Wallpaper drying solutions

Feasibility study of a low temperature drying process

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Master’s Thesis in Energy Systems
Preface

First of all we want to thank all the people of Högskolan I Gävle whom welcome us so kindly, the staff of the international office and the teachers. Thanks also to the University of Pau and especially Jean-Pierre Bédécarrats that gave us the possibility to study in Sweden.

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Abstract

The wallpaper company Duro Sweden AB, one of the most important Scandinavian wallpaper manufacturers, wants to decrease its energy use and costs and make its production more environmentally friendly. It implies changes in the key process energy use whom consists mainly by drying process using heat production from oil.

The purpose of this project, studied by the consulting company Sweco Theorells AB, is to determine the feasibility of a change in the energy utilisation implemented to the most representative process to propose future solutions’ basis on the future energy question.

The company use mainly two kind of energy, electricity with 1055MWh per year and oil with 1985MWh per year. The oil power consumption and cost represent respectively 65% and 73% of the global part.

Several proposed changes with better energy efficiency are presented: use of district heating as a heat source, Infrared Drying, combination, etc; but due to the important rebate make by the Swedish government on the oil price, they are not currently viable to achieve.

But the constant rise of the oil price could be sooner a strong incentive to make these improvements, strongly environmental friendly and power consumption reducer, economically viable in the long term.

Are shown below the result of the study with in % the increase or decrease on different view\(^1\) compared to the existing process.

\(^1\) The Optimisation's numbers refers to the use of a new heat recovery exchanger, use of only district heating as heat source, use of only Infrared Drying and finally combination with infrared drying and district heating.
Figure 1: Solution comparison radar graphs
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<tr>
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<td>Velocity</td>
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<td>( E )</td>
<td>Energy</td>
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<td>( m )</td>
<td>Mass</td>
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<td>( g )</td>
<td>Gavitational acceleration</td>
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<td>height</td>
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<td>( V )</td>
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<td>( h )</td>
<td>enthalpy</td>
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<td>( k )</td>
<td>thermal conduction</td>
<td>( \text{W.m}^{-1}.\text{K}^{-1} )</td>
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<td>( e )</td>
<td>thickness</td>
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<td>( A )</td>
<td>Area</td>
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<td>( T )</td>
<td>temperature</td>
<td>( \text{K or °C} )</td>
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<tr>
<td>( h \text{c} )</td>
<td>Convection coefficient</td>
<td>( \text{W.m}^{-2}.\text{K}^{-1} )</td>
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<td>( P )</td>
<td>Pressure</td>
<td>( \text{Pa} )</td>
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<td>( \text{RH} )</td>
<td>Relative humidity</td>
<td>%</td>
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<td>( \nu^* )</td>
<td>Specific volume</td>
<td>( \text{m}^3.\text{kg}^{-1} )</td>
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<td>( S )</td>
<td>entropy</td>
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<td>( n )</td>
<td>Mole number</td>
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<td>( \text{Ex} )</td>
<td>Exergy</td>
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**Subscripts**

- \( \text{a} \): air
- \( \text{in} \): inlet
- \( \text{out} \): outlet
- \( \text{wp} \): Water paper
- \( \text{wev} \): Water evaporate
- \( \text{k} \): kinetic
- \( \text{p} \): potential
- \( \text{t} \): total
- \( \text{cd} \): conduction
- \( \text{cv} \): convection
- \( \text{r} \): radiation
- \( \text{fg} \): vaporization
- \( \text{th} \): thermal
- \( \text{sat} \): saturation
- \( \text{0} \): Reference state
- \( \text{dest} \): destructed
- \( \text{gen} \): generated
- \( \text{ex} \): exergetic
- \( \text{L} \): loss
- \( \text{tr} \): transit
- \( \text{ch} \): chemical

**Greek letters**

- \( \omega \): Specific humidity \( \text{kg.kg}_{\text{product}}^{-1} \)
- \( \phi \): Thermal flux \( \text{kW} \)
- \( \varepsilon \): Radiation coefficient
- \( \sigma \): Stephan-Boltzmann constant \( \text{W.m}^{-2}.\text{K}^{-4} \)
- \( \pi \): Pi
- \( \eta \): efficiency \%
- \( \mu \): Chemical potential \( \text{J.mole}^{-1} \)
- \( \psi \): Specific exergy \( \text{kJ.kg}^{-1}.\text{K}^{-1} \)
- \( \Delta \): Difference

**Exposant**

- \( . \): Flow rate
1 Introduction

1.1 Background

The part of industry’s power consumption is an important one in the energetic balance of Sweden (35-40%). It implies the economical and environmental impacts make the study of the industrial systems a major issue with wide prospects of energy savings.

The wallpaper company Duro Sweden AB, one of the most important Scandinavian wallpaper manufacturers, wants to decrease energy use and energy costs and make its production more environmental friendly mainly by changing the heat production from oil to another form. Indeed the still rising oil cost and its impact on the environment are the mean incentives to this decision.

The production processes of the company consist mainly in drying processes and represent the main part of the global energetic consumption. Because of the high latent heat of vaporization and the inherent inefficiency of using hot air as the (most common) drying medium, drying process are ones of the most energy intensive operations with a great industrial significance.

1.2 Purpose and report contents

The purpose of this study is to determine the feasibility of a change in the energy utilisation implemented to the most representative process to propose future solutions’ basis on the future energy question.

The report begins by introducing the company, the drying process in question and the different measurements tools in our possession necessary to understand the process behaviour.

Then presentation of the applied theory is showed concerning the energy, exergy, environmental and economical analysis including the aims and limitations.

Next, follows a deeper insight of the existing process with the measurement and the assumptions made and presentation for process improvement.

To conclude, discussion and comparison of all the proposed changes are showed.

1.3 Company

The thesis subject was ordered by a company called Duro Sweden AB, situated in Gävle, Sweden. Their purpose is to produce different types of decoration wallpaperto suit any kind of surface and indoor climate. Duro Sweden AB makes a point to be as
environmentally friendly as possible. All their wallpapers are produced from harmless raw materials for the environment and health. The ink used in the printing process is a water-based ink also harmless for the environment. This also results in that no harmful waste is produced in the wallpaper production process.

In order to extend the environment friendly matter and to be in ad equation with the increasing economical competition, they purchased a study to reduce the energy cost of producing the wallpaper.

1.4 Process

The factory has several dryers and the process studied is the dryer number 3. This one is applied to dry the simplest wallpaper (only one color with no patterns). Several kinds of water based inks and different types of paper are used. The characteristics of the different papers and inks used on the device studied are indicated in Appendix 4.

The objective of the dryer is to supply the product with more heat than is available under ambient conditions thus removing a significant part of the moisture content of the product. Wet wallpaper covered by paint is introduced into the device at a constant speed. Some drying air is supplied at a certain temperature and humidity to absorb the water content of the wallpaper, contained in the ink. The moist air is then rejected to the outside. The device by its geometry and its size is losing a small part of energy to the surrounding (Figure 2).

**Figure 2: Schematic wallpaper drying process**
1.5 Tasks

The main objective of the company is to take off the oil as the primary energy source because of this still rising price and for strong environmental reasons.

There are some limitations on the energy sources that we can use to implement the future proposed changes. Indeed, Duro Sweden AB wants to know if it's possible and realistic for it to use heat from district heating\(^2\), means dry at a lower temperature than the current one used.

Then other means can be studied to achieve the drying process. From all the heat transfer methods to dry, are studied only the convection and radiation. Indeed the conduction is usually used by huge drying systems with high speed rate (paper pulp industry) with steam cylinders as pre-dryer because they are not suitable when a surface effect is required. Furthermore, the uses of gases and oil are to avoid as much as possible. For example a studied was achieved few years ago about the possibility of using chip wood in a boiler as heat source, but the lack of flexibility and the short response's time are determinant for the company.

In order for us to better understand the current process, an energy survey has been achieved on the power and the energy needs, a measurement campaign was achieved, by a top-down approach, to figure out some unknown parameters like the power and energy need, temperatures, air flow rates, electrical powers and relative humidity contents concerning the process studied.

Then, after stated the working references of this process, the alternatives proposed will be compared with the same references in order to be as accurate as possible and see instantly the differences.

\(^2\) Called DH in abbreviated form.
2 Theory

2.1 Mass conservation

The air conditioning as well as the wallpaper conditioning can be modelled as steady-flow processes that are analyzed by applying the steady-flow conservation of mass (for dry air, dry wallpaper and moisture).

General equation of mass conservation of drying air:

\[ \sum \dot{m}_{a,\text{in}} = \sum \dot{m}_{a,\text{out}} \]

General equation of mass conservation of dry wallpaper:

\[ \sum \dot{m}_{wp,\text{in}} = \sum \dot{m}_{wp,\text{out}} \]

General equation of mass conservation of moisture:

\[ \sum (\dot{m}_{w,\text{in}} + \dot{m}_{w,\text{ev}}) = \sum \dot{m}_{w,\text{out}} \]

\[ \sum (\dot{m}_{a,\text{in}} \omega_{a,\text{in}} + \dot{m}_{w,\text{ev}}) = \sum \dot{m}_{a,\text{in}} \omega_{a,\text{out}} \]

\[ \sum \dot{m}_{wp,\text{in}} \omega_{wp,\text{in}} = \sum (\dot{m}_{wp,\text{in}} \omega_{wp,\text{out}} + \dot{m}_{w,\text{ev}}) \]

2.2 Energy analysis

2.2.1 Energy conservation

William Rankine amalgamated these definitions with the laws of thermodynamics and defined the first law of thermodynamics. Energy cannot be destroyed:

\[ dU = \delta Q - \delta W \]
where $\delta Q$ is the amount of energy added to the system by a heating process, $\delta W$ is the amount of energy lost by the system due to work done by the system on its surroundings and $dU$ is the increase in the internal energy of the system.

2.2.2 Energy conservation applied in an open system.

![Figure 3: schematic open system](image)

The energy exchanges of mechanical and thermal origin involve a variation of energy of the system or total energy $\Delta e_t$. When the system is opened, for matter flows through the border (exchanges), it is necessary to take account of energy accompanying the matter which enters or leaves the system by various drains $i$. This energy arises in three forms (in the usual studies of thermal energy) which, for a lapse of time $t$ are written:

- intern energy = $\sum u_i m_i$
- kinetic energy = $\sum \frac{1}{2} m_i c_i^2$
- potential energy = $\sum m_i g_i z_i$

where $m_i$ is the mass of fluid corresponding to the matter flow in drain $i$ during time $t$; it is positively counted if the fluid enters the system; $u_i$, $c_i$, $z_i$ are respectively mass internal energy, the speed and the altitude of the fluid when this one crosses the border between the system and the external medium. Taking a single value for $u$, $c$ and $z$ supposes that the temperature, the pressure, speed and altitude are constant at the point where the fluid crosses the border. It is a simplifying assumption, justified in the majority of the applications. Note that if the fluid is a gas, the variation of potential energy is always negligible compared to the other terms.

In the energy balance of an open system, one considers separately the mechanical energy exchange $\partial W_t$ of the system with the outside except the contribution drains ($\partial W_t$
corresponds to the energy recovered or produced on the moving parts of the system. It is necessary thus to introduce in addition into the assessment, the energy transfer by the piston effect of the fluid in transit in the drains. This energy has as an expression:

\[ \sum_i P_i \Omega_i l_i \]

or, if considering \( \Omega_i l_i = m_i \nu_i \),

\[ \sum_i m_i \nu_i P_i \]

Thus, for an evolution in an infinitely short lapse of time \( dt \), the first principle of thermodynamics is written:

\[
\partial W_i + \partial Q + \sum_i h_i dm_i + \sum_i \frac{c_i^2}{2} dm_i + \sum_i \zeta_i g dm_i = dU + dE_c + dE_p
\]

If: \( h_t = h + \frac{c^2}{2} + g \cdot z \) the total enthalpy by mass unity of fluid.

And:

\[ E_i = U + E_p + E_c \]

The equation becomes

\[
\partial W_i + \partial Q + \sum_i h_t dm_i = dE_t
\]

The equation [7] is valid whatever the number of flow matters (or of drains), whether the mode is permanent or transitory. One can give him a form in power by dividing it by the lapse of time \( dt \):

\[
\dot{W}_i + \dot{Q} + \sum_i h_t \dot{m}_i = \dot{E}_t
\]

with

- \( \dot{W}_i \): technical power of system or mechanical power exchanged between fluid and variable components of machines found inside border
- \( \dot{Q} \): thermal power exchanged between system and external medium
- \( \dot{m}_i \): mass throughput of fluid through drain \( i \) (positive if the fluid enters the system)
- \( \dot{E}_t \): variation of the total energy of the system during the unit of time.

This equation is doubtless the most important of all the relations attached to the first principle of thermodynamics presented in its technical form.

In our drying process, we will take in consideration the kinetic energy of the fan while the potential and kinetic energy in other parts of the process are neglected. The equation above then becomes for the air side:

\[
\dot{Q} - \dot{W}_t = \sum \dot{m}_{out} \left( h_{out} + \frac{c_{out}^2}{2} \right) - \sum \dot{m}_{in} \left( h_{in} + \frac{c_{in}^2}{2} \right)
\]
2.2.3 Heat transfer

\[ \dot{Q} = \dot{Q}_{in} - \dot{Q}_{out} \]

The amount of loss of heat is exchanged with the surrounding by three modes: conduction, convection and radiation.

2.2.3.1 Conduction

For a heat transfer through a plane surface (external body of the dryer for example) we will use the following equation:

\[ \Phi_{cd} = \frac{k}{e} \cdot A \cdot \Delta T \]

with 
- \( k \) thermal conduction coefficient (W.m\(^{-1}\).K\(^{-1}\))
- \( e \) thickness of the surface (m)
- \( A \) area of the surface (m\(^2\))
- \( \Delta T \) difference of temperature between the limits of the surface (K)
- \( \Phi_{cd} \) thermal flux by conduction (W)

2.2.3.2 Convection

For a heat transfer between moving media will use the following equation:

\[ \Phi_{cv} = h c \cdot A \cdot \Delta T \]

with
- \( h c \) convection coefficient (W.m\(^{-2}\).K\(^{-1}\))
- \( A \) area of the surface (m\(^2\))
- \( \Delta T \) difference of temperature between the limits of the surface (K)
- \( \Phi_{cv} \) thermal flux by convection (W)

2.2.3.3 Radiation

For a heat transfer by radiation will use the following equation:

\[ \Phi_{r} = \varepsilon \cdot \sigma \cdot A \left( T_1^4 - T_2^4 \right) \]

with
- \( \sigma \) Stefan-Boltzmann constant = 5.67.10\(^{-8}\) (W.m\(^2\).K\(^{-4}\))
- \( \varepsilon \) coefficient (1 for a black body)
- \( A \) area of the surface (m\(^2\))
- \( T \) temperature (K)
- \( \Phi_{r} \) thermal flux by radiation (W)
2.2.4 Phase change

2.2.4.1 Evaporation

Evaporation of water from the Earth’s surface forms one part of the water cycle. At 100°C, the boiling point, all water will rapidly be turned to vapour, for the energy supplied to the water is enough to break apart all the molecular bonds in water.

\[ Q_{\text{evap}} = \dot{m}_{\text{wev}} h_{fg} \]

with
- \( \dot{m}_{\text{wev}} \) Water evaporation flow rate (kg.s\(^{-1}\))
- \( h_{fg} \) heat of vaporization (kJ.kg\(^{-1}\))
- \( Q_{\text{evap}} \) Power of evaporation (kW)

At temperatures between 100°C and 0°C, only some of the molecules in the water have enough energy to escape to the atmosphere and the rate at which water is converted to vapour is much slower.

The rate of evaporation will depend upon a number of factors. Rates increase when temperatures are higher. An increase of 10°C will approximately double the rate of evaporation. The humidity of the surrounding air will also influence evaporation. Drier air has a greater "thirst" for water vapour than humid, moist air. It follows therefore, that the presence of air flow will also increase evaporation. Water evaporating to the air remains close to its source, increasing the local humidity. As the moisture content of the air increases, evaporation will diminish. If, however, a steady flow of air exists to remove the newly formed vapour, the air surrounding the water source will remain dry, "thirsty" for future water.

\[ \dot{m}_{\text{evap}}/m^2 = \left( P_{\text{vapor}} - P_{\text{ambient partial}} \right) \frac{M_{\text{water}}}{2.\pi.R.\text{T}} \]

A real situation involves the fact that the humidity near the interface is much higher than even a short distance away, and that the water vapor must diffuse away. This effect will slow the evaporation down quite a lot because the evaporation rate is proportional to the difference between the vapor pressure and the partial pressure of the substance, and diffusion can only take water away so fast. As the water evaporates, the partial pressure of water in the gas right over the water will be nearly equal to the vapor pressure, and then it will drop as you go away from the surface, and how steeply this drops (which depends on the airflow rate and how long the water has been there evaporating)
determines the rate at which water will diffuse away. Even with a fan blowing air past the surface, the process is limited by diffusion very close to the surface because a thin layer of air (called the "boundary layer") right next to the surface does not move relative to the surface. We won’t do the work on the diffusion as it takes a long time to calculate and it depends on the setup of the machine which is difficult to know. We will assume that the theoretical difference of evaporating rate will change the same as in the reality. Therefore, by finding a ratio between the theoretical evaporation rate at 100°C and at 60°C, we will apply this ration to the real process (Appendix 1).

2.2.5 Energy efficiency

2.2.5.1 Thermal efficiency

The thermal efficiency ($\eta_{th}$) is a dimensionless performance measure of a thermal device such as an internal combustion engine, a boiler, or a furnace, for example. The input, $Q_{in}$, to the device is heat, or the heat-content of a fuel that is consumed. The desired output is mechanical work, $W_{out}$, or heat, $Q_{out}$, or possibly both. Because the input heat normally has a real financial cost, a memorable, generic definition of thermal efficiency is:

$$\eta_{th} = \frac{\text{What you get}}{\text{What you paid for}}$$

The energy efficiency chosen to compare the current process and the proposed changes is:

$$\eta = \frac{\text{Energy needed to heat and evaporate the water of the product}}{\text{Energy input in the system}}$$

2.2.6 Air characteristics

We consider wet air as a perfect gas. As a result, the following equations are used.

2.2.6.1 Specific humidity:

$$\omega = 0,622 \frac{P_v}{P - P_v}$$

$\omega$ in kg.kg$^{-1}$, $P$, $P_v$ in Pa

2.2.6.2 Enthalpy of the mix:

$$h = (1,006 + 1,826\omega)T + 2500\omega$$

$\omega$ in kg.kg$^{-1}$, $T$ in °C, $h$ in kJ.kg$^{-1}$
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2.2.6.3 Wet temperature:

\[ T_w \approx T - \frac{2500(\omega_{sat}^w - \omega)}{(1,006 + 1,826 \omega_{sat}^w)} \]

\( T_w \) in °C, \( \omega_{sat}^w \) and \( \omega \) in kg.kg\(^{-1}\)

2.2.6.4 Relative humidity:

\[ HR = \frac{P_v}{P_{sat}(T)} \]

\( P_v, P_{sat} \) in Pa, \( \varphi \) in %

2.2.6.5 Liquid/vapor equilibrium:

\[ \log P_{sat} = \frac{7,625}{241 + T} + 2,7877 \]

\( P_{sat} \) in Pa, \( T \) in °C

2.2.6.6 Solid/vapor equilibrium:

\[ \log P_{sat} = \frac{9,756}{272,7 + T} + 2,7877 \]

\( P_{sat} \) in Pa, \( T \) in °C

2.2.6.7 Specific volume:

\[ v'' = \frac{461,52(0,622 + \omega)T}{P} \]

\( P \) in Pa, \( T \) in K, \( v'' \) in m\(^3\).kg\(^{-1}\)\(\cdot\)s\(^{-1}\), \( \omega \) in kg.kg\(^{-1}\)

2.2.6.8 Determination of the fan outlet conditions:

\[ h_{f,out} = \left[ \left( \frac{W_f}{2 \times 1000} \right) \left( \frac{1}{\dot{m}_{da}} \right) \right] + h_{f,in} \]

\( h_{f,out,in} \) in kJ.kg\(^{-1}\), \( W_f \) in W, \( V^2_{f,out} \) in m\(^2\).s\(^{-1}\), \( \dot{m}_{da} \) in kg.s\(^{-1}\)

2.2.7 Heat exchanger\(^3\)

Only counter courant heat exchanger will be consider in the study. In this type of HEX, the two fluids go in a different way, the inlet of one a the fluid being the exit of the second one. The equation that refers to an HEX is the following:

\[ \Phi = U \cdot A \cdot \Delta TLM \]

\(^3\) Called HEX in abbreviated form.
Where \( U \) is the global exchange coefficient (W.m\(^2\).K\(^{-1}\))

\[ \text{A the surface area of exchange (m}^2) \]

\[ \Delta T_{LM} \] the mean logarithmic difference (K)

\[ \Delta T_{LM} = \frac{(T_{h_{in}} - T_{c_{out}}) - (T_{h_{out}} - T_{c_{in}})}{\ln \left( \frac{T_{h_{in}} - T_{c_{out}}}{T_{h_{out}} - T_{c_{in}}} \right)} \]

Where \( T_{h_{in}} \) id the hot fluid inlet (K)

\( T_{h_{out}} \) is the hot fluid outlet (K)

\( T_{c_{in}} \) is the cold fluid inlet (K)

\( T_{c_{out}} \) is the cold fluid outlet (K)

### 2.3 Exergy analysis

#### 2.3.1 Exergy concept

Exergy is that part of energy that is convertible into all other forms of energy.

\[ H.D. \text{ Baehr (1965)} \]

The exergy concept has its roots in the early work of what would later become thermodynamics. The concepts of energy and exergy are related to the first two laws of thermodynamics: The amount of energy in the universe remains constant (First Law), but exergy is constantly used up (Second Law), proportionally to the entropy increase of the system together with its surroundings.

While the first law generally fails to identify losses of work and potential improvements or the effective use of resources, the second one shows that, for some energy forms, only a part of the energy is convertible to work.

Indeed the exergy concept is a general concept of quality, i.e. the physical value of a system in the form of how large quantity of purely mechanical work can be extracted from the system in its interaction with the environment. It permits to measure the quality of a system or a flow of energy and matter. [5]

Let us illustrate the meaning of exergy by two simple examples:
• A system in complete equilibrium with its environment does not have any exergy. There is no difference in temperature, pressure, or concentration etc. that can drive any processes.
• A system carries more exergy the more it deviates from the environment. Hot water has a higher content of exergy during the winter than it has on a hot summer day. A block of ice carries hardly any exergy in winter while it does in summer.

During the past few decades, thermodynamic analysis, particularly exergy analysis, has appeared to be an essential tool for system design, analysis and optimization of thermal systems.

The main objective of using the exergy concept on industrial processes is to provide an estimate of the minimum theoretical resource requirement (requirement for energy and material) of a process. This in turn provides a better foundation for improvement and for calculating expected savings information on the maximum savings that can be achieved by making use of new technology and new processes.

It represents a complement to the present materials and energy balances, by giving a deeper insight in the process to show new unforeseen ideas for improvements.

Despite there is limited information and research on the energy and exergy analyses of the drying process in the literature, especially concerning the wallpaper drying process, we will tempt to apply this concept and use the useful information pointed by this analysis.

2.3.2 Calculation of exergy

Are considered only physical exergy in this analysis and potential and kinetic ones are negligible. First, it’s important to choose the reference conditions to which all resource flows are related.

Thus, the general exergy rate balance can be expressed as follows:

$$\sum \dot{E}_{x,\text{in}} - \sum \dot{E}_{x,\text{out}} = \dot{E}_{x,\text{dest}}$$

Or:

$$\dot{E}_{\text{heat}} - \dot{E}_{\text{work}} + \dot{E}_{\text{mass,in}} - \dot{E}_{\text{mass,out}} = \dot{E}_{\text{dest}}$$

And more explicitly,
\[
\sum \left(1 - \frac{T_0}{T_k}\right) Q_L - W + \sum \dot{m}_\text{in} \psi_\text{in} - \sum \dot{m}_\text{out} \psi_\text{out} = E_{\text{dest}}
\]

Where \( \dot{Q}_L \) is the heat transfer loss rate crossing the boundary at temperature \( T_k \) at dryer’s outer surface, \( W \) is the work rate, \( \psi \) is the flow "specific” exergy.

The specific exergy for the general thermal system can be defined as:

\[
\psi = (h - h_0) - T_0 (s - s_0)
\]

With \( h \) is enthalpy, \( s \) is entropy, and the subscript zero indicates properties at the restricted dead state of \( P_0, T_0 \).

The exergy destroyed or the irreversibility may be expressed as follows

\[
\dot{E}_{\text{Dest}} = \dot{i} = T_0 S_{\text{gen}}
\]

With \( S_{\text{gen}} \) is the rate of entropy generated.

The traditional exergetic efficiency is the ratio of the total outgoing exergy flow to the total incoming exergy flow:

\[
\eta_e = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}}
\]

However, this efficiency does not always provide an adequate characterization of the thermodynamic efficiency of processes, such as heat transfer, separation, expansion etc. Often, there exists a part of the output exergy that is unused, wasted to the environment \( \dot{E}_{\text{waste}} \) which is called external exergy losses.

2.3.2.1 Heat loss exergy

Exergy flow due to heat loss can be identified as follows:

\[
\dot{E}_{\text{waste}} = \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_L
\]

Thus, the utilized exergy is given by \( \dot{E}_{\text{out}} - \dot{E}_{\text{waste}} \), which we call the produced utilizable exergy \( \dot{E}_{\text{pr}} \). The output consists of two parts. Sometimes a part of the exergy going through the system is unaffected. This part of the exergy is named the transit exergy \( \dot{E}_{\text{tr}} \).
2.3.2.2 Chemical exergy

Chemical reactions occurring in combustion processes often result in extensive exergy destruction. Evidently no energy losses occur in the reaction. Only exergy calculations show that the production of entropy can cause a large percentage of potential work to be destroyed in the reaction. For pure reference components, which exist in the environment, their chemical exergy consists of the exergy that can be obtained by diffusing the components to their reference concentration $c_{i0}$.

For gases and when the ideal gas law is employed, this can be written as

$$\dot{E}_{x, \text{ch}} = n \cdot R \cdot T_0 \cdot \ln \frac{P_i}{P_{i0}}$$

With $P_i$ and $P_{i0}$ refer to the partial pressures of the gas, in the emission and in the environment, respectively.

2.3.3 Aims

By comparing this exergetic diagram flow with the energy one, it's easy to distinguish the losses that occur in the process, and also whether exergy is destroyed from irreversibilities or whether it is emitted as waste to the environment. This information is very useful when considering the ecological effects of an activity.

It also gives a hint about the possibilities of improving the process and where to direct the efforts of improvement. However, in the exergy flow diagram the temperature of the waste heat is close to ambient so the exergy becomes much less.

The ecological effects are more related to the exergy flows than to the energy flows, which makes exergy flows better as ecological indicators.

This often leads to a better insight and understanding of the system and its characteristics, which implies a better basis for improvement considerations.
2.4 Environmental analysis

2.4.1 Background

Sweden share 1.6% of the total European Union with 67 Mton of CO2 emissions, with a part of 10% for the industrial processes, for the year 2005. Main factors for decreasing emissions with regard to 2004 were decreasing fossil fuel use in heat and power production (partly due to higher hydro power production), in manufacturing industries and in households and services.

From 1990 to 2005, reductions in fuel use in households and services, partly due to increases in district heating, contributed most to emission decreases. The use of district heating as a heat sink in some industrial processes is now more and more implemented.

Sweden also managed to limit emission growth from heat and power production despite sharp increases in thermal power production mainly due to increased use of biomass. [6]

2.4.2 Aims

In order to apply future implementations to reduce the environmental impact of the energy use, an environmental analysis will be done to each of the solutions suggested to compare.

The study of the existing process will be the comparative basis for the next optimisations suggested. By calculating the impact on the environment, the reference will be set.

2.4.3 Assumptions

The electricity supplier of the company is *Fortum* with an average net CO2 emission of 0.064kgCO2.kWh\(^{-1}\) [7].

In Gävle and its surrounding, *Gävle Energi* provides heat (district heating) from the Combined Heat and Power (CHP) bio-fuel plants with a CO2 net emission of 0.0185kgCO2.kWh\(^{-1}\) [3].

The net emissions of carbon dioxide for producing heat in an oil boiler are about 0.3kgCO2.kWh\(^{-1}\). [6]
2.5 **Economical analysis**

In this study the economical benefits of the altered energy use will be calculated firstly for the process studied and then for the whole company.

This analysis is based on previous average energy costs (year 2007) which are determined in the Appendix 2.

Oil for industrial use is not subject to taxation by the Swedish government. The non-taxation of oil helps the companies to stay competitive in the European and worldwide economy. It will be considered in the study as a refund (more than 60%) on the company's oil invoice in order to compare the price in case of policy's change. Thus the oil price will be given with and without this rebate.

Then will be discussed the energy choice’s motivations regarding the future economical, political and environmental prospects.

2.6 **Measurement tools**

2.6.1 Temperature meters

All the air flow temperatures have been measured with the VelociCalc Plus tool from TSI with an accuracy of ±0.3°C.

![Figure 5: TSI VelociCalc plus tool](image)

As the temperature range of the VelociCalc is not wide enough, we extended our measurements with some PT100 sensors connected to an AT 40 Universal recorder from Mitec.

![Figure 6: Mitac AT40, PT100](image)
Temperatures of water inlet and outlet have been read on thermometer installed on the pipes.

2.6.2 Air flow rate controller

All the air flow rate have been measured with the Velocicalc Plus from TSI with the average method, by measuring different velocity at different key positions in the surface and then taking the average value.

2.6.3 Electrical consumption controller

Fan electrical powers have been measured with a MX 240 from Metrix. (Accuracy ±0.3%)

![Figure 7: Metrix MX 240](image)

2.6.4 Relative humidity controller

Humidities have been measured with the Velocicalc Plus from Tsi. (Accuracy of ±3%)

2.6.5 CO2 concentration controller

CO2 concentrations have been measured with a Telaire sensor plugged to the Mitec AT 40 Universal recorder. (Measure given in ppm) (Accuracy ±40ppm)
3 Limitations

3.1.1 Evaporation rate

Calculating the evaporation rate is hard to manage mainly because of the water diffusion in the air that will dramatically reduce the evaporation rate. The diffusion of water in the air is strongly dependant on the setup of the machine that is to say the air distribution and how the air jet impacts the wallpaper. It is really difficult to study this on the existing machine as it is impossible, because of the level temperature and the machine itself, to measure the velocity of the jet while the production is running.

Therefore evaporation rates have been calculated with empirical formulas found with other experimentations. Even if the velocity range of these formulas has been respected, the setup and air distribution differences inside the machine might have increase the incertitude of the result.

3.1.2 Measurements

Some measurements were impossible to perform, like temperature measurement when it’s located on the top of the machine where surrounding temperature can reach 80°C mainly because of the radiations.

Also, some temperatures were out of range when measuring the velocity and relative humidity. Therefore some assumptions had to be taken.

The same with the turbulences in the pipes when measuring the air flow. The average value has been taken as the value used in the calculations.

3.1.3 Investment costs

Because of the lack of time, some investment costs had to be evaluated. These evaluations are our guesses dependent on information from manufacturers and district heating supplier.
4 Processes, calculations and results

This chapter is divided in one “existing system” part studying the current process and one “improvement” part divided according to improvement possibilities.

4.1 Existing process

4.1.1 Principle

The process is a double pass convective dryer. The drying medium is air heated by steam water produced from two boilers. These boilers provide heat to all the processes including the support and production ones. The flow of product (paper + ink) is and should remain constant to 150m.min⁻¹ [1]. The sketch below (also available in Appendix 3) shows the general principle of the drying process.

![Figure 8: Existing process schematic drawing](image)

The drying machine is composed of four zones but only three recirculation fans. Each heat exchanger heats a mixture of preheated fresh air and recycled air. Then this hot mixture is blown directly on the wallpaper first pass.

The recirculation loops take some inside air and directly blow it on the second pass of the wallpaper without being treated. Some inside air is taken out and then cooled before being released outside to preheat the fresh air. Regulation systems control the steam flow to keep constant the air temperature around 120-130°C in the dryer, thus there are no significant temperature gradient all along the device.
4.1.2 Energy survey

The whole factory consumption is 3040MWh per year with 1055MWh of electricity (35%) and 1985MWh of oil (65%). The production process oil consumption represents more than 65% of the total oil one.

![Power consumption of the whole factory (MWh)](image)

**Figure 9: Power consumption of the whole factory (MWh)**

4.1.2.1 Measurement campaign

All the results of the measurements are shown in the Appendix 3. These results have been used to determine the energy needed to dry the product.

4.1.2.2 Assumptions

The complexity of the system from a thermodynamic point of view make compulsory to do some assumptions. Moreover, the machine itself makes some measurements impossible to do.

Therefore we assume:

- Engines and fans used to blow air in the modules are the same thus same air flow and electrical power.
- HEXs are considered to not loose heat to the surroundings.
• Air pressure in the dryer is assumed to be around the atmospheric pressure (pressure difference negligible)
• Outlet product temperature equal to the air temperature measured inside the dryer very close to the paper exit.
• The measurements have been made during the drying of a non-woven 2 paper type with standard ink (Appendix 4).

By the study of the existing process the references will be set in order to better compare it with proposed change.

4.1.2.3 Calculations

**Water evaporation**

The ink application process makes impossible to determine the amount of wet ink applied on the inlet product. Is only known the amount of dry ink applied once the wallpaper is processed and dried. This amount is given at 37g.m\(^{-2}\) for standard ink on a non-woven 2 paper. The standard ink has a dry content of 54% when it’s applied on the paper. The outlet product total humidity is given at 5%. The paper water content at the inlet is 3g.m\(^{-2}\), and supposed to be constant (only water from the ink is taking out). With all these information, are known the total amount of water applied on the inlet ink and then the amount of water needed to be evaporate, 33.3g.s\(^{-1}\). We also need first to heat the liquid water in the ink from 21°C to 100°C. The energy corresponding to this heating and evaporation is around 86kW (see appendix 5).

**Heating supplied by steam**

It is not possible to measure the steam flow in this installation. But, because of the no-losses to the surrounding assumption, the power from the air side through the HEXs can be calculated. The amount of water in the air is the same in and out from the HEXs. Therefore, are known the air characteristics in and out. With the incertitude of the measurement and regarding the results of the measurement campaign, the power of the four HEXs can be considered identical, that is to say 36.5kW each.

The boiler is set to have an efficiency of 90%. Therefore, to produce 146kW of steam, 162kW of fuel is needed, the difference being lost in the fumes, 16kW (see Appendix 5).

**Heating supplied to paper**
This is the power needed to bring the paper and its water from 21°C to 100°C, the evaporation temperature. The evaporation's power of the water contained in only the wet ink has been considered previously. The specific heat of paper is taken equals to 1.2kJ.kg⁻¹.K⁻¹ and 4.18kJ.kg⁻¹.K⁻¹ for the water, the speed of paper to 2.5m.s⁻¹. Therefore, the heat power for the paper is equal to around 13kW as the heat power for the water is 3kW (see Appendix 5).

**Electrical power of the fans**

The electrical characteristics are known from the measurements. The electrical power from fans is then calculated to be around 26.15kW.

**Heating supplied to the surrounding by convection and radiation losses**

The surrounding temperature is measured at 28°C and the machine surface temperature at 50°C. The machine surface area is 68m². The convection coefficient is taken equals to 13J.m⁻².K⁻¹ as the convection mode is natural and the machine is inside a building where no air streams are taking place. The heat losses are then equal to around 29.5kW (see Appendix 5).

**Heating supplied to the surrounding by leakages**

The difference of air mass flow rate between fresh air inlet and waste air outlet is supposed to be lost in leakages during the process. The temperature and humidity of the leakages is set to be equal to the machine inside temperature. Therefore, the heat loose through leakages is equal to around 14.5kW (see appendix 5)

4.1.2.4 Results

**Energy Flow chart**

The electricity used for the fan engines is just indicated and do not take part of the thermal energy flow, it is only use for the air motion.

![Energy Flow chart](Figure 10: Existing process energy flow chart)
This machine is then using $75.2 \text{kJ.m}^{-1}$ of produced wallpaper. The drying surface inside the machine is $19 \text{m}^2$. The evaporation capacity of it is $1.75 \text{g.m}^{-2}. \text{s}^{-1}$.

**Efficiency**

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 45.7%.

**Psychometric chart**

![Psychometric Chart](image)

**Figure 11: Existing process psychrometric chart**

The psychometric chart above shows the temperature and the specific humidity of the air from the inlet (16°C and 3g/kgda) to the outlet (52°C and 40g/kgda) of the process.

4.1.3 Exergy survey

4.1.3.1 Assumptions

The complexity of calculating the enthalpy and entropy of the product, air and steam makes us analyse exergy from the heat's point of view except for the CO2 release in the outside. The exergy destruction is dependent on the temperature decreasing.
Therefore the assumptions are:

- No chemical reactions in the ink.
- Exergy in the fans is totally destructed.
- The matter of paper is a transient exergy. Only the heat content is considered.
- Reference temperature is 15°C.
- Fresh air inlet is at reference temperature.

4.1.3.2 Calculations

**Boiler exergy**

Burning fuel has a flame temperature of around 2000°C. Therefore the boiler could produce 141kW of exergy but only heat at 150°C is produced. The exergy destruction is thus 46.6kW. In the steam water production process, fumes are loose around 250°C, which means 7kW of wasted exergy to the outside (Appendix 6).

**Heat exchanger exergy**

Once more exergy is lost in the process of heating air. From 150°C steam is produced 128°C hot air. The exergy left on air is then 41.1kW (Appendix 6).

**Exergy losses by the paper**

The paper exits the machine at 100°C. Wasted exergy is then 3.6kW (Appendix 6).

**Exergy losses to the surrounding**

The 50°C body of the machine is losing exergy through radiations and convection. It’s a very low exergy lost though because of the temperature level, 3.2kW (Appendix 6).

**Exergy losses through leakage**

Supposing that the air leakage temperatures is at 100°C, the exergy loss is then 3.3kW (Appendix 6).

**Exergy released the environment by the CO2 emissions**

The net emissions of CO2 are assumed to be 0.300kg.kWh⁻¹. The molar mass of CO2 is 64g.mol⁻¹, the outside temperature 15°C. The exergy release is then 25kW (Appendix 6).

**Exergy released the environment by the waste air**
Once the process of drying is done, the humidity taking from the paper is released to
the environment at 52°C. It is then 9.8kW of exergy released (Appendix 6).

4.1.3.3 Results

**Exergy Flow chart**

![Exergy Flow chart](image)

**Efficiency**

By applying the definition of exergy efficiency, the overall machine exergy efficiency
is 11.7%.

4.1.4 Environmental survey

4.1.4.1 Calculations

**CO2 emissions**

The total yearly production hours of the machine are 1436 hours [1]. The boiler has a
power of 162kW dedicated to the machine studied and the electrical power of all the fans
is 26.15kW. Thus the net total amount of CO2 emissions is around 72.2 tonCO2 per year
with 69.8 tonCO2 created by the boilers and 2.4 tonCO2 due to the electricity
consumption. That is to say a total of 5.6 gCO2 per meter of produced wallpaper.

**Exergy released**

As previously explained, exergy released has an impact on the environment. In
addition of the 4kW due to the CO2 emissions, the wasted exergy also has to be
considered. It’s then 64.9kW of exergy that is exhausted in the environment.
4.1.5 Economical survey

4.1.5.1 Calculations

Calculation based on year 2007 invoices show that the production process oil cost represents 70% of the total one. With the electricity and heat power determined for the machine and also the production hours [1] the energy cost of the drying process n°3 can be calculated for one year.

Thus the process cost 214.7kSEK per year with 21.8kSEK of electricity and 192.9kSEK of oil. The part of electricity is low in the power consumption and also in the energy cost compared to the oil ones.
4.2 **Process solution: Better heat recovery exchanger**

4.2.1 **Aims**

The first obvious optimisation possible for a minimum investment cost would be to replace the heat recovery heat exchanger which has a low efficiency of around 43% as shown in Appendix 7.

In this part the effect of a new exchanger with 90% of efficiency is studied on the existing process.

4.2.2 **Energy Study**

4.2.2.1 **Calculations**

The assumptions are:

- a new heat recovery exchanger with 90% of efficiency
- the same fresh air mass flow rate
- the same drying temperature level

We can save up to 36.2kW (see Appendix 7). This energy is saved in oil consumption as the new mixture of recycled air and fresh air temperature is around 99°C.

4.2.2.2 **Results**

**Energy flow chart**

As nothing has changed except the new exchanger, the energy flow chart looks the same except for the primary oil consumption.

![Energy flow chart](image)

Figure 13: Optimisation 1 energy flow chart

This machine is then using 59.2kJ.m\(^{-1}\) of produced wallpaper


**Efficiency**

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 58.1%.

**Psychometric chart**

![Figure 14: Optimisation 1 psychrometric flow chart](https://via.placeholder.com/150)

The psychometric chart above shows the temperature and the specific humidity of the air from the inlet (16°C and 3g/kgda) to the outlet (37°C and 40g/kgda) of the process.

As shown in this diagram, some water will condense in the heat recovery exchanger. This is due to the surface temperature which is lower (around 17°C) than the saturation temperature of wet air with 40g.kgda⁻¹ (27°C as shown on the diagram).

As the mass flow rate of wasted air is around 1kg.s⁻¹, the amount of condensate is around 25g.s⁻¹, 90l.h⁻¹.

**New exchanger technology and specifications**

Only cross flow plate exchanger can reach an efficiency of 90%. In the calculation, we assume the overall heat transfer coefficient to be 450W.m⁻².K⁻¹. That means the flow in the HEX is fully turbulent.
With these new features considerate, the new HEX needs to have a 20m² transfer area (see appendix 7).

4.2.3 Exergy Study

4.2.3.1 Calculations

**Boiler exergy**

As 36kW are saved on the process boiler power, the used exergy will also decrease to around 107kW. The same with losses from the fumes around 5kW (see Appendix 7).

**Exergy losses by the paper**

The paper exits the machine at 100°C. Wasted exergy is then 3.6kW (Appendix 7).

**Exergy released the environment by the waste air**

The new temperature of waste air outlet is 20°C, therefore the exergy release is only 1kW (see Appendix 7).

**Exergy released the environment by the CO2 emissions**

The emission of CO2 is 0.300kg.kWh⁻¹. The molar mass of CO2 is 64g.mol⁻¹, the outside temperature 15°C. The exergy release is then 3kW (Appendix 7).

4.2.3.2 Results

**Exergy flow chart**

![Exergy Flow Chart](image)

*Figure 15: Optimisation 1 exergy flow chart*

**Efficiency**
By applying the definition of exergy efficiency, the overall machine exergy efficiency is 14.7%.

4.2.4 Environmental survey

4.2.4.1 Calculations

**CO2 emissions**

The boiler has now a power of 122kW dedicated to the machine studied; Therefore, the net total amount of CO2 emissions is around 55tonsCO2 with 52.6tonsCO2 due to the oil burned oil and 2.4tonsCO2 due to the electricity used. That is to say 4.26gCO2 per meter of produced wallpaper (see Appendix 7).

**Exergy released**

In addition of the 3kW due to the CO2 emissions, the wasted exergy also has to be considered. It’s then 52.9 kW of exergy that is exhausted in the environment, modifying it.

4.2.5 Economical survey

4.2.5.1 Calculations

Replacing the heat recovery exchanger leads to a decrease of the boiler oil consumption. The total cost is 167kSEK. The electric cost remains the same (21.8kSEK) and the new oil cost is 145.3kSEK.
4.3 Process solution: Reducing the air temperature.

4.3.1 Aims

The first objective for Duro Tapet AB would be to take off the boilers. That means drying the product at a lower temperature. As a result we could use heat from the DH network and because the supply pipe is really close to factory (under the main street leading to it), it could be convenient. Nevertheless, Gävle Energi, the energy provider company in Gävle, supply a DH temperature of around 73°C in summer like it is shown in the following diagram.

![District heating temperature vs. outdoor temperature](image)

Figure 16: Gävle district heating temperature supply

Like said previously the evaporation rate is dependent on the difference of vapour pressure in the air and the water vapour pressure at the surface temperature. As the real evaporation rate is hard to determine due to unknown phenomena like humidity diffusion and the effect of the air flow, the solution would be to determine the difference between the theory and the reality with the current machine (Appendix 8).

The ratio of evaporation rate is supposed to be around 0.2. Therefore for the same machine, which is evaporate 1.75 g.m^{-2}.s^{-1} when air is blown at 127°C will now evaporate 0.35 g.m^{-2}.s^{-1} if we assume no air recirculation. For evaporate the same amount of water and respect the actual paper speed and air flow, a drying length of 170 meters would be needed. A length of 17 meters is available so that would mean a 10 pass drying machine.
4.3.2 Schematic drawing

![Schematic drawing](image)

**Figure 17: optimisation 2 schematic drawing**

4.3.3 Energy Study

4.3.3.1 Calculations

**Heat recovery exchanger**

As air recirculation would decrease the evaporation rate, the drying process would occur with 100% fresh air. Air wasted to the surrounding needs to be recovered to improve the energy efficiency. The actual heat recovery exchanger has an efficiency of around 44% (Appendix 8). Nowadays, heat recoveries can achieve an efficiency of around 90%.

Therefore, as the inlet wasted air temperature would be around 55°C (assumption due to losses) the new fresh air outlet temperature would be around 50.7°C. It is corresponding to a heat exchanger power of 273kW and exchange area of 142m² (Appendix 8).

**District heating power**

The district heating has to heat the air from 50.7°C to 65°C. As the water content of the air is known, it is easy to calculate the enthalpy and then the power needed from the DH (Appendix 8). It is then 101kW needed of district heating.

**Heat losses**

Heat losses are strongly dependent on the temperature of the process. As the air temperature decreases, the machine body temperature will decrease too. We can assume a body temperature around 35°C if the new machine is well isolated. The heat losses are
then quite negligible compared to the heat supply. No air leakages are supposed on a new machine.

In the existing setup, the production buildings are not heated by any other mean than the losses of the drying machines. Nevertheless, during summer, the temperatures of the buildings are too hot. Therefore lowering the losses are a solution to increase the cost efficiency of the machine, but lowering too much would means to invest in a new heating system for the building during the strong Swedish winter.

**Heat losses on paper**

As the air temperature is lower to around 65°C, the paper will be heated around 60°C and will exit at this temperature. As the paper energy losses are proportional of the temperature difference between inlet and outlet, the energy losses will be decreased around 50%, around 8kW.

4.3.3.2 results

**Energy flow chart**

![Energy flow chart](image)

*Figure 18: Optimisation 2 energy flow chart*

**Efficiency**

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 72.4%.
4.3.4 Exergy Study

4.3.4.1 Calculations

**District heating power**

The DH network supplies water at 73°C, that is to say in our case, as the reference is 15°C (outside temperature), 15.6kW.

**Heat exchanger exergy**

Exergy is lost when the air is heated at 65°C. Air receive only 13.8kW of exergy

**Exergy losses by the paper**

The paper exits the machine at 60°C. The wasted exergy is then 1kW

**Exergy released the environment by the waste air**

The waste air is released at around 27°C therefore almost no exergy is lost to the surrounding, 3kW.
4.3.4.2 Results

Exergy flow chart

Efficiency

By applying the definition of exergy efficiency, the overall machine exergy efficiency is 32.7%.

4.3.5 Environmental survey

4.3.5.1 Calculations

CO2 emissions

The heat from the DH network release around 18.4gCO2net.kWh\(^{-1}\) produced [?]. The heat exchanger has a power of 101.1kW dedicated to the machine studied. Therefore, the net total amount of CO2 emissions is around 5.1 tonCO2 per year (with 2.7tonC02 due to district heating and 2.4 due to the electricity used); that is to say 0.18gCO2 per meter of produced wallpaper.

Exergy released

Waste air is released in the air at around 27°C so the environment will be very less impacted, 4kW.

4.3.6 Economical survey

4.3.6.1 Calculations

Studying only one device, an average price is calculated on the actual power consumption of the whole factory\(^4\) assuming that the whole factory could be connected to the DH network. But by using the DH as a new heating method, the power consumption of the production processes are reduce by 38% which is the consumption reduction of the production processes applied on the new calculations as shown in Appendix 9. Thus, the

\(^4\) Based on a previous study in 2003 but corrected with the oil power utilisation for the year 2007.
heat price for only the device is 88.4kSEK per year and 940.5kSEK per year for the whole factory. The electricity price remains the same so the global energy price for the device would be 110.2kSEK per year. The investment (only pipes) to connect the factory to the DH network is around 175 kSEK (3500SEK per meter [1] to connect around 50m of connection.

The production workshop is heated by the heat load of the dryers due to the losses so if these ones are negligible with this optimisation, the building has to be heat by another method.
4.4 Process solution: using infrared dryer

4.4.1 Aims

As previously shown above, drying by using a convective process is difficult to conceive and too related to uncertain parameters when it is used at low temperature. Furthermore, there is tremendous loss of thermal energy at high temperature in the convective drying, making it a less efficient process.

That's why a new method using infrared drying (IRD) is studied and could be a good alternative of optimisation.

In an IRD system, the heat for the drying process comes directly from infrared radiation. All bodies emit IR radiation corresponding to their temperature.

Minimal radiation is absorbed by the air, but it heats the material from inside the product, not only on the surface, due to the short wavelength of the infrared radiation.

This makes the temperature distribution in the paper uniform, allowing higher drying load without overheating and over-drying the surface.

The practical consequence of this is that the IR dryer can be located on the opposite side to the coated side and still dry with the same efficiency.

![IRD principle](image)

**Figure 21 : IRD principle [2]**

The main advantages of the IR dryer are:

- Floor space saving due to smaller size
- Heats only the product without heating the surrounding
- Can be easily be added to an existing drying process to increase line speed
Infrared energy can be generated by electric or gas infrared heaters or emitters. Both electric and gas infrared typically are controlled by thermocouple feedback control loops that regulate the electrical power or fuel mixture going to the infrared heaters and by moisture control devices. It's almost essential to run trials in lab or on the pilot line to confirm the design.

The electric IR dryer is only studied in our case due to the small difference of price between gas and electricity and of the high investment cost because it requires safety controls and gas-handling equipments. Furthermore, the modularity is limited and the global efficiency is less than the electric one.

By contrast, electric infrared is likely better for sensitive substrates such as film and certain fabrics, where extreme control and uniformity is required. Electric infrared heaters can be divided into multiple, separately controlled temperature zones with tight tolerances.

Advantages of the electric IR dryer:

- High efficiency conversion of electrical energy into heat
- High rate of heat transfer
- Quick start and shut down
- Faster response to changing process conditions
- Easy to zone for uniform heating of the product
- Lower capital and installation cost

In the following chapters, the properties of the IR device are related to products of the manufacturer IRCON drying Systems AB. The IRD system is composed of frames with a power of 86kW.m⁻¹.

The air system to cool the IRD works at 3500 Nm³.h⁻¹ with a temperature of 85°C for the exhaust air.
4.4.2 Energy Study

4.4.2.1 Calculations

Water evaporation

The powers needed to heat the water in the ink and evaporate 33g·m⁻² are respectively 6.8kW and 77.7kW so a total of 84.5kW at the IRD processing temperature of 70°C as shown in the Appendix 10.

Heat losses on paper

The paper will be heated around 70°C and will exit at this temperature. As the paper energy losses are proportional of the temperature difference between inlet and outlet, the energy losses will be 10kW.

Energy efficiency

The conversion in electric energy into radiation is around 85%. Depending on the reflector design and the design of the air system, the global efficiency of an electric dryer (calculated as the amount of heat delivered to the paper divided with the consumed electric power) can vary until 60%. The example of IR dryer studied is the Drymaster of the Swedish company Ircon Drying System AB and the model is guaranty with a global efficiency of 55%.
It results an electric power of the IR device around 172kW to provide the heat around 70°C to the product.

4.4.2.2 Results

Energy flow chart

![Energy flow chart](image)

**Efficiency**

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 49%.

4.4.3 Exergy survey

**Electric exergy**

Electricity is a form of energy which contains pure exergy so the total exergy put in the system is 172kW.

**Exergy of electric/heat conversion**

The process heats the paper at 70°C. The product needs a thermal power of 84.5kW to heat and dry the water of the ink. Thus the heat exergy is 13.5kW.

**Exergy losses by the paper**

The paper exits the machine at 70°C. The wasted exergy is then 1.6kW

**Exergy released to the environment by the losses**

The losses are 77.5kW. They are assumed mostly created by the air cooling system with a temperature of 85°C. The exergy lost to the surrounding is thus 15kW.
4.4.3.1 Results

**Exergy flow chart**

![Exergy flow chart](image)

*Figure 25: Optimisation 3 exergy flow chart*

**Efficiency**

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 7.8%.

4.4.4 Environmental survey

CO2 emissions

The only energy used is electricity so the CO2 net emission is 15.8 ton CO2 per year.

Exergy released to the surroundings

The total wasted exergy released to the environment is 16.6 kW.

4.4.5 Economical survey

The energetic consumption is only electrical and is around 143.1 kSEK per year. The investment cost is around 1000 kSEK [2]. The typical service cost is less than 2% per year of the investment cost.
4.5 process solution: Combining the two optimisations to fit in the existing machine

4.5.1 Aims

As Duro Sweden AB not ready to change the all the process because it would cost too much to invest in a new machine, the solution could be to combine low temperature drying with infrared drying to impact as less as possible on the existing machine.

First, this means that a 10 pass drying machine not suits the requirements as nothing can be changed inside the machine in terms of paper path.

Secondly, a 100% infrared drying as the existing machine represents an important investment too eager in electricity.

Therefore we could imagine adding an IR before the first zone when the rest of the machine finishes the drying with low humidity and temperature air drying.

Five combinations will be studied here:

- IR drying first to heat the paper at 120°C then 2 pass district heating convection drying with air at 65°C
- IR drying first to heat the paper at 60°C then 2 pass district heating convection drying with air at 65°C
- Variable pass IR post-drying product with district heating convection drying with air at 65°C

Then the best compromise will be studied in the energy, exergy, environmental and economical points of view.
4.5.2 IR pre-drying product at **120°C** then 2 pass district heating convection drying with air at **65°C**

4.5.2.1 Schematic drawing

![Schematic drawing](image)

**Figure 26: Optimisation 4 schematic drawing**

4.5.2.2 Energy Study

**Assumptions**

- Keep the machine dimensions
- Each zone has a length of 4.25 meters
- Only the first pass first zone is equipped with IRD
- The paper exits the IRD at 120°C

**Calculations**

**Evaporation rate**

As an air of 65°C is blown on a paper at 120°C, it will result a decrease of the paper temperature. By dividing the machine in 34 sections of 1 meter, it’s possible to evaluate the paper temperature at every section depending on the previous section:

\[
T_{\text{paper}}^n = T_{\text{paper}}^{n-1} - \frac{(Q_{\text{conv}} + Q_{\text{evap}})^{n-1}}{(m_{\text{paper}} \cdot C_{p_{\text{paper}}})^{n-1}}
\]

This method is only applied on the convective drying zone, the IRD zone temperature levels being assumed. In order to know \(Q_{\text{evap}}^{n-1}\), the evaporation rate at is calculated with the paper temperature at \(n-1\).
Then, by summing every evaporated water mass of every section, the evaporated mass flow is found: 8g.s$^{-1}$. The rest of the evaporated mass flow, 25.3 g.s$^{-1}$ is perform by the IR drying zone.

**Supplied air flow rate**

As the convection drying zone length is reduced the air flow rate will also be reduced. To keep the exit velocity at the same level as in the existing machine, a 6,125kg.s$^{-1}$ air flow rate is needed.

**District heating power**

It’s then a power of 19kW needed from the district heating network.

**IR drying power**

The power needed to heat and evaporate this amount at 120°C is 89.5kW. Keeping the same IRD efficiency as in the previous chapter, the electric power needed is 162.8kW. The total electric power including the fan motors is 189kW.
4.5.3 IR pre-drying product at 60°C then 2 pass district heating convection drying with air at 65°C

4.5.3.1 Schematic drawing

![Schematic drawing](image)

**Figure 28: Optimisation 4 schematic drawing of pre-drying**

4.5.3.2 Energy Study

**Calculations**

**Evaporation rate**

By following the same method as previously, the figure 25 is found. The evaporated mass flow is 5.85 g·s⁻¹. The rest of the evaporated mass flow, 27.45 g·s⁻¹ is performed by the IR drying zone.

![Graph](image)

**Figure 29:**

*Figure 29: Paper temperature (°C)*
Supplied air flow rate

As the convection drying zone length is reduced the air flow rate will also be reduced. To keep the exit velocity at the same level as in the existing machine, a 6,125 kg.s\(^{-1}\) air flow rate is needed.

District heating power

It’s then a power of 14 kW needed from the district heating network.

IR drying power

Thus the power needed to heat and evaporate this amount at 60°C is 78 kW. Keeping the same IRD efficiency as in the previous chapter, the electric power needed is 142 kW. The total electric power including the fan motors is 168 kW.

4.5.4 Variable pass IR post-drying product with district heating convection drying with air at 65°C

4.5.4.1 Schematic drawing

![Schematic drawing](image)

**Figure 30**: Optimisation 4 schematic drawing of pre-drying

4.5.4.2 Energy Study

**Calculations**

Evaporation rate

By following the same method as previously, the figure 29 is found. The evaporated mass flow in the convective dryer is:

- For 2 passes: 5.32 g.s\(^{-1}\) (27.98 g.s\(^{-1}\) in IRD zone).
- For 3 passes: 8.52 g.s\(^{-1}\) (24.78 g.s\(^{-1}\) in IRD zone).
- For 4 passes: 11.72 g.s\(^{-1}\) (21.58 g.s\(^{-1}\) in IRD zone).
District heating power

The heat power needed is:
- For 2 passes: 26kW
- For 3 passes: 33kW
- For 4 passes: 41kW

Electrical power

The IRD electrical power and total electrical power (with fan engines) are respectively:
- For 2 passes: 120kW and 146kW.
- For 3 passes: 106kW and 132kW.
- For 4 passes: 92kW and 118kW.

In order to have a relevant comparison (lowest investment costs possible) between the combination and the other proposed changes, only the post-drying IR, 2 pass process will be studied furthermore.

Energy flow chart

![Energy flow chart](image)

Figure 31: Optimisation 4 energy flow chart

Efficiency

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 49%.

4.5.4.3 Exergy study

Electrical exergy

Electricity is pure exergy; therefore this process uses 146kW of exergy.
District heating exergy

The district heating is supplied at 73°C, therefore only 4.4kW is consumed.

Exergy released to the environment by the losses on the waste air

The losses are 54kW. They are assumed mostly created by the air cooling system with a temperature of 85°C. The exergy lost to the surrounding is thus 10.6kW.

The waste air of the device by the use of the DH's heat is released at around 27°C therefore almost no exergy is lost to the surrounding, 3kW.

Exergy flow chart

Figure 32: Optimisation 3 exergy flow chart

Efficiency

By applying the definition of thermal efficiency, the overall machine thermal efficiency is 7.6%.

4.5.4.4 Environmental study

CO2 emissions

The CO2 net emissions are 14ton CO2 per year with 13.72ton CO2 for the electricity and 0.69tonCO2 for district heating.

Exergy released to the surrounding

The total exergy released is 10.6kW.
4.5.4.5 Economical study

The heat power supplied to the process by the district heating is now low so the permanent fee also. It results a decrease in the DH price. The power of the production processes is corrected compared to the proposed change with only DH (see Appendix 9). It results a total cost of 142.8kSEK per year with 121.5kSEK of electricity and 21.3kSEK of DH.
5 Discussion

In 2005 the government of Sweden announced their intention to make Sweden the first country to break its dependence on petroleum, natural gas and other ‘fossil raw materials’ by 2020. In making this decision, four reasons were cited by the Government:

- The impact of oil prices on Swedish economic growth and employment;
- The link between oil, peace and security throughout the world;
- The great potential to use Sweden’s own clean renewable energy resources in place of oil;
- The threat of climate change resulting from the extensive burning of fossil fuels. [9]

A summary with all the important values, found out above and used in the discussions below, is shown in Appendix 12.

5.1 Energy study

Drying at a lower temperature imply globally better overall efficiency with a reduction of the losses, except for the proposed change with only IRD because of its lamp cooling system that reduce the overall efficiency of the device (see figure 32 and 33).

Up to 24.7% of oil power consumption can be saved just with a better heat recovery and 37.6% by coupling better heat recovery and lower air temperature. The proposed changes involving DH include also the use of a new heat recovery exchanger.

Combining IRD and DH permits to lower the electric power and thus the losses to the surrounding. For example with the change involving no modification on the current device (IRD + DH 2 passes), the power is reduce by 8.5% and this change implies no oil utilisation.

As said previously the heat load of the devices are used to heat the workshop so with an only DH system, the power of a new installation might be added. The exhaust air of the IRD cooling system might be used to heat the building (air at 85°C and at 3500m³.h⁻¹).
Figure 33: Power balance (kW)

Figure 34: Losses balance (kW)
5.2 Exergy study

![Comparison charts of the exergy consumed and wasted (kW)](chart)

Figure 35: Comparison charts of the exergy consumed and wasted (kW)

On the exergetic point of view, the most important factor to determine the impact on the environment is the exergy wasted i.e. rejected to the environment. This represents the direct impact on the environment; in this case it's the reject of heat. As shown above, the exiting process released a lot of exergy to the surrounding (65kW) due to the important losses of the device and the high temperature of the wasted air, but a part of it, is used in the building heating (less than 10kW).

By using a new heat recovery exchanger, the exergy released to the surrounding is lower than previously (49kW) but still important due to the CO2 emissions counted as chemical exergy.

By using only the heat from the DH network, the amount exergy wasted is very low (3kW) because of the low processing temperature.

Because electricity is a high potential energy, the last four solutions consume a lot of exergy and this exergy is most partly destroy in infrared radiations.
5.3 Environmental study

The change from oil to other energies (electricity and/or DH) entails a high drop on the CO2 emission and also on the exergy released in the environment so a less environmental impact. Thus it makes this future change essential in to reduce the impact of CO2 emissions.

![Figure 36: CO2 emissions (tonCO2 per year)](image)

5.4 Economical study

5.4.1 General

The propositions are currently not feasible due to the high refund on the company's oil bill by the government. That's why oil represents the cheapest energy for the moment.
As shown above, the current cost reduction if the proposed changes are implemented now is really low.

But the motivations of the company to be oil independent are the same as the Swedish government ones. One of the targets for the government is to cut the consumption of oil in industry by 25–40%.

The still rising oil price (see figure 37 below) could in the future accelerated the implementation of the process modifications.

Figure 37: Cost (kSEK)

Figure 38: Evolution of the oil price from 1996 to 2008
The future goal of the company is to change all the processes, thus increasing the electrical bill by the use of IRD or/and DH network. A probable rise of the electricity price is expected in the future due to the entrance of Sweden in the developing deregulated electricity market.

Indeed, in 2004 Sweden became part of a common European electricity market. This implies that the price of electricity in Sweden will adapt to a higher European electricity price due to the increase in cross-border trading as shown by figure 38. Swedish plant is characterized as more electricity-intensive than plant on the European continent, and this, in combination with a higher European electricity price will lead to a precarious scenario. [8]

![Figure 39: possible scenario for the progress of electricity prices in Sweden](image)

The change of energy use can be implemented by some helps from the government to help the industry to be accelerated the oil phase out (refund on district heating installations, investment helps…)

The more interesting proposition would be to connect the support process to DH and sharing the energy use of the process with a good balance to reduce the cost and the environmental impact to the maximum.

5.4.2 Prediction

The interesting thing could be that, depending of the energy prices (electricity, DH and oil), to know when to decide that a change is necessary and economically viable.
A simple prediction could just show that with a slight increase of the oil price, the proposed change could in an immediate future be viable.

The assumptions made are.

- DH price and electricity price would remain constant.
- The average oil price for the next years would increase around 20% compared to the year 2007 one. Since December 2007 the oil energy price of the company with the refund increases by 20%.

![Figure 40: Cost savings on the energy use (kSEK per year)](image)

It is easily visible that an increase of 20% can have a non negligible impact on the energy cost savings. The difference between these two values influences greatly the return on investment (ROI).

Furthermore combining IRD and DH reduce the electric power of the IRD and thus, instead of investing in 3 frames like for a 100% IRD installation, 2 frames are sufficient.
By the way the electric installation of the company might be renewed, due to its age, in order be adapted to high voltage needed by IR devices.

Our advice is to reduce at the maximum the power consumption of the boilers by using a better heat recovery exchanger to decrease the energy use. And be prepared by studying more in detail by contacting and asking for study the district heating provider and the different manufacturers of heat exchanger and IR drying.
5.5 Overall comparison

In order to have a quick overlook of the characteristics of each possible solutions, compare them in a radar diagram can be useful. By choosing 6 relevant characteristics:

- Power consumption
- Energy efficiency
- Exergy consumption
- Exergy efficiency
- Environment impact
- Energy costs

And by ordering them properly, 3 zones can be defined (Figure 40):

- Low impact solution
- High impact solution
- Inverse impact solution

The scale is in percent where 0 is the reference value of the existing process. From there, solutions can be compared (Figure 41):
Figure 42: Solution comparison radar graphs
5.6 Future

Some other alternatives were not studied due to the wish of the company to be focus on DH and IR. But we can also propose some high investment alternatives such as the use of a bio-fuel boiler, either as a separate solution or as a temperature booster for a DH system, or microwave drying.

We assumed that electricity used is generated by Fortum considering the values given by this company but we could also considered the European average CO2 per kWh.

We recommend for the future to study more the evaporation process under 100°C. As the diffusion strongly dependent on the setup of the machine or the convection flow turbulences, it would be relevant to perform a CFD study with dedicated software such as ANSYS® for example.

After having studied many different convection processes, it appears that other jet stream technologies exist to improve the convection and the diffusion process and where the wet air is more efficiently remove from the critical zone once more the increase the diffusion of moisture in the air.

Moreover, further studies could be performed to anticipate the behaviour of the machine when the relative humidity of the fresh air is high during hot summer day (Can rise up to 60% as Gävle close to the sea). This study could decide whether or not a dehumidification machine is needed.

Also, regarding the investment costs, lack of time made no possible to precisely define accurate investments costs especially when a new machine with more than 2 passes is suggested. As the investment cost to connect the factory to the district heating is high and almost constant, it’s better to use this source of energy as much as possible but it would mean a higher investment cost in the new machine with more passes. Therefore we suggest calculating furthermore this balance point where the use of DH and new machine investment costs are optimum.
6 Conclusion

The current company oil price make not feasible because non-economically viable, for the moment, the change in the energy utilization of the production process. But later the necessity to change them to more efficient technology with less environmental impact associated will be necessary. To connect all the support processes and part of the production processes with another energy sources could be the most interesting proposed change to implement.
References

[1] - Information given by our supervisors at Paul Larsson (Duro Sweden AB) and Anders Kedbrant (Sweco Theorells AB).

[2] – Information given by the company Ircon Drying System AB.


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Appendix 1: Evaluation of the evaporation rate

\[
\dot{m}_{\text{evap}} = \left( P_{\text{vapor}} - P_{\text{ambient partial}} \right) \sqrt{\frac{M_{\text{water}}}{2 \pi R T}}
\]

Actual machine:

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<tr>
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<th>Value</th>
<th>Unit</th>
<th>Second pass</th>
<th>Value</th>
<th>Unit</th>
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<td>Pa</td>
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<td>m²</td>
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Theoretical evaporation rate

Theoretical evaporation rate | 892 | kg/s |
|-----------------------------|-------|

New machine, no recirculation:

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<th>Unit</th>
<th>With dehumidification</th>
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Ratio* ≈ 0,20

Ratio* ≈ 0,22

New evaporation rate with air at 65°C:

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<tr>
<th>Without dehumidification</th>
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<td>g/m².s</td>
<td>Real actual evaporation rate</td>
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<td>g/m².s</td>
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<tr>
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<td>New length</td>
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Number of passes*** 10

Number of passes*** 9,1

*ratio = New theoretical evaporation rate/actual theoretical evaporation rate

** considering the machine setup as the same

*** considering a length available of 17 meters
### Appendix 2: Energy cost and consumption

#### Electricity

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<th>Month</th>
<th>Electricity price</th>
<th>Charge</th>
<th>Electricity certificate</th>
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<th>Electricity consumption</th>
<th>Cost</th>
<th>Grid use cost</th>
<th>Total cost</th>
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<tr>
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**General informations:**

<table>
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<tr>
<th>Value</th>
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<td>1055 MWh</td>
</tr>
<tr>
<td>Total cost electricity</td>
<td>611 kSEK</td>
</tr>
<tr>
<td>Average price</td>
<td>0,579 kSEK/MWh</td>
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<tr>
<td>Cost dryer n°3</td>
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#### Oil

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<th>Oil price</th>
<th>Cost</th>
<th>Order 2</th>
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<td>SEK/l</td>
<td>SEK</td>
<td>I</td>
<td>SEK/l</td>
<td>kSEK</td>
<td>MWh</td>
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<tr>
<td>Jan</td>
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<td>93</td>
<td>16027</td>
<td>6,84</td>
<td>110</td>
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<tr>
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<td>6,94</td>
<td>104</td>
<td>14004</td>
<td>6,81</td>
<td>95</td>
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<td>6,99</td>
<td>105</td>
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### General informations:

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<td>m³</td>
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<tr>
<td>Total energy delivered</td>
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### Actual oil prices:

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Appendix 3: Measurement results
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<td>T °C</td>
<td>12</td>
<td>46</td>
<td>54</td>
<td>90</td>
</tr>
<tr>
<td>HR %</td>
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<td>21</td>
<td>40</td>
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<td>V m/s</td>
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<td>density kg/m³</td>
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<td>1,01</td>
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<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>V m/s</td>
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<td>3,7</td>
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<td>1</td>
<td>2</td>
</tr>
<tr>
<td>V m/s</td>
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<td>3,7</td>
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<td>1</td>
<td>2</td>
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<tr>
<td>V m/s</td>
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<td>3,7</td>
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<tr>
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<td>0,85</td>
<td>0,90</td>
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<tr>
<td>T: °C</td>
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<td>127</td>
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<tr>
<td>HR: %</td>
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<td>V: m/s</td>
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<td>0,85</td>
</tr>
<tr>
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<td>g/kg</td>
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Appendix 4: Paper and coating information (confidential)

### Paper Qualities

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<tr>
<th>Paper Qualities</th>
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<th>Non-Woven 2</th>
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<td>Gramage</td>
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</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
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<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>%</td>
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</tr>
<tr>
<td>Moisture content</td>
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<tr>
<td>Density</td>
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### Standard ink in M3

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<th>Non-Woven 2</th>
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<tbody>
<tr>
<td>Dry content in</td>
<td>%</td>
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<td></td>
</tr>
<tr>
<td>Temperature in</td>
<td>ºC</td>
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<td></td>
</tr>
<tr>
<td>Maximum ink applied out</td>
<td>g/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Ink applied out</td>
<td>g/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum total moisture out</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum total moisture out</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum water in</td>
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<tr>
<td>Minimum water in</td>
<td>g/m²</td>
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<tr>
<td>Maximum water out</td>
<td>g/m²</td>
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<tr>
<td>Minimum water out</td>
<td>g/m²</td>
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### Silver ink in M3

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<th>Non-Woven 2</th>
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</thead>
<tbody>
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<td>Dry content</td>
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<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>ºC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum ink applied out</td>
<td>g/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Ink applied out</td>
<td>g/m²</td>
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<td></td>
</tr>
<tr>
<td>Maximum total moisture out</td>
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<tr>
<td>Minimum total moisture out</td>
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<tr>
<td>Maximum water in</td>
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<tr>
<td>Minimum water in</td>
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<td>Maximum water out</td>
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## Appendix 5: Energy Calculations

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<tr>
<td>Mass flow rate of water to evaporate</td>
<td>33.3</td>
<td>g/s</td>
</tr>
<tr>
<td>Inlet water temperature</td>
<td>21</td>
<td>°C</td>
</tr>
<tr>
<td>Outlet water temperature</td>
<td>100</td>
<td>°C</td>
</tr>
<tr>
<td>Specific heat of water @ inlet temperature</td>
<td>4,18369</td>
<td>kJ/kg.K</td>
</tr>
<tr>
<td>Water heat of vaporization @ 100°C</td>
<td>2256.4</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Sensible energy: m.cp.ΔT</td>
<td>-11.01</td>
<td>kW</td>
</tr>
<tr>
<td>Latent energy: m.hfg</td>
<td>-75.14</td>
<td>kW</td>
</tr>
</tbody>
</table>

Total power for the evaporation process: -86.14 kW

### Steam power:

<table>
<thead>
<tr>
<th>HEX Zone 1</th>
<th>Value</th>
<th>Units</th>
<th>HEX Zone 3</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air mass flow rate</td>
<td>0.942525</td>
<td>kg/s</td>
<td>Air mass flow rate</td>
<td>0.95407</td>
<td>kg/s</td>
</tr>
<tr>
<td>Air inlet enthalpy</td>
<td>141.97</td>
<td>kJ/kg</td>
<td>Air inlet enthalpy</td>
<td>155.68</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Air outlet enthalpy</td>
<td>181.62</td>
<td>kJ/kg</td>
<td>Air outlet enthalpy</td>
<td>193.48</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Power on air</td>
<td>37.37</td>
<td>kW</td>
<td>Power on air</td>
<td>36.06</td>
<td>kW</td>
</tr>
</tbody>
</table>

### HEX Zone 2

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air mass flow rate</td>
<td>0.943943</td>
<td>kg/s</td>
<td>Air mass flow rate</td>
</tr>
<tr>
<td>Air inlet enthalpy</td>
<td>148.65</td>
<td>kJ/kg</td>
<td>Air inlet enthalpy</td>
</tr>
<tr>
<td>Air outlet enthalpy</td>
<td>187.37</td>
<td>kJ/kg</td>
<td>Air outlet enthalpy</td>
</tr>
<tr>
<td>Power on air</td>
<td>36.55</td>
<td>kW</td>
<td>Power on air</td>
</tr>
</tbody>
</table>

### Total

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power on water</td>
<td>146.07</td>
</tr>
<tr>
<td>Boiler efficiency</td>
<td>90</td>
</tr>
<tr>
<td>Total power on fuel</td>
<td>162.30</td>
</tr>
<tr>
<td>Losses in fumes</td>
<td>16.23</td>
</tr>
</tbody>
</table>

### Heat power from paper and water:

<table>
<thead>
<tr>
<th>Paper</th>
<th>Value</th>
<th>Units</th>
<th>Water</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass flow rate</td>
<td>135.8</td>
<td>g/s</td>
<td>mass flow rate of non evaporate water</td>
<td>9.45</td>
<td>g/s</td>
</tr>
<tr>
<td>Inlet paper temperature</td>
<td>21</td>
<td>°C</td>
<td>Inlet water temperature</td>
<td>21</td>
<td>°C</td>
</tr>
<tr>
<td>Outlet paper temperature</td>
<td>100</td>
<td>°C</td>
<td>Outlet water temperature</td>
<td>100</td>
<td>°C</td>
</tr>
<tr>
<td>Specific heat of paper @ inlet temperature</td>
<td>1.2</td>
<td>kJ/kg.K</td>
<td>Specific heat of water @ inlet temperature</td>
<td>4.18</td>
<td>kJ/kg.K</td>
</tr>
<tr>
<td>Total power on paper</td>
<td>-12.87</td>
<td>kW</td>
<td>Total power on non evaporate water</td>
<td>-3.12</td>
<td>kW</td>
</tr>
</tbody>
</table>


Heat power from convection and radiation losses:

<table>
<thead>
<tr>
<th>Convection</th>
<th>Value</th>
<th>Units</th>
<th>Radiation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convection coefficient</td>
<td>13</td>
<td>J/m².K</td>
<td>Boltzmann constant</td>
<td>5,67E-08</td>
<td>J/m².K⁴</td>
</tr>
<tr>
<td>Machine outside area</td>
<td>68</td>
<td>m²</td>
<td>Machine outside area</td>
<td>68</td>
<td>m²</td>
</tr>
<tr>
<td>Machine outside temperature</td>
<td>50</td>
<td>°C</td>
<td>Machine outside temperature</td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Surrounding temperature</td>
<td>28</td>
<td>°C</td>
<td>Surrounding temperature</td>
<td>28</td>
<td>°C</td>
</tr>
<tr>
<td>Total power on convection losses</td>
<td>-19,448</td>
<td>kW</td>
<td>Total power on radiation losses</td>
<td>-10,3325</td>
<td>kW</td>
</tr>
</tbody>
</table>

Heat losses from leakages:

<table>
<thead>
<tr>
<th></th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>leaked air mass flow rate</td>
<td>0,2</td>
<td>kg/s</td>
</tr>
<tr>
<td>Specific heat of air at outlet temperature</td>
<td>1</td>
<td>kJ/kg.K</td>
</tr>
<tr>
<td>Surrounding temperature</td>
<td>28</td>
<td>°C</td>
</tr>
<tr>
<td>Outlet leaked air temperature</td>
<td>100</td>
<td>°C</td>
</tr>
<tr>
<td>Total power on convection losses</td>
<td>-14,4</td>
<td>kW</td>
</tr>
</tbody>
</table>
Appendix 6: Exergy Calculations

<table>
<thead>
<tr>
<th>Exergy produced by boiler:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>162.3</td>
<td>kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>2000</td>
<td>°C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>141</td>
<td>kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exergy of Steam:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>146.07</td>
<td>kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>150</td>
<td>°C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>46.6</td>
<td>kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exergy of Hot air:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>146.07</td>
<td>kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>128</td>
<td>°C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>41.1</td>
<td>kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exergy lost in fumes:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>16</td>
<td>kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>250</td>
<td>°C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>7</td>
<td>kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exergy lost by the paper:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>16</td>
<td>kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>100</td>
<td>°C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>3.6</td>
<td>kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exergy lost to the surrounding:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>30</td>
<td>kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>3.2</td>
<td>kW</td>
</tr>
</tbody>
</table>
### Exergy lost by leakage:

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>14.4  kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15 °C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>100 °C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>3.3 kW</td>
</tr>
</tbody>
</table>

### Exergy release to the environment:

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 molar flow rate</td>
<td>$1.3 \times 10^{-6}$ Mol/s</td>
</tr>
<tr>
<td>Reference temperature T0</td>
<td>15 °C</td>
</tr>
<tr>
<td>Atmospheric CO2 concentration</td>
<td>300 ppm</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>4 kW</td>
</tr>
</tbody>
</table>
## Appendix 7: New Heat exchanger

### Exergy produced by boiler:

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>122 kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15 °C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>2000 °C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>107 kW</td>
</tr>
</tbody>
</table>

### Exergy lost in fumes:

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>12 kW</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>15 °C</td>
</tr>
<tr>
<td>Process temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>5 kW</td>
</tr>
</tbody>
</table>

### Exergy release to the environment:

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 molar flow rate</td>
<td>1.3E-06 Mol/s</td>
</tr>
<tr>
<td>Reference temperature T0</td>
<td>15 °C</td>
</tr>
<tr>
<td>Atmospheric CO2 concentration</td>
<td>300 ppm</td>
</tr>
<tr>
<td>Total exergy power</td>
<td>3 kW</td>
</tr>
</tbody>
</table>
Appendix 8: Heat recovery

<table>
<thead>
<tr>
<th>New fresh air outlet temperature</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature inlet fresh air</td>
<td>12</td>
<td>°C</td>
</tr>
<tr>
<td>Temperature inlet wasted air</td>
<td>55</td>
<td>°C</td>
</tr>
<tr>
<td>New efficiency</td>
<td>90</td>
<td>%</td>
</tr>
<tr>
<td>Fresh air outlet temperature</td>
<td>52</td>
<td>°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area of exchange</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td>7</td>
<td>kg/s</td>
</tr>
<tr>
<td>Exchanger power</td>
<td>273</td>
<td>kW</td>
</tr>
<tr>
<td>DTLM</td>
<td>4.3</td>
<td>°C</td>
</tr>
<tr>
<td>Area of heat exchange</td>
<td>141.9</td>
<td>m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>District heating power</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td>7</td>
<td>kg/s</td>
</tr>
<tr>
<td>Air inlet enthalpy</td>
<td>58.78</td>
<td>kJ/kg.K</td>
</tr>
<tr>
<td>Air outlet enthalpy</td>
<td>73.25</td>
<td>kJ/kg.K</td>
</tr>
<tr>
<td>Power on district heating</td>
<td>101.2</td>
<td>kW</td>
</tr>
</tbody>
</table>
Appendix 9: District Heating cost

### District heating energy price and annual charges

<table>
<thead>
<tr>
<th>Price level</th>
<th>E</th>
<th>Permanent charge/years</th>
<th>Effect charge/kilowatt, years</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0-20</td>
<td>842 SEK</td>
<td>1 102 SEK x E</td>
</tr>
<tr>
<td>3</td>
<td>21-100</td>
<td>5 438 SEK</td>
<td>881 SEK x E</td>
</tr>
<tr>
<td>4</td>
<td>101-500</td>
<td>32 375 SEK</td>
<td>622 SEK x E</td>
</tr>
<tr>
<td>5</td>
<td>501-</td>
<td>64 750 SEK</td>
<td>561 SEK x E</td>
</tr>
</tbody>
</table>

*"E" is normal or corrected mean of measured average effect in kilowatt for the period nov - mar the two last seasons before the debit year's beginning.*

### Movable energy pinch - price level 2 - 5

<table>
<thead>
<tr>
<th>Energy pinch</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter price</td>
<td>397 SEK /MWh</td>
</tr>
<tr>
<td>Summer price</td>
<td>335 SEK /MWh</td>
</tr>
</tbody>
</table>

The energy charge is charged according to measured energy use.

Source Gävle Energi "Fjärrvärmepriser 2007"

### District heating study (year 2005)

<table>
<thead>
<tr>
<th>Power E</th>
<th>Working hours</th>
<th>Energy consumption</th>
<th>Permanent charge</th>
<th>Effect charge</th>
<th>Energy cost</th>
<th>Total energy cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW</td>
<td>h</td>
<td>Winter</td>
<td>Summer</td>
<td>kSEK</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production process</td>
<td>540</td>
<td>1316</td>
<td>709</td>
<td>710,8</td>
<td>392,7</td>
<td>64,8</td>
</tr>
<tr>
<td>Support process</td>
<td>200</td>
<td>2700</td>
<td>1559</td>
<td>540,0</td>
<td>311,9</td>
<td>4455</td>
</tr>
</tbody>
</table>

Energy cost: 0.6093 kSEK/MWh

### District heating study corrected with the power reduction (38\%) applied on production processes

<table>
<thead>
<tr>
<th>Power E</th>
<th>Working hours</th>
<th>Energy consumption</th>
<th>Permanent charge</th>
<th>Effect charge</th>
<th>Energy cost</th>
<th>Total energy cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW</td>
<td>h</td>
<td>Winter</td>
<td>Summer</td>
<td>kSEK</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production process</td>
<td>337</td>
<td>1316</td>
<td>709</td>
<td>443,1</td>
<td>238,6</td>
<td>64,8</td>
</tr>
<tr>
<td>Support process</td>
<td>200</td>
<td>2700</td>
<td>1559</td>
<td>540,0</td>
<td>311,9</td>
<td>4455</td>
</tr>
</tbody>
</table>

Energy cost: 0.5980 kSEK/MWh
District heating study corrected and applied on the optimisation IR + DH 2 passes

<table>
<thead>
<tr>
<th>Power E</th>
<th>Working hours</th>
<th>Energy consumption</th>
<th>Permanent charge</th>
<th>Effect charge</th>
<th>Energy cost</th>
<th>Total energy cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kW</td>
<td>h</td>
<td>MWh</td>
<td>kW</td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>Production process</td>
<td>182</td>
<td>2216</td>
<td>709</td>
<td>299,4</td>
<td>129,0</td>
<td>32,4</td>
</tr>
<tr>
<td>Support process</td>
<td>200</td>
<td>2700</td>
<td>1559</td>
<td>540,0</td>
<td>321,9</td>
<td>214,4</td>
</tr>
</tbody>
</table>

Energy cost: 0.5773kSEK/MWh
Appendix 10 : IR Drying calculations

<table>
<thead>
<tr>
<th>Water evaporation:</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate of water to evaporate:</td>
<td>33,3 g</td>
<td>s</td>
</tr>
<tr>
<td>Inlet water temperature</td>
<td>21 °C</td>
<td></td>
</tr>
<tr>
<td>Outlet water temperature</td>
<td>70 °C</td>
<td></td>
</tr>
<tr>
<td>Specific heat of water @ inlet temperature</td>
<td>4,18369 kJ/kg.K</td>
<td></td>
</tr>
<tr>
<td>Water heat of vaporization @ 70°C</td>
<td>2332 kJ/kg</td>
<td></td>
</tr>
<tr>
<td>Sensible energy: m.cp.∆T</td>
<td>-6.8 kW</td>
<td></td>
</tr>
<tr>
<td>Latent energy: m.hfg</td>
<td>-77.7 kW</td>
<td></td>
</tr>
<tr>
<td>Total power for the evaporation process</td>
<td>-84.5 kW</td>
<td></td>
</tr>
</tbody>
</table>

Heat power from paper and water:

<table>
<thead>
<tr>
<th>Paper</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass flow rate</td>
<td>135,8</td>
<td>g/s</td>
</tr>
<tr>
<td>Inlet paper temperature</td>
<td>21 °C</td>
<td></td>
</tr>
<tr>
<td>Outlet paper temperature</td>
<td>70 °C</td>
<td></td>
</tr>
<tr>
<td>Specific heat of paper @ inlet temperature</td>
<td>1,2 kJ/kg.K</td>
<td></td>
</tr>
<tr>
<td>Total power on paper</td>
<td>-7.98 kW</td>
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<th>Water</th>
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<td>mass flow rate of non evaporate water</td>
<td>9,45 g</td>
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<tr>
<td>Inlet water temperature</td>
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<tr>
<td>Outlet water temperature</td>
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<tr>
<td>Specific heat of water @ inlet temperature</td>
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<tr>
<td>Total power on non evaporate water</td>
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# Appendix 11: Heat recovery with solution 4

## New fresh air outlet temperature:

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<td>Temperature inlet fresh air</td>
<td>12</td>
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<tr>
<td>Temperature inlet wasted air</td>
<td>55</td>
<td>°C</td>
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<tr>
<td>New efficiency</td>
<td>90</td>
<td>%</td>
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<td>Fresh air outlet temperature</td>
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## Area of exchange:

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<td>kg/s</td>
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<tr>
<td>Exchanger power</td>
<td>237</td>
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<tr>
<td>DTLM</td>
<td>4.3</td>
<td>°C</td>
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<tr>
<td>U</td>
<td>450</td>
<td>W.m².K⁻¹</td>
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<td>Area of heat exchange</td>
<td>122.5</td>
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## District heating power:

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</tr>
<tr>
<td>Air inlet enthalpy</td>
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<td>kJ/kg.K</td>
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<tr>
<td>Air outlet enthalpy</td>
<td>73.24</td>
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<tr>
<td>Power on district heating</td>
<td>88.6</td>
<td>kW</td>
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</table>
Appendix 12: Summary

Existing process:

- Power: 188kW (162 kW fuel, 26kW electricity).
- Energy efficiency: 45.7%
- Exergy efficiency: 11.7% (exergy wasted: 64.9kW)
- CO2 emissions per year: 72.2 tonCO2 (oil: 69.8 tonC02 and electricity: 2.4 tonCO2)
- Energy cost per year: 214.7kSEK (oil: 192.9kSEK and electricity: 21.8kSEK)

New heat recovery exchanger:

- Power: 148kW (122 kW fuel, 26kW electricity).
- Energy efficiency: 58.1%
- Exergy efficiency: 14.7% (exergy wasted: 49kW)
- CO2 emissions per year: 55 tonCO2 (oil: 52 tonC02 and electricity: 2.4 tonCO2)
- Energy cost per year: 167kSEK (oil: 145.3kSEK and electricity: 21.8kSEK)

DH:

- Power: 127kW (101 kW fuel, 26kW electricity).
- Energy efficiency: 72.4%
- Exergy efficiency: 32.7% (exergy wasted: 4kW)
- CO2 emissions per year: 5.1 tonCO2 (DH: 2.7 tonC02 and electricity: 2.4 tonCO2)
- Energy cost per year: 110.2kSEK (DH: 88.4kSEK and electricity: 21.8kSEK)

IRD:

- Power: 172kW (only electricity)
- Energy efficiency: 49%
- Exergy efficiency: 7.8% (exergy wasted: 16.6kW)
- CO2 emissions per year: 15.8 tonCO2 (electricity)
- Energy cost per year: 143.1kSEK (electricity)
- Investment: 1000kSEK for three frames of IRD device.
IRD + DH 2 passes:

- Power: 172kW (DH: 26kW and electricity 146kW)
- Energy efficiency: 45.3%
- Exergy efficiency: 7.6% (exergy wasted: 13.6kW)
- CO₂ emissions per year: 14tonCO₂ (electricity: 13.72tonCO₂ and DH: 0.69tonCO₂)
- Energy cost per year: 142.8kSEK (electricity: 121.5kSEK and DH: 21.3kSEK)
- Investments: 175kSEK for the pipes and 720kSEK for two frames of IRD device.

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<tr>
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<th>Heat power DH</th>
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### Energy

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<td>tonCO₂</td>
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### CO₂ emissions
### Exergy

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### Cost

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**Heat power oil**

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**Elec power**

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**Total consumed**

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**Wasted**

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**Exergy**

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<td>Current process (with refund)</td>
<td>125,40</td>
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<td>94,44</td>
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