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Energy Efficiency Opportunities within the Heat Treatment Industry

Master's Thesis within the Sustainable Energy Systems programme

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Division of Heat and Power Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2012

MASTER’S THESIS

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Cover:
The front side of the large furnace line with the loading trolley seen to the right in the picture.

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ABSTRACT

Energy efficiency measures have become a top priority for large energy consuming companies because of the increasing energy prices and implemented energy policies. Many companies also receive demands from their customers to reduce their climate impact. Heat treatment processes are performed at high temperature, sometimes up to 1000°C, and the holding time can be up to several hours. A large amount of energy is needed for these processes and this reflects in a large energy cost for these companies.

The purpose of this project was to identify advantageous, both economically and environmentally, energy efficiency improvements in a specific steel heat treatment plant. The first part of the project was to perform an energy audit and map the energy consumption in the plant. When the distribution of the energy consumption had been determined, the largest energy consumers could be identified. The search for energy efficiency opportunities was then focused on the largest energy consumers in the plant. The profitability of the identified energy saving possibilities was evaluated as well as the environmental benefits of the suggestions.

The energy audit showed that the major part of the energy was consumed in the process itself and that the largest energy consumer among the support processes is the ventilation system. The hardening and nitrokarburizing furnaces, or the main furnaces, are the largest energy consumers of the process equipment.

It was found that 753 MWh/year (7.7%) of electricity can be saved by housekeeping measures. The suggested measures were to remove unnecessary lighting, turn off the manual equipment during weekends, plan the production more energy efficiently, search the compressed air system for leaks and close a damper in a preheating furnace.

The proposed energy saving investment measures will all together save 418 MWh/year (4.3%) of electricity and remove the district heating demand. The suggested investments were to switch the lighting to low energy lamps, insulate the door hoods of the main furnaces, move the intake to the compressor outdoors, heat exchange exhaust furnace gases with washing water and heat exchange the waste heat from the compressor with the heating of the offices. All suggested investment were shown to be profitable, i.e. having a positive net present value. However, the payback periods for the heat exchanging between the compressor and the offices and the low energy lighting may be regarded to be too long as they were more than five years.

If all housekeeping measures and all investment measures were implemented, the energy cost for the plant would decrease with almost 1 MSEK/year.

Key words: heat treatment, energy audit, energy efficiency

Energieffektiviseringsmöjligheter i värmebehandlingsindustrin
Examensarbete inom mastersprogrammet *Sustainable Energy Systems*
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SAMMANFATTNING

Energieffektivisering har blivit allt viktigare för företag som konsumerar stora mängder energi i sin verksamhet. Detta beror på de stigande energipriserna och de politiska styrmedel som har trätt i kraft för att minska utsläppen av växthusgaser. Många företag får också krav från sina kunder att minska sin klimatpåverkan. Värmebehandlingsprocesser utförs vid höga temperaturer, ibland upp till 1000°C, och hålltiden kan vara flera timmar lång. Stora mängder energi går åt till dessa processer, vilket avspeglas i en stor energikostnad för företagen.

Syftet med projektet var att hitta ekonomiskt och miljömässigt fördelaktiga energieffektiviseringsåtgärder i en specifik värmebehandlingsanläggning. Den första delen av projektet var en energikartläggning av anläggningen. När fördelningen av energikonsumtionen hade bestämts, kunde det identifieras var den största mängden energi behövs. Arbetet med att hitta energieffektiviseringsåtgärder fokuserades sedan på de största energikonsumenterna i anläggningen. Till sist utvärderades lönsamheten och minskningen av växthusgaser för de föreslagna åtgärderna.

Energikartläggningen visade att den största delen av energin förbrukas i själva processen och att den stödprocess som förbrukar mest energi är ventilationen. Den största delen av energiförbrukningen i processen sker i härdugnarna och nitrokarbureringsugnarna.

Undersökningen visade att 753 MWh/år elektricitet (7.7%) kan sparas genom energibesparande åtgärder. De åtgärder som föreslogs var att ta bort onödig belysning, att stänga av den manuella utrustningen under helger, att planera produktionen mer energieffektivt, att läcksöka tryckluftsystemet och att stänga ett spjäll i en förvärmningsugn.

De föreslagna energibesparande investeringarna kan tillsammans spara 418 MWh/år elektricitet (4.3%) och ta bort behovet av fjärrvärme. De föreslagna investeringarna var att byta ut belysningen till lågenergilampor, isolera mellandörrshuvarna på värmebehandlingsugnarna, flytta intaget till kompressorn utomhus, värmeväxla rökgaserna från värmebehandlingsugnarna med tvättvatten och värmeväxla spillvärme från kompressorn med uppvärmningen av kontoren. Alla föreslagna investeringar visade sig vara lönsamma, dvs. de hade ett positivt nuvärde. Dock har värmeväxlingen mellan kompressorn och kontoren och lågenergibelysningen återbetalningstider på mer än fem år och det kan anses vara för långt.

Om alla föreslagna energibesparande åtgärder och investeringar genomförs kommer energikostnaderna för anläggningen minska med nästan 1 MSEK/år.

Nyckelord: värmebehandling, energikartläggning, energieffektivisering

Contents

Preface

This master thesis has been conducted at Swerea IVF in Mölndal and has been a part of the ENIG project. The energy audit and the following suggestions were made for Bodycote Värmebehandling AB at their plant in Angered. The project was carried out from December 2011 to May 2012.

My supervisor at Swerea IVF, Charlotte Bergek, has been very committed to the project and a great help and I would like to thank her for all the support during this project. I would also like to thank my supervisor at Chalmers, Mathias Gourdon, for his help and support.

Thomas Grivander and Dan Svensson at Bodycote Värmebehandling AB have patiently answered all my questions and been very dedicated to the project. Martin Olsson at Bodycote has been of great help with the electricity measurements.

Finally, I would like to thank Eva Troell and Nils-Erik Strand at Swerea IVF for their thoughts and ideas for improvement possibilities.

Göteborg May 2012

Malin Källén

Notations

Roman upper case letters

A	Area [m²]
C_p	Heat capacity [J/(kgK)]
I	Investment cost [SEK]
I_f	Phase current [A]
NPV	Net present value [SEK]
$NPVR$	Net present value ratio [-]
P	Active power load [W]
PP	Payback period [year]
Q	Reactive power load [W]
Q_{el}	Electricity consumption [Wh]
Q_{hl}	Heat loss [J]
Q_{hr}	Heat recovery [J]
S	Apparent power load [W]
T	Temperature [K]
T_{in}	Inlet temperature [K]
T_{new}	New inlet temperature [K]
U_f	Phase voltage [V]
U_h	Principal voltage [V]

Roman lower case letters

a	Annual cost saving [SEK/year]
h_o	Outer convective heat transfer coefficient [J/(m²K)]
k_{ins}	Conductive heat transfer coefficient through insulation [J/(mK)]
$\dot{m}$	Mass flow [kg/s]
r	Cost of capital [-]
t	Time frame of calculation [year]
t_{logg}	Logging time [s]
x_{ins}	Thickness of insulation [m]

Greek lower case letters

$\cos\varphi$	Power factor [-]

1 Introduction

All heat treatment processes consist of three steps: heating, holding time (during which the temperature is kept constant) and cooling. The temperature kept during the holding time is usually very high, sometimes up to 1000°C, and the holding time can be up to several hours. This taken into account, it is obvious that a large amount of energy is needed for the processes and this reflects in a large energy cost. [1]

Driven by today's increasing energy prices and implemented energy policies, energy efficiency measures have become a top priority for large energy consuming companies. Many companies also receive demands from their customers to reduce their climate impact.

1.1 Background

Sweden's energy consumption for 2010 was 612 TWh of which almost 200 TWh was used in the industry sector. The engineering industry consumes 7% of the energy used in the industry in Sweden. Even though the engineering industry is not an energy intense sector, it accounts for a significant share of the energy consumption since this sector is large in Sweden. There has been a steady decrease in energy usage within the industry since 1970. This depends on energy efficiency measures and a transition from oil to electricity. The electricity share of the energy consumption has increased from 21% to 35% since 1970. The specific energy consumption, energy used per value added to the products, decreased by 66% between 1970 and 2010. [2]

In 2007, EU established the 20/20/20 target which implies that the emissions of greenhouse gases should be 20% lower than the 1990 level, 20% of the energy should come from renewable energy sources and that the energy use should be 20% lower than the forecasts. This should be realised before the end of 2020. One of the five priority areas is energy efficiency measures. To steer the development in the right direction, a number of energy policies are implemented. [2]

In Sweden there are both an energy tax and a carbon dioxide tax. The energy tax is based on the energy content and is paid for most fuels. The carbon dioxide tax is paid per weight of emitted carbon dioxide for all fuels except biofuels and peat. Sweden has a goal that the electricity produced from renewable energy sources should increase with 25 TWh compared to the 2002 level before the end of 2020. This is encouraged by a requirement to buy electricity certificates for all electricity suppliers. Electricity producers that have a renewable energy source get electricity certificates to sell and all electricity suppliers must buy electricity certificates which correspond to a certain amount of their electricity sale. [2]

Sweden is also a part of EU's emission trading scheme, which works as a 'cap-and-trade' system. A 'cap' is set for all greenhouse gas emissions in EU and all large emitters are given certain allowances that correspond to how much greenhouse gases they are allowed to emit. If they emit more, they have to buy allowances and if they emit less, they can sell allowances. [2]

ENIG is a network for support of energy efficiency in Swedish industries. The network is a collaboration between Swerea SWECAST, Swerea IVF and FSEK (Föreningen Sveriges Regionala Energikontor). The Swedish Energy Agency is a partner and one of the funders of the project. The aim of the network is to gather, collect and share knowledge about energy efficiency measures together with the industry. One of the tasks included in ENIG is to establish a database with specific energy usage indicators for industries. A webpage is created where companies can upload their own profile and compare it with other companies in the same sector. This master thesis was carried out as a part of the ENIG network. [3] [4]

1.2 Purpose

The main purpose of this project was to identify advantageous, both economically and environmentally, energy efficiency improvements in a specific steel heat treatment plant. To be able to achieve this, a number of sub-purposes needed to be fulfilled:

- Assimilate relevant background information about steel heat treatment.
- Collect energy usage data and map the energy consumption distribution.
- State energy saving possibilities.
- Make evaluations of the stated possibilities.

1.3 Limitations

The project was limited to a site-specific study. The suggested energy saving possibilities were evaluated for the conditions of the specific steel heat treatment plant. The suggested improvement possibilities mainly include improvements of the heating and cooling in the process and the overall process outline. Modifications in the actual heat treatment method were not made, since the time for gathering knowledge of steel heat treatment processes for this project was limited.

1.4 Problem Analysis

The problem addressed in this project could be broken down to a number of questions that needed to be answered in order to fulfil the purpose. The first two were very general and straightforward and that was how much energy is used in the plant and where in the process the energy is consumed. Earlier energy saving measures, which have already been implemented in the plant, were also investigated.

The main question for this project was how the energy consumption can be decreased. For each potential energy saving possibility that had been identified, a number of additional questions needed considering. Is this idea economically feasible? Is it technically possible? What will the environmental impact be? When these questions had been addressed, it was possible to evaluate if the energy saving proposals should be kept for further discussion.

The final part of the project was to decide whether any of the ideas from the previous evaluation was recommendable. The suggestion needed to be technically feasible, as well as contributing with economic and environmental benefits to the heat treatment plant.

1.5 Outline of the Report

The following chapter named 'Theory' gives a brief presentation of steel and the steel industry. The heat treatment processes that are relevant for this project are also described. The next chapter, named 'Plant Description', is a presentation of the plant including process equipment, the yearly energy consumption and the outline of the plant. The 'Method' chapter describes how the measurements were made, the equations used for the calculation and the assumptions that had to be made. The remaining chapters include the results from the study, a discussion of the results and the conclusions that could be made.

2 Theory

Steel heat treatment processes are carried out either during or after the production of steel objects. These processes are based on the changes in the microstructure when the steel is heated or cooled. This chapter presents the basic principles of these changes and of different steel heat treatment processes. The chapter also includes the theory and the equations for all calculations in this project.

2.1 Steel

Steel has traditionally been the name for an alloy of iron with up to 2% carbon and small amounts of other elements. [5] Today the name has a wider use for many different alloys of iron with carbon and for example silicon, manganese, boron, chromium, nickel, molybdenum, tungsten, titanium and vanadium. [6] Steel is currently one of the most used construction materials and will keep this position for many years to come. [1]

2.1.1 The Steel Industry

Iron is the main component of steel and is made from iron ore and some kind of reduction agent, which usually consists of coke, coal and a reducing gas. Although pure iron is very rarely found in the earth crust [6], iron is the fourth most abundant element in the crust [7]. Iron is mostly found in different combinations with oxygen, so called iron ore. Crude iron consists of up to 4% carbon and is very brittle. To get steel with the desired properties, most of the carbon is removed and alloy elements are added. [6] The steel is most often also heat treated to achieve even better properties for the intended application. The heat treatment is either performed during the production of a steel component or as a final production step. [1]

The global production of crude steel is around 1300 Mton per year. China is the largest steel producer and contributes today with one third of the total steel production. The steel production in Sweden amounts to 0.4% of the global steel production. [8]

2.1.2 The Microstructure of Steel

The iron and carbon atoms in steel can be close-packed in different arrangements. These arrangements are referred to as different phases of the steel. Pure iron has two stable solid phases. At low temperature, the iron atoms are packed in a body centred cubic (BCC). This is called ferrite or α-iron. At high temperature, over 912°C, the iron atoms will be arranged in a face centred cubic (FCC). This is called austenite or γ-iron. The carbon in the steel will affect the stability of the iron phases and other phases can be formed from iron-carbon compounds. The most important iron-carbon compound is cementite, Fe_3C. The effects of the temperature and carbon content on the phases are usually summarized in a phase diagram, see figure 1. [1]

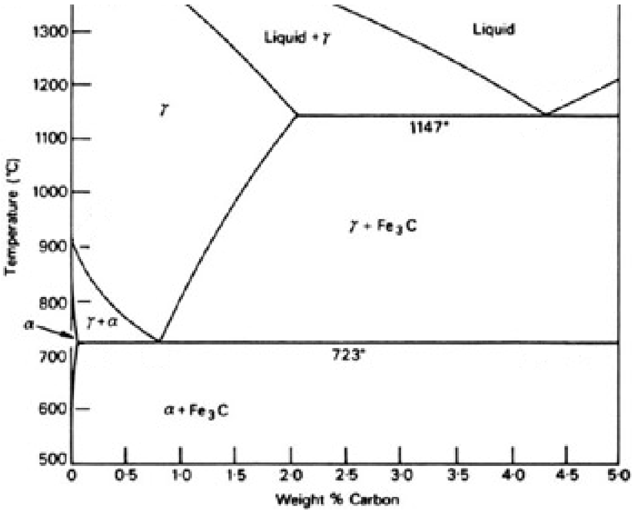

Figure 1. Phase diagram for iron-carbon alloys.

Steel is a crystalline material consisting of a large number of crystals which for steel are called grains. A grain is normally 10-100µm in diameter. The packing of the atoms differ between the grains and the grain boundaries. The presence of those boundaries increases the internal energy of the material and can be described as a sort of surface tension. Therefore a driving force exists which decreases the number of grain boundaries and thus increase the grain size. The grain growth rate is higher at high temperatures. Grain growth is often undesirable since smaller grains will give a higher durability of the steel. Most phase transformations in steel occur by diffusion of the atoms. The diffusion rate is often slower than the grain growth rate and this will affect which phases that are formed. [1]

Phase transformations are usually caused by heating or cooling of the steel and these are the mechanisms occurring in heat treatment processes. Depending on temperature level and the rate of the temperature changes, different phases are formed. Important phases in addition to ferrite, austenite and cementite are pearlite, bainite and martensite. Pearlite is formed when ferrite and cementite grow into austenite and form a lamellar structure. Bainite resembles pearlite, but is more irregular and coarser and is formed at lower temperatures. Martensite is formed when the steel is cooled very fast and the diffusion rate is too slow for ferrite to form. Martensite is a very hard material and is formed almost instantaneously. [1]

2.2 Heat Treatment Processes

There are many different heat treatment processes, some making the steel harder and some making it softer and easier to work with. Another way to categorize the processes is to divide them into thermal processes and thermo-chemical processes. In thermal processes, the properties of the steel are altered solely by undergoing a certain temperature course. In thermo-chemical processes, chemical reactions occur during the temperature course. [1] The processes that will be included in this thesis are categorized in figure 2 and will be explained in the sections below.

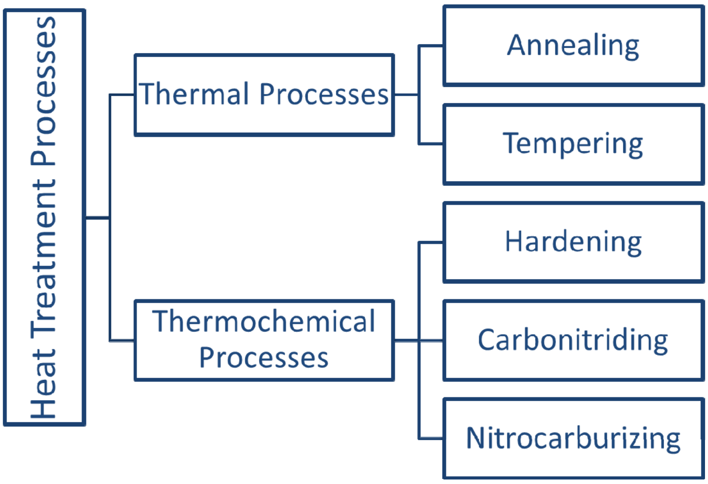

Figure 2. Categorization of heat treatment processes.

2.2.1 Hardening and Tempering

Hardening is a generic name for all processes that make the steel harder and/or increase the durability of the steel by creating a martensite or bainite structure. The steel is first heated to its hardening temperature and austenite is formed. The hardening temperature and the holding time are determined by the hardenability of the steel and the dimensions of the steel object. The steel is then cooled down, either directly or in stages. It is the cooling course that defines the hardening process. [1]

The direct cooling will cause formation of martensite and the process is called direct hardening. When the cooling is performed in stages, so called martempering, the steel is first cooled to a temperature slightly above the temperature at which martensite will be formed. The steel is kept at this temperature until the temperature is constant throughout the steel object. The steel is then cooled to room temperature and martensite is formed. The steel will get almost the same structure from direct hardening and martempering, but martempering will give less residual stress. If the steel needs to become more ductile, tempering is performed. [1]

The fast cooling in hardening processes causes martensite to form instead of ferrite because the cooling is faster than the diffusion of carbon. The carbon atoms will then slowly diffuse from the martensite at room temperature after the cooling is completed. This will cause a variation in time of the properties of the steel. To avoid this, a process called tempering is performed. The steel is heated to 160-650°C to cause a faster precipitation of the carbon atoms. It should be carried out shortly after the steel has cooled down after the hardening. Hardening followed by tempering will give steel with a desired hardness and toughness. [1]

2.2.2 Case hardening and Carbonitriding

Case hardening is a hardening process which is carried out in a carburizing atmosphere. It is usually performed at 850-950°C. The steel will get a surface layer with higher carbon content than the core of the steel object. This will result in a very hard surface and a much softer and tougher core. The hard surface is obtained when martensite is formed from austenite by a fast cooling process. [1]

Carbonitriding is a form of case-hardening where both carbon and nitrogen are added to the steel. This is achieved by performing the case hardening in an atmosphere containing ammonia. The presence of nitrogen increases the hardenability of the steel, and makes it possible to case-harden also low-alloy steel. [1]

2.2.3 Nitriding and Nitrocarburizing

Nitro-processes are performed to increase the fatigue strength and the load-bearing capacity of the steel. Nitriding is a process where nitrogen is added to the surface of the steel from an atmosphere containing nitrogen. The process is usually carried out at 500-550°C. Ammonia, diluted by hydrogen or nitrogen gas, is usually the nitrogen donating medium. The atmosphere is completely free from oxygen to avoid the risk of explosion. The concentration of ammonium is highest in the beginning of the process and is then decreased. The nitriding continues until a desirable nitride depth is achieved. The ammonium gas is then removed from the oven and the steel is washed in nitrogen gas. The cooling is also usually carried out in nitrogen gas. [1]

Nitrocarburizing is a nitriding process where both nitrogen and carbon are transferred to the surface layer of the steel. The temperature is slightly higher than for nitriding, usually 550-580°C. A variety of gases is used as carbon donator, for example carbon monoxide and carbon dioxide. Nitrocarburizing is easily mixed up with carbonitriding, since both processes aim at adding carbon and nitrogen to the steel. However, nitrocarburizing is carried out at a much lower temperature than carbonitriding. [1]

2.2.4 Annealing

The term annealing refers to processes that reduces the hardness of the steel or gives it a microstructure that is better suited for subsequent processes. The collective name annealing usually means soft annealing, which is a process that maximizes the softness of the steel. It is usually used for low alloy steels with a high carbon fraction. The steel is heated to 700-800°C and kept at this temperature for several hours before it is slowly cooled down again. If cold processing is carried out before the annealing, the process time can be significantly reduced. [1]

2.3 Energy Audit

A complete energy audit should consist of five parts according to the Swedish Energy Agency:

- A description of the plant.
- Mapping of the current energy consumption in the plant.
- The short-term energy consumption in the plant.
- The long-term energy consumption in the plant.
- A search for energy efficiency improvement possibilities.

The description of the plant works as a definition of the system boundaries for the energy audit. A suitable way to describe the plant is to draw block diagram over the process. A plant usually refers to a geographically connected facility. The block diagram can be an important tool in the entire energy audit. [9]

The mapping of the current energy consumption in the plant is the foundation for the following analysis. It should give an overview of the systems and equipment which affect the energy consumption. Already existing data need to be complemented with measurements, assumptions and calculations to get a comprehensive overview. The results may be presented in form of energy balances for the plant. External factors which have influenced the energy consumption, as well as recurring variations in the energy consumption, should also be accounted for. [9]

The assessment of the short-term energy consumption is based on already planned and expected changes in the plant. The long-term energy consumption assessment can be used for the short-term energy consumption planning. The long-term energy consumption assessment should investigate future production conditions, if these are likely to differ from the present. The main purpose of an energy audit is usually to identify energy efficiency improvement possibilities. The improvement possibilities should be evaluated based on their technical and economic potential. [9]

2.4 Three Phase Electricity System

A three phase system consists of three sinus-shaped alternating currents which are 120° out of phase with each other. The three phases are connected to a neutral conductor. The voltage between two phases is called principal voltage and the voltage between one phase and the neutral conductor is called phase voltage, see figure 3. [10]

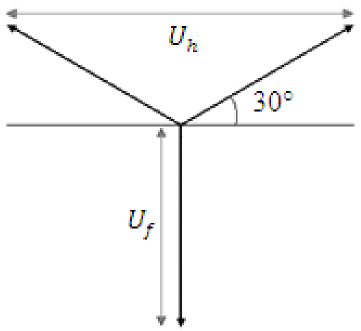

Figure 3. The relationship between the phases and the voltages where U_h is the principal voltage and U_f is the phase voltage.

The following equation can be derived from figure 3:

$$U_f = \frac{U_h}{2\cos 30°} = \frac{U_h}{\sqrt{3}} \tag{1}$$

where U_h is the principal voltage and U_f is the phase voltage.

The power load for a three phase system is called apparent power load and consists of a constant part, called active power load, and a varying part, called reactive power load. The reactive power load is zero over time. The angle between the active power load and the apparent power load is called the phase difference and is denoted φ, see figure 4.

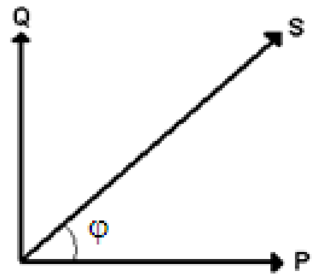

Figure 4. The relationship between the power loads where S is the apparent power load, P is the active power load and Q is the reactive power load.

The apparent power load can be calculated according to:

$$S = 3U_f I_f \qquad (2)$$

where U_f is the phase voltage and I_f is the phase current. Using equation (1) and (2) and the relationship shown in figure 4, the active power load can be calculated according to:

$$P = \sqrt{3} U_h I_f \cos\varphi \qquad (3)$$

The principal voltage and the phase difference are obtained from the instantaneous measurements and the phase current is the mean value for the logging period. The electricity consumption is then calculated by:

$$Q_{el} = P t_{logg} \qquad (4)$$

where is t_{logg} the logging time.

2.5 Heat Recovery from Exhaust Gases

The possible heat recovery from heat exchanging the exhaust gases has been calculated according to:

$$Q_{hr} = (\dot{m}C_P)_{out} \Delta T \qquad (5)$$

where Q_{hr} is the heat exchanger load, $(\dot{m}C_P)_{out}$ is the summation of the mass flow times the heat capacity for each component and ΔT is the temperature difference between the gas flow before and after heat exchange. In the case of heat exchange with the inlet gases, the new inlet temperature was calculated according to:

$$T_{new} = \frac{Q_{hr}}{(\dot{m}C_P)_{in}} + T_{in} \qquad (6)$$

where T_{new} is the new inlet temperature and T_{in} is the gas inlet temperature without heat exchanging.

2.6 Insulation

Two equations have been used for the insulation calculations. The heat loss from an uninsulated wall has been calculated according to:

$$Q_{hl} = \frac{1}{1/h_o} A\Delta T \tag{7}$$

where Q_{hl} is the heat loss from the wall, h_o is the heat transfer coefficient from the wall to the surrounding air, A is the area of the wall and ΔT is the temperature difference between the wall and the surrounding air. The heat loss from an insulated wall has been calculated according to:

$$Q_{hl} = \frac{1}{x_{ins}/k_{ins} + 1/h_o} A\Delta T \tag{8}$$

where x_{ins} is the thickness of the insulation, k_{ins} is the heat transfer coefficient through the insulation and h_o is the heat transfer coefficient from the insulation to the surrounding air. h_o will be the same in both equations since this coefficient is determined by the fluid and the velocity of the fluid.

2.7 Economic Evaluation

This section describes the equations used for the economic evaluations in the project.

2.7.1 Payback Period

The payback period method is one of the simplest ways to evaluate an investment. The payback period is the investment divided by the annual cost savings according to:

$$PP = I/a \tag{9}$$

where PP is the payback period, I is the total investment cost and a is the annual cost savings due to the investment. Since the method is simple, it has some major drawbacks. The method does not include anything that happens after the payback period, such as future costs or benefits from the investment. It also ignores the time value of money; it only takes the current value of the investment and cost savings into account. Therefore this method should only be used as a way to evaluate the risk of an investment. [11]

2.7.2 Net Present Value

The net present value is the difference between the investment and the present value of future cost savings due to the investment. The present value of future cost saving is calculated with an interest rate, usually the cost of capital. The net present value is calculated according to:

$$NPV = \sum_{i=1}^{t} \frac{a_i}{(1+r)^i} - I \tag{10}$$

where NPV is the net present value, t is the time frame for the calculation, a_i is the annual cost saving due to the investment, r is the cost of capital and I is the total investment cost. This method considers the time value of money and accounts for all cash flows during the time frame for the calculation. It can be used to evaluate an investment and to compare the profitability between investments. A good investment will have a high net present value. [12]

Another way to compare investments is to calculate the net present value ratio which is the net present value divided with the initial investment according to:

$$NPVR = {}^{NPV}\!/_{I} \tag{11}$$

where $NPVR$ is the net present value ratio, NPV is the net present value and I is the total investment cost. A higher net present value ratio indicates a more profitable investment.

3 Plant Description

Bodycote Värmebehandling AB is a subsidiary to Bodycote Thermotreat AB. Bodycote Värmebehandling has eight plants where steel and other metal objects are heat treated. The customers are mainly the Swedish engineering industry. The energy audit presented in this report has been carried out at one of the heat treatment plants, which is located in Angered outside Göteborg. 35 employees work fulltime at the site, of which 27 in the production, see table 1.

Table 1. Plant specification for Bodycote Värmebehandling AB in Angered.

Company	Employees	Production time (h/year)	Production rate (ton/year)
Bodycote Värmebehandling AB - Angered	35	8 400	3 300

The plant is operated for approximately 8400 h/year and around 3 300 tons of steel were heat treated during 2011. This corresponds to an average production rate of 0.4 ton/h.

3.1 Process Equipment

The process equipment in a heat treatment plant is mainly furnaces, with one or two chambers, and washes. The basic principles of the operation of the equipment are described below.

3.1.1 Furnaces

A large consumer of energy in steel heat treatment plants is the furnaces, which usually are driven by electricity or LPG (Liquefied Petroleum Gas). The furnaces in this plant are all driven by electricity and perform batch heat treatment processes. Electrical furnaces have a lower investment cost than LPG-fuelled furnaces and demand less service. Other advantages are that they do not produce fuel exhaust gases or disturbing noise. The main drawback with electrical furnaces is the usually high electricity price, which is likely to increase in the future. [1]

Most of the furnaces in the plant are so called two-chamber furnaces. The loading is done at the front side, the charge is then moved from one chamber to the other inside the furnace and then unloaded at the back side. The first chamber is called the heating chamber and the other is called the quenching chamber. The two chambers are separated by an inner door and are enclosed in a gas-tight furnace housing. [13]

Tubular heaters, which are heated by electricity, are installed inside the heating chamber. The charge is moved from the heating chamber to the quenching chamber by two conveyor chains when the holding time is reached. The quenching chamber consists of a lowering unit which will immerse the charge into the cooling medium. The cooling medium, oil or salt baths, is heat exchanged with cooling water. Both the front door and the rear door are equipped with a flame curtain to burn off the furnace gases. The doors cannot be opened until the flame is initiated. This is a safety mechanism to ensure that the furnace atmosphere will not flow out to the indoor air. [13]

A one-chamber furnace mainly works in the same way as a two-chamber furnace, except that the heating and cooling is done in the same chamber. Some of the thermo-chemical processes are performed in one-chamber furnaces. The furnace is first loaded and the pressure is decreased so that the furnace gases will not leak out from the furnace. When a certain pressure is reached, the furnace gases are introduced into the furnace. The furnace and the charge are then heated together. After the holding time is reached, the heaters are turned off and cold gas streams into the chamber. When the charge has been cooled, it is unloaded and a new cycle can begin. [14]

The purpose of the protective atmosphere in the furnaces is either to maintain the carbon content of the steel or to increase it by a certain amount. The hardening processes are performed in an atmosphere of nitrogen gas, methanol, propane and ammonia. Carbonitriding and nitrocarburizing are performed in nitrogen gas, propane, ammonia and carbon dioxide.

The heat treatment processes carried out in the main furnaces are all performed in protective atmosphere. The gases are flowing through the furnace according to figure 5.

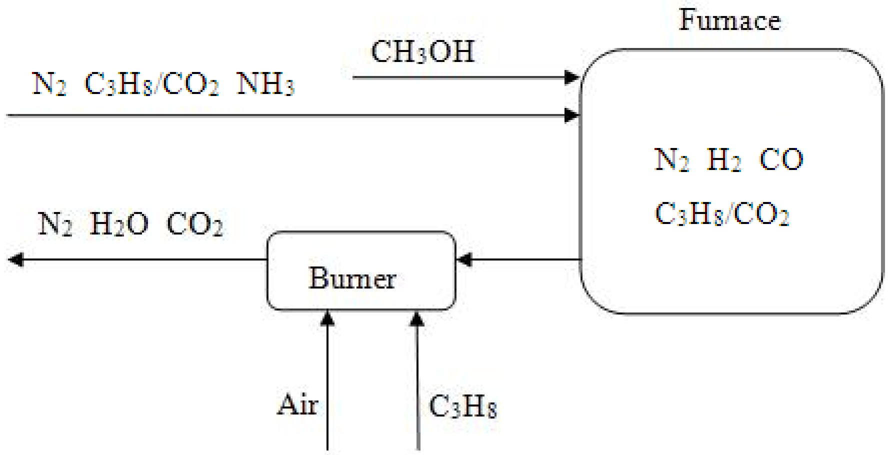

Figure 5. The gas flows in a heat treatment furnace.

At the inlet, a spray of methanol is created by the gas flow of nitrogen gas, ammonia and propane in the hardening furnaces and carbon dioxide in the nitrocarburizing furnaces. Methanol is immediately disintegrated to carbon monoxide and hydrogen gas in the furnace according to:

$$CH_3OH \rightarrow CO + 2H_2$$

Ammonia is disintegrated to nitrogen and hydrogen in the furnace according to:

$$2NH_3 \rightarrow N_2 + 3H_2$$

When the gases leave the furnace chamber, they are combusted in a propane/air flame. Complete combustion was assumed according to:

$$2CO + O_2 \rightarrow 2CO_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

Both nitrogen gas and carbon dioxide are assumed to act as inert gases in the furnace system. The temperature of the gases after combustion have been measured to 855°C close to the flame and 560°C approximately 0.5 m from the first measure point. The inlet gases are assumed to be at room temperature.

3.1.2 Washes

The charges are washed after heat treatment to remove the cooling oil. When thermo-chemical processes are performed, the charges need to be washed before heat treatment as well. Since chemical reactions are a part of the treatment, the surface of the steel objects need to be clean. All washes in the plant use alkaline detergents, except one wash which uses degreasing solvents as detergent.

A wash consists of a washing chamber with a number of tanks underneath. The charge is loaded into the washing chamber and the loading door is closed. The chamber is filled with wash solution which is pumped from the tanks below. The liquid passes a filter when it leaves the washing chamber. The tanks are insulated and are heated by an electric heater with a thermostat. The washing is performed at 60-80°C. [15]

3.2 Plant Outline

The studied heat treatment plant consists of three areas. Two areas are furnace lines, one larger and one smaller, where the processes are coordinated automatically. The third area includes manually operated furnaces. The location of the production lines and areas can be seen in figure 6 which is not to scale. The indoor area of the plant is 7000 m² of which 200 m² is office area.

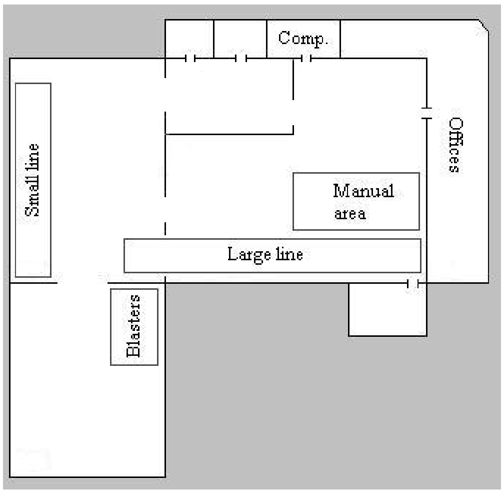

Figure 6. The location of the production lines (Comp. stands for compressor).

The larger line includes six hardening furnaces where the hardening processes (hardening, case hardening and carbonitriding) are performed. These furnaces are two-chamber furnaces, where the charge is heated in one chamber and then moved to the other chamber in which it is cooled. The line also includes one furnace which is used for nitrocarburizing, see figure 7. In all seven furnaces, the cooling chamber consists of an oil bath. The charges can either be cooled in the oil bath or by cold air fanned into the quenching chamber. For each of these furnaces, there are also one preheating furnace and one tempering furnace, which are all one-chamber furnaces.

The charges treated in the nitrocarburizing furnace are washed in wash W1, see figure 7, before heat treatment. All charges are preheated in the preheating furnaces (PF in figure 7) to about 400°C and then moved to one of the hardening furnaces. The hardening processes are carried out at approximately 950°C. The preheating furnaces are constantly kept at the preheating temperature. The tempering furnaces (TF in figure 7) are used to perform tempering on the hardened charges after heat treatment. The tempering furnaces are only heated when they are used. The tempering is performed at 160-650°C. The charges are washed in wash W2 after heat treatment to clean them from the cooling oil.

All the furnaces in this line are controlled and loaded automatically. The loading is organized by a computational queuing system where the charges are moved by loading trolleys between the furnaces. The trolley at the front side loads the preheating furnaces and then moves the charges to the hardening furnaces. The trolley at the back side moves the charges from the cooling baths on to the tempering furnaces, see figure 7.

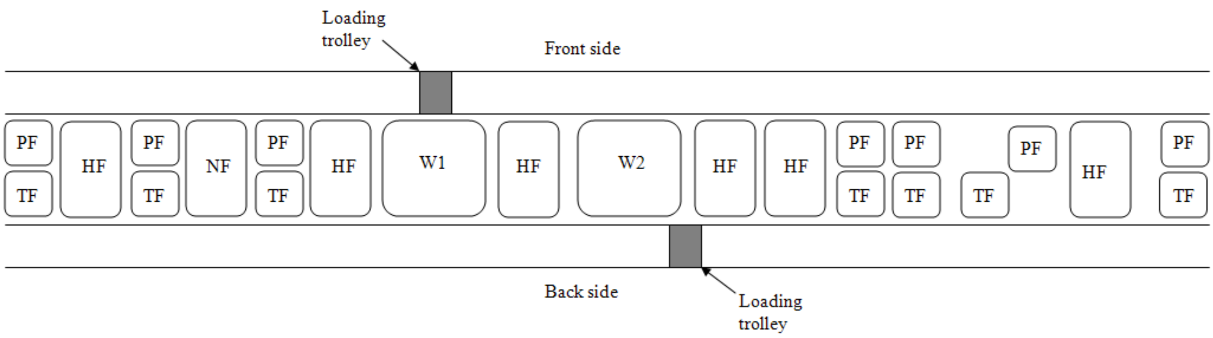

Figure 7. An overview of the large line of furnaces, where PF stands for preheating furnace, TF for tempering furnace, HF for hardening furnace, NF for nitrocarburizing furnace and W1 and W2 for washes.

The smaller line consists of five furnaces where the thermo-chemical processes are performed at approximately 600°C. There are two two-chamber furnaces and three one-chamber furnaces. In a one-chamber furnace, the heating and the cooling are performed in the same chamber. This is done by introducing cold gas to the chamber when the holding time is reached. The line also includes two washes, one preheating furnace and one tempering furnace. The charges are washed before heat treatment to assure that they are completely clean, which is necessary for these processes. One wash uses water and alkaline detergent, W1 in figure 8, and one wash uses degreasing solvents, W2 in figure 8. This line is controlled in the same way as the large line.

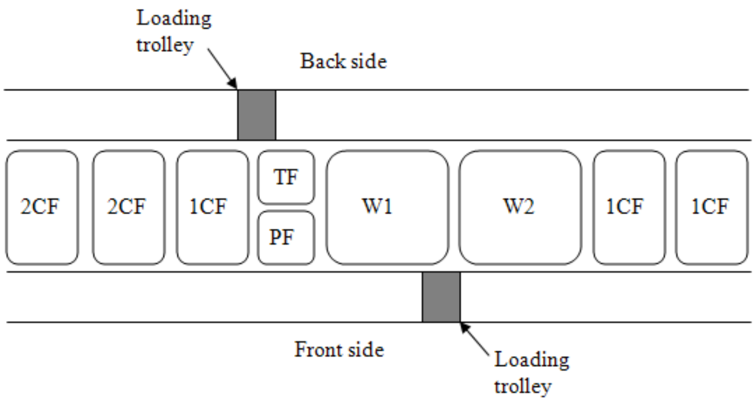

Figure 8. An overview of the small line of furnaces, where PF stands for preheating furnace, TF for tempering furnace, 1CF for one-chamber furnace, 2CF for two-chamber furnace and W1 and W2 for washes.

The two manually loaded furnaces are two-chamber furnaces with oil baths in the cooling chambers, see figure 9. These furnaces also have the possibility to cool the charges in adjacent salt baths. This part of the plant also includes two preheating furnaces, seven tempering furnaces and one wash using alkaline detergents.

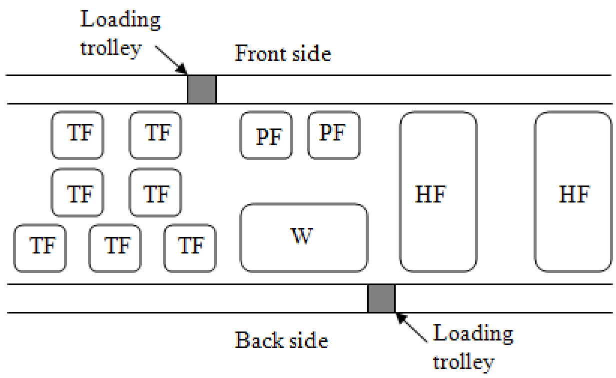

Figure 9. An overview of the manually operated furnaces, where PF stands for preheating furnace, TF for tempering furnace, HF for hardening furnace and W for wash.

The cooling oil and salt baths are both heated and cooled depending on the use frequency and the temperature of the charges. The cooling is done by heat exchanging the oil or salt with cooling water, which is then cooled in two open cooling towers. The heating is done by electric heaters.

A more detailed outline of the furnace lines can be found in appendix A, where the identification number for each process equipment also is indicated.

The plant has a compressor supplying a compressed air system, which drives the furnace doors and is also used for packing the charges after heat treatment. The ventilation in the plant consists of six units, five for the workshop area and one for the offices. The office ventilation is completely shut off during weekends.

3.3 Current Energy Consumption

The only energy source for the process equipment in the plant is electricity. The workshop area is heated by recycled process heat. A small amount of district heating is used for heating the offices and for the tap water heater, see figure 10. During 2011, 9 590 MWh electricity and 120 MWh district heating was consumed in the plant.

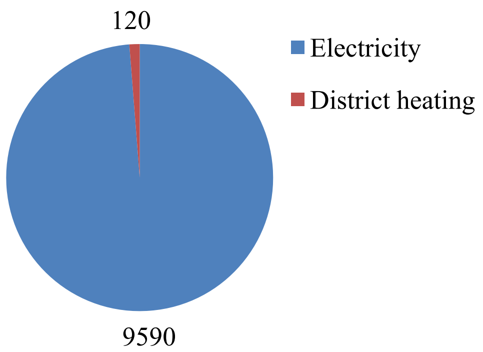

Figure 10. The energy consumption for 2011 in MWh.

The process is operated continuously day and night, seven days a week. The energy consumption during an average day can be seen in figure 11.

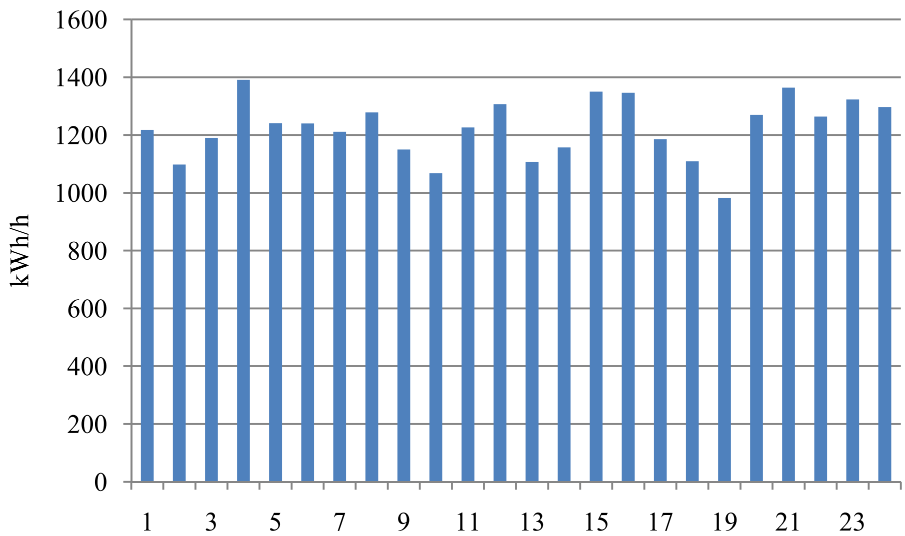

Figure 11. The energy consumption during an average day in kWh/h.

The production rate is equal for weekdays and weekends. The operating staff works in three shifts during weekdays and two shifts during weekends. The plant operates unmanned two nights during the weekend with ordinary production rate.

The energy consumption distribution over one year can be seen in figure 12. The production is stopped during two weeks in summer for vacation and partly decreased during Christmas time. Even though the production is stopped in summer, not all equipment is turned off. For example, pumps and the compressor need to be operating so that the equipment does not get damaged.

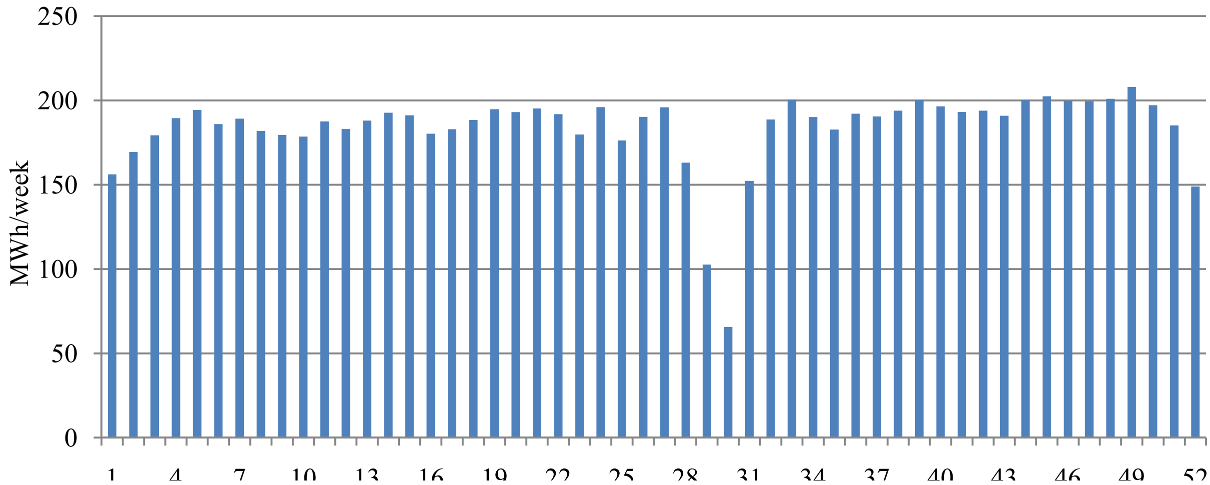

Figure 12. The energy consumption during one year in MWh/week.

The specific energy usage for the plant can be seen in table 2. The numbers are based on the production rate and energy consumption in 2011.

Table 2. Specific energy usage in the plant.

Energy use/Production time (MWh/h)	Energy use/Turnover (MWh/kSEK)	Energy use/Amount goods (MWh/ton)
1.16	0.18	2.93

3.4 Earlier Energy Saving Measures

The plant is currently using 120 MWh/year of district heating which is less than 10% of the original consumption of 1 400 MWh/year. This immense decrease in district heating use is due to three energy saving measures.

In 2004, it was discovered that the control system of the ventilation was not working properly. This was investigated and a new ventilation supplier was chosen. In 2007, a modification of the ventilation heating was made. The supply air in the ventilation aggregate called TA2 was heat exchanged with some of the exhaust air from the area that is supplied by ventilation aggregate TA4, instead of the exhaust air from the TA2 area, see figure 13. This was beneficial because the exhaust air from the TA4 area is hot because of the many hardening furnaces in the area. These two changes decreased the district heating consumption to 382 MWh/year from 1 400 MWh/year.

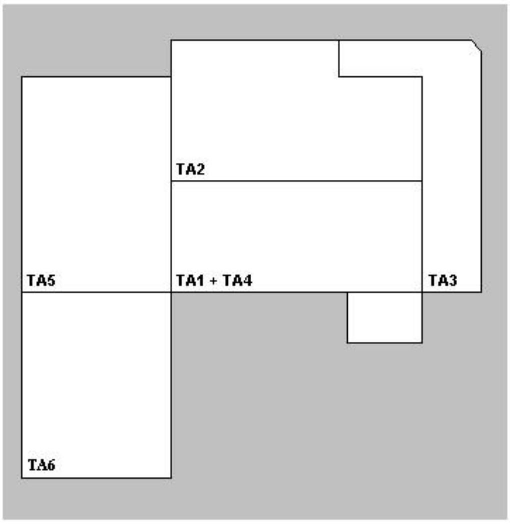

Figure 13. The outline of the areas supplied by each ventilation aggregate.

The supply air in TA2, TA5 and TA6 is heated with the cooling water from the process. However, the supply air in TA1, TA3 and TA4 was previously heated by district heating. In February 2011, an attempt was made to switch to cooling water in these heat exchangers instead of district heating water. The experiment was successful and this measure decreased the district heating consumption from 382 MWh/year to 120 MWh/year. However, the piping and heat exchanger will need to be exchanged into a material that can resist the oxidising cooling water to make the installation permanent.

4 Method

This chapter describes the electricity measurements and the data collection for the energy audit. The data needed for the economic and environmental calculations are described. All assumptions used in the project are stated in this chapter.

4.1 Electricity Measurements

To obtain the electricity consumption of the individual equipment in the plant, the electricity was first measured instantaneously and then logged for one week. The electricity distribution in the plant consists of a three phase system and the instantaneous measurements were done to check if the phases were behaving identically. If there were no differences between the phases, either one of them could be logged. If the phases differed from each other, the phase closest to the mean behaviour was logged. The principle voltage and the power factor were only measured instantaneously.

Since there was a limited number of ampere meters available, not all equipment could be measured. Using the values for the measured equipment and information about operating routines, the electricity consumption of the remaining equipment could be estimated, see appendix B. The electricity consumption for lighting was calculated with the known power of the armature.

The utilization ratio and the specific electricity consumption were calculated for the equipment that had available holding time data. The utilization ratio was defined as the time the equipment was used divided by the total measured time. The specific electricity consumption was calculated both as electricity consumption per holding time and electricity consumption per amount heat treated goods.

4.2 Data Collection

A power and energy analyser from Chauvin Arnoux was used for the instantaneous electricity measurements. The logged phase current was measured with electricity tongs from Chauvin Arnoux. The equipment has a margin of error of 0-3%. The logging was conducted during three periods to be able to measure most of the process equipment. The logging periods were: 16-23th of January, 24-30th of January and 1-6th of February. An additional measurement period for the manual equipment was conducted during one weekend 2-5th of March. Eleven electricity tongs were used for the measurements and the phase current was measured once every minute. The software DataView was used to handle the data from the tongs.

The gas flows to the furnaces were provided by Thomas Grivander, Bodycote Värmebehandling AB. The temperature of the gas flow leaving the furnace was measured with a thermocouple. The surface temperatures of the furnaces were measured with a Testo thermo camera.

4.3 Economic Calculations

The profitability of the energy saving measures has been investigated using two capital budgeting methods: payback period and net present value. The cost of capital was 20% and the time frame for the calculations was set to 10 years. A sensitivity analysis was carried out for the economical calculations with an increased energy price. It was assumed that the electricity price will be 25% higher in 10 years and that the district heating price will be 15% higher [16].

4.4 Environmental Calculations

The environmental assessment of the energy saving measures has been based solely on carbon dioxide emissions. Emission values of 600 $kgCO_2/MWh$ for electricity and 106 $kgCO_2/MWh$ for district heating have been used. The emission value for electricity is based on the effect of a change in the electricity use in the electricity grid in northern Europe, so called marginal electricity [17]. The emission value for district heating is based on the district heating mix in Gothenburg [18].

4.5 Assumptions

A number of assumptions have been used throughout the project and they are all listed in the following sections.

4.5.1 Production

The plant was assumed to have 8 400 h of production each year. This corresponds to 50 weeks of full production during one year, the summer vacation and the reduced production rate during Christmas taken into account. The measured weeks were assumed to represent a standard production week and all calculated electricity consumptions for each week was multiplied with 50 to get figures for one year. The calculated utilization ratios were also assumed to represent a standard production week.

4.5.2 Electricity Measurements

The principle voltage and the power factor were measured instantaneously and those values were assumed to be constant. The phase current used in the calculations was the mean value for the measured period. The equipment power loads calculated during operation was based on the electricity consumption for the equipment during one batch. This batch was assumed to be a standard batch. Each batch has individual holding time and weight, which both affects the electricity consumption.

4.5.3 Heat Transfer

For the insulation calculations, the saved electricity consumption was assumed to be equal to the difference in heat leakage with and without insulation. This implies that the efficiency of the electrical heaters in the furnaces was assumed to be 100%. All heat leaks from the furnaces heat the indoor air, but since the investigated areas are located on the roof of the furnaces this heat will increase the temperature of the air above the furnaces. It was therefore not considered to be a loss of useful indoor heating as this heat would only have increased the temperature at the ceiling.

For all heat exchange calculations, a ΔT_{min} of 20 K was assumed.

4.5.4 Investment Costs

The investment costs used in the economic calculations come from various sources. The investment cost for low energy lighting is based on an offer from Göteborg Energi. The cost for insulating the door hoods is based on insulation prices from Profisol Teknisk Isolering. The investment cost for moving the intake to the compressor is an approximate estimation of the cost for insulated pipes and a small installation cost. The cost for investing in heat exchange between the furnace exhaust gases and washing water is given by the consulting company Jerrex, which has been involved in similar installations. The investment cost for removing the district heating demand is based on an offer from Atlas Copco. The investment includes heat exchanging the waste heat from the compressor and the heating of the offices and installing new piping for heat exchange in three ventilation aggregates.

4.5.5 District Heating

The current consumption of district heating in the plant is 120 MWh/year. Even though the consumption would be 382 MWh/year if a planned investment is not made, all calculations are based on a consumption of 120 MWh/year. However, the percentages for case III in table 10 are based on a total consumption of 382 MWh/year. The reason for this is that the investment for reducing the district heating demand is included in this scenario.

Another district heating price is used for case III for the calculation of the annual savings for this scenario. Since this scenario includes the reduction of the district heating demand, the annual cost savings for removing the remaining district heating demand by heat exchanging the waste heat from the compressor is based on a lower district heating price. This is because the district heating price would decrease if the total demand was reduced. The price would decrease because a part of the tariff is based on the highest load during the previous year.

5 Results

The results from the energy audit are presented in this chapter. First is a description of the current energy consumption distribution in the plant. The next sections present the possible energy saving measures that have been investigated during the project. The last part of this chapter includes the results from the evaluation of these suggestions.

5.1 Energy Consumption Distribution

The energy supplied to the plant is distributed according to figure 14. The category named process includes all furnaces, washes and blasters. The ventilation category includes the ventilation for both the workshop and the offices. Cooling includes the energy used in the pumps and cooling towers for the water circuit that cools the oil and salt baths. The category other includes for example loading of trucks and use of computers. It should be noted that all categories in the figure represent electricity usage except the district heating bar which includes heating of the offices and the tap water.

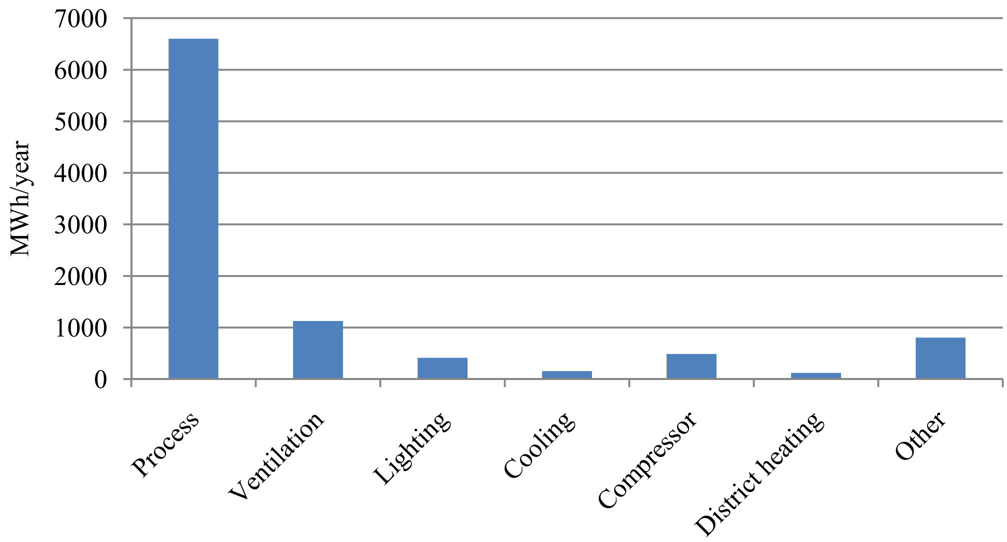

Figure 14. Distribution of the energy usage during one year in MWh.

The category process is further divided into main furnaces, preheating furnaces, tempering furnaces, washes and blasters in figure 15. As can be seen in the figure, the main furnaces have the largest energy demand. This depends on that the main furnaces are the largest equipment and that many of these are kept at very high temperatures. The main furnaces in the manual area have a very large energy demand, even though there are only two of them and they are not used during weekends. These furnaces are the oldest in the plant and therefore not very energy efficient.

The preheating furnaces and tempering furnaces consume less electricity than the main furnaces. The preheating furnaces are kept at lower temperatures than the main furnaces and the tempering furnaces are shut off when they are not used. What should be noted in the figure is the very large electricity demand for preheating in the small line. This line only has one preheating furnace and it consumes much more energy than the preheating furnaces in the large line, which are identical to the preheating furnace in the small line. This was further investigated and the result from that investigation is described in section 5.2.6.

The washes generally consume much less electricity than the furnaces since these are only heated to 60-80°C and much of the heat is added by the charges washed after heat treatment. There are two washes both in the large and the small line. The electricity consumption for the washes is larger in the small line because one of these washes is a so called alcowash which uses degreasing solvents. This wash is the newest in the plant and it is the wash with the largest energy consumption. The blasters consume very little energy since these only consume electricity when they are used.

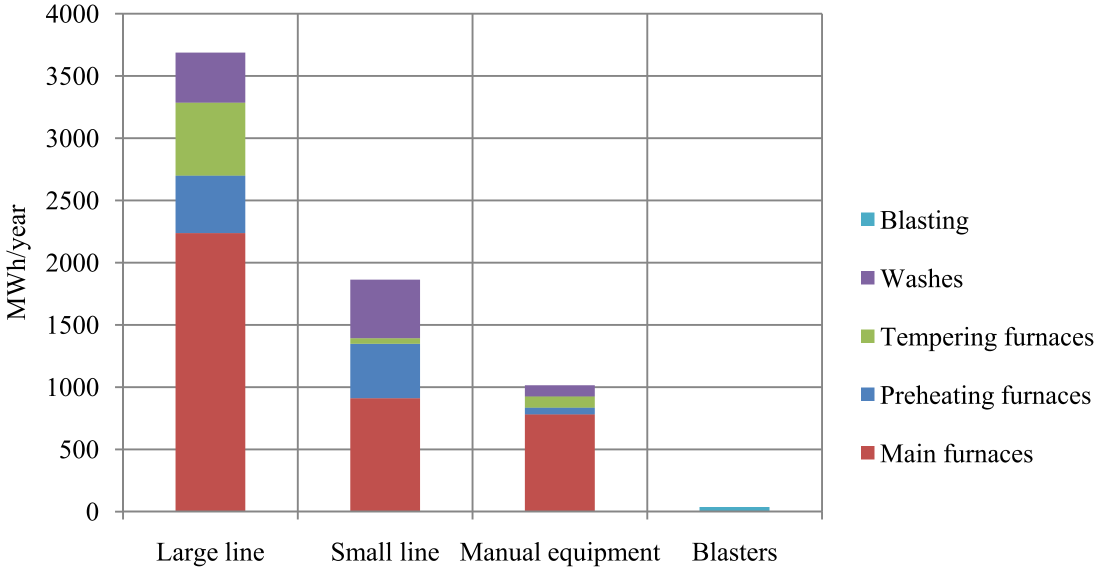

Figure 15. Distribution of the energy usage in the process during one year in MWh.

The energy consumption distribution is presented as a fish bone diagram in figure 16. This figure summarises the results presented in figure 14 and 15 with exact numbers. The three largest energy consumers are the hardening furnaces, the nitrokarburizing furnaces and the ventilation. There are eight hardening furnaces and six nitrokarburizing furnaces in the plant and the consumption in the hardening furnaces is almost three times as large as the consumption in the nitrokarburizing furnaces. As mentioned in section 2.2, hardening processes are performed at a higher temperature than nitrocarburizing. This illustrates the connection between the holding temperature and the electricity consumption. Another factor that should be mentioned is that some of the hardening furnaces are quite old compared to the nitrokarburizing furnaces.

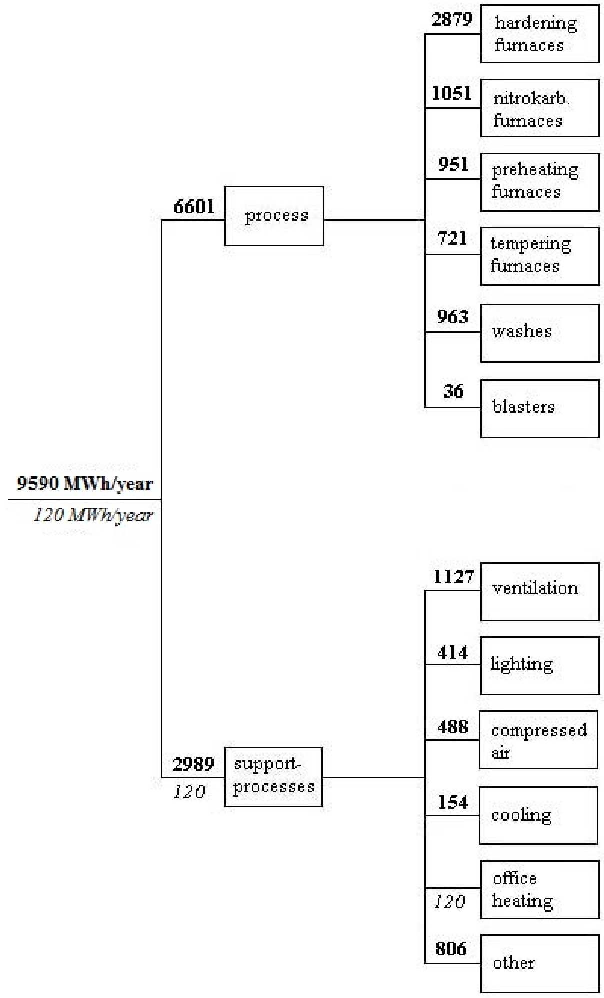

Figure 16. The energy consumption distribution in MWh/year in the plant presented as a fish bone diagram. The numbers in bold are electricity demand and the numbers in italic are district heating demand.

The total energy cost for one year can be seen in figure 17.

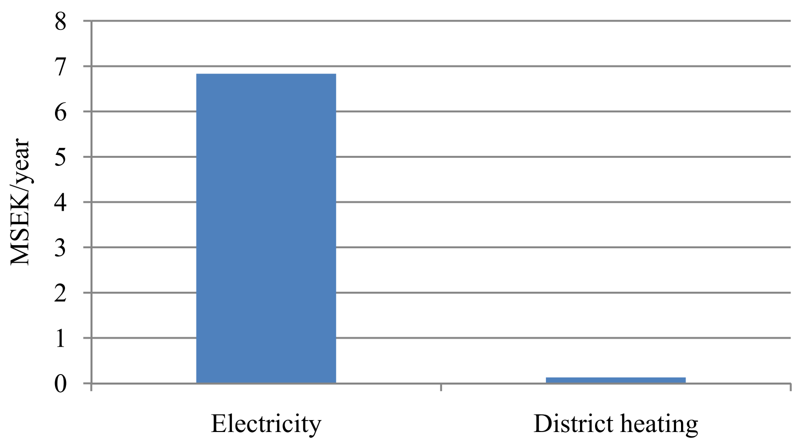

Figure 17. The energy cost during one year in MSEK.

The mean power load for the measured process equipment can be seen in figure 18.

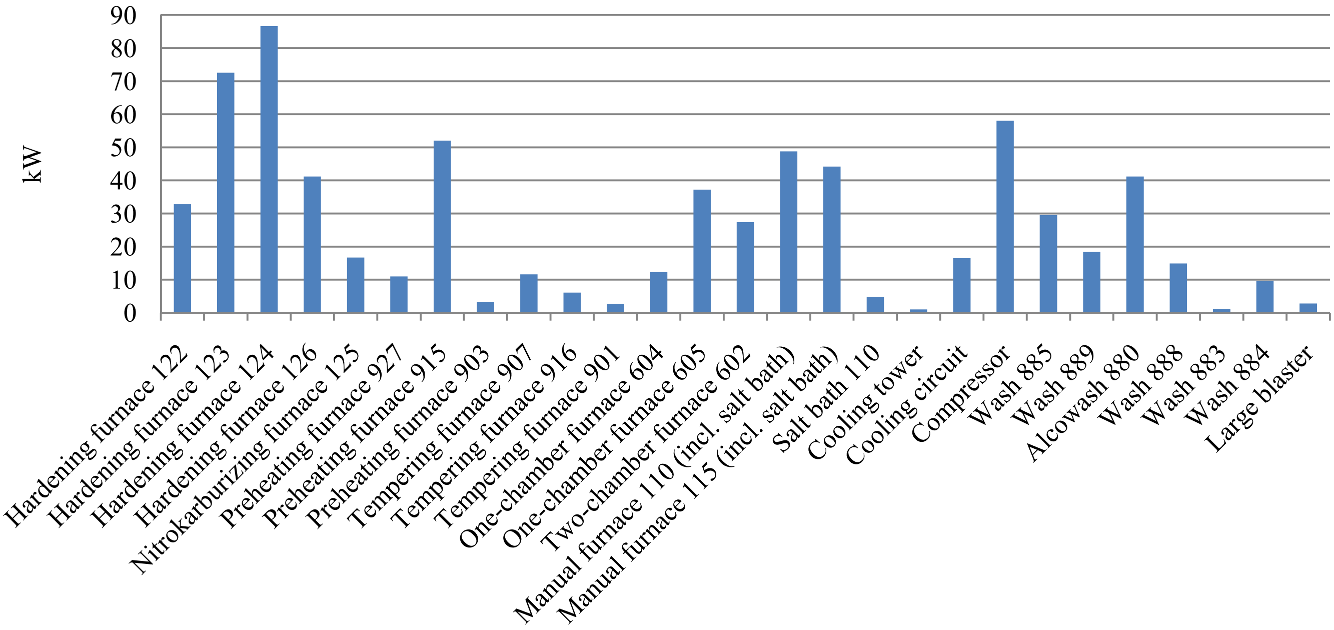

Figure 18. The mean power load in kW for the process equipment.

It was possible to find out the exact holding times and thus also the power load during operation and during stand-by for some of the equipment. The different power loads can be seen in figure 19. The power loads in the figure represent randomly chosen batches and it should be noted that the batches differ from each other depending on holding time and weight.

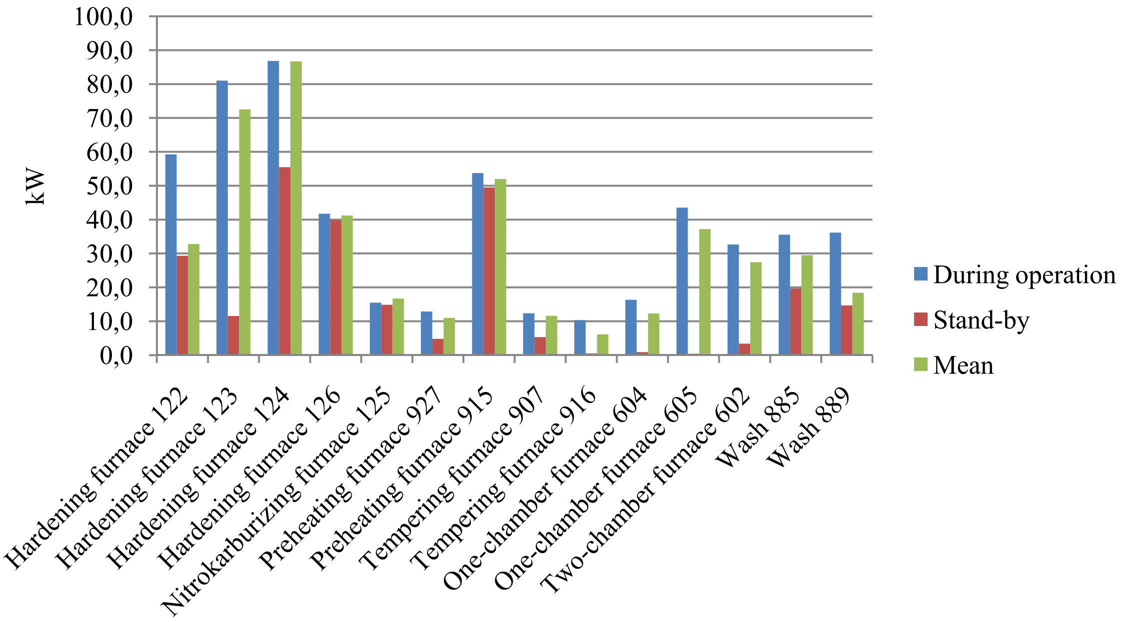

Figure 19. The power load in kW during operation and in stand-by for the process equipment.

To be able to compare the energy efficiency of the furnaces, the utilization ratio and the specific electricity consumption were calculated, see table 3. The utilization ratio is an important factor to account for, especially for equipment with high electricity consumption during stand-by. The utilization ratio for hardening furnace 122 is very low and this affects the specific electricity consumption of this furnace. This makes it hard to compare this furnace to the other hardening furnaces. Hardening furnace 126 has the lowest specific electricity consumption of the hardening furnaces and this is probably because it is the newest. Hardening furnace 123 is older than hardening furnace 124, but the higher utilization ratio contributes to a lower specific electricity consumption in this furnace. From the utilization ratios and the specific electricity of these furnaces it can be assumed that the utilization ratio affects the specific electricity consumption more than the age of the furnace. If it is possible to increase the utilization ratio for these furnaces, it would be a great possibility to decrease the electricity consumption for the hardening furnaces.

Table 3. Utilization ratio and specific electricity consumption for the measured equipment, where HF stands for hardening furnace, NK for nitrokarburizing furnace, PF for preheating furnace, TF for tempering furnace and W for wash.

Furnace/ Wash	Utilization ratio ($h_{holding\ time}$/h)	Specific electricity consumption (kWh/$h_{holding\ time}$)	Specific electricity consumption (kWh/kg)
HF122	0.22	151	2.28
HF123	0.86	85	0.43
HF124	0.78	111	0.71
NK125	0.69	24	0.25
HF126	0.82	50	0.26
NK602	0.50	55	1.12
NK604	0.87	14	1.62
NK605	0.94	40	0.51
PF915	0.23	222	0.96
PF927	0.38	29	0.24
TF916	0.28	17	0.23
TF907	0.65	18	0.10
W889	0.26	71	0.15
W888	0.10	152	0.35
W885	0.52	57	0.05

It is harder to detect a similar relationship for the nitrokarburizing furnaces since these differ more from each other. For example, this category includes both one-chamber and two-chamber furnaces.

Both preheating furnaces have a rather low utilization ratio and it could possibly be an energy saving measure to try and increase these ratios. When comparing the numbers for the preheating furnaces, it can also in this case be seen that the preheating furnace in the small line, PF915, has much higher energy consumption than the preheating furnace in the large line, PF927.

The utilization ratios for the tempering furnaces should not considerably affect the specific electricity consumption since these furnaces are shut off between the batches. The specific electricity consumption is probably more affected by the fact that the holding temperature for these batches vary.

The utilization ratios for the washes are quite low, as are the specific electricity consumption. It is not probable that the utilization ratio can be increased for the washes since each batch is only washed for half an hour and all washes need to be in operation because they are not interchangeable. Some washes are used before and some after heat treatment.

5.2 Energy Housekeeping Measures

This section includes all energy saving measures that do not need an investment to be realised.

5.2.1 Lighting

The armature in the workshop area was counted to 405 pieces. 38 of these were regarded as unnecessary (by only lighting pipes and walls for example) and can be removed without decreasing the amount of light in the area. This would save 40.4 MWh/year.

5.2.2 Manual Equipment

The manual equipment is not used at all during weekends, but is not turned off. The electricity consumption was measured for the manual equipment one weekend when the manual hardening furnaces were kept at 500°C instead of 950°C and the preheating furnaces and the washes were turned off. The electricity consumption for the weekend decreased with 0.97 MWh, which would give 48.4 MWh/year in decreased electricity consumption.

5.2.3 Production Planning

The results in table 3 were used to find measures to decrease the electricity consumption by production planning. According to the specific electricity consumption for each hardening furnace the following priority order could be stated:

1. 126
2. 123
3. 124
4. 122

Using the priority order for the hardening furnaces and the assumption that the utilization ratio could be up to 90%, it was found that the electricity consumption could be decreased with 219.5 MWh/year. This high number is due to that 122 could be turned off when the production was relocated to the other furnaces. The difference between the saved electricity/year and the total consumption in 122 during one year amounts to the increased consumption of the other furnaces when they were given a higher utilization ratio. This may not be possible to do continuously, since the oil bath in 122 contains a different cooling oil than the other furnaces and this oil is preferred for some batches.

The utilization ratio of 38% in the preheating furnace in the large line was considered to be unnecessary low. Five preheating furnaces are assumed to be used in the large line and if the batches for one of the preheating furnaces could be relocated to the other furnaces, 66.3 MWh of electricity could be saved each year.

5.2.4 Compressed Air System

The compressed air system is not regularly checked for leaks today. If the leaks in the systems were fixed, approximately 20% of the electricity consumption of the compressor could be saved. [19] This amounts to 97.5 MWh/year. The electricity consumption of the compressed air system could be further decreased if the system was sectionalised so the supply of compressed air could be turned off for equipment not currently in operation.

5.2.5 Preheating Furnace

As the energy consumption distribution was completed, it was found that the preheating furnace 915 was consuming almost four times as much electricity as corresponding preheating furnaces. When the furnace was investigated it was found that a damper in the ceiling of the furnace was open. After the damper had been closed, the electricity consumption of the furnace was measured again. The furnace now consumes 155.8 MWh/year compared to 436.9 MWh/year before, which is a decrease of 281.1 MWh/year.

5.2.6 Ventilation

The ventilation is a large energy consumer in this plant with a yearly consumption of 1 127 MWh. To be able to make any suggestions about energy saving measures in the ventilation system, measurements of the indoor air has to be made to see if it is possible to decrease the ventilation rate. This should be carried out by somebody with expertise within this area. For example: if the ventilation in the workshop area could be decreased by 10%, the saved electricity cost would be 78 900 SEK/year. A large concern with decreasing the ventilation is the leakage of carbon monoxide from the furnaces. One possibility could be to adjust the ventilation rate to the production rate, since the major function of the ventilation is to limit the amount of furnace gases in the indoor air. This could be realised by installing gas meters to control the amount of furnace gases in the indoor air.

5.2.7 Total Savings by Energy Housekeeping Measures

The saved energy, costs and carbon dioxide emissions for the energy housekeeping measures have been summarised in table 4. As can be seen in the table, approximately 750 MWh/year of electricity and more than 500 000 SEK/year can be saved by these measures. As a comparison, the emissions saved by the energy housekeeping measures equals 322 modern cars in Sweden each driving 10 000 km/year. [20]

Table 4. Energy, cost and emission savings for the energy housekeeping measures.

Measure	Saved energy consumption (MWh/year)	Saved energy cost (SEK/year)	Saved carbon dioxide emission ($tonCO_2$/year)
Lighting	40.4	28 800	24
Manual equipment	48.4	34 500	29
Production planning	285.8	203 700	172
Compressed air system	97.5	69 500	59
Preheating furnace	281.1	200 200	169
Total	753	536 700	453

5.3 Energy Saving Investment Measures

This section includes all energy saving measures that need an investment to be realised.

5.3.1 Low Energy Lighting

The lighting in the workshop area consists of 58 W fluorescent tubes assembled two in each armature. The tubes could be changed into a low energy alternative, usually with 35 W instead. The old fluorescent tubes have a total load of 71 W with choke and igniter included and new tubes would have a total load of 38.5 W with their equivalent of choke and igniter. The lighting energy consumption would therefore be decreased with 45.8%. In this case, that corresponds to 168.8 MWh/year of saved electricity. [21]

5.3.2 Insulation

The surface temperatures of the furnaces were investigated and all the main furnaces in the large line had one area with very high surface temperature. When the door between the heating chamber and the quenching chamber is opened, it is elevated into a hood which is not as insulated as the heating chamber. The surface of the door hood had a temperature of 80-160°C for furnace 120 – 126. The area with high temperature was estimated to 3m² for each furnace. If additional external insulation was attached to these high temperature areas, the electricity consumption in the furnaces could be decreased. If, for example, a 0.08m thick insulation weave was attached to the hoods on all main furnaces in the large line, the energy consumption in these furnaces would decrease with 108.7 MWh/year. See section 2.6 for the equations used for these calculations.

5.3.3 Exhaust Gas Cooling

The exhaust gases leaving the heat treatment furnaces have a temperature of approximately 600°C. The gases are mixed with the ventilation outlet, which is heat exchanged with the ventilation inlet. The outlet gas pipes are not insulated and a lot of the heat is leaking to the workshop indoor air. This heat could instead be used in the process.

The furnace gases are entering the heating chamber at room temperature and a part of the electricity consumption in the furnaces is used to heat the gases. If the outlet gases were heat exchanged with the inlet gases, the electricity consumption in the furnaces could be decreased. The possible heat exchanger loads and the saved electricity are presented in table 5. As can be seen in table 5, the largest saving possibilities are to heat exchange the furnace gases in furnace 125 and furnace 602. Furnace 601 would have the same theoretical possibility, but it is currently not in use and has not been measured.

Table 5. The heat exchanger loads and electricity saving possibilities by heat exchanging the inlet and outlet furnace gases in the main furnaces.

Furnace	122	123	124	125	126	602
HX load during operation (kW)	0.81	0.81	0.81	4.15	0.86	5.03
HX load in stand-by (kW)	0.52	0.52	0.52	3.07	0.52	1.11
Utilization ratio (-)	0.22	0.86	0.78	0.69	0.82	0.50
HX mean load (kW)	0.58	0.77	0.75	3.82	0.80	3.07
Saved electricity consumption (MWh/year)	4.9	6.5	6.3	32.0	6.7	25.8

The larger saving possibilities for 125 and 602 are because of the higher gas flows in these furnaces. However, one of the furnace gases is ammonia and it can be problematic to preheat it before entering the heating chamber. Since ammonia is disintegrated in the furnace chamber, the same could happen in the heat exchanger when a sufficiently high temperature is reached. [22] This would decrease the amount of nitrogen that can be transferred to the steel objects in the furnace, since the transfer occurs when ammonia is cracking on the steel surface. This possibility was not investigated further since the heat exchanger loads would be very small and even smaller if ammonia cannot be preheated.

Another possibility could be to heat exchange the outlet gases with water in one of the washes. The water in the wash is kept at 80°C and is heated by electrical heaters. If a part of the washing water was lead out of the tank and heat exchanged with the furnace outlet gases, the electricity consumption in the wash could be decreased. If the outlet gases from the four mostly used furnaces in the large line were used to heat the water in wash 889, 124.9 MWh/year of electricity could be saved, see table 6.

Table 6. The heat exchanger loads and electricity saving possibilities by heat exchanging the outlet furnace gases in the main furnaces with the water in wash 889.

Furnace	123	124	125	126	Total
HX load during operation (kW)	2.16	2.16	8.88	2.16	15.37
HX load in stand-by (kW)	1.79	1.79	7.90	1.79	13.27
Utilization ratio (-)	0.86	0.78	0.69	0.82	0.79
HX mean load (kW)	2.11	2.08	8.57	2.10	14.86
Saved electricity consumption (MWh/year)	17.7	17.5	72.0	17.6	124.9

At normal production rate, the exhaust gases from these four furnaces would be sufficient to heat wash 889. The furnace 602 is located further away from this wash and it would be much piping to connect this furnace to the same heat exchanger. To use the waste heat from furnace 602, a similar solution could be installed in the small line. This would however have a smaller chance to be profitable since it would only include one furnace and it would not replace all heating in the wash.

5.3.4 Compressor

The inlet to the compressor is situated in the compressor room. If the inlet was moved outdoors, electricity could be saved due to the lower inlet temperature. The average room temperature was assumed to be 20°C and the average outdoor temperature was assumed to be 8°C. A 12°C lower inlet temperature would give 4% lower electricity consumption in the compressor. [19] This would save 15.6 MWh/year of electricity.

Approximately 85% of the electricity consumption of a compressor will be transformed into waste heat. [19] There is currently no waste heat recovery in the compressor. The electricity consumption of the compressor would be 368.2 MWh/year instead of 488 MWh/year, if the compressed air system was searched for leaks and those were fixed and the inlet was moved outdoors. It would then generate 328.3 MWh/year of waste heat. This heat could for example replace the district heating that is used to heat the offices and the tap water, since the cooling circuit in the compressor has a high enough temperature. This would save 120 MWh/year of district heating and there would be no need to buy district heating.

It would be desirable to use the remaining waste heat in the process. One alternative is to heat the water in one wash with waste heat from the compressor. This could however be difficult to achieve in reality since the washes are located far from the compressor room. The investment was considered to be too complicated to be further investigated.

5.3.5 New Installation in Ventilation Heat Exchangers

To completely remove the need for district heating, another investment also has to be made. The piping and heat exchangers for the heat exchange between the cooling water and the ventilation inlet in three of the aggregates was only a temporary solution to reduce the need for district heating. The piping would need to be substituted with corrosion resistant tubes making it a permanent installation. If this is not done, an additional 262 MWh/year of district heating will be needed in the plant.

5.3.6 Total Savings by Energy Saving Investment Measures

The saved energy, costs and carbon dioxide emissions for the energy saving investment measures have been summarised in table 7. As can be seen in the table, approximately 400 MWh/year of electricity and almost 400 MWh/year of district heating can be saved by these measures. This would save more than 650 000 SEK/year in energy cost. The carbon dioxide emissions from the plant would decrease with approximately 300 tonCO_2/year. It should be noted that 262 MWh/year of the saved district heating consumption is not a direct decrease, but an avoided increase of consumption.

Table 7. Energy, cost and emission savings for the energy saving investment measures.

Investment	Saved energy consumption (MWh/year)	Saved energy cost (SEK/year)	Saved carbon dioxide emission (tonCO_2/year)
Low energy lighting	168.8	120 300	100
Insulation of inner door hoods	108.7	77 400	65
Move compressor intake	15.6	11 100	9
HX exhaust gases/ washing water	124.9	89 000	75
HX compressor/ offices	120.0 (district heating)	100 500	13
New HX ventilation air/ cooling water	262.0 (district heating)	278 400	28
Total	800	676 700	290

5.4 Economic and Environmental Assessment

The energy saving measures described in section 5.3 all need an investment to be realised. The investment costs for measure 1-6, which are used for the economic assessment are listed in table 8.

Table 8. Investment costs for the economic assessment.

Measure	Investment Cost (SEK)
1. Low energy lighting	1 081 000
2. Insulation of door hoods	5 700
3. Move intake to compressor	10 000
4. Heat exchange furnace gas/washing water	150 000
5. Heat exchange compressor/offices	570 000
6. Install new piping for heat exchange in three ventilation aggregates	350 000

The above listed measures have all been evaluated both by the payback period method and by the net present value method, see section 4.5. The results from the economic assessment can be seen in table 9. The payback period should mainly be used as a risk analysis, since it only regards the present value of an investment. The net present value is based on all costs and cost savings during the next ten years after the investment is made, and is a better measurement of the profitability. The net present value ratio can be used to compare the investments with each other.

Table 9. Economic assessment of the six energy saving measures that need an investment to be realised.

Measure	Annual savings (SEK/year)	Payback period (year)	Net present value (SEK)	Net present value ratio (-)
1. Low energy lighting	120 300	8.99	2 666 600	2.7
2. Insulation of door hoods	77 400	0.07	2 406 200	422.1
3. Move intake to comp.	11 100	0.90	336 300	33.6
4. HX furnace gas/wash	89 000	1.69	2 622 100	17.5
5. HX compressor/offices	100 500	5.67	2 560 600	4.5
6. New piping in ventilation	278 400	1.26	8 321 500	23.8

As can be seen in table 9, all the investments can be considered profitable over a ten year period since all net present values are positive. The heat exchange between the waste heat from the compressor and the heating of the offices and the low energy lighting have much longer payback periods than the other investments. The payback period for the heat exchanging is over five years and this investment has a low net present value ratio. The payback period for the low energy lighting is nine years and has the lowest net present value ratio. These investments could be regarded as a high risk due to the long payback periods. When comparing the net present value ratios, it is found that the insulation of the door hoods is the most profitable investment. However, the much longer life time of low energy lighting is not included in the annual cost savings for the low energy lighting investment. If these were included, the payback period would be shorter.

A sensitivity analysis based on increased energy prices has been carried out. The results are presented in table 10. It was assumed that the energy prices will increase linearly over the next ten years and reach levels of 25% above the current price for electricity and 15% above the current price for district heating. As can be seen in table 10, including increasing energy prices in the calculations results in more profitable investments.

Table 10. Economic assessment with increasing energy prices of the six energy saving measures that need an investment to be realised.

Measure	Annual savings (SEK/year)	Payback period (year)	Net present value (SEK)	Net present value ratio (-)
1. Low energy lighting	135 300	7.99	3 135 000	2.9
2. Insulation of door hoods	87 100	0.07	2 707 700	475.0
3. Move intake to comp.	12 500	0.80	379 600	38.0
4. HX furnace gas/wash	100 100	1.50	2 968 600	19.8
5. HX compressor/offices	108 000	5.28	2 795 400	4.9
6. New piping in ventilation	299 300	1.17	8 971 900	25.6

5.5 Total Savings

To be able to compare different investment possibilities, four different scenarios have been investigated. The first scenario is that nothing is changed in how the plant is run, except that the damper in the ceiling of preheating furnace 915 has been closed. This case is called ‘Today’ in the figures and tables. The second scenario is called ‘Case I’ and includes all energy housekeeping measures described in section 5.2. This scenario does not imply any investments at all. The third scenario, called ‘Case II’, includes all energy housekeeping measures and investment measures 2 and 3, i.e. insulation of door hoods and moving the intake to the compressor. These measures need smaller investments to be realised. The last scenario is called ‘Case III’ and includes all proposed energy saving measures, i.e. both the energy housekeeping measures and investment measure 1-6.

The energy consumption in the plant for the different cases can be seen in figure 20. As shown in the figure, the need for district heating is constant for all cases except for case III where it is completely removed.

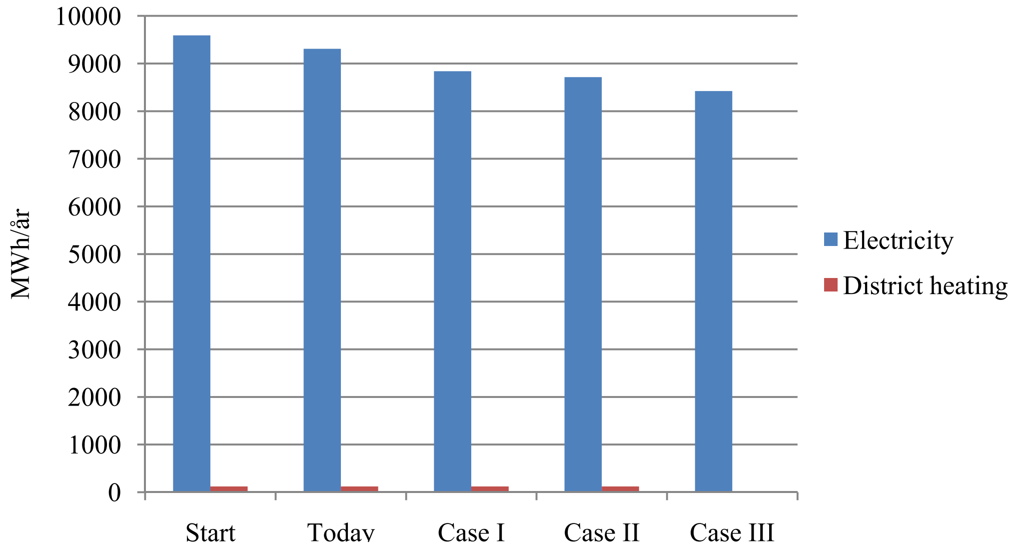

Figure 20. The energy consumption in the plant at the start of the project, today and for the three cases.

The total energy cost for the cases is shown in figure 21. As can be seen in the figure, implementing case III would lower the energy costs with almost 1 MSEK/year.

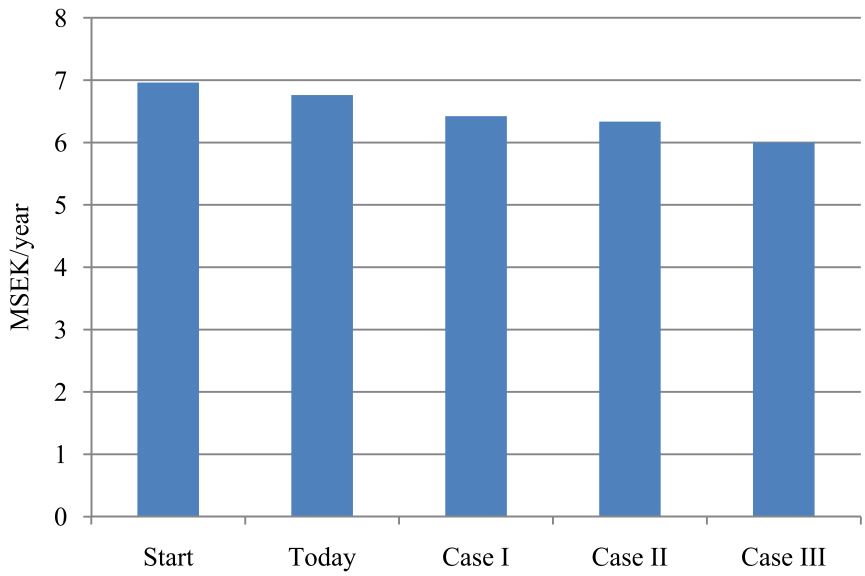

Figure 21. The energy cost at the start of the project, today and for the three cases.

The saved carbon dioxide emissions for the cases can be seen in figure 22. The large difference between case II and case III is mainly due to the investment in low energy lighting. However, the difference between these two scenarios is not that large, even though case III includes all the investment measures. This depends on that district heating has a much lower emission value than electricity and case III mostly includes measures that remove the need for district heating.

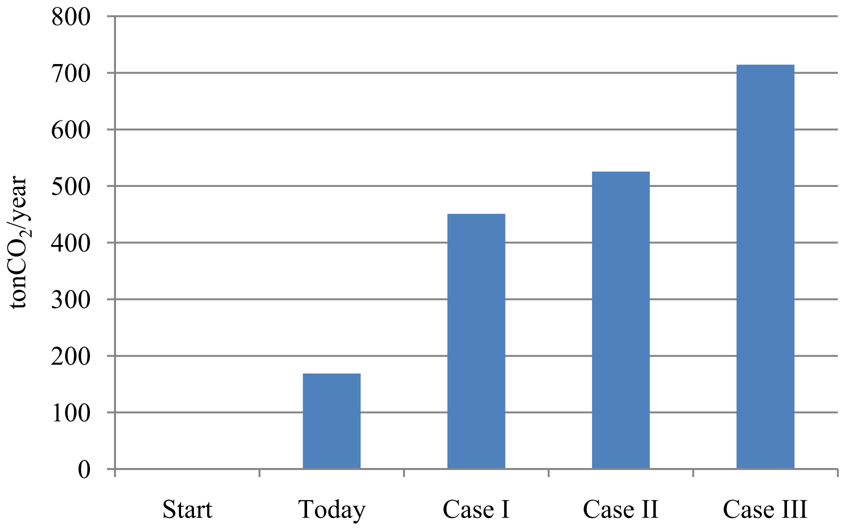

Figure 22. The saved carbon dioxide emissions today and for the three cases.

The results in figure 20-22 are summarised in table 11. The carbon dioxide emissions are not presented as percentage of the total emissions, since the entire electricity consumption in the plant should not be regarded as marginal electricity. Marginal electricity is a good measure when considering changes in electricity consumption, but for an existing, continuous consumption, average electricity should be used.

Table 11. The saved energy, costs and carbon dioxide emissions presented in numbers and as percentage of the total in brackets.

Scenario	Energy savings (MWh/year)	Cost savings (SEK/year)	CO_2 emission savings ($tonCO_2$/year)
Today	281 (2.9%)	200 200 (2.9%)	169
Case I	753 (7.7%)	536 600 (7.7%)	452
Case II	876 (9.0%)	624 100 (9.0%)	526
Case III	1 552 (15.5%)	1 208 500 (16.7%)	742

As can be seen in table 11, the decreases in energy consumption, energy cost and carbon dioxide emissions for case III do not match the shown decreases in figures 20 and 21. This depends on that the avoided increase in district heating consumption (by investing in new pipes and heat exchangers in three ventilation aggregates) is included in table 11, but not in figures 20 and 21.

An economic assessment of case II and case III has been made. The results can be seen in table 12 and 13. Increasing energy prices have been included in the results in table 13. Only the savings due to the investments are included in the annual savings for the cases in these tables.

Table 12. Economic assessment of case II and case III.

Measure	Investment (SEK)	Annual savings (SEK/year)	Payback period (year)	Net present value (SEK)	Net present value ratio (-)
Case II	15 700	88 500	0.18	2 742 500	174.7
Case III	2 166 700	676 700	3.20	18 913 300	8.7

Table 13. Economic assessment of case II and case III including increasing energy prices.

Measure	Investment (SEK)	Annual savings (SEK/year)	Payback period (year)	Net present value (SEK)	Net present value ratio (-)
Case II	15 700	99 600	0.16	3 087 300	196.6
Case III	2 166 700	742 400	2.92	20 958 200	9.7

As can be seen in the tables above, case II has a very short payback time and a high net present value ratio and can be seen as a profitable investment. Case III should also be regarded as profitable since the net present value is positive. Even though the net present value ratio is much lower than for case II, the payback time for case III is only around three years and its net present value is very high.

The specific energy usage in the plant for case III can be seen in table 14. The specific energy usage at the start of the project is also included as a comparison.

Table 14. Specific energy usage in the plant at the start of the project and if case III is implemented.

	Energy use/Production time (MWh/h)	Energy use/Turnover (MWh/kSEK)	Energy use/Amount goods (MWh/ton)
Start of project	1.16	0.18	2.93
Case III	0.97	0.15	2.47

Figure 23 illustrates a fish bone diagram for case III. The energy demands on the left side of the boxes are the demands at the start of the project and the energy demands on the right side of the boxes are the energy demands if case III is implemented.

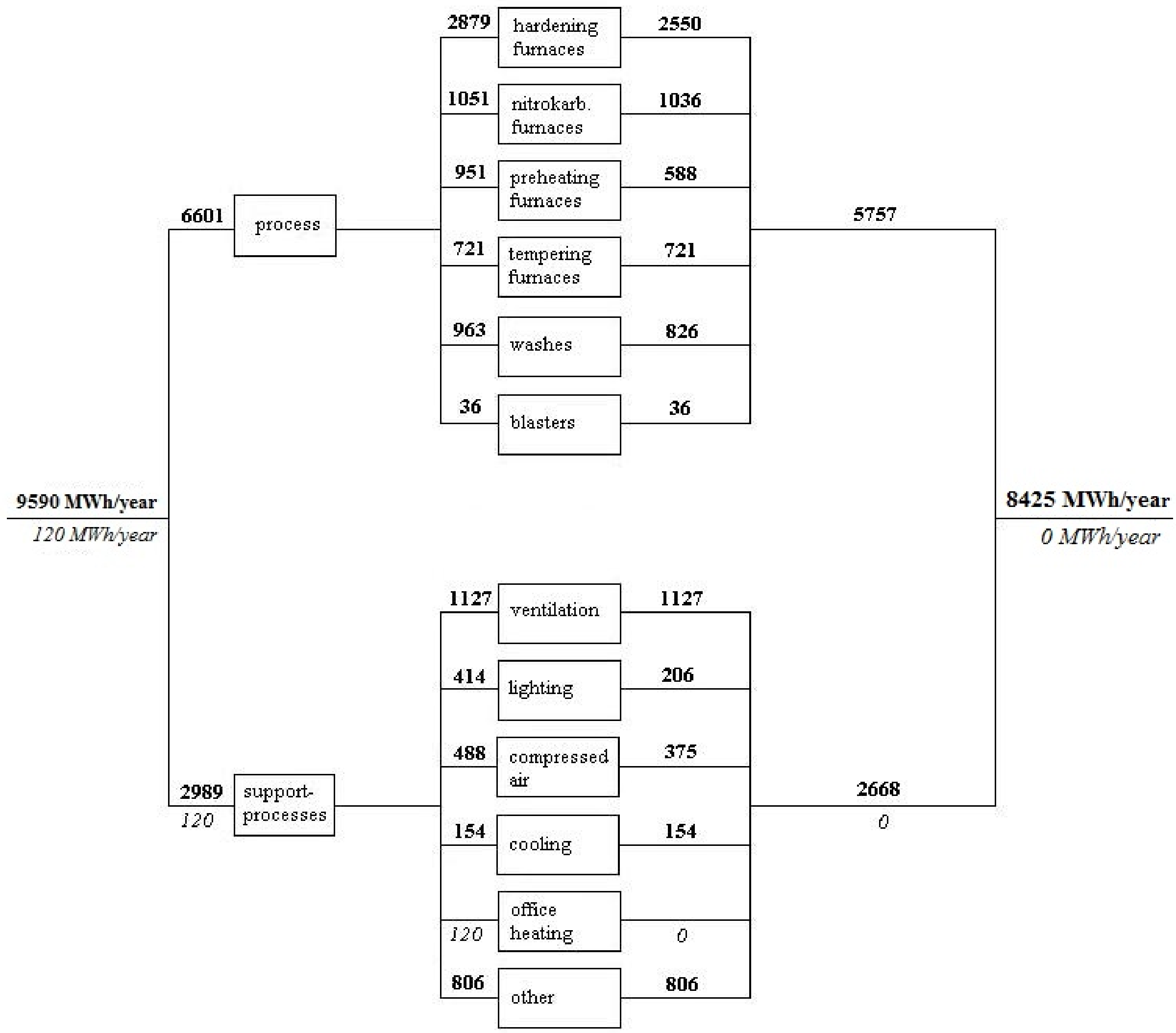

Figure 23. The energy consumption distribution in MWh/year in the plant at the start of the project and after implementation of case III presented as a fish bone diagram. The numbers in bold are electricity demand and the numbers in italic are district heating demand.

6 Discussion

Bodycote Värmebehandling AB in Angered is already working with energy saving measures. In the past, they have managed to decrease their district heating demand with more than 90%. However, a large amount of electricity is consumed in the plant and this could be reduced by energy housekeeping measures and some investments. The largest possibility to reduce the electricity demand is by planning the production in a more energy efficient way. The utilization ratios for most of the furnaces and washes were calculated in this project and it was found that many of them were very low, some less than 50%. By planning the production so no more than the necessary number of furnaces is operating could save much electricity as stated in section 5.2.4. The washes have very low utilization ratios, but these cannot be turned off since some of them are used before heat treatment and some after treatment.

The production is already planned so that none of the manual equipment is used during weekends. To turn off the washes and preheating furnaces and lower the temperature in the hardening furnaces in this area during weekends, could save electricity without affecting the production at all. The effect of this will occur on Monday mornings when the equipment is turned on again. Power load peaks should be avoided by not turning all the equipment on at the same time.

The compressed air system is a large electricity consumer and could be decreased by a number of measures. To search the system for leaks would considerably decrease the electricity demand in the compressor since this is not regularly done. Another measure could be to sectionalise the system to reduce leaks and to be able to turn off for example the compressed air to the manual area during weekends.

The electricity demand in the compressor could be further reduced by moving the intake outdoors. It is a small investment cost and the payback period is shorter than one year. As the net present value is high, it can be regarded as a profitable investment.

Even if these measures mentioned above were implemented, the compressor still consumes much electricity and thus produces a lot of waste heat. This could be used to heat the offices and the tap water, for which district heating is used today. According to the calculation in section 5.4 this would be a fairly profitable investment, but the payback time is considered to be too long by Bodycote. The investment cost in this calculation is based on an offer and is considered to be very high. Therefore new offers will be requested by Bodycote and if the investment cost is reduced to 300 000 SEK, the payback time would be less than three years.

The investment for new piping in the ventilation aggregates can be considered profitable with a short payback time and high net present value and net present value ratio. An even more profitable investment is to insulate the door hoods on the furnaces in the large line. That investment would be repaid almost at once.

The furnaces produce a large amount of waste heat which currently is used only when the indoor exhaust air is heat exchanged with the indoor inlet air. This means that the waste heat is used after it is mixed with the ambient indoor air. The waste heat from the furnace gases could be used more efficiently as proposed in section 5.3.3. The heat exchanging of the exhaust furnace gases with the washing water can be regarded as a profitable investment. The payback period is less than two years and the net present value is positive and quite large.

It will become even more important in the future to use the waste heat from furnaces. EU is working on the Energy Using Product Directive (EuP) and this will include heat treatment furnaces. [23] According to Anders Jerregård at Jerrex, it will be standardised in the future to use these kinds of solutions to recover the waste heat from industrial furnaces.

The evaluation of the cases presented in section 5.5 showed that the investment scenarios case II and case III can be regarded as profitable investments. Two investments included in case III (heat exchange between the waste heat from the compressor and the heating of the offices, and low energy lighting) had a payback time of more than five years when they were evaluated individually. However, if all measures included in case III can be seen as one large investment, it is a profitable investment which is paid back in three years.

Compressed air is not an efficient energy carrier and it should be regarded when new furnaces are purchased. To install new furnaces with electrically driven doors would reduce the demand for compressed air. However, as long as some furnace doors still are driven by compressed air, the compressed air system will remain in operation. It may not be a considerable energy saving to use electrically driven furnace doors until all furnaces are replaced. To rebuild the existing furnaces to only use electricity does not seem not to be a possible alternative today.

Another concern to keep in mind when investing in a new furnace is the preheating of the batches. Today the preheating furnaces are completely detached from the main furnaces and one preheating furnace is not specifically connected to one main furnace. This allows for a flexibility of the production. However, the charge is cooled down when it is transported from the preheating furnace to the main furnace and this could be avoided by having so called three-chamber furnaces. In a three-chamber furnace, the furnace consists of a preheating chamber, a heating chamber and a quenching chamber. This configuration reduces the heat losses from the preheating chamber and the heating chamber, and eliminates the heat losses from the transport between the preheating furnace and the main furnace.

When investing in new nitrocarburizing furnaces the energy efficiency should be regarded when choosing between one-chamber and two-chamber furnaces. It is very uncommon to use two-chamber furnaces for these processes and most heat treating plants only have one-chamber furnaces. Much energy is lost in one-chamber furnaces since the entire furnace is cooled together with the charge and needs to be heated for the next batch.

7 Conclusions

The energy audit and the investigation of energy efficiency opportunities at Bodycote Värmebehandling AB in Angered can be summarised with the following conclusions:

- The plant consumed 9 590 MWh/year of electricity and 120 MWh/year of district heating at the start of the project.
- 68% of the energy was consumed in the process and 32% of the energy was consumed in the support processes.
- The largest part of the energy consumption in the process is consumed in the main furnaces.
- The electricity consumption could be decreased with 753 MWh/year by energy housekeeping measures.
- The electricity consumption could be further decreased with 418 MWh/year and the district heating demand could be removed by energy saving investment measures.
- The proposed energy housekeeping measures and energy saving investment measures could together reduce the energy cost with approximately 1.2 MSEK7year and reduce the carbon dioxide emissions with approximately 740 tonCO_2/year.
- If all proposed measures were implemented, the combined investments would have a payback time of three years and a net present value of almost 19 MSEK over a time frame of ten years and with current energy prices.

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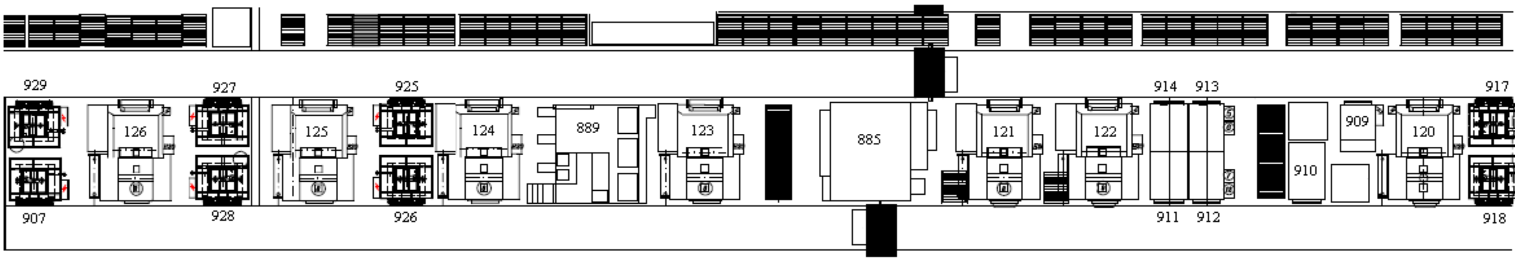
Appendix A – Detailed Plant Outline

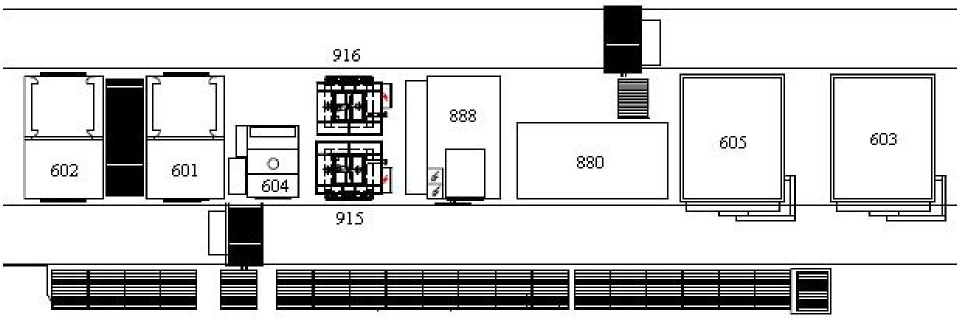
The arrangement of the equipment in the large line can be seen in figure I.



120	Hardening furnace	913	Preheating furnace	911	Tempering furnace
121	Hardening furnace	914	Preheating furnace	912	Tempering furnace
122	Hardening furnace	917	Preheating furnace	918	Tempering furnace
123	Hardening furnace	925	Preheating furnace	926	Tempering furnace
124	Hardening furnace	927	Preheating furnace	928	Tempering furnace
125	Nitrocarburizing furnace	929	Preheating furnace	885	Wash
126	Hardening furnace	907	Tempering furnace	889	Wash
909	Preheating furnace	910	Tempering furnace		

Figure I. The equipment arrangement in the large line.

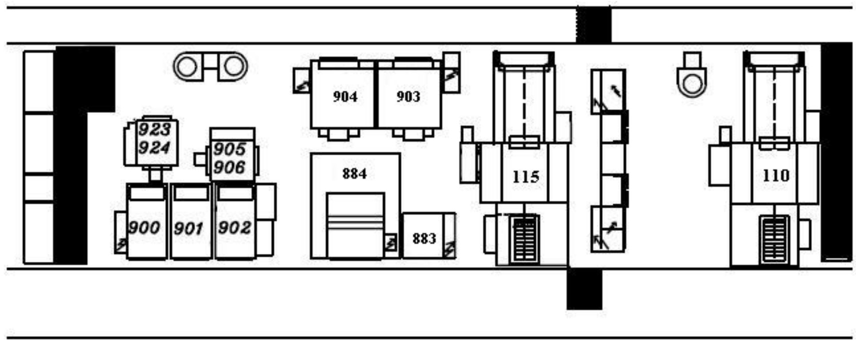
The arrangement of the equipment in the small line can be seen in figure II.



601	Two-chamber furnace	915	Preheating furnace
602	Two-chamber furnace	916	Tempering furnace
603	One-chamber furnace	880	Wash
604	One-chamber furnace	888	Wash
605	One-chamber furnace		

Figure II. The equipment arrangement in the small line.

The arrangement of the equipment in the manual area can be seen in figure III.



110	Manual hardening furnace	923	Tempering furnace
115	Manual hardening furnace	924	Tempering furnace
900	Tempering furnace	903	Preheating furnace
901	Tempering furnace	904	Preheating furnace
902	Tempering furnace	883	Wash
905	Tempering furnace	884	Wash
906	Tempering furnace		

Figure III. The equipment arrangement in the manual area.

Appendix B – Assumptions for Consumption Mapping

Table I. Outline of the assumptions made for the electricity consumption mapping for the large line and the manual area.

Large line		Manual area	
Furnace 120	One furnace is assumed to be turned off	Furnace 110	Measured
Furnace 121	Assumed to consume half as much as furnace 122	Furnace 115	Measured
Furnace 122	Measured	TF 900	Assumed to consume same amount as TF 901
Furnace 123	Measured	TF 901	Measured
Furnace 124	Measured	TF 902	Assumed to consume same amount as TF 901
Furnace 125	Measured	TF 905	Assumed to consume same amount as TF 901
Furnace 126	Measured	TF 906	Turned off
PF 909	Turned off	TF 923	Turned off
PF 913	Assumed to consume same amount as PF 927	TF 924	Turned off
PF 914	Assumed to consume same amount as PF 927	Wash 883	Measured
PF 917	Turned off	Wash 884	Measured
PF 925	Assumed to consume same amount as PF 927	PF 903	Measured
PF 927	Measured	PF 904	Assumed to consume same amount as PF 903
PF 929	Assumed to consume same amount as PF 927		
TF 907	Measured		
TF 910	Turned off		
TF 911	Assumed to consume same amount as TF 907		
TF 912	Assumed to consume same amount as TF 907		
TF 918	Assumed to consume same amount as TF 907		
TF 926	Assumed to consume same amount as TF 907		
TF 928	Assumed to consume same amount as TF 907		
Wash 885	Measured		
Wash 889	Measured		

Table II. Outline of the assumptions made for the electricity consumption mapping for the small line and the remaining equipment.

Small line		Other	
Two-chamber furnace 601	Turned off	Ventilation 1	Measured instantaneously
Two-chamber furnace 602	Measured	Ventilation 2	Measured instantaneously
One-chamber furnace 603	Assumed to consume same amount as 605 in stand-by and to be used half as much as 605.	Ventilation 3 Ventilation 4	Measured
One-chamber furnace 604	Measured	Ventilation 5	Measured instantaneously
One-chamber furnace 605	Measured	Ventilation 6	Measured
PF 915	Measured	Cooling tower 1	Measured
TF 916	Measured	Cooling tower 2	Assumed to consume same amount as cooling tower 1
Wash 880	Measured	Cooling (total)	Measured
Wash 888	Measured	Compressor	Measured
		Blasting unit 1	Measured
		Blasting unit 2	Assumed to be used half as much as blasting unit 1
		Lighting	Calculated

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