CHALMERS

Energy recovery from destruction of VOC's

An analysis of the possibilities at Tetra Pak Inventing AB in Fjällbacka

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Abstract

Making industry more energy efficient and thereby reducing their environmental impact is a widely discussed topic and an important problem to solve to reach a sustainable society. This report identifies the possibilities of making use of recovered energy from the destruction of methyl-ethyl-ketone(MEK) at Tetra Pak Inventing AB in Fjällbacka and thereby reducing energy use.
MEK is an organic solvent used in the process of making plastic strips used in Tetra Pak's packages. MEK is also a toxic VOC that has to be destroyed in order to keep it from getting into the environment. Today MEK is destroyed by catalytic combustion in a catox. This process generates heat which is recovered and used for heating the facilities. However the heat from the catox exceeds the heat demand for large part of the year. This means that around 50 percent of the available heat is not used. Tetra Pak inventing AB is to face an expansion in which the amount of MEK would approximately double. This would mean that even more energy goes to waste. Through a literature study a model is constructed and 4 different scenarios are modelled to investigate how much energy that can be recovered and reused. The model also investigates the environmental and economical impact of the energy savings. The 4 scenarios are:

- Reference scenario - A scenario that tries to describe the current situation.
- 2007 scenario - A scenario that uses the 2007 conditions at Tetra Pak Inventing AB but adds new technology for generating cold and electricity. The technology used is comercially available today.
- Future scenario - A scenario that assumes that planned expansion has occurred and thereby the amount of MEK, the heat demand and the cooling demand has increased. The technology is the same as for the 2007 scenario.
- Turbine scenario - A scenario that assumed that a micro turbine for destruction of VOC is commercially available and replaces the catox. The amount of MEK, heat demand and cooling demand is the same as the future scenario.

The results from the model shows that there are possibilities to recover and use the energy in the MEK to a higher extent than today. There are two main alternatives:

- Using catalytic combustion producing electricity with a low temperature power plant and cold with sorption chillers. This solution is both economical and environmental beneficial.
- Using a micro turbine for destruction of VOC's. This would generate more electricity and be more sensitive to electricity prices and a somewhat more uncertain technology.

Both solutions are economically feasible and environmental beneficial.

Sammanfattning

Energieffektivisering inom industrin som ett verktyg för att minska miljöpåverkan är en relevant fråga för att nå ett hållbart samhälle. Den här rapporten undersöker möjligheterna att tillvarata energin i den metyl etyl keton (MEK) som destrueras vid Tetra Pak Inventing AB i Fjällbacka. MEK är ett organiskt lösningsmedel som används i processen för tillverkning av plastmaterial för användning i förpackningar. MEK är även ett flyktigt organiskt kolväte som inte får spridas utan måste fångas in och förstöras. MEK från fabriken i Fjällbacka är i dagsläget destruerat via katalytiskt förbränning i en så kallad catox anläggning. Denna process genererar värme som används för att värma lokalerna. Tillgången på värme överstiger under en stor del av året värmebehovet. Detta innebär att runt 50 procent av värmen går till spillo. Tetra Pak Inventing AB kommer inom en nära framtid att utöka sin produktion i Fjällbacka. En sådan produktionsökning skulle innebära mer outnyttjad spillvärme.

Efter en litteraturstudie konstrueras en modell och 4 olika scenarier är modellerade för att undersöka hur mycket av spillvärmen som kan tas tillvara. Med hjälp av modellen undersöks de ekonomiska och miljömässiga konsekvenserna av ett ökat utnyttjande av spillvärme. De fyra scenarierna är:

- Reference scenario - Ett scenario som beskriver dagens situation.
- 2007 scenario - Ett scenario som bygger på 2007 års förhållanden i Tetra Pak Inventing ABs fabrik i Fjällbacka men lägger till tekniker för generering av el och kyla från spillvärme.
- Future scenario - Ett scenario som antas äga rum efter den planerade expansionen och därmed ha ökad tillgång på MEK, större värme och kylbehov. Tekniken är densamma som för 2007.
- Turbine scenario - Ett scenario som bygger på att en mikroturbin för destruering av VOC har blivit kommersiellt tillgänglig och ersätter catox anläggningen. Mängden MEK, kyl-och värme behovet är samma som för future scenariot.

Två möjligheter att öka tillvaratagandet av energin i MEK identifieras. En möjlighet är att använda befintlig catox teknologi för destrueringsprocessen och sedan tillvarata värmen för produktion av electricitet via lågtemperaturkraftverk och kyla via absorption/adsorptions kylare. Det andra alternativet är att använda sig av en mikroturbin för nedbrytning av VOC's. Det alternativet skulle producera en högre andel electricitet och därmed vara känsligare för elpris samtidigt som det bygger på en mer oprövad teknik. Båda alternativen visar sig vara både ekonomiskt genomförbara och miljömässigt gynnsamma.

Preface

This Project is carried out as a master thesis within the master program of industrial ecology. I am grateful to Mats Lindblad and Tetra Pak Inventing AB for giving me the opportunity and support for this thesis. I am thankful to Anders Lindberg and Jörgen kristiansson for providing necessary data. I would also like to thank my supervisor Erik Ahlgren for valuable input and guidance.

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1 Introduction

1.1 Tetra Pak Inventing AB

Tetra Pak Inventing AB is a company fully owned by Tetra Pak AB situated in Fjällbacka in northern Bohuslän. Tetra Pak Inventing AB is one of three companies that deliver plastic films for use in Tetra Paks packages. The other ones are located in Hjörring, Denmark and Rayong, Thailand. The factory has three main production lines for plastic films, the 3-layer blown film line, the 5-layer blown film line and the coating line. Tetra Pak has set a goal to reduce their greenhouse gas emissions by 10 percent. 10 percent is in this case an fixed number and disregards any increases in production.

The production line of interest for this project is the coating line. The coating line starts with a thin polyester film that is coated with a primer mix that consists of primer, hardener and the organic solvent methyl-ethyl-ketone (MEK). The plastic film is lead through a heating tunnel where the MEK is evaporated. The MEK is gathered and destroyed by catalytic combustion in the catox. The plastic film is thereafter coated with two layers of polythene and rolled up and put in storage for approximately 3 days before the other side of the plastic film is treated the same way.

The destruction of MEK is necessary since it is a volatile organic compound and is therefore not allowed release into the air. In the catalytic combustion process heat is generated. During the cold parts of the year this heat is used for space heating and thereby reducing the need for other heat sources such as oil or electricity. Figure 1.1 shows the heat produced by the catox in relation to the heat demand.

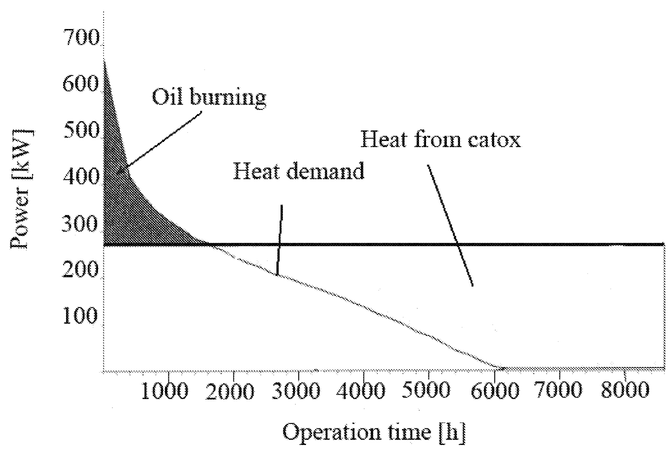


Figure 1.1. The heat situation 2001 at Tetra Pak Inventing AB (Moberg 2001)

A more complete picture of the present energy situation is presented in the reference energy system in fig 1.2.

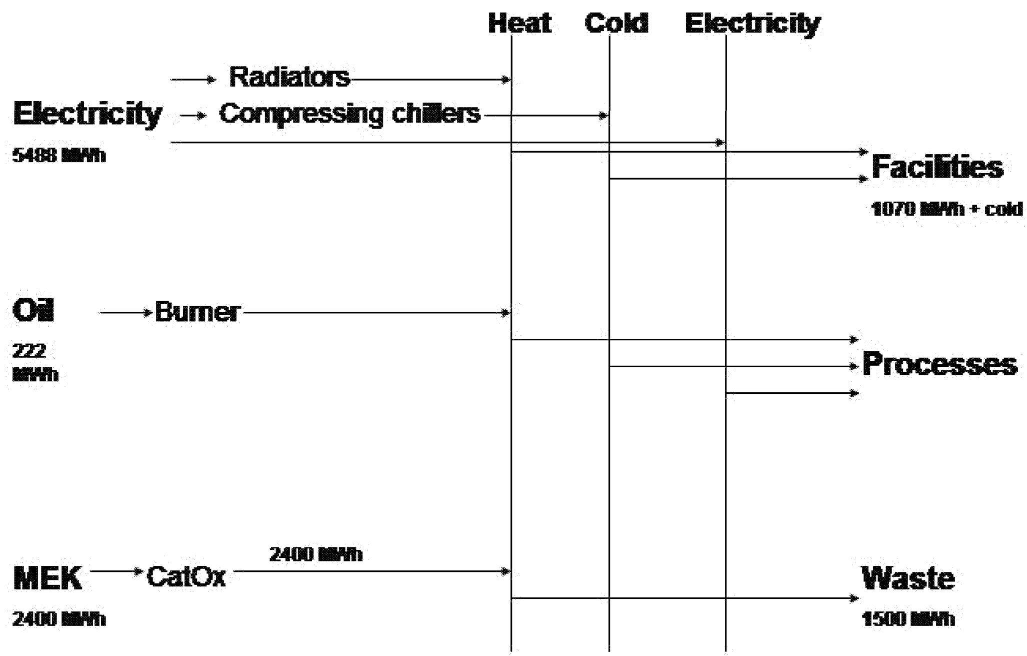


Figure 1.2. Reference energy system for 2007 at Tetra Pak inventing

1.2 Problem definition and limitations

This project aims to minimize waste energy from destruction of MEK. The project will identify solutions to make use of the energy from the destruction of MEK used in the process at Tetra Pak Inventing AB in Fjällbacka. These solutions will also be evaluated from an economical and environmental point of view.
This project does not deal with any solutions to reduce the amount of MEK in the process or to recycle MEK. It is assumed that the MEK is a waste product that has to be destroyed. Further on the project focuses on Fjällbacka and will not make extensive comparisons between production in Fjällbacka, Rayong or Hjörring.

2 Background

2.1 Volatile organic compounds

Volatile organic compounds, VOC's are a group of compounds that, has several toxic effects on humans causing headaches, loss of coordination, liver and kidney damage. Some VOC's has even been shown to be cancerogenic. They also contribute to the formation of ground level ozone and enhance the global warming potential of methane (EPA 2008). The Swedish Environmental Protection Agency has identified VOC as a threat to the second environmental goal, clean air which states that "The air should be clean enough not do damage human health, animals, plants or cultural values" (Naturvårdsverket 2008*a*) As a sub target to this there is the goal to reduce VOC to 241 000 tonnes by 2010. This target was already met several years ago (Naturvårdsverket 2008*b*). A reason for these targets being met is the regulations put on, and responsibilities taken by VOC producing industries. There are possibilities to destroy VOC, leaving only CO_2 and water. A widespread technology is the catalytic combustion process that is used in Tetra Pak Inventing AB's facilities in Fjällbacka. In many applications the destruction of VOC's is an energy demanding process often driven by natural gas. In some cases however VOC's has a high enough energy content to sustain the destruction and even make the process exothermal. VOC's that has a high enough energy content to make the destruction process exothermal could be considered as a fuel rather than a waste product.

2.2 Using low energy waste gases

MEK has an energy content of 32 MJ/kg (Sjöö 2006*b*). This is around 50 percent of that in pure methane. This makes MEK a so called low BTU gas or low energy gas. There are examples of power plants that have used low energy gases as a fuel for producing heat and power. Just outside Edinburgh there is a 3.5 MW power plant driven by the waste gas from a landfill which typically contains 45-55 percent methane. (Packham 2007). With an increasing electricity price there is an increased interest in harvesting low energy gases for heat and power production. Research is done on several both old and new technologies such as sterling engines, gas turbines and fuel cells to find an efficient way of producing heat and electricity from these gases (Bove 2006).

There are two main differences between the situation in Fjällbacka and the successful projects of which the Edinburgh landfill gas is one example. The first difference is the potential. The successful examples that can be found in literature are often around a few MW electricity whereas in the case of Tetra Pak Inventing AB the potential is a couple of 100 KW electricity. The second difference is the nature of the fuel. MEK is a toxic VOC which has to be destroyed to more than 99 percent.

With landfill Methane or other low energy gases a certain leakage or incomplete combustion can be tolerated but the regulations are harder on the MEK which has to be destroyed

2.3 Technologies

There are three main energy sources that supplies Tetra Pak inventing with energy; electricity, oil and MEK. These sources are transformed into three main carriers; heat, electricity and cold. As shown in the reference energy system in figure 1.2 a lot of the heat is going to waste. Several studies (Deng *et al.* 2008, Chicco and Mancarella 2007) has shown that the concept of trigeneration, combined production of heat, power and cold offers energy efficient solutions. Therefore trigeneration will be considered the main alternative. In this section technologies that has the capability of transforming low to medium heat to other energy carriers or technologies for making good use of the MEK as a fuel for trigeneration are introduced. Detailed technology descriptions are not needed for this project but a brief introduction to technologies that might improve the situation in Fjällbacka will be given. The technologies are presented under their respective energy carrier.

2.3.1 Heat

Part of the heat produced by the destruction of MEK is needed to sustain the process. Around 40 percent of the heat is used for evaporating the MEK in the drying tunnel and preheating the waste gas before it reaches the reactor chamber. The remaining 60 percent is available for other recovery (Topsoe 1989). Some of this heat is used today for space heating. As shown in fig 1.1 the supply exceeds the demand for a large part of the year. Space heating is the main use of heat within the factory. Melting plastic granulates also consumes heat but the heat for this is supplied to 85 percent from friction from the feeding screw. The remaining 15 percent is supplied by electricity. The electricity is mainly used to regulate the temperature and create different temperature zones to give the plastics the desired properties. Since the regulation capacity is of the essence heat from the catox will not be used for this purpose.

2.3.2 Electricity

The traditional way of turning heat into electricity is the Clausis-Rankine cycle. The CRC uses heat to evaporate water to steam that runs a turbine. The main problem with the CRC when producing electricity from low or medium temperature waste heat is the very low conversion efficiency at these temperatures. This makes the CRC unfavourable both from a technical and economical point of view. There are however modified rankine cycles that are more suited for the using low or medium temperature heat. To be able to use lower temperature the working fluid is changed to a pure organic fluid such as iso-butane or propane(Organic Rankine Cycle) or the cycle is redesigned and working fluid changed to a water ammonium mix (Kalina cycle). The difference in conversion efficiency between the Kalina cycle and the ORC is dependent on the operation conditions which one is the most efficient solution is therefore very dependent on the location (Kaltschmidt 2006). The Kalina cycle and the organic rankine cycle are rather similar in conversion efficiencies and installation demands and will therefore be treated as the same technology even though the cycles somewhat differs. As mentioned earlier in section **??** it is possible to use MEK directly as a fuel instead of trying to recover the heat from the destruction. One option that makes this possible is a micro turbine designed for the destruction of VOC's. Such a patent was granted James b. Kesseli in 2005 (Kesseli 2005) The newly formed company Flexenergy.inc is trying to make a micro turbine than can run on low energy waste gases at the same time as it destroys VOC's available to the market(Flexenergy 2008). A micro turbine would offer higher conversion efficiency than both the Kalina cycle and the ORC.

2.3.3 Cold

There are several ways of supplying cooling. The most common way is to cool down a cooling media with the help of a compression chiller driven by electricity. There are however alternatives. An adsorption or absorption chiller is driven by heat. The basic principle behind these chillers is evaporation of the working media under low pressure and thereby cooling a cooling media. Thereafter the vapour is absorbed/adsorbed by an absorbent/adsorbent. The heat is used for separating the working media from the absorbent/adsorbent. The working fluid is lead to a condenser where it is condensed in and the cycle can start over again. Both adsorption and absorption chilling will hereafter be referred to as sorption chilling and treated as the same technology since they are very similar regarding operation conditions. They are basically heat driven cooling machines.

3 Method

3.1 Industrial ecology

One of the major principles of Industrial Ecology (IE) is that we should model our industrial systems after biological ecosystems if we want them to be sustainable. When taking the nature as a role model we will minimize the harmful waste that we create and maximize the use of waste and products at the end of their useful lives such that they become the inputs to new processes and industries.(Haskins 2006) When trying to apply this in an industrial ecosystem the goal is therefore very often to minimize the linear flows either by using less material and hence reducing the flows or by closing the flows so they become circular. Often it is not possible to entirely close a flow at once but rather recykling parts of it and thereby reducing the need for virgin input. Industrial ecology also stresses the importance of interconnectedness between processes where the waste from one process becomes input to another. This was done with success in Kalundborg, Denmark where an industrial ecopark took form. The driving forces behind this ecopark was the search for reduced waste management costs, reduced raw material costs and to make a profit from the by-products of their own production.(Haskins 2006). The driving forces have been purely economical and in the same time the result shows environmental benefits in form of reduced environmental impact from production. Fjällbacka is a significantly smaller community than Kalundborg and consequently there are fewer industries. Tetra Pak Inventing AB is the only larger industry to be found at the location so an industrial eco park in traditional sense is hard to achieve in the present situation. The same principles used in an industrial ecopark is however applicable, the difference is that in the case of Tetra Pak Inventing AB it is a question of increasing the interconnectedness between different processes within the industry and between the industry and the public community. One waste product from Tetra Pak Inventing AB today is MEK or heat that origins from MEK. An industrial ecology approach to handling this problem is to identify other processes that might use this waste as input. This is one of the strategies for closing the material flows identified by Ayres in his book Industrial ecology: towards closing the materials cycle (Ayres and Ayres 1996).

3.2 Modeling

The reference energy system in figure 1.2 shows that there are three main energy carriers within Tetra Pak Inventing AB heat, cold and electricity. Figure 1.2 also shows that a large amount of the heat is discarded as waste. It would therefore be desirable to either turn the MEK into another carrier or transform the heat into other carriers since the availability of heat clearly exceeds the demand for a large

part of the year. Different technologies that can manage to either destroy VOC and generate heat, cold and electricity or transform waste heat into cold and electricity are investigated. The most favourable technologies are chosen and used in a model to investigate how much of the energy that could be recovered and reused and how this would effect the economical and environmental performance of the company.
Since the company is to face a larger expansion within the near future four different scenarios are modelled.

- Reference scenario - Describing today's situation
- 2007 scenario - Describing what could be done today
- future scenario - Describing what could be done after the expansion with today's technology
- Turbine scenario - Describing what could be done after the expansion with technology close to commercialisation.

The scenarios are described in more detail in chapter 4 scenarios and modelling.

The results from the model will show how much recovered energy that is possible to use, how much it will cost, the environmental benefits and the limitations that hinders more waste energy of being used. To show how the energy is possible to recover a The limitations will be shown in form of shadow prices for the different technologies. The shadow price shows among other things if the limitation is active or not. If a shadow price is separated from zero the limitation is active and if the shadow price is equal to zero the limitation is passive and there would be no changes in the result if this limitation was removed.
After the result from the different scenarios is obtained a sensitivity analysis will be performed. The main uncertainties that could have a negative impact on the result is the degree of expansion and the change in heating demand therefore these parameters effect on the result will be examined. Since electricity production or reduced use of electricity is a part of all scenarios electricity prices will also be a part of the sensitivity analysis. For future Technologies conversion efficiencies will also be altered.

4 Scenarios and Model

The model deals with four different scenarios; reference, 2007, future and turbine. These scenarios are described below. The base of the model is the same for all three scenarios but some minor differences have to be made therefore the scenarios are presented before describing the model.

4.1 Scenarios

The modelling will be carried out with four scenarios. One reference scenario, one that deals with today's situation one scenario that deals with a future situation with today's technology and one scenario that uses technology that is not commercially available today to solve the situation of tomorrow. The future situation is based on an application for expansion written by ÅF (Sjöö 2006*a*).

4.1.1 Reference

The reference scenario is a business as usual scenario with no increase in production or new investments in technology.

4.1.2 2007

The 2007 scenario shows what could be done in the scenario described by industripartner. Heat production, cooling demand and operational hours are obtained from 2007 years operational data. All investments are considered as new investments that has to pay for themselves

4.1.3 Future

The future scenario is based on the investigation performed by ÅF as a part of the application to expand the production. This simulation is assumed to take place when the production is fully expanded. The expansion will mean that the production capacity of the coating line is doubled. A doubling of production in the coating line will mean a doubling of primermix used which means that heat production doubles. Increased production also means increased cooling need. Further on the facilities will also be expanded requiring more heating. Fjällbacka is a small community and there are no plans of constructing any kind of district heating system within the near future so the use of the energy for district heating or district cooling is not an option. This scenario assumed that no major technology changes compared to the 2007 scenario. The investment cost for the sorption chiller is changed to be the difference between the price of a compressor chiller that needs to be invested in anyhow and the more expensive sorption chiller.

4.1.4 Turbine

The turbine scenario is based on the assumption that the micro turbine for combustion of VOC is successfully commercialised and available for use in trigeneration. The destruction of VOC will in this case primarily produce electricity and the waste heat is used to supply heating and cooling. The rest of the data is the same as for the future scenario.

4.2 Model

The model is based on the linear programming tool in Matlab. Linear programming is used to maximize or minimize a function under given constraints. This is done with a resolution of one hour. The function to minimize in this model is waste energy. Waste energy will be minimized by maximizing the used energy. Further on it is desirable to minimize waste in the most economical favourable way. Using the technologies described in section **??** the profit function to maximize can be written as

$$P = S_{electricity} + S_{cold} + S_{heat}$$

Where P is the profit function. $S_{electricity}$, S_{cold}, S_{heat} is the savings generated from electricity generation, sorption chilling and space heating respectively. The savings from electricity generation is given by

$$S_{electricity} = E_{electricity} * ef_{conv} * P_{el}$$

where P_{el} is the electricity price and $E_{electricity}$ is the energy input to the electricity generation and ef_{conv} is the conversion efficiency. The sorption chiller will produce cold and thereby reducing the need of cold produced by electricity. The COP for a sorption chiller is however substantially lower than that of a electric compression chiller. The savings from the sorption chilling is therefore depending on the difference in COP for the different chillers. The savings from sorption chilling can be expressed as

$$S_{cold} = E_{cold} * (COP_{sorption}/COP_{el}) * P_{el}$$

When energy from the destruction of MEK is used for space heating it replaces oil burning and thereby generates savings according to

$$S_{heat} = E_{heat} * P_{oil}$$

Where E_{heat} is the amount of energy used for heating and P_{oil} is the price heating with oil for an oil burner with an efficiency of 90-95 percent. Since all the terms of the profit function are increasing with increased energy input maximizing profit also means maximizing energy use. Investment and running costs are not included in this part of the model but examined separately in a later part. As mentioned earlier the maximization is done under certain constraints. The constraints in this model are:

- The energy used must not exceed the energy available.
- The energy used for heating must not exceed the heating demand.
- The produced cooling must not exceed the cooling need.
- The electricity output must not exceed the installed generation capacity.

These constraints can be expressed in equations

-
  - $E_{heat} + E_{electricity}{*}eff_{conversion}{*}2 + E_{cold}\leq \mathrm{E}_{available}$
  - $E_{heat} + E_{cold}\leq$ (eff_{tot}-$eff_{conversion}$-$E_{sustainingprocess}$)$*E_{fuel}$.
- $E_{heat}\leq \mathrm{Demand}_{heat}$
- $E_{cold}{*}COP_{sorption}\leq \mathrm{Demand}_{cold}$
- $E_{electricity} \leq \mathrm{E}_{available}{*}eff_{conversion}$

The first contraint is described two equations. One for the 2007 and future scenario where electricity os produced from waste heat. The other one is for the turbine scenario where electricity is produced by the turbine and the waste heat is used for heating and cooling. The term E in the equations is the energy input to the different processes. For heat and cold processes all of the energy is used. For electricity generation in 2007 and future scenario however only a part of the heat is consumed, a part that corresponds to two times the produced electricity. The rest is available for further use. The last equation shows that the conversion efficiency and available energy determines how much capacity that is installed for electricity generation.
To satisfy the first constraint the model needs an expression for available energy. The energy available is calculated from the energy content in the waste gas that is delivered to the catox today. To calculate the amount exhaust gas the model takes

origin in amount MEK used and the exhaust gas composition. This means that the amount of waste gas delivered for destruction is given by

$$AmountSolvent = AmountMEK/PercentMekinexhaustgas$$

This means that the energy available for use during one year is calculated as

$$Energy_{available}[MJ] = Amountsolvent[Kg]*Energycontentingas[MJ/Kg]*(1-Sust)$$

where Sust is the percentage of energy needed to sustain the process of gathering and destroying MEK.Since the model has a resolution of one hour the available energy/hour is of interest.Assuming that the energy is evenly distributed over the operation hours of the coating line the available energy per hour from destruction of MEK is

$$E_{available}[MJ] = Energy_{available}[MJ]/Operationtime[h]$$

4.2.1 Energy

Using data from the linear programming the model constructs graphs for the different scenarios where potential use of the energy is shown.The graphs are a combination of a duration and load graph. The heating demand is shown as a duration graph, thereby sorting the hours with the coldest hours to the left and the warmer on the right. The supply will be shown in a form of load curve with the hours sorted according to the previous duration graph. The result is presented in this way since the only data on heat demand is a duration graph. Therefore the cooling demand is also modelled with a duration graph that is assumed to be inverted to the heat demand in the meaning that the highest demand for cooling is when the demand for heating is low. The model also shows how the recovered energy is distributed and what limitations that are hindering further reduction of waste heat.

4.2.2 Economy

with origin in the changes in energy consumption and energy mix the model shows which investments that are economically feasible and which ones will give the largest benefits for the company. The payback time is used as a measure on economic feasibility

$$PBT = CC/AS$$

Where PBT is the payback time in years and CC is the capital cost and AS is the annual savings. If payback time is five years or less the investment is considered favourable on pure economic basis. if the payback time exceeds five years other arguments e.g. CO_2 mitigations has to be considered.

4.2.3 Environment

Using the modelled data on changes in energy consumption and energy mix environmental effects are calculated. Emissions are calculated according to

$$e_f = E_i * ef_i$$

where e_f is the emissions from fuel i , E_i is the energy input from the fuel in MWh and ef_i is the emission coefficient for the pollutant calculated in kg/MWh. The environmental part of the model investigates how emissions will change if the new applications are installed.
The emission factors for electricity are somewhat complicated. There are several ways of estimating the emissions caused by electricity production. The different methods is discussed in a report published by the Swedish Energy Agency (Andersson 2007). The two main approaches are to use the average emission factor from all production or use the emission factors from the electricity produced at the margin. The average method can be used when describing the current situation but the margin method is better to show the effects of a small change in the electricity system (Andersson 2007). The model will therefore use the margin electricity approach, the marginal approach is however not uncomplicated. To decide which emissions factors to use the marginal production must be identified and to identify marginal production one has to decide on system boundaries for the electricity system. If the boundaries are set to the Swedish borders the marginal production will be different from that of the Nordic system. This model will consider the Nordic energy system and therefore assume coal condensing power on the margin in the short run and combined cycle natural gas for the future. This change in marginal production is assumed to occur for pure economic reasons due to higher conversion efficiency. The change in electricity use in Tetra Pak Inventing AB in Fjällbacka is far to small to have any influence on the installed production mix. The emission factors for coal condense and natural gas are obtained from a report produced for the Swedish Energy Agency and Environmental Protection Agency(Gode 2007) and presented in table 4.1

Emission	Coal	Natural Gas
CO_2[kg/MWh]	969	374
N_2O[kg/MWh]	0.44	0.48
CH_4[kg/MWh]	11	0.075

Table 4.1. Emission factors for marginal production source

These greenhouse gases are weighted with their global warming potential in a hundred years perspective. The global warming potential is presented in table 4.2

Emission	GWP
CO_2	1
N_2O	296
CH_4	23

Table 4.2. Global warming potential hundred years perspective (IPCC 2001)

5 Data and assumptions

5.1 Data

The operational conditions will change for the different scenarios but some technical data will be the same and other data will have the same base and only me modified for the scenario.

5.1.1 Technical data

For the sorption chiller a COP of 0.8 is assumed in the 2007 scenario and 1.0 in the future and turbine scenario, 0.8 can be found both in academic literature (Lindmark 2005) and more commercial information (Mahone 1998) the increase from 0.8 to 1.0 is to account for technical development. The COP of the existing compression chiller is, according to Kent Hibell, between 4-7 depending on operation conditions and most often around 7(Hibell n.d.). The model will use a constant COP of 7

The conversion efficiency for the low temperature electricity generation is according to academic literature somewhere between 7 and 20 percent (Badr *et al.* 1990). This corresponds pretty well with commercial information which has a span from 11 percent (Energy 2008) to 17,6 percent(Biddle 2005). For the model the higher value of 17,6 percent is chosen.

The turbine is assumed to have a conversion efficiency to electricity of 30 percent and an overall efficiency of 90 percent.

It is assumed that all the MEK put into the process is collected and destroyed. The true value can be assumed to be close to this since the losses to air of solvents according to ÅF is less than 0.5 percent.

It is assumed that the waste gas has the same energy content as MEK, 32 MJ/kg. According to ÅF the composition of the exhaust gas is 91 percent MEK, 8 percent toluene and 1 percent ethylacetat.

All of the energy in the fuel is not available for recovery and reuse since some of it is already reused in the process of gathering and destroying MEK. Approximately 42 percent of the energy is required for sustaining the process(Topsoe 1989).

5.1.2 Physical conditions

The input data for the today model is obtained from the operational data for 2007. Since the heat used for space heating is to a large extent waste heat the available data on heat demand is scarce. The available data is the duration graph produced by Industripartner. When using this graph as input to the model it is approximated with a piecewise linear function. The data for future production is gathered from the environmental consequence description by ÅF. The future heat demand takes its origin in 2001's duration curve and is assumed to be proportional to the surface of the facilities. Future cooling demand is based on 2007 operational data for the compression chiller and is assumed to be proportional to production rather than surface. Since the only information available on the heat demand is a duration graph the chilling demand will also be expressed with a duration graph. The duration graph for cooling however is assumed to be inverted compared to the heat demand. This means that the maximum required cooling will be when there is no demand for heat. The assumptions for heating and cooling demand is summarized in table 5.1 According to Jorgen Christansson production manager at Tetra Pak Inventing AB there are two planned stops for the coating line, 31 day in the summer and 14 day around Christmas and new year. Since the model is based on duration graphs estimations has to be done on where these operational stops fit in on the duration graph. The 14 days stop around Christmas and new years is assumed to be placed to the left on the duration curve i.e. in the coldest part of the year. The 31 day in summer however is placed on the right, warmer part of the year. This gives that the coating line has a maximum operation time of 320 days or 7680 hours. This is without the unplanned stops for maintenance and accidents during the year.

Scenario	Available energy[GWh]	Heat demand[%]	Cooling Demand[%]
Ref	1.95	100	100
2007	1.95	100	100
Future	4.53	187.5	150
Turbine	4.53	187.5	150

Table 5.1. Input data

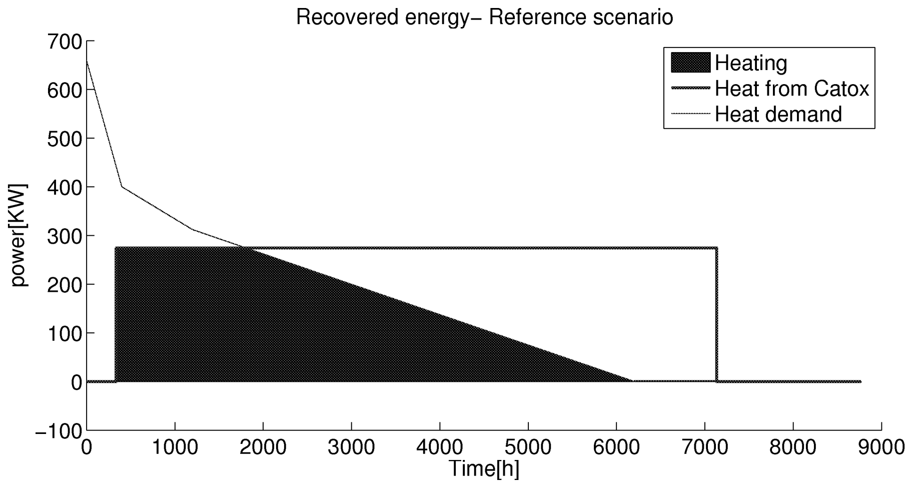
5.1.3 Oil and electricitry prices

One of the hardest things to estimate is the future oil and electricity prices. This is due to the fact that oil and electricity prices is not only dependent on facts put also to a large extent on the market and politicians. The exact prices are only available for the 2007 scenario for the future scenario rough estimates will have to be done. In the model it is assumed that electricity prices will increase from 0.5 to 0.7 SEK/kWh. Oil price is set to be 0.1 SEK lower than the Electricity price. These are uncertain assumptions and the uncertainty will be dealt with in the sensitivity analysis.

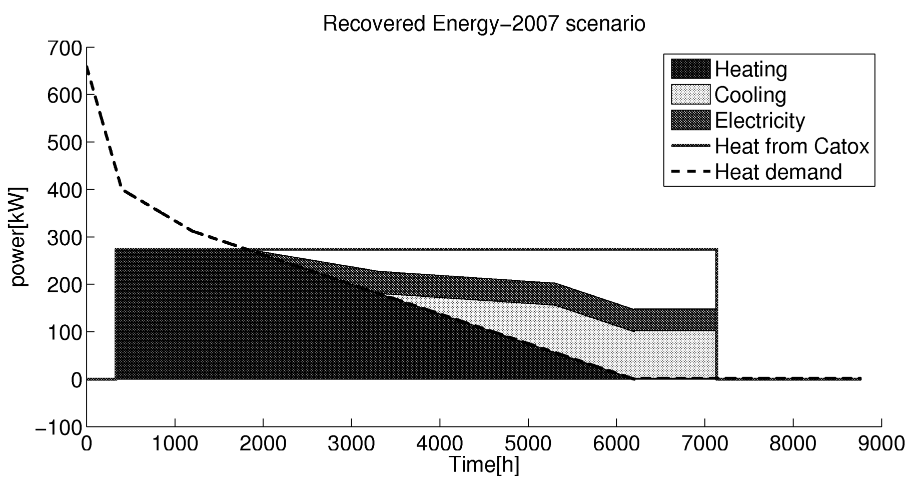
6 Results

6.1 Energy

The different scenarios will offer different possibilities for using the recovered energy. Figure 6.1 shows the availability and uses of energy for the reference and 2007 scenario.



(a) Use of heat supplied from Catox and heat demand - reference scenario

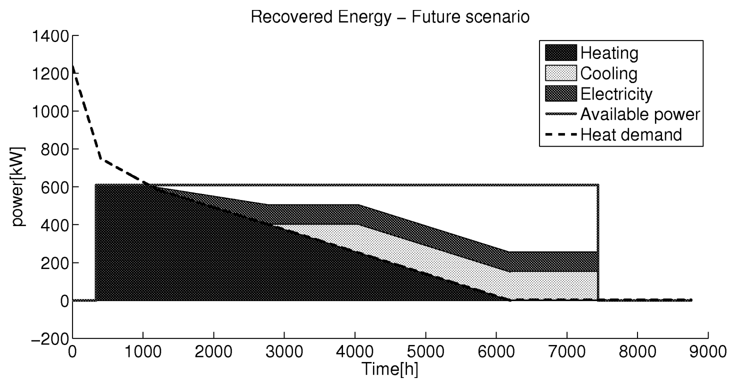


(b) Use of heat supplied from catox and heat demand - 2007 scenario

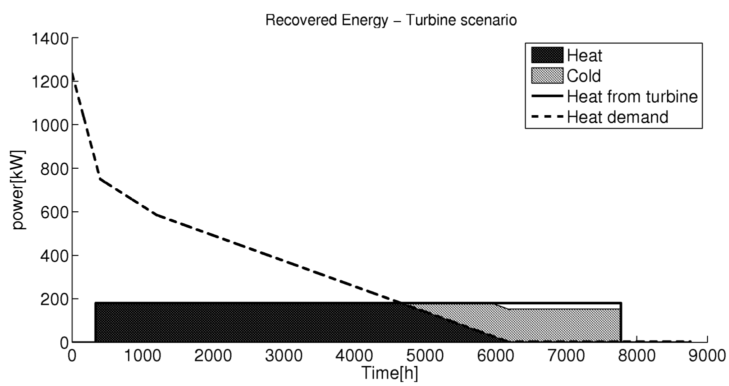
Figure 6.1. Use of recovered heat and heat demand for reference and 2007 scenario.

The reference scenario in 6.1 a shows to large extent the same situation as figure

1.1 from Industripartner. Figure 6.1 b shows areas for heat use that would be made possible by the investment in new technology as described in chapter 4. As Shown in the figure it is possible to reduce the amount of waste heat by turning it into cold and electricity. The model gives that sorption chilling has a potential of saving 40 MWh and the electricity generation 216 MWh. The reason that electricity generation has greater savings potential than sorption chilling even though it looks the other way in the figure is the high COP for the compression chiller. A COP of 7 means that every kWh of cold produced from heat will save 1/7 kWh of electricity.
Figure 6.2 shows the possible use of waste heat in two scenarios placed in the future.



(a) Use of heat supplied from catox and heat demand - Future scenario



(b) Use of heat supplied from catox and heat demand - Turbine scenario

Figure 6.2. Use of recovered heat and heat demand for future and turbine scenario.

The scenarios differ when it comes to available heat. The reduction in available heat in the turbine scenario comes from the increased electricity production. The electricity production for the turbine scenario is not shown in the figure since it is not generated by waste heat in that scenario but rather from the fuel. Figure 6.3 shows a more complete picture of what happens to the energy content in the fuel using a micro turbine.

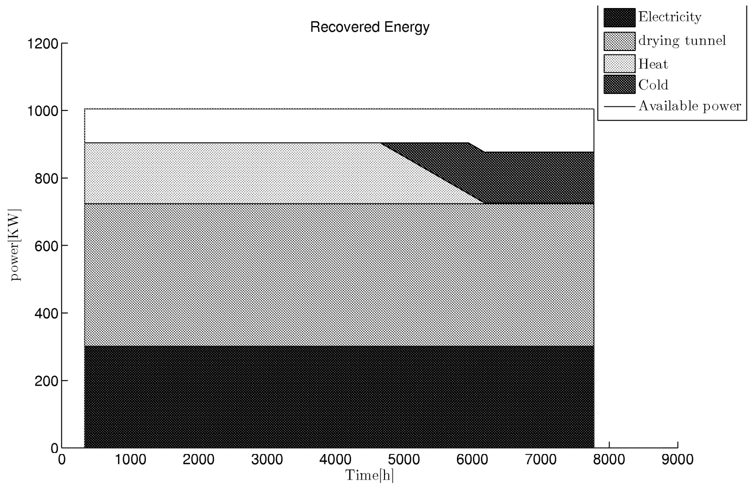
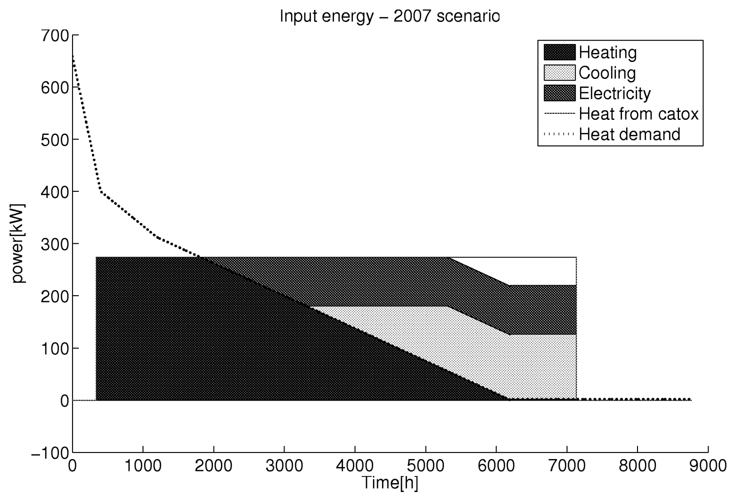
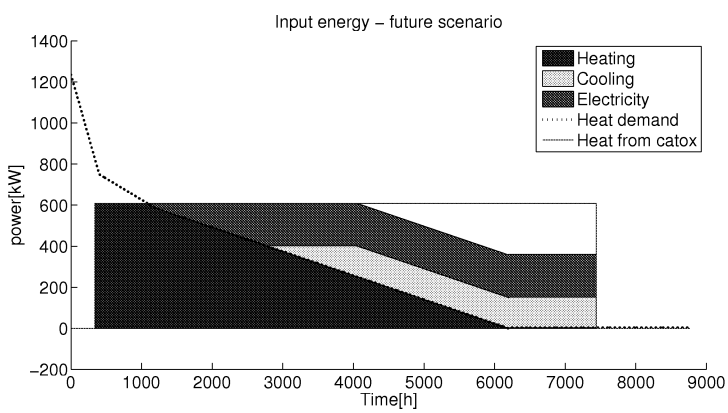


Figure 6.3. Usage of energy from destruction of MEK with a micro turbine.

In figure 6.2 it is shown how the heat is divided between different processes. In the case of the turbine scenario the heat input is the same as the useful energy since both heat and cold has a conversion efficiency of one. In the 2007 scenario however there are losses connected to cold and electricity generation and in the future scenario there are losses connected to electricity generation. Figure 6.4 shows how much of the heat that is used as input to cold and electricity generation processes.



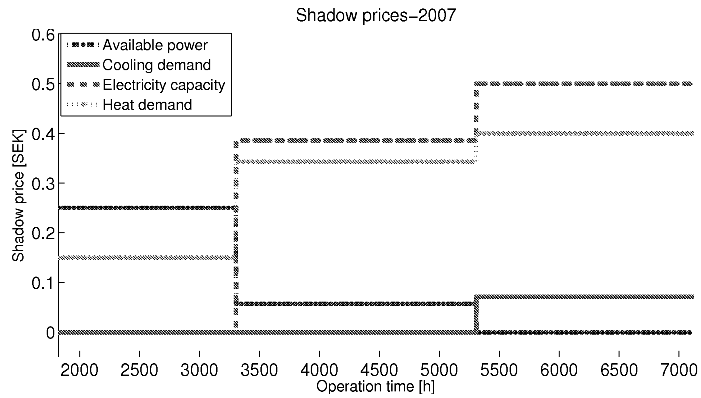
(a) Energy input to heating, cooling and electricity generation - 2007 scenario



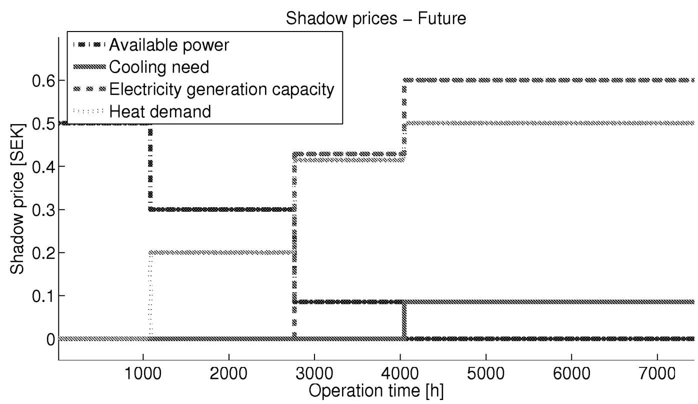
(b) Energy input to heating, cooling and electricity generation - Future scenario

Figure 6.4. Energy input to heating, cooling and electricity generation.

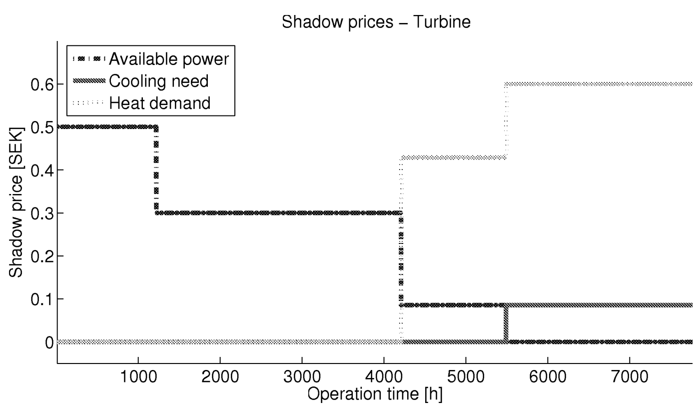
Figure 6.4 shows that all available heat is used as input in the colder part of the year while there still is unused heat in the warmer part of the year. This makes probable that the limitation for increased use of heat is, in the colder part of the year, the availability of heat. In the warmer parts of the year however it is the demand for heating and cooling as well as the capacity for electricity generation that appears to be the active limitations. The shadow prices shown in fig 6.5 shows that this is the case.



(a) Shadow prices - 2007 scenario



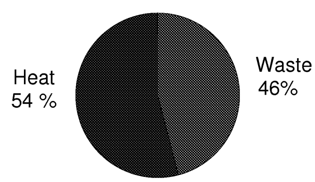
(b) Shadow prices - Future scenario



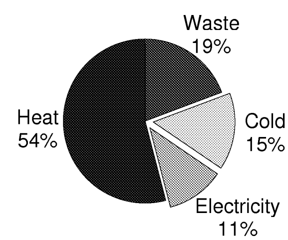
(c) Shadow prices - Turbine scenario

Figure 6.5. Shadow prices

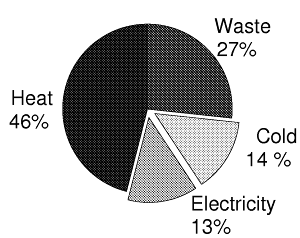
The shadow prices varies some between the scenarios but the common trend is that the shadow price for available heat is above zero in left, colder part of the year while it is zero in the right warmer part. The opposite goes for heating demand, cooling demand and electricity generation capacity. These are zero in the colder part of the year and higher for the warmer part. This supports what was suggested in figure 6.4 that it is the heat produced in the warmer part of the year that is the hardest to find use for. The shadow prices for cooling and heating is an indirect shadow price and shows the gain in meeting an increased demand with heat from MEK instead of electricity. The turbine scenario shows only three shadowprices where the others show four. This is due to the fact that electricity generation is set to a fixed level and not part of the optimization.
As shown in earlier figures the introduction of new technology has potential of reducing the amount of waste heat. Figure 6.6 shows how the energy in the MEK is distributed. The energy needed to sustain the process is not included in the figures.



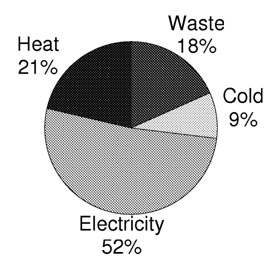
(a) Distribution - Reference scenario



(b) Distribution - 2007 scenario



(c) Distribution - Future scenario

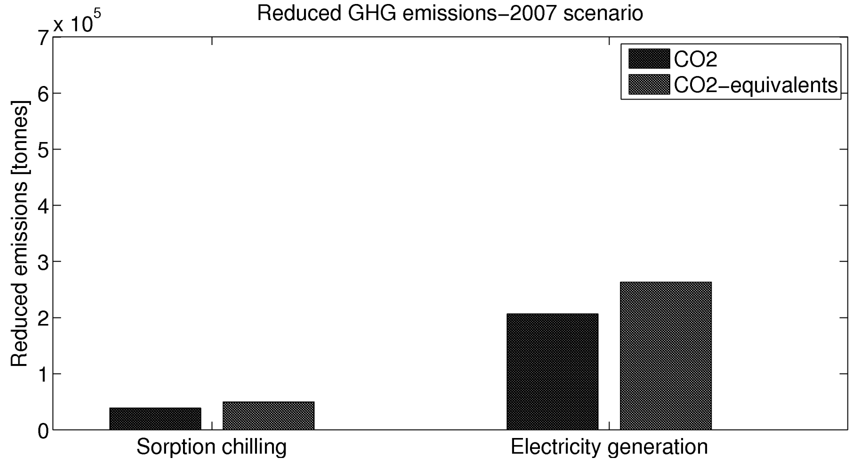


(d) Distribution - Turbine scenario

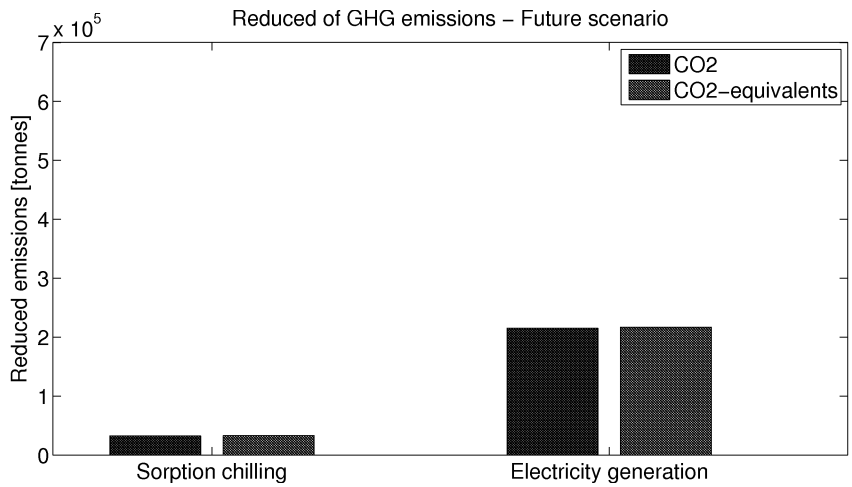
Figure 6.6. Distribution of recovered energy.

6.2 Environment

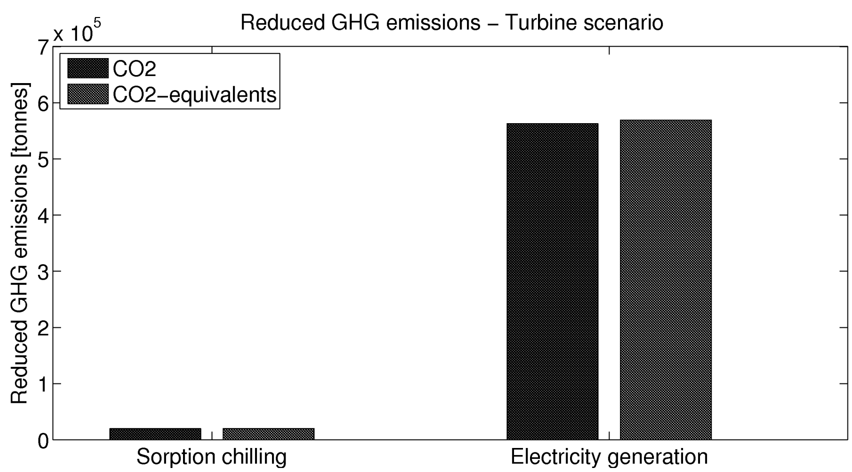
The main environmental benefit from saving electricity is reduced greenhouse gas emissions. Figure 6.7 shows the potential for reducing GHG for the different scenarios.



(a) Potential for reducing GHG emissions - 2007 scenario



(b) Potential for reducing GHG emissions - future scenario



(c) Potential for reducing GHG emissions - Turbine scenario

Figure 6.7. Potential for reduction in GHG emissions

Figure 6.2 shows that there are less potential of reducing emissions i a future scenario compared to 2007 even though it has been shown earlier that there is a greater potential of recovering energy in this scenario. The reason for this is the change in marginal production from coal condensing power to combined cycle natural gas. In the turbine scenario the reduction in GHG emissions is a result of two changes, both reduced electricity consumption and increased oil use since there will be less heat available for space heating. The potential for GHG emission reduction in the turbine scenario would be larger if the additional space heating was supplied from some kind of bio fuel.

6.3 Economy

The different scenarios will offer different economic conditions for investments. Tables 6.1 and 6.2 show the annual savings and payback time for the investments.

Scenario	Annual savings El [SEK]	Annual savings Chiller [SEK][%]
2007	92 000	20 000
Future	398 000	60 000
Turbine	900 000	37 000

Table 6.1. Results

Scenario	PaybacktimeEl[years]	Payback time Chiller[years][%]
2007	14	21
Future	3.7	3.4
Turbine	4.9	5.6

Table 6.2. Results

The payback time and annual savings are based on an electricity price of 0.7 SEK/kWh for the future and turbine scenario and 0.5 SEK/kWh for the 2007 scenario. Even though the annual savings only has increased from 20 000 SEK to 60 000 SEK between the 2007 and future scenario the payback time has been reduced from 21 years to just over 3 years. This is due to the changed investment cost for the sorption chiller.

6.4 Sensitivity analysis

The model gives results for two possible alternatives for the future. Since the future is inherently connected with uncertainties it is important to investigate the robustness of the results. There are several parameters that are uncertain in the model. Te sensitivity analysis will try to investigate those which are believed to have the greatest impact on the result. These parameters are

- Production increase - Will the production of the coating line increase with 100 percent?
- Heat demand - Temperature and building improvements will effect the heat demand. what happens then?
- Technology - When it comes to technology that is not available today the parameters on their performance is connected with uncertainties. The one that will have the greatest impact will be the conversion efficiency of the turbine
- Electricity prices - Since reducing waste energy means reducing electricity consumption the price of electricity will have an impact.

6.4.1 Payback time

When looking at the future scenario the uncertainties in technology are low since all the technology data is gathered from existing data sheets. Factors influencing the future scenario are changes in heat demand and degree of expansion. The effects of changes in heat demand are shown in figure 6.8

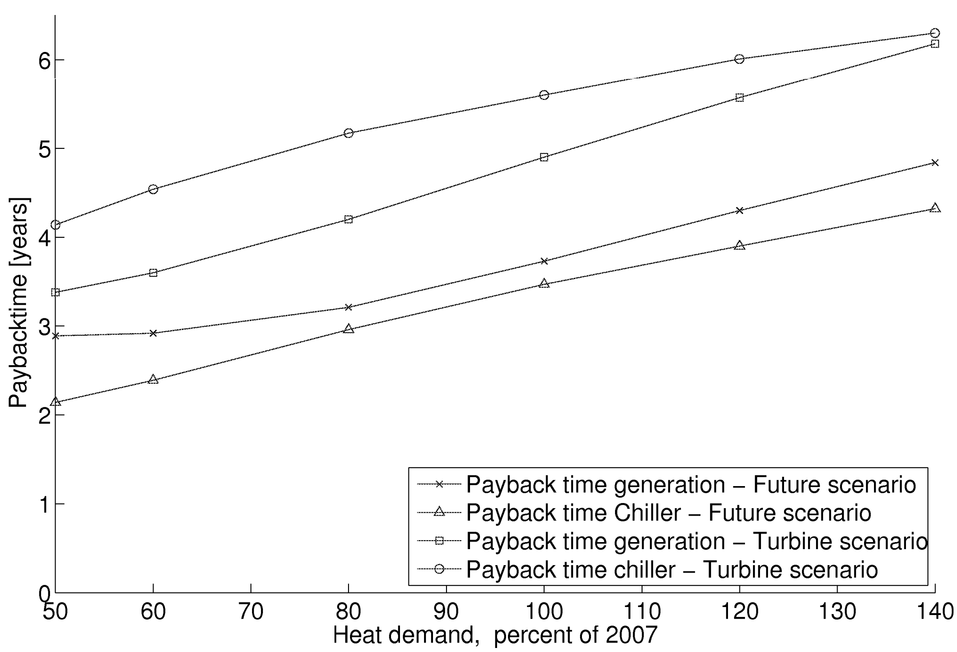


Figure 6.8. Effects on payback time of changes in heat demand and production

The payback time time in theses scenario varies rather little with the heat demand. Even the higher payback times stays within reasonable time even though some exceed the limit of five years with increased heat demand.

Another parameter that is associated with some uncertainty is the degree of expansion. The results assume a doubling of the production in the coating line. However if the production increase turns out to be less than applied for this will have an impact on available MEK and thereby also on available energy. This will effect payback time as shown in figure 6.9

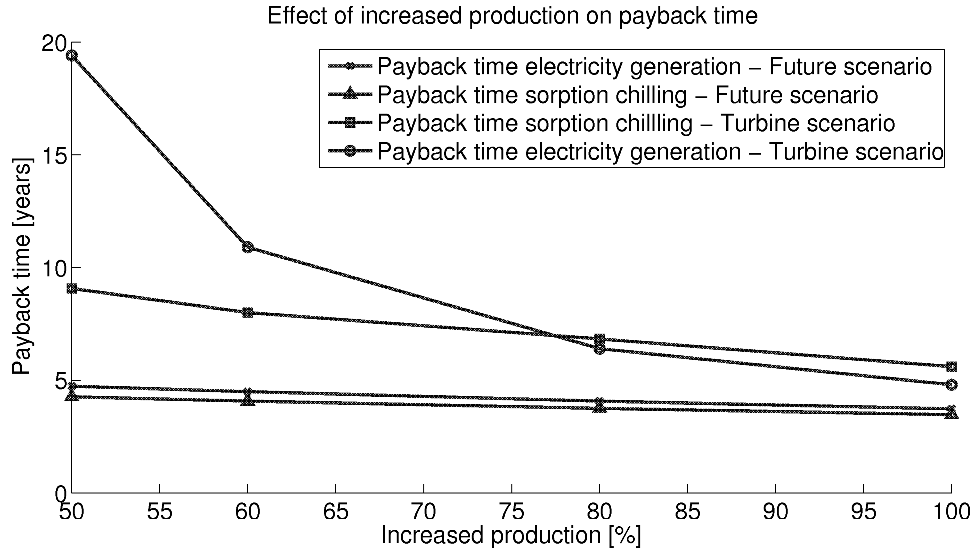


Figure 6.9. Effects of production increase on payback time

Figure 6.9 shows that the future scenario is less sensitive to changes in production increase. The investment in a micro turbine shows to be very sensitive to changes and requires a large amount of fuel to become a reasonable investment.
The turbine scenario comes with uncertainties in technology. Even though micro turbines have been operated for a while this particular kind of micro turbine has only been used for demonstrations. The most critical uncertainty is of course the degree of destruction. How much of MEK is destroyed? This factor however is not investigated by a sensitivity analysis. It is just assumed that the turbine will reach the degree of destruction it claims. If this should not be the case the turbine can not be used no matter how good the economics or energy recovery looks. The conversion effiency however might effect the payback time and energy recovery to such a degree that it will effect the will to invest in the technology. Figure 6.10 shows the conversion efficiency effect on payback time. Figure 6.10 shows that the payback time does not vary a lot between different conversion efficiencies. The payback time for the sorption chilling increases when the conversion efficiency goes up, this is a consequence of less available heat. The payback time for the turbine is more stable since lower conversion efficiency means more heat available and higher conversion efficiency means less heat but more power.
Since these technologies aim to reduce electricity consumption the electricity price will have an impact on the payback time. The impact of electricity price is show in figure 6.11

The turbine shows to be the most sensitive to electricity price. This is due to the

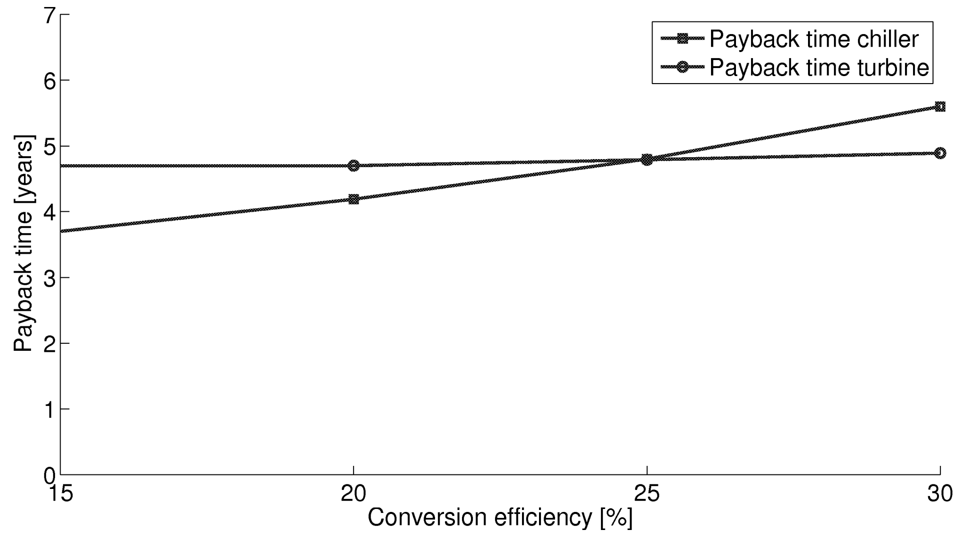


Figure 6.10. Payback time for different conversion efficiency

fact that it reduces the need to buy electricity significantly more than the other technologies.

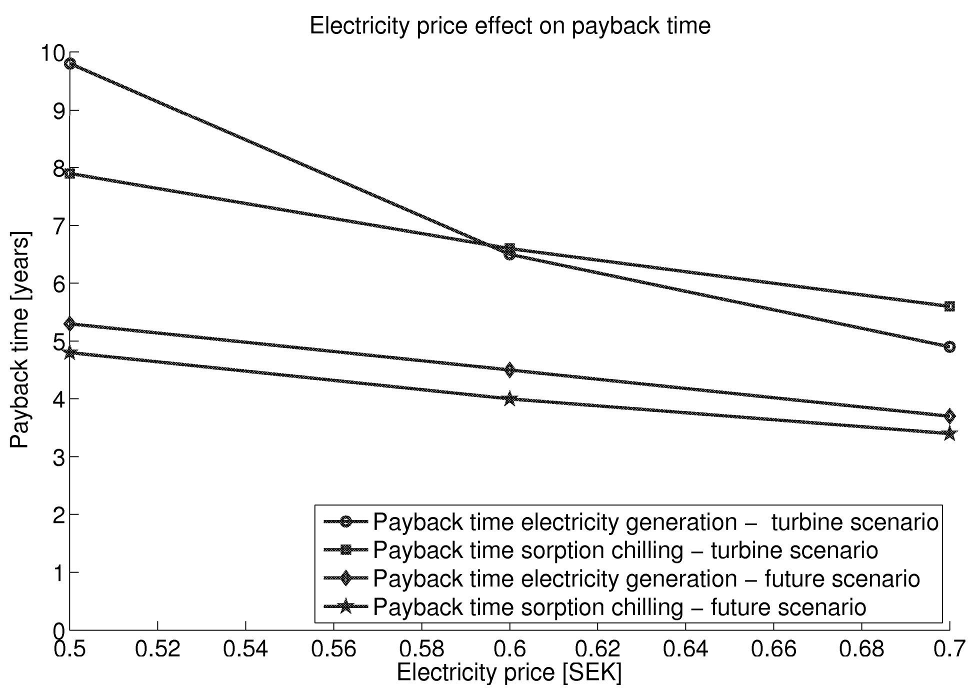


Figure 6.11. Impact of electricity price on payback time

6.4.2 Waste

In this sensitivity analysis the amount of wasted energy will be taken as a measure on environmental impact, reduced waste is seen as reduced environmental impact. Changes in conversion efficiency for the turbine will have an impact on the amount of wasted energy. Figure 6.12 shows the effects of conversion efficiency on wasted energy.

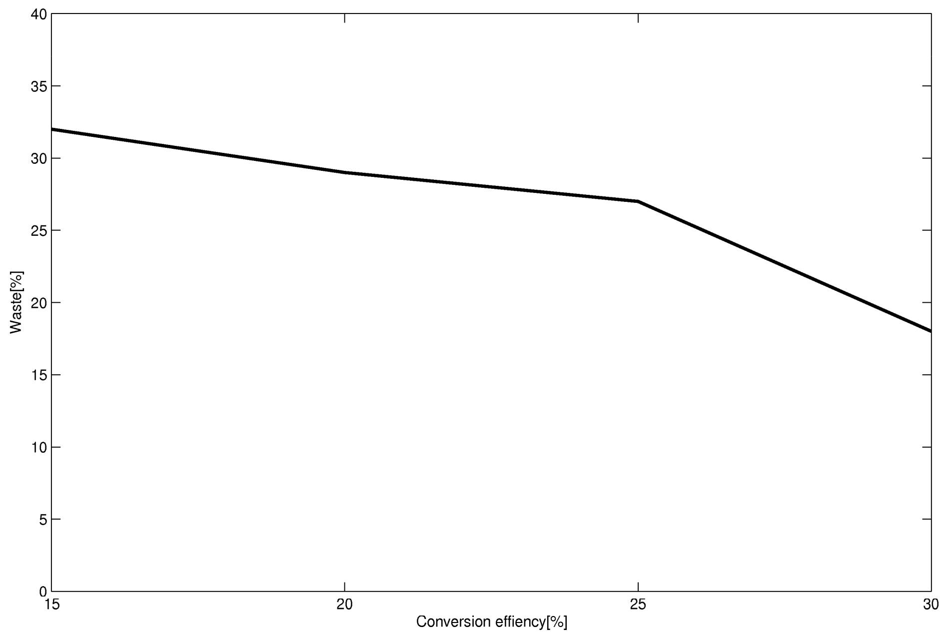


Figure 6.12. Effects of conversion efficiency on waste

Different production increases and changes in heat demand will also effect the amount of energy wasted. This is shown in figure 6.13. The hundred percent on the X-axis represents either 2007's heat demand or hundred percent expansion of the production. The figure shows that the turbine scenario is less sensitive to changes in production or heat demand. Figure 6.13 shows that the turbine solution is the better option, from a waste point of view, for all situations except the case where the production is expanded with less than 60 percent.

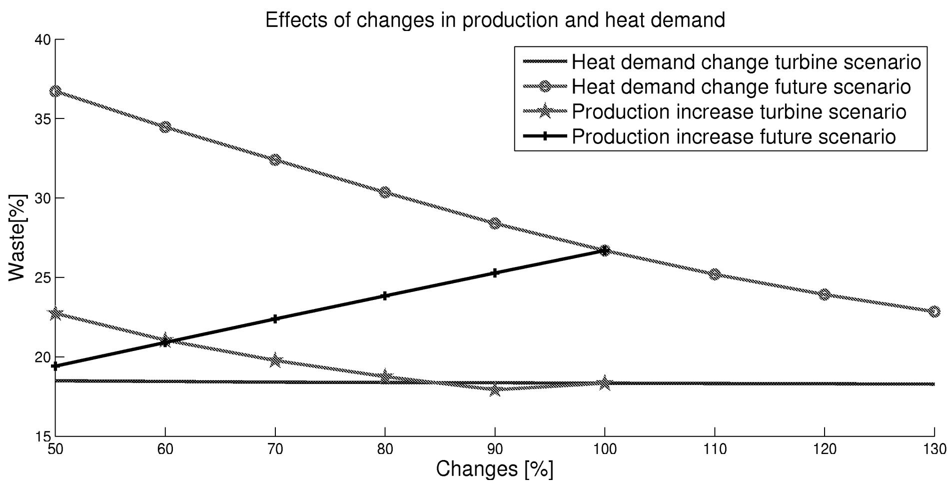


Figure 6.13. Effects waste energy of production increase and heat demand changes

7 Discussion

The result shows two main solutions for the future, one using waste heat from a catox and one using MEK as a fuel for a micro turbine. Both these solutions have strengths and weaknesses. A weakness they share is that they could both be considered end of pipe solutions. An end of pipe solution tends to solve the problem in a late stage of the process. In this case recover wasted heat or make efficient use of a waste product. If the goal is to reduce environmental impact from production it is often more efficient to change the process in an earlier stage. In this case reducing the need for VOC in the production would be more environmental beneficial. Therefore it is important that a solution for reducing wasted energy does not serves as an excuse to stop looking for alternatives for MEK in the process. Even with 100 percent energy recovery reduced use of MEK would be preferable.

The results presented in this thesis shows that both solutions offers increased use for recovered energy than today for reasonable investment costs. The results are however not reality but output from a model of reality. The output from a model is never better than the input and since a lot of the input to this model is connected with great uncertainties so are the results. The sensitivity analysis tries to deal with these uncertainties and shows that the future scenario is less sensitive to changes than the turbine scenario. This is especially obvious with lower electricity prices and a reduced expansion. Reality might show other conditions and limitations than those foreseen in this report. That is why this report should be seen as an identification of possibilities rather than an attempt to in detail describe the future.

One parameter that surely will change is the oil and electricity prices. The sensitivity analysis tries to deal with that uncertainty but one assumption still remains. The electricity price is always higher than the oil price. If the oil price where to stabilize on a higher level than the electricity price, it would be profitable to use electric heating instead of oil heating this would also mean that producing more electricity would become more favourable since this would be a way to store energy from warmer to colder seasons if the heating is done by electricity.

The numbers in the results speaks in favour of the turbine solution from an environmental point of view as long as the production increase is 60 percent or more. The turbine is a newer invention and compared to the catox there are very little operational data. The sensitivity analysis deals with the uncertainty in conversion efficiency but what is more critical is the uncertainty in degree of destruction. There is a risk that the turbine solves the problem with wasted energy but creates increased emissions of VOC. This is something that needs to be discussed in detail with the manufacturer before moving on with this alternative.

The results show that there is an advantage of considering the MEK as a fuel instead of trying to make use of the wasted heat. This advantage can be taken even further than is done in this report. A fuel has storage possibilities and could therefore be stored and used when there is a demand. If the MEK is produced from renewable sources one could even argue that it is refined biomass and should therefore grant green electricity certificates. When using MEK as a fuel for generating electricity

with a micro turbine significantly less heat is available for space heating, this means that more heat needs to be supplied by another source. At present this source is oil burning. It would be desirable from both an environmental and economical point of view to change this to some cheaper renewable source such as biomass or ground heat, especially if this source is to meet such a large part of the heat demand that is suggested in the turbine scenario
looking at different other options than presented in this project relocating production is perhaps not a realistic option but it is interesting to see how much the conditions in Fjällbacka limits the use of recovered heat.
In the environmental consequence description done by ÅF the production increase in Fjällbacka is compared to the option that the same production increase would occur either in Tetra Pak's facilities in Hjörring, Denmark or Rayong, Thailand. ÅF comes to the conclusion that relocating the production increase would not make any difference in environmental impact. This is true if the system boundaries are set to the walls of the factory. However if the entire city in which the factory is located is within the system this might not be the case. Both Rayong and Hjorring are larger cities than Fjällbacka with 50 000 and 25 000 inhabitants respectively. With a higher population comes an increased possibility for use of recovered energy. The limitations for heat use in Fjällbacka i.e. lack of district heating grid, small population are not limitations in Hjorring. Hjorring has a population of 25 000 people and a grid used for both district heating and district cooling. This means that there is a possibility of using all heat MEK destruction in the community and thereby reducing the operation of thermal plants. Rayong in Thailand has a larger population than both Fjällbacka and Hjorring. However since it is situated in south east Asia the heat demand is limited. District cooling is however expanding in Thailand and there might be possibilities to serve Rayong with cooling service. Both these locations has the possibility of using all the recovered heat so if heat recovery where the main question when deciding the location for the production increase the possibilities of heat recovery on these sites should be investigated since they show larger potential for use of recovered energy than Fjällbacka.
This project has investigated the possibilities to make destruction of MEK more energy efficient. A more fundamental view on the problem would have been to reduce the need for destruction, either by reducing the use of MEK or by recycling the used MEK. This would have been a more substantial project but is something that should be done to make production more sustainable.

8 Conclusion

The report shows that it is possible to reduce the amount of waste heat produced at Tetra Pak Inventing AB in Fjällbacka. The waste heat can be reduced from above 50 percent to around 20 percent of the surplus energy in the fuel i.e the energy content in the fuel not needed to sustain the process. Even though it is possible to reduce the amount of waste heat this late in the process it is more efficient to deal with the problem earlier in the process by reducing the use of MEK or recovering and reusing the MEK. Reducing the waste heat also means reducing the amount of greenhouse gases caused by production with somewhere between 200 and 600 CO_2 equivalents depending on the technology used. The report shows two alternatives for increasing the energy recovery from the combustion of MEK. The first alternative uses the waste heat for electricity and cold generation. The other alternative is the use of a micro turbine for destruction of VOC in combination with a sorption chiller. The later alternative makes more efficient use of the energy in the MEK but is on the other hand a newer and more uncertain technology and comes with higher investment costs. The use of waste heat for electricity and cold generation is a second best alternative that gives slightly more waste energy but uses more established technology, has a lower investment cost and is overall a more stable solution. Therefore this is the recommended solution. This project has identified possibilities for reducing waste heat. A next step would be to initiate a study with more technical focus.

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