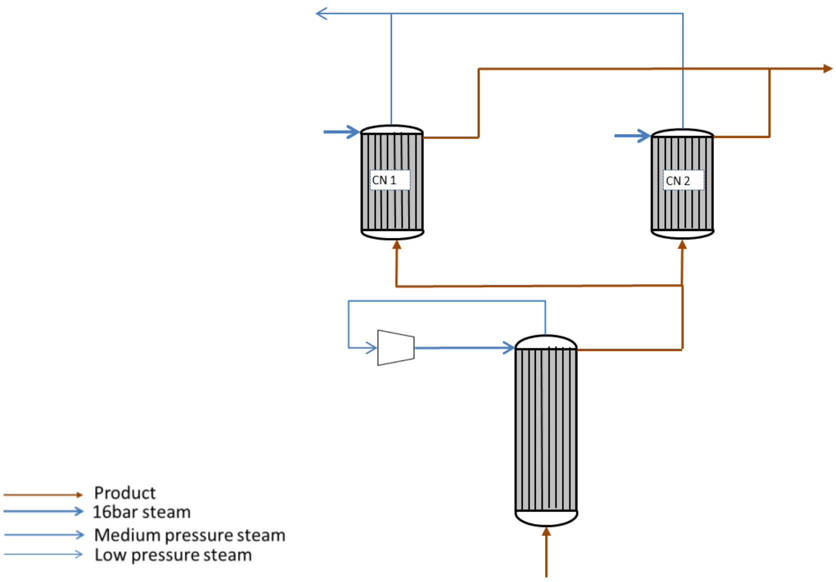

Figure 7: New MVR self-sufficient evaporator **(Ingebrigtsen, 2012)**.

This is the most complex new design with a new unit separate to the existing system. The new unit is also self-integrated with recompressed vapor and is therefore self-sufficient with energy.

The larges benefit is the design point witch can be made to be precisely the energy savings that needs to be done in order to retire both electrical consumption in boilers, and free precisely as much excess heat needed for other tasks. As option one this solution is robust in case of downtime, with the ability to switch back to the old solution.

On the other hand this is the most expensive solution. All extra piping and equipment to make this a self-sufficient unit is costly, but in the light of the savings possible with this solution they might as well be worth it.

The performance based on Epcon solution in master thesis (Ingebrigtsen, 2012) is shown in Table 4:

Table 4: **New MVR evaporator performance (Ingebrigtsen, 2012).**

Total steam use	Electricity use	Evaporated mass	Steam savings	Energy savings in EGA boilers	
$\left[\frac{tons}{h}\right]$	$[MW]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$\left[\frac{tons}{h}\right]$	$[GWh]$
10	0,9	16	12	7,5	35

Benchmark and recommendations

Performance Calculation and benchmark

In order to do the best decision making the analytical data from the different suggestions needs to be evaluated and measured against cost. Master thesis provides these definitions and benchmark parameters (Ingebrigtsen, 2012):

Definitions:

The values included in the performance parameters are the following:

$$\dot{\boldsymbol{m}}_{\boldsymbol{s}} \sim steam\ use\ [tons/h]$$

Definitions

$$\dot{\boldsymbol{m}}_{\boldsymbol{v}} \sim evaporated\ vapor$$

$$[tons/h]$$

$$\boldsymbol{E}_{\boldsymbol{el}} \sim electricity\ use\ [MW]$$

$$\boldsymbol{E}_{\boldsymbol{st}} = \dot{m}_s * h_{fg_{16bar}}$$

$$\sim energy\ content\ of\ steam\ u$$

$$\boldsymbol{E} \sim total\ energy\ use\ [MW]$$

Steam use and performance

First up is how much steam a selected solution will save. This is given by the energy transfer in the unit, made possible by compressor work and *latent heat* from either the unit itself (FFE-MVR) or the next effect. This energy is integrated in the system and need not be supplied by live steam. Hence the *steam savings* is given by the unit duty:

$$\dot{m}_{saved} = \frac{\dot{Q}_{unit}}{h_{fg_{16bar}}} [tons/h]$$

The total steam consumption is the consumption of the existing evaporator system minus the savings.

$$\dot{m}_s = (22 - \dot{m}_{saved\ steam})$$

$$[tons/h]$$

The complete evaporator system for CN-evaporation is designed to evaporate a given amount of water, calculated earlier in this text, in order to maintain a certain concentration out of the system. The mass of evaporated vapor is known to be:

$$\dot{m}_v = 16tons/h$$

The energy that follows the steam use is identified by this text as E_{st}. Steam use is here defined as total mass flow of live steam to the whole CN-evaporation system identified m_s.

$$E_{st} = m_s * h_{fg_{16bar}}\ [MW]$$

Specific steam energy use is a performance parameter defined to be the energy content of the steam use divided by mass flow of evaporated vapor. The specific steam energy use is given in tons steam per ton evaporated vapor, and is identified e_{st}:

$$e_{st} = \frac{E_{st}}{\dot{m}_v} \left[\frac{kWh}{ton}\right]$$

Next performance parameter is the *specific steam use,* defined as the use of live steam divided by evaporated vapor mass in tons per ton:

$$s = \frac{\dot{m}_s}{\dot{m}_v} \left[\frac{tons}{ton}\right]$$

Electricity use and energy performance

The electrical input to the process equals the compressor work. The performance parameter is here called *specific electrical energy use* and is the net input of work on the compressor divided by evaporated mass:

$$e_{el} = \frac{E_{el}}{\dot{m}_v} = \frac{W_c}{\dot{m}_v} \left[\frac{kWh}{ton}\right]$$

To make a figure of the complete energy use of the system both steam and electrical energy is needed. The performance parameter *specific energy use* is defined by this text as the total energy input in form of steam E_{st} and compressor work W_c, divided by evaporated vapor mass. The specific energy use is in kWh per ton evaporated vapor, identified *e*:

$$e = \frac{E}{\dot{m}_v} = \frac{E_{st} + W_c}{\dot{m}_v} \left[\frac{kWh}{ton}\right]$$

$$e = e_{st} + e_{el} \left[\frac{kWh}{ton}\right]$$

Benchmark parameters

The benchmark parameters are gathered in Table 5. The table is also added some details concerning price, technology and additional comments. In this way Table 5 has distinctive value for the reader.

Performance of existing systems at Yara Glomfjord and Yara Porsgrunn are also added in order to benchmark new parameters against existing solutions.

Table 5: **The benchmark parameters** (Ingebrigtsen, 2012).

		Yara Glomfjord existing system	Two-effect new design cascade	Two-effect cascade using old equipment	New design separate falling film MVR evaporator
Technology		Short tube evaporator with preheating of feed	Long tube evaporator in cascade with MVR	Short tube evaporators in cascade with MVR	Separate FFE with MVR
Total steam use $\dot{m}_s$	$\left[\frac{tons}{h}\right]$	22	12	14,2	**10**
Total steam saved $\dot{m}_{saved}$	$\left[\frac{tons}{h}\right]$	-	10	7,8	**12**
Total evaporated vapor $\dot{m}_v$	$\left[\frac{tons}{h}\right]$	16	16	16	16
Electricity use E_{el}	$[MW]$	0	**0,5**	**0,5**	0,82

Steam energy use E_{st}	$[MW]$	11,8	6,4	7,6	**5,4**
Specific steam use s	$\left[\frac{tons}{ton}\right]$	1,38	0,75	0,89	**0,63**
Specific steam energy use e_{st}	$\left[\frac{kWh}{ton}\right]$	737,5	400	475	**337,5**
Specific electricity use e_{el}	$\left[\frac{kWh}{ton}\right]$	-	**31,3**	**31,3**	51,3
Specific total energy use e	$\left[\frac{kWh}{ton}\right]$	737,5	431,3	506,3	**388,8**
Energy savings in EGA boilers	$[GWh]$	0	**35**	**35**	**35**
Excess heat	$\left[\frac{tons}{h}\right]$	0	2,5	0,3	**4,5**
Total energy savings	$[GWh]$	0	45,0	36,2	**53,5**
Cost	$[-]$	-	Medium	**Low**	High
Savings	$[-]$	-	Medium	Low	**High**
Repayment time	$[-]$	-	Medium	**Low**	High
Comments		Least energy efficient. Large energy recovery potential.	Simple yet effective solution. Old solution can still be used.	Not possible to recouple to old solution.	Most expensive and energy efficient. Old solution can be used.

Recommended Actions

First of all it is inevitable to avoid recommendation of the use of MVR and heat integration in the CN-evaporator system. All suggested solutions serve the purpose of retiring the EGA boilers, and hence a large portion of the project goal is achieved. The question is therefore no longer whether MVR should be used but how.

Benchmark points

To recommend any action all the parameters from the benchmarking needs to be taken into account. One easy way of doing this is to give the different solution points for performance in every benchmark category. Underneath the best performer is given the value 3, second best is 2 and the poorest performer is given the value 1. The values are then added together to make up *a performance score* for the individual solution in Table 6:

Table 6: **Benchmark points**.

	Two-effect new design cascade	Two-effect cascade using old equipment	New design separate falling film MVR evaporator
Total steam use $\dot{m}_s$	2	1	3
Total steam saved $\dot{m}_{saved}$	2	1	3
Total evaporated vapor $\dot{m}_v$	3	3	3
Electricity use E_{el}	3	3	1
Steam energy use E_{st}	2	1	3
Specific steam use s	2	1	3
Specific steam energy use e_{st}	2	1	3
Specific electricity use e_{el}	3	3	1
Specific total energy use e	2	1	3
Energy savings in EGA boilers	3	3	3
Energy savings in oil consumption	2	1	3
Total energy savings	2	1	3
Cost	2	3	1
Savings	2	1	3
Repayment time	2	3	1
SUM	**34**	**27**	**37**

From the figures in this table it is clear that the two solutions that demands new evaporator equipment outperforms the re-build. On the basis of this and on the basis of the two-effect with old equipment having operational condition issues, this text *recommends the investment in new equipment.*

Oil savings

The important factor of investing in new equipment is not really the details of the solution but the larger context in which the evaporator equipment will be put. The benchmarking has been done on background of generating excess heat. At Yara Glomfjord excess heat is needed to do heating task presently done with oil, and hence very valuable. The investment of switching from oil to steam as heating medium is therefore one of the most stressed future work assignments. This text argues on the basis that heating medium will be switched. In this case this text *recommends aiming for energy savings in both EGA boilers and in oil consumption*.

Sub atmospheric pressure

The sub atmospheric solution instead of compressed vapor is more energy efficient in cascade evaporation. In fact the energy need is about ~5kW (Evenmo, 2012) of operating a vacuum pump and extra pumping in the process. This number compares to the compressor work of about ~500kW.

The issue however, is how the liquor at a certain concentration behaves under low pressure. In theory the boiling is possible, but one never knows what scaling and fouling effects that appears under a certain condition. If the liquor operates good under submerged boiling pressure this text *recommends the use sub atmospheric boiling* based on energy concerns and because of compressors being heavy equipment that is both expensive and demanding in form of maintenance.

Final recommendation

As an end result this text will recommend investment in new equipment under the following requirements:

- If investment in evaporator equipment is done simultaneously with investments or investigation of oil replacement with steam; this text recommends the investment in a *new independent MVR-evaporator*, that retires both EGA boilers and oil consumption completely
- If investment in evaporator is done without investigation of oil replacement with steam; this text recommends the investment of a *new two-effect cascade evaporator with submergence of boiling pressure** that retires the use of EGA boilers completely and gives large amounts of excess heat for utilization in the future.

*This text recommends the use of submergence of boiling pressure in choice of a *new two-effect cascade evaporator*, if good test results of feed at boiling temperature and pressure in interest is provided.

Discussion

Results from Analysis

Energy flow analysis

From the energy flow analysis the conclusion was made that the large energy streams in the Yara Glomfjord process are preserved as *latent heat* (Ingebrigtsen, 2012).

An assumption for heat pumping of latent heat was also made, and at this part of the project it was concluded that a potential for heat pumping or mechanical vapor recompression exists. A rough estimate was made and COP was found to be ~6,8. For the new two effect design the COP is found to be (Ingebrigtsen, 2012):

$$COP = 10{,}76$$

COP is higher than first assumed because it is applied on the first effect and not on the whole unit as in the estimate, because of lower temperature lift than first assumed.

CN-evaporator system design

The next analytical step is the suggested designs improvements in the CN-evaporation system. The intention was here to address the largest potential for integration of latent heat, which was found to be the CN-evaporators.

It has been stated that heat integration of latent heat in the CN-evaporator system has a huge energy savings potential. Remembering Anon's effect formula, one extra effect will improve the total evaporator system with 50%:

$$Savings = \left[1 - \left(\frac{N}{N+n}\right)\right] 100\%$$

$$N \sim effects$$

$$n \sim additional\ effects$$

$$Savings = 50\%$$

The two recommended solutions save between 10-12tons/h steam out of a previous steam use of 22tons/h, Anon's suggestion therefore holds.

The New Steam Balance

In the suggestions given in this text the goal of retiring EGA boilers have been successful, and to some extent the retirement of oil, based on which suggestion to choose. The energy balance of the factory for troubled conditions was given in Figure 2. This text will here redo the figure for suggested improvements. By using 11tons/h of live steam savings, slightly more than *new two-effect* and slightly less than *new independent MVR*, the steam balance is given in Figure 8:

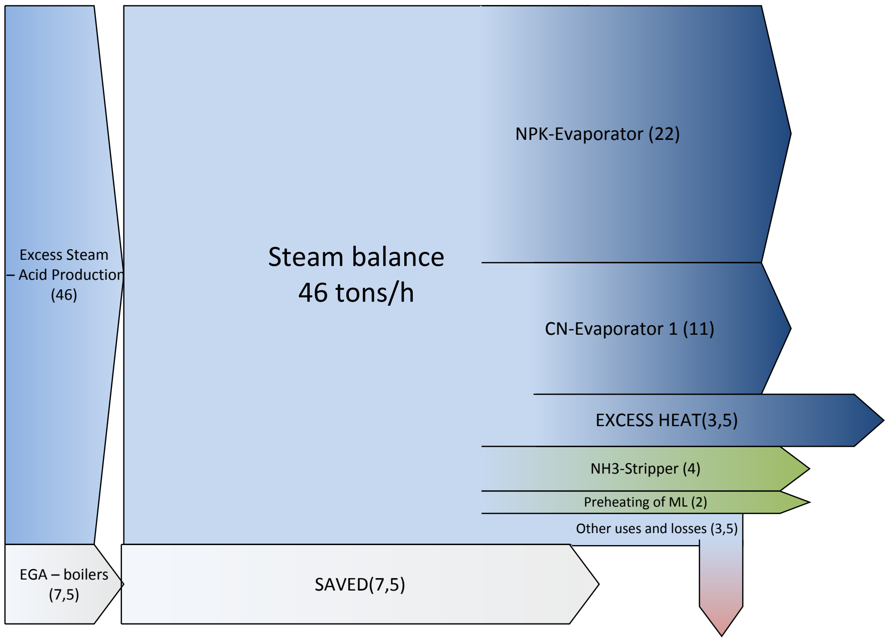

Figure 8: Steam balance for troubled operation scenarios at Yara Glomfjord, with improvements **(Ingebrigtsen, 2012)**.

In gray Figure 8 shows the significance of the old EGA boiler use at troubled conditions. It is also notable that a new arrow marked excess heat has appeared. This heat is now free to use for other heating tasks in the factory e.g. retirement of oil consumption.

What have been done at Yara Glomfjord

It is an important fact that this thesis is written in collaboration with Yara Glomfjord. The engineering staff at the factory is working with the issues discussed here on a daily basis. While this thesis have been written Yara Glomfjord have kept an ongoing dialog with Epcon Evaporation Technology AS, and a pilot test of new evaporator equipment was held in the Epcon testing facilities in Trondheim in May 2012.

The striking results are no scaling and fouling under submergence of boiling temperature for the relevant concentration in a simulated first effect evaporation step. This strongly supports the recommendations of this master thesis and the way towards investment in a new two-effect evaporator at Yara Glomfjord. The situation is presently a very good project for Yara that is up for evaluation for economic support, and will very likely be initiated.

Conclusion

The bottom line conclusion of the *Energy Analysis of Evaporation Equipment in Fertilizer Production* is at this point very simple:

From the energy flow analysis it is evident that the *latent heat* is of far greater importance than *sensible heat* in heat integration tasks at the Yara Glomfjord production site. This text therefore concludes that the best path ahead is to consider energy recovery of latent heat.

In addressing this task *the evaporator equipment for CN-evaporation* is found to have a huge potential, in magnitude 50% energy recovery potential.

The technologies *mechanical vapor recompression* and *submergence of boiling pressure* for the relevant concentration are both found possible. For a cascade solution submergence of boiling pressure is preferred to avoid the need for compressor.

All recommendation in this text is found to retire the EGA boilers completely. The economic savings drown up for the EGA boilers are found to be: *17,5MNOK annually*. In doing recommended improvements excess heat is also gained, which can be utilized to retire some or all of the oil consumption in the factory.

Appendix C: Conversions

This appendix is made to clarify the difference in steam energy and the energy needed to produce steam in boilers.

Operational time at Yara Glomfjord is known to be 342 days a year.

Steam Savings in EGA Boilers

EGA Boilers have 98% regularity and are in use 75% of operational time. It is known from Torgersen (Torgersen, 2003), that 1MW electricity consumption in boilers refers to this amount of live steam:

$$1MW = 1{,}3 tons/h$$

$$1GWh\ electricity\ use = 1{,}3 * 10^3 tons\ live\ steam$$

An example from the text is that EGA boilers use 35GWh annually. To retire the boilers this amount of stem must therefore be saved:

$$\frac{35GWh}{year} = \frac{35 * 1{,}3 * 10^3 tons}{0{,}98 * 0{,}75 * (342 * 24)h} = 7{,}5 tons/h$$

Hence, 7,5tons/h of steam savings retires the EGA boilers.

Energy Content of Steam

The energy content of steam is in this text modeled as the condensing energy.

$$Steam\ energy = \dot{m}_{steam} * h_{fg_{16bar}}$$

An example from the text is the energy content of the steam produced as excess heat in the nitric acid factory. The production is 46tons/h of live steam which transfers to this steam energy:

$$Steam\ energy = \left(46 * \frac{1}{3{,}6}\right)\frac{kg}{s} * 1933\frac{kJ}{kg} * (342 * 24)h = 200GWh$$

Appendix D: Energy in the Neutralization section

This appendix is a small comment on the energy in the neutralization section of NPK production. This text models the energy in the neutralization section as the latent heat of vaporization needed to go from 34% dry substance concentration to 13% in ML. In chapter 3.2.1 this energy is found in Torgersen (Torgersen, 2003), to be:

$$Energy\ from\ exothermic\ reaction = 80\frac{GWh}{year} \sim 9{,}8MW$$

In chapter 4.3.1, however the latent heat model is used and the energy content is found to be:

$$Vapor\ energy = \dot{m}_{vapor} * h_{fg_{1bar}} = 12{,}5MW$$

And for low N/P, this text adds the preheating of ML at 1200kW.This preheating is not needed for High N/P, and therefore the energy supply in the neutralization section is higher. This text models the high N/P energy supply to the neutralization section is 11,3MW and the low N/P energy supply is 12,5MW.

In reality this does not account for the sensible heat transfer in the process, and the real numbers are supplied by Morten Høvset: high N/P: 20 MW and low N/P: 15,8MW. This does not have any dramatic implications on this text, but must be noted for further work on the energy streams in the neutralization section. A final comment is that this is a large energy flow, in the form of the vapor energy that this text models, but it is also very unpredictable and difficult to utilize.

Appendix E: Calculations done in Excel

The calculations done in excel are supplied as electronic copies. The files of interest are:

- Streams.xls
- Pinch_LowNP.xls
- Pinch_HighNP.xls