Lappeenranta–Lahti University of Technology LUT
School of Energy Systems
Energy Technology

Roni Veikkolainen

Profitability evaluation for wastewater heat recovery system

Karjaa 8.12.2022

Examiner: Professor Esa Vakkilainen
Instructors: Joachim Lund, Jonna Uggeldal, Tomas Gustafsson

ABSTRACT

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Profitability evaluation for wastewater heat recovery system

Master's Thesis
2022
85 pages, 20 figures and 14 tables
Examiners: Professor Esa Vakkilainen
Supervisor: Joachim Lund,
Jonna Uggeldal,
Tomas Gustafsson

Keywords: Waste heat, Wastewater, Heat pump, Profitability, Investment, Clean energy

ViskoTeepak Oy wanted to find out if heat recovery from wastewater is technologically viable and if it is profitable. The study is conducted in ViskoTeepak's Hanko plant. The viability of this kind of system has been studied previously, but at that time heat pump technology could not cost-effectively provide the sufficient temperature. This master's thesis goes through current heat pump technology in similar cases, other wastewater heat recovery plants in Finland, and investment calculations. The profitability of the system is studied with a number of different investment calculation methods. A comprehensive sensitivity analysis is conducted for the system to find out which parameters affect the profitability the most. Costs in the system are gotten from quotations provided by four Finnish companies. Non-variable costs are estimated from one quotation and knowledge of maintenance managers at ViskoTeepak from similar cases.

In this case, all possible system solutions stayed profitable for most of the scenarios. In his case differences in quotations, like the number of heat pumps and power, have some effects on how profitable the solution is. Baseline values, in this case, are from 2021 public sources and internal data from ViskoTeepak Oy. Internal data is used in energy scenarios to provide a more accurate prediction of how well systems can handle changes. Sensitivity analysis showed that internal interest rate and heat price inflation have large effects on the profitability of the system. Electricity price inflation and yearly operating time have a much lower effect on profitability. The main investment calculation method, in this case, is net present value because it can take into account changes to operating values in the lifespan of the system. Because this case is energy savings project heat price used is the market buy price, not the heat selling price.

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Roni Veikkolainen

Jäteveden talteenotto järjestelmän kannattavuuden arviointi

Diplomityö
2022
85 sivua, 20 kuvaajaa ja 14 taulukkoa
Tarkastaja: Professor Esa Vakkilainen
Ohjaajat: Joachim Lund,
Jonna Uggeldal,
Tomas Gustafsson

Avainsanat: Hukkalämpö, Jätevesi, Lämpöpumppu, Kannattavuus, Investointi,
Puhdas teknologia

ViskoTeepak Oy halusi selvittää jäteveden lämmöntalteenoton kannattavuutta ja teknistä toimivuutta Hangon yksikössään. Tehtaalla on tutkittu kyseisen investoinnin kannattavuutta aikaisemminkin, mutta edellisillä kerroilla lämpöpumpputeknologia ei ole ollut taloudellisesti kannattavaa käytössä olevilla lämpötiloilla. Tässä diplomityössä käsitellään lämpöpumpputeknologian nykytilannetta vastaavia tilanteita silmällä pitäen, Suomessa valmistuneita muita jäteveden lämmöntalteenottolaitoksia ja investointilaskentaa. Lämmöntalteenottojärjestelmän kannattavuutta tarkastellaan useammalla investointilaskentamenetelmällä, sekä järjestelmälle on toteutettu kattava herkkyysanalyysi tärkeiden parametrien todentamiseksi. Järjestelmän aiheuttamien kustannusten laskemiseksi käytetään neljältä suomalaiselta yritykseltä saatuja järjestelmätarjouksia. Työssä osa kuluista on arvioitu olevan muuttumattomia lämpöpumpputoimittajasta riippumatta, näiden kulujen arviontiin on käytetty yhtä tarjousta, sekä ViskoTeepakin kunnossapitohenkilöstön tuntemusta vastaavien projektien kuluista.

Työssä havaittiin projektin olevan kannattava useissa skenaarioissa. Tarjousten ja niiden kokoonpano, tehon ja laitemäärien havaittiin vaikuttavan kannattavuuteen. Laskennassa lähtöarvona on käytetty 2021 energiadataa, jonka lisäksi energia skenaarioita tehdessä on hyödynnetty ViskoTeepakilta saatua energian hinnan datasta muodostettua trendiä. Herkkyysanalyysin perusteella havaittiin, että lämmön hinnan inflaatiolla ja sisäisen korkokannan muutoksella on suuri vaikutus projektin kannattavuuteen, kun taas sähkön hinnan inflaation ja vuosittaisen käyttöajan vaikutus investoinnin kannattavuuteen on huomattavasti pienempi. Investoinnin kannattavuuden arvioinnissa on käytetty nykyarvomenetelmää, sillä nykyarvomenetelmällä on helppo havaita investoinnin kannattavuus tilanteessa, jossa lähtöarvot eivät pysy tasaisena koko investoinnin käyttöaikaa. Koska kyseessä on energiansäästöprojekti, lämmön hintana on käytetty ostetun kaukolämmön hintaa myydyn hinnan sijasta.

Starting words

This work has been the biggest project in my career this far. On those days when I have had some doubts, the amazing team at ViskoTeepak have had my back and helped me through the hard moments. I want to say big thank you for all the colleagues who have had understanding when some timelines have stretched because of this work. Large thank you is for Joachim Lund, Jonna Uggeldal and Tomas Gustafsson for making my dream of becoming engineer a reality. Thank you for whole ViskoTeepak for welcoming me to factory and into working life. Thank you, Esa Vakkilainen, for giving me good directions how to go with my master's thesis.

I need to thank my friend and family also, because this thesis is just the final chapter in my educational journey. I would not be here writing these words if I would not have that good backbone in my life. I hope the best for all of you who have been part of this journey.

Haluan kiittää kollegoita ViskoTeepak:lla kun mahdollistitte minulle tämän diplomityön ja otitte minut avosylin vastaan ensimmäiseen työhön korkeakoulutettuna. Kiitos ymmärryksestänne, niinä hetkinä aikataulut venyivät, jotta tämä työ eteni. Kiitokset Joachim Lund, Jonna Uggeldal ja Tomas Gustafsson, kun katsoitte työni perään ja mahdollistitte unelmani valmistua insinööriksi. Kiitos Esa Vakkilaiselle, kun valvoit tämän työn ja ohjasit työskentelyäni oikeille urille.

Suuri kiitos perheelle ja ystäville, kun olette, seisseet rinnallani tämän työn kirjoittamisen ajan, kun olen epäillyt itseäni, olette luoneet minuun uskoa. Tämä työ on ollut vain viimeinen kappale pitkällä koulutus polulla, enkä kirjoittaisi näitä sanoja ilman teiltä saamaani tukea tässä matkan varrella. Toivon kaikille, jotka olette olleet mukana tällä matkalla kaikkea hyvää tulevaisuuteen.

Roni Veikkolainen

Karjaalla 6.12.2022

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SYMBOLS AND ABBREVIATIONS

Romans

AN	Annuity	€
ANF	Annuity factor	-
COP_c	Coefficient of performance for cooling use	-
COP_h	Coefficient of performance for heating use	-
COP_M	Measured coefficient of performance	-
COP_T	Theoretical coefficient of performance	-
$COP_T(t)$	Hourly theoretical coefficient of performance	-
COP(t)	Hourly coefficient of performance	-
C_p	Heat capacity	kJ/kgK
$f_T(t)$	Loss factor of the system	-
h	Enthalpy	kJ/kg
i	Calculation interest rate	%
i_r	Inflation-adjusted interest rate	%
IR	Internal rate of return point	-
NPV	Net present value	€
NPVd	Net present value discounting rate	€
n	Investment keeping time	a
P	Power	W
q_m	mass flow rate	kg/h, kg/s
RE	Return of investment in time period	€
ROI	Return on the investment	%
s	inflation rate	%
t	Time	h
TC	Investment total cost	€
T_H	temperature to the side of operation where the temperature will get higher	°C/°K
T_L	temperature to the side of operation where the temperature will get lowered	°C/°K
WO	Write-off	€

Creek

Δ	Delta
η_s	Efficiecy

Abbereviations

ASHP	Air source heat pump
AHP	Absorption heat pump
C	Condenser
C	Cost
CDHP	Compressor driven heat pump
CFC	Chlorofluorocarbon
CHP	Combined heat and power
COP	Coefficient of performance
E	Evaporator
EU	European union
GSHP	Ground source heat pump
GWP	Global warming potential
HACHP	Hybrid absorption compressor heat pump
HFC	Hydrofluorocarbon
ODP	Ozone depletion potential
SPF	Seasonal performance factor
UK	The United Kindoms
WW	Wastewater

Subscripts

c	Cooling
e	Electricity
h	Heating
hp	Heat pump
in	Inlet
out	Outlet
1	Point one
2	Point two
2s	Point two s
3	Point three
4	Point four

1 INTRODUCTION

This master's thesis is done in partnership with ViskoTeepak Oy. The main research question in this thesis is figuring out the viability of the wastewater heat recovery system at ViskoTeepak's Hanko factory. The company is in pursuit of more efficient operations including energy usage, waste management, and production. One of the biggest single points of energy loss is heat energy in wastewater and that is what this thesis is trying to solve.

1.1 Background

As the carbon neutrality target of the EU and Finland are getting increasingly stricter everyone needs to make some adjustments to energy usage. EU's target of carbon neutrality before 2050 will need big improvements in every sector. (Valtioneuvosto 2019, 33)(European Comission). The industrial sector is one of the leading producers of CO2 emissions and because of that focus on emission reduction should be aimed there.

Because the industrial sector operates based on profits, it can be directed in a more environmental direction by sanctions or investment aids. Sanctions work on companies by making usage of old technologies and methods more expensive than investing in alternatives. Investment aids on the other hand work by lowering the investment cost and making it more profitable. A combination of sanctions and aid should work best, as the sanctions make companies think of new solutions and how to avoid sanctions, and at the same time, investment aid lowers the cost of the investment and makes it more attractive.

New green electricity projects make heat production from electricity a better opportunity to lower carbon footprint. Usage of a heat pump's to upgrade low-grade waste heat flows to useful heat with renewable electricity is a good way to make EU emission targets more attainable. If the green transition is done correctly it can help to increase profits.

From a consultation conducted by Pöyry main finding was that one of the biggest waste heat flow at Hanko factory is the wastewater. From that study topic for this thesis was chosen as it has the biggest potential for profits. Other possibilities for improvements found are minor changes and have a lesser impact on profits or the environment.

1.2 Topic and objective

The topic for this master's thesis is to study the possibility of recovering heat from warm wastewater and using that heat back in the manufacturing process. This thesis aims to answer the following questions: How much heat energy can recover from a wastewater stream? What are the main limiting factors in heat recovery in this kind of situation? What is the total investment cost for this kind of project and how it is formed? How long is the payback time for investments like this?

Recovery of the heat from wastewater would help to lower emissions in the whole energy chain as more energy would be used in manufacturing rather than released into the environment. Currently, heat in wastewater goes to a wastewater treatment plant where it is released into the ocean. By using these secondary energy flows efficient amount of fuel needed to heat the main water flow is lower because heat losses from the whole system are lower. As the wastewater temperature is low compared to the temperature needs in the factory usage of heat pumps is necessary which, in turn, will increase the consumption of electricity.

1.3 Structure, cropping, and implementation

A Master's thesis is structured by splitting work into two main parts, general- and case parts. In this thesis chapters, two to four are the general part, chapters five to eight are the case part, and the summary of the whole thesis is in chapter seven.

The idea for the general part is to provide sufficient information to the reader so that reader can understand the important parts of the work without prior knowledge of the topic or need for additional reading. The general part will build the foundation for the understanding of the case part of the thesis. Chapter two outlines basic information about heat pumps as technology. By reading that chapter readers should have an understanding of how heat pumps work, and the limitations and possibilities of that technology. Chapter three outlines basic models of heat transfer. That chapter should help the reader to understand the challenges in designing the working system in the case presented in this thesis. Heat transfer is also one major part of any heating system including heat pumps. Chapter five outlines a bit of theory behind the investment calculation models used in the casework.

Chapter five introduces the heat source used in this case study. In that chapter, the aim is to find out the energy potential in the heat source, what are the biggest obstacles to harnessing that energy, and lay out some possibilities where heat can be used in the factory. Chapter six is for dimensioning the heat pumps and heat transfer surfaces needed in the case. That chapter will outline major investment costs for this kind of system. Chapter seven focuses on investment calculations. In chapter seven the aim is to find a cost-effective system for heat sources outlined in chapter five. Lastly, chapter eight is for discusses the viability of the whole investment. Chapter eight pulls previous chapters together and gives a final taught about the viability of the heat recovery system.

2 HEAT PUMP TECHNOLOGY

Heat pumps are used to supply heating and cooling widely across different applications. Heat pumps use reversed Carnot cycle to move heat energy from lower temperature sources to a higher temperature for utilization. This reverse direction to normal heat flow means that the process needs added energy in form of electricity in the case of a compressor-operated heat pump or heat energy in the case of an absorption heat pump. The usage of reversed Carnot cycle makes the utilization of low-grade heat sources possible. This possibility is helping to minimize heat losses in the industrial sector as the side flows can be upgraded and put back into the system. When heat can be produced from the low-grade heat source by using sustainable electricity CO_2 emissions can be lower, because the need for heat from burning fossil fuels or biomass is lower. (IEA-ETSAP 2013)

As the concern about the climate is growing year by year, it is important that the utilization of more environmentally friendly technologies keeps growing. If the Paris climate agreement target is pursued with real intentions making heating less carbon-intensive should be one of the main focuses. This is because the heating sector accounts for almost 50% of all energy demands in the EU and 75% of this demand is provided by fossil fuels. According to the source, only 3% of heating in the buildings is provided by heat pumps. These facts make heat pump a very attractive investment for environmentally concerned people. As the transition from fossil fuel-based energy system to renewables are imminent can heat pumps play a huge role because produced electricity to heat ratio will move towards electricity and in that way, new ways to produce heating are needed. Although the transition toward heat pump-based heating is beneficial to the environment it is not enough on its own. Heat pumps need an energy source to work and if the energy source is not renewable some benefits of the transition are not collected. (Gaur, Fitiwi et al. 2021)

Heat pumps are used to heat and cool spaces, heat water, refrigerate and freeze (IEA-ETSAP 2013). Advances in heat pump technology have enabled the usage of drying applications and the generation of high-temperature steam up to 150°C. New technologies are researched to provide even higher temperatures. These advances are widening applications for heat pump systems. Currently, the problem with high-temperature applications of heat pumps is that COP goes down quite drastically when the difference between heat pump sides increases. The need for heat up to 150°C in Europe is large and that is why a lot of research effort is put into finding solutions for how low-temperature waste heat flows could be upgraded into useful temperatures. Even with lower COP studies show that payback time for high-temperature applications can stay in an economically interesting range. (Liu, Han et al. 2022)

Heat pumps are well known and matured technology with wide utilization starting in the mid-part of the 20th century. Heat pumps usage for space heating applications started by using ground source heat because air temperatures for air-to-air heating were too low. Nowadays heat pumps using outdoor air as the heat source can be an effective way of heating when the temperature is at -25°C. Heat pumps can use many different heat sources, the main ones being air, surface waters, ground thermal, and waste heat streams. The usage of heat pump shares has been increasing rapidly since the 1970s. In 2008 it was estimated that Switzerland alone had more than 30 000 ground source heat pumps and the United States America market was installing more than 50 000 units annually. These units have long lifespans as proven by knowledge from Finnish Lämpöässä data that tells more than 4 000 units of 20 000 installed units are working after 30 years. (Finn Geotherm UK Limited 2022)

Because principles of heat pump systems have been known for many decades utilization of different heat sources is possible. New research has shown that one heat pump system can provide heating and cooling simultaneously even when heating and cooling demands are not equal. Figure 1 shows a schematic of a heat pump system that combines the water-water cycle with the water-air cycle to increase its range of usage. This advance in technology will increase possibilities for the utilization of heat pumps as one of the biggest hurdles to wider use of heat pumps has been fluctuations in heating and cooling demands. This can be done by coupling water to an air heat pump to a water-to-water heat pump. In normal operations where heating and cooling demand is equal, the water-to-water is the only operational system and as the demand fluctuates in some direction water-air system can be used to increase heat put into the system or heat rejected. (Lun, Tung 2020)

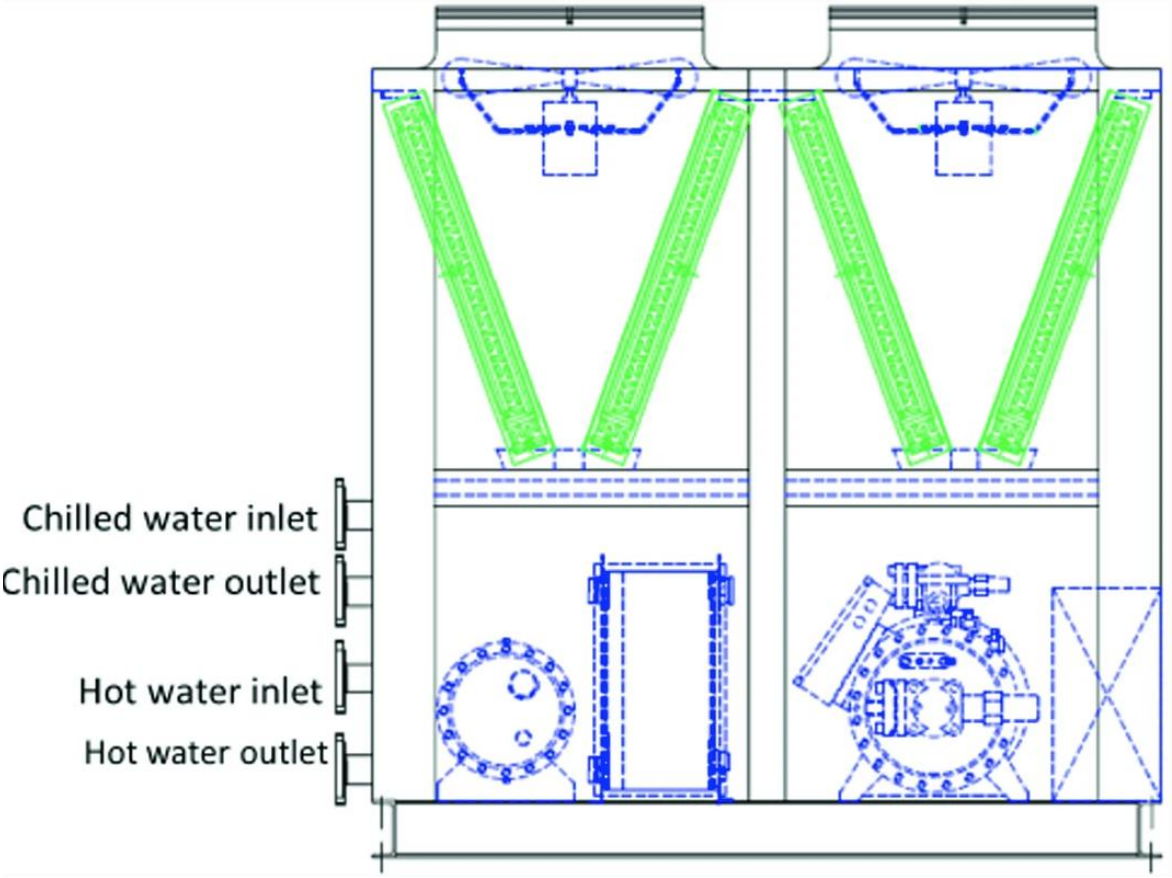

Figure 1 Total energy heat pump providing both cooling and heating (Lun, Tung 2020)

Seasonal performance factor (SPF) is another widely used performance measurement. SPF is defined as the division of energy output by used energy. SPF can be calculated for a wider time than COP and that way represents operating conditions better. The problem with SPF is that it is not standardized yet and that way results can vary between providers. (Laitinen et al. 2014,)

Coefficient of performance (COP) is one of the main ways to evaluate the performance of a heat pump. COP is the relationship between how much energy has been put into the system compared to how much heat energy is delivered by the heat pump. Even though heat pumps rarely operate at full design load level it is still a good way to compare systems. (Laitinen et al. 2014) COP for heat pump used in heating can be calculated by equation 1 and for cooling by using equation 2

$$COP_h = \frac{T_H}{T_H - T_L} \quad (1)$$

$$COP_c = \frac{T_L}{T_L - T_H} \quad (2)$$

Where

COP_h	Coefficient of performance for heating use
COP_c	Coefficient of performance for cooling use
T_H	temperature to the side of operation where the temperature will get higher
T_L	temperature to the side of operation where the temperature will get lowered

By using equations 1 and 2 COP is calculated as it is in optimum conditions. Because the ideal situation is not the real working condition, as the compressor and other parts have some losses those need to be accounted for more accurate estimations. This can be done by calculating the loss factor by equation 3.

$$f_T(t) = \frac{COP_M}{COP_T} \quad (3)$$

Where

$f_T(t)$	Loss factor of the system
COP_T	Theoretical coefficient of performance
COP_M	Measured coefficient of performance

The loss factor can be assumed to be constant throughout the operating window, but for more accurate measurements it is beneficial to measure COP_M in the numeral situation. Accuracy at points that don't have measures COP_M can be linearly interpolated, or calculations can use the closest known point. With the loss factor known, hourly COP can be calculated with equation 4.

$$COP(t) = f_T(t) * COP_T(t) \quad (4)$$

Where

$COP(t)$	Hourly coefficient of performance
$COP_T(t)$	Hourly theoretical coefficient of performance

COP is a good indicator to compare efficiencies between two heat pumps of the same type, but it is not well applicable when comparing different types of heat pumps. This is because for the compressor it is simpler to calculate how much additional energy is put into the system, but for the absorption heat pump, COP doesn't take into account the biggest benefit of that system, heat recovered from waste heat source. That is why it is important to look for multiple performance parameters when comparing different types of heat pumps.

2.1 Compressor-driven heat pumps

Compressor-driven heat pumps CDHP are the most common variant of heat pump technology in use today. This is because in most usage cases it is the simplest and most efficient solution as the cycle is easy to implement and can use a lot of different heat sources. Different kinds of CDHP:s have replaced direct electrical heating in many places because of the higher efficiency.

2.2 Working principles

The main thermodynamical principle in heat pumps is reversed Carnot cycle. For compressor-driven heat pumps CDHP this cycle has five main components: compressor, condenser, expansion valve, evaporator, and working fluid. In typical usage heat flow direction is from the evaporator side to the condenser side. On the evaporator side the working fluid absorbs heat energy from the heat source in use leading to evaporation of the working fluid. After that compressor is used to pressurize and increase the temperature of the evaporated working fluid. In the next step condenser heat energy is released from the working fluid by condensing it back to a liquid state from a gaseous state. Lastly, an expansion valve is used to lower pressure and temperature to the level below the temperature of the heat source to restart the process. Because heat is moved from a lower temperature level to a higher system needs the energy to work. This energy is mostly provided in form of electricity to the compressor. (IEA-ETSAP 2013) This cycle is shown in Figure 2.

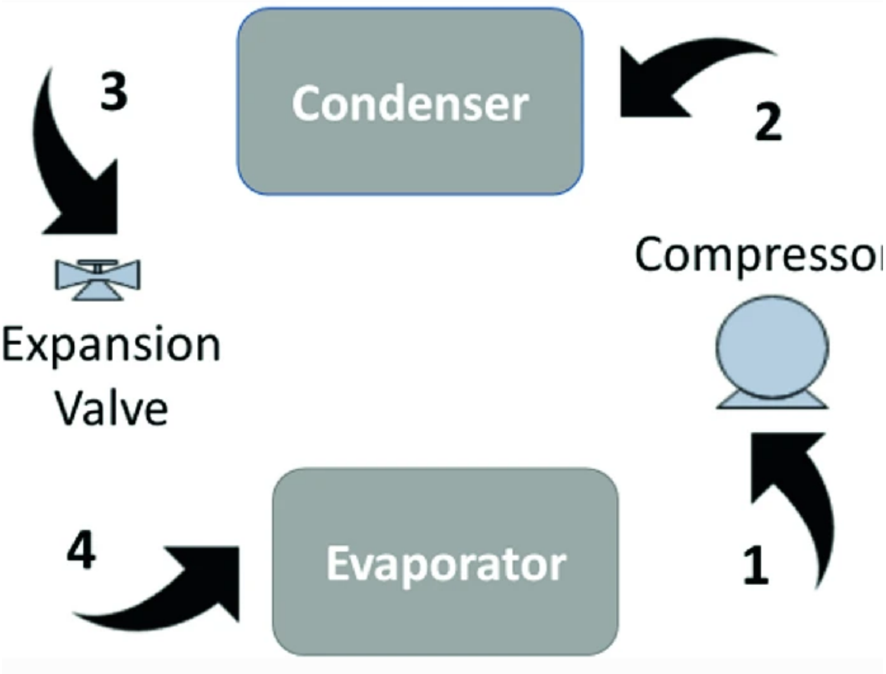

Figure 2 Vapor compression refrigeration system (Lun, Tung 2020)

Heat pumps are a great alternative for direct electric heating systems as the COP of heat pumps can reach up to 6-7 and in some specific cases even to 20. Co-efficient of performance COP is a good way to measure how well the heat pump is working. COP indicates how many units of heat can be supplied for every unit of consumed electrical energy. Because the COP of heat pumps exceed one, they are a good way to lower emissions because more useful heating is gotten from every unit of electricity when compared to direct heating. Air-to-air heat pumps have a wide working range, where they have high COP, although the best performance is achieved when the temperature of the heat source is close to the wanted temperature. Because it is beneficial to have heat difference as low as possible for best performance ground source heat pumps (GSHP) have better all-year COP than air source heat pumps (ASHP). This benefit is somewhat neglected for customers as GSHP is more expensive in upfront investment costs. Costs have been one of the reasons why ASHP has been so widely used in the near past. (IEA-ETSAP 2013) GSHP has an advantage compared to ASHP as the ambient temperature fluctuations don't affect GSHP efficiency as much as it does for ASHP (Gaur, Fitiwi et al. 2021).

2.2.1 Performance

The performance of the heat pump is greatly affected by its operational conditions. From the equation for ideal COP can be seen that temperature lift will affect greatly to COP of the system. So the other main component affecting performance is losses that occur in the system. Heat pump performance is closely linked to the properties of the selected working fluid so when designing heat pumps working fluid should be optimized for the operating conditions of the whole system.

From the experimental study, it can be drawn that COP is dependent on the pressure of the system. This is because high-pressure determines condensing temperature of the working fluid at the condenser, so to low pressure can limit the heat transfer potential of the condenser. Exceeding the optimum pressure range will also lead to lower COP. This is because compressors have optimum working ranges also and when exceeded the mass flow of refrigerant decreases while the energy needed by the compressor increases. From the study, it can be drawn that the effect of under pressuring system is much bigger than the over-pressuring. (Verdnik, Rieberer 2022)

Suction gas superheating is one parameter that affects the performance of the system. In the study superheating temperatures of 15°K and 35°K were compared and the result is that increase in temperature lifts COP by 0,1. This temperature lift will also lower the optimum pressure of the system by 5 to 6 percent. This study is conducted by using R600 as a working fluid and in the study, the temperature lift is higher than in most usage cases. (Verdnik, Rieberer 2022)

The performance of heat pumps is closely linked to the economic aspect of the whole system and in that way selecting the right working fluid for the application can decide if it will be economically viable or not. Figure 3 shows the viability of 6 different setups. From a study conducted by Ommen et al. can be drawn that several different natural working fluids can be used economically.

From the working fluids studied R717 (ammonia) is the only one that can achieve payback time under four years in some operating conditions. Other studied working fluids can achieve under an eight-year payback period in some operating conditions. In this study heat pumps are compared to the economics of natural gas boilers in the mid-2010s so payback time is most likely lower, as the price of natural gas is changed since then. (Ommen, Jensen et al. 2015)

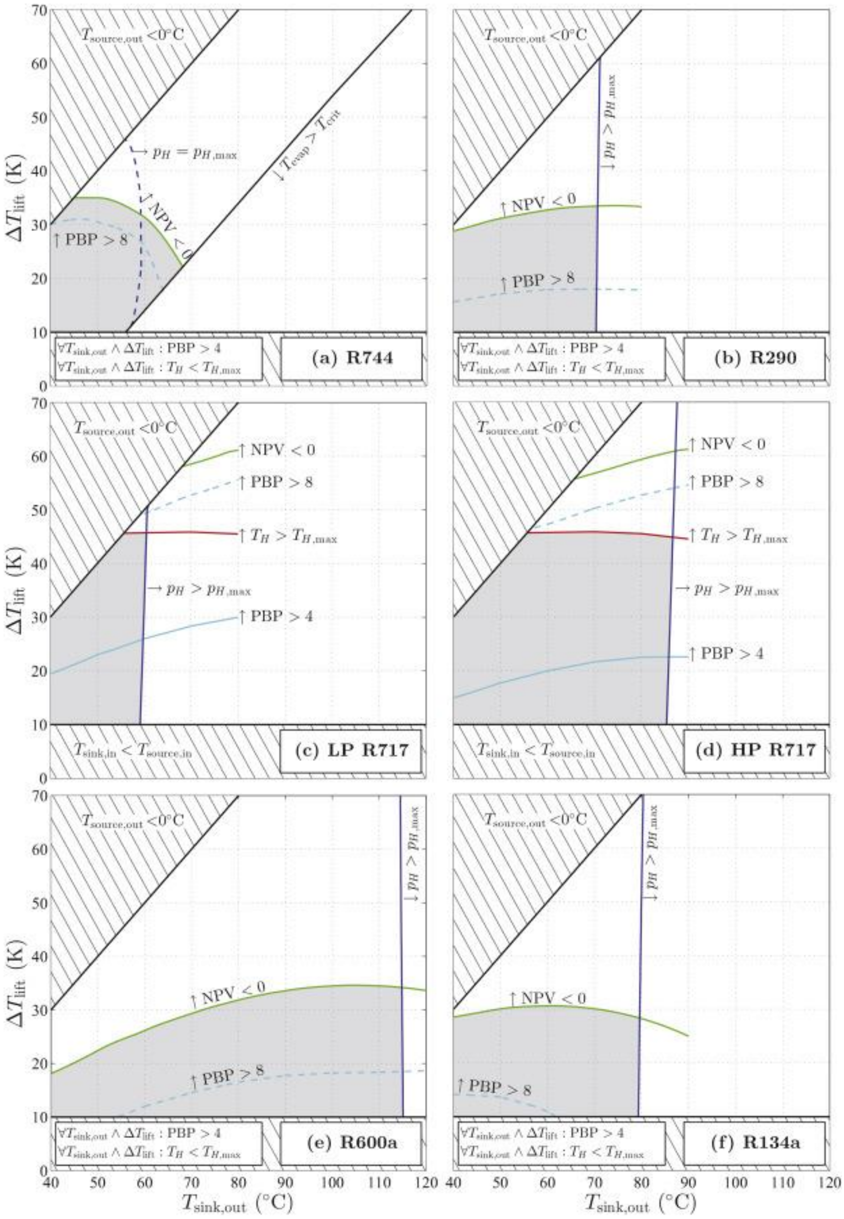

Figure 3 Economically viability of different working fluids, the grey area is economically viable, dashed technically not possible. Source: (Ommen, Jensen et al. 2015)

Heat pumps like other thermal machines are designed with some operating conditions in mind and if the machine is operating outside of these optimal parameters some losses will occur. One clear inefficiency is thermal losses due to on/off cycles on the compressors. This cyclical operation is due cyclical nature of heat need and temperature of heat supply. For example in a cold area where apartment heating is needed, heat need is mostly at night, and at day time heat need can be minimal or there can even be a cooling need. This makes the need for on/off cycling when the minimum temperature that a heat pump can deliver is too high to upkeep the temperature at good level, but losses out of the apartment are too much to keep the temperature in a comfortable range for the whole day time. Many times heat pumps need to be designed for the harshest conditions possible (Xu, Zhaowei, Li et al. 2022). In this kind of case, it is advantageous to install a thermal storage system. Usage of thermal storage to minimize on/off cycling and letting the heat pump run on the maximum can lead to up to 10% to 20% of energy saving on a seasonal basis (Conti, Franco et al. 2022).Start/stop loss is measured to be 2% to 17.3% in one study (Xu, Li et al. 2022). So it is important to try to design the whole system in a manner that partial loads are avoided, and even more crucial is to try to keep operating conditions as close as possible to design values.

2.3 Absorption heat pump

The absorption heat pump (AHP) is another way to utilize heat pump technology to move heat energy from one place to other. Where a compressor-driven heat pump uses electrical energy from the compressor to provide the necessary energy for system absorption AHP uses a secondary heat source as the driver. These secondary heat sources range from geothermal to natural gas burners. Absorption heat pumps can similarly provide heating or cooling as compressor-driven heat pumps. (Office of Energy Efficiency & Renewable Energy 2022)

The cycle for AHP is similar to CDHP with a couple of big differences. The compressor is replaced with an absorber, desorber, and low-pressure pump. This combination of components is often referred to as a generator. Another big difference is that AHP uses a two-part solution as a working fluid for the system. This solution contains refrigerant, most commonly ammonia but other refrigerants are studied for better performance and absorption medium. (Office of Energy Efficiency & Renewable Energy 2022)

2.3.1 Working principles

AHP operates in a dual cycle. The first cycle is very similar to the CDHP cycle. In that cycle, heat is released at the condenser from the refrigerant and high-pressure condensate moves through the expansion valve, where pressure is lowered. After that refrigerant is heated back up in the evaporator, which leads to the generator. At the generator, refrigerant is absorbed by the absorption medium at the absorber releasing some heat. This leads to a pump where the pressure of the solution can be increased with little effort compared to CDHP. The last step for refrigerant is desorber, where heat energy is brought into the system, and refrigerant is heated above its boiling point and can be separated from the absorption medium and that way put back into the condenser. (Office of Energy Efficiency & Renewable Energy 2022)

The cycle for absorption medium is much simpler. At the absorber the medium absorbs refrigerant releasing heat in the process. After that solution is pumped forward and the pressure increases. At desorber, the refrigerant leaves the solution and the absorption medium is heated in the process. Lastly, the pressure of the medium is lowered at the expansion valve. After that step cycle starts over. AHP can have an internal heat exchanger for better efficiency between the pump, desorber, and expansion valve. (Office of Energy Efficiency & Renewable Energy 2022)

2.3.2 Performance

An absorption heat pump is not very efficient when strictly compared to a compressor-driven counterpart. This is mostly due to the more efficient cycle used on compressor-driven heat pumps. AHP still has its applications as it provides more flexibility in working principles and a more adjustable cycle structure. Studies show that AHP can achieve COP of 1.77 with output temperature around 80°C and a temperature drop of waste heat source from 35°C to 28°C. (Xu, Z. Y., Gao et al. 2022)

The basic cycle shown in 2.3.1 is not always the optimum cycle for AHP. For specialized use, it can be better to double lift or double effect cycle, because those cycles can provide higher temperature output (Xu, Gao et al. 2022). There is also the possibility to implement a compressor to increase the overall efficiency of the system and to get best of the both types of heat pumps.

This kind of hybrid system between compressor and absorption heat pumps can provide good efficiencies in places where waste heat source for driving absorption part is available, but it is not economical on its own. A hybrid absorption compressor heat pump (HACHP) using modern components designed for other applications has a wide application range, where it is economically viable. This includes applications where high output temperature is needed and also an application where the high-temperature lift is important. For most situations, the payback time for HACHP is somewhere between four and eight years, but it is possible that with well-optimized operating conditions payback time can be lower than four years, which is very low in energy-saving investments. In this study heat pumps are compared to a natural gas boiler, so payback times can be changed radically as the prices have changed. (Jensen, Ommen et al. 2015)Figure 4 shows 2 different HACHP setups using ammonium water as working fluid in two different operating temperatures.

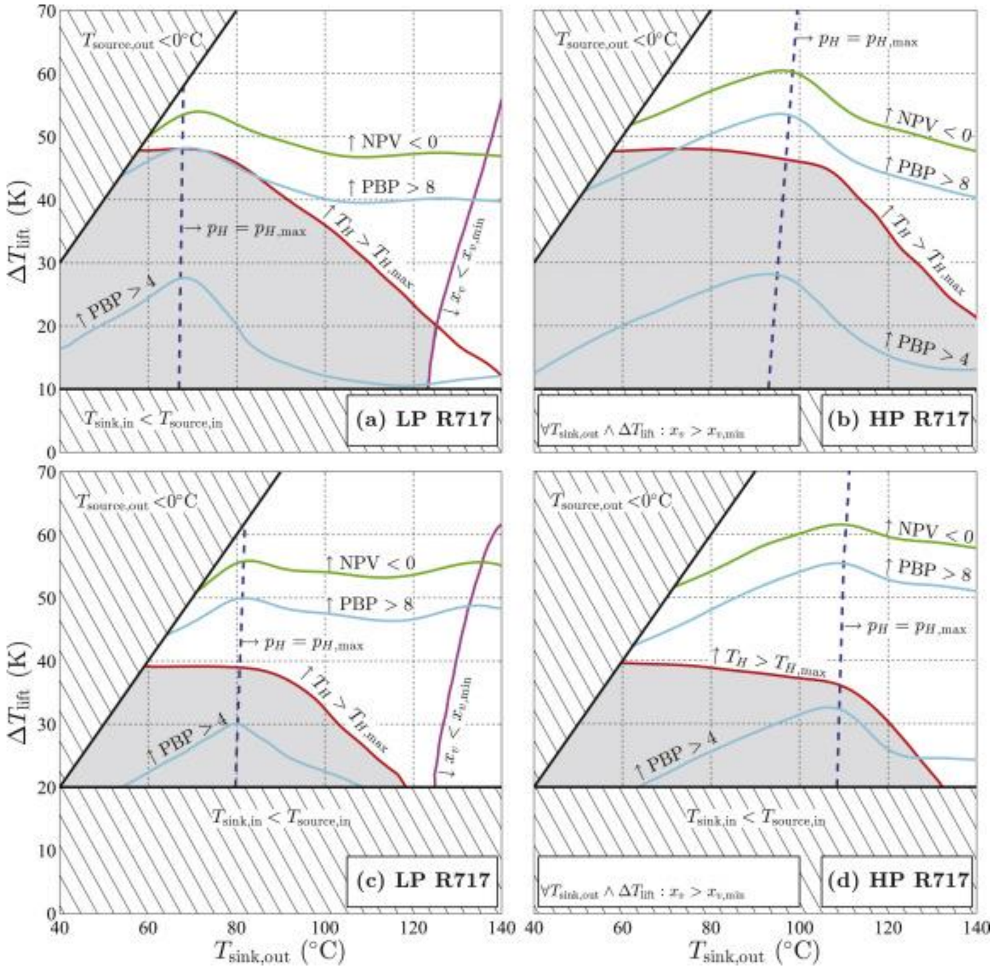

Figure 4 Economically viability of different setups LP low-pressure compressor and HP high pressure, the grey area is economically viable, dashed technically not possible. Source: (Jensen, Ommen et al. 2015)

2.4 Refrigerants

Refrigerants are one of the most impactful components of the whole heat pump operations as it determines the operating range. Refrigerants have different boiling points and operating pressures which affect the possible temperature ranges of heat pumps, as the boiling temperature of refrigerant needs to be lower than the temperature of the heat source and in a pressure range that is achievable. Refrigerants have been an influential part of how heat pumps and other refrigerant applications came to be so successful.

2.4.1 History

The history of refrigerants and refrigeration spans 1748 when it was discovered that evaporation of some ether under 1 bar pressure can chill space around it. This invention was not commercially viable straightaway as the gaseous ether was not condensed back to liquid. In 1805 first theorized version was proposed using an evaporator and condenser, this was produced in 1834. The first, commercialized versions were produced in the 1850s, and that technology was in use till the early 1900s. (Darment 2019a.)

After the turn of the century importance of cooling was noticed and innovations in refrigerant space started to pick up the pace. The first, really closed cycle refrigerating machine was invented in 1905 and it used sulfur dioxide as a refrigerant. The 1910s marked start of research on different refrigerants. The research focused on to finding refrigerants that minimized combustibility, corrosiveness, and toxicity. Potential for carbon dioxide was noticed but large scale adaption was prevented by sizing issues and increased risk for leaks. (Darment 2019a.)

1920's refrigerators as they are known these days gained traction. The first working concept of an absorption heat pump was made in 1922. The working principles in refrigerators have not changed much from the 1920s, but refrigerants have changed a lot. In the early days, many applications used toxic and/or flammable gasses such as sulfur oxides and methyl chlorides. Air-conditioning started to become more common in places like cinemas and hotels in the same decade. (Darment 2019a.)

The 1930s marks the start of the usage of chlorofluorocarbons (CFC). CFCs gained traction because they were safer, more efficient, and non-flammable. After the first discoveries of CFC, the trademark for Freon was published. After the trademark for freon-12 many other CFC compounds were studied and put in use. (Darment 2019a.)

In the 1940s DuPont freed naming rights for CFC compounds so everyone could use the same naming pattern and in that way mixups would be eliminated. In the 1950s CFC-14 came to markets and it started to be used in spray bottles. Also in the 1950s, freon 13 was invented. It makes low temperatures of -100°C and under achievable. The 1960s saw an increase in usage of all CFC compounds and demand kept rising. (Darment 2019a.)

1970s energy crisis led to the development of efficient air-conditioning units. Concern that CFCs are harming the ozone layer leads to the development of the first hydrofluorocarbons (HFC) first one being HFC-134a. In 1976 HFC-134a starts to replace CFC-12 and production of aerosols started to diminish. (Darment 2019a.)

In the 1980s scientific studies of the ozone layer started to be published and it lead them to the Wien conference where more studies are issued. Later in 1987 Montreal deal is signed that required reduction of CFC usage by 50% in the following 10 years. After the signing number of factories are committed to finding alternatives and stopping the production of environmentally harmful chemicals. At the turn of the decade, DuPont invested hundreds of millions of dollars in finding new environmentally friendly alternatives to CFC compounds. They succeeded and the DuPont Suva product line became world widely noticed environmentally friendly alternative to CFCs. (Darment 2019a.)

21 century has been for the invention of even more new alternatives. In the 2000's Ozone depletion potential ODP and global warming potential, GWP has become widely known indicators of the harmfulness of some refrigerants. The mandates to stop using CFCs and HFCs have led to a new rise in flammability and toxicity, but these can be managed with the right kind of care. EU banned the manufacturing of CFCs in 1995 and is banning HFCs too. (Darment 2019a.)

2.4.2 Common fluorocarbons

R134a 1,1,1,2 tetrafluoromethane is widely used HFC refrigerant. It was designed to replace R12 and R500 refrigerants in automotive and household applications. Even though this is a 0 ODP solution it has its problem namely a high GWP of 1430. R134a works well in mid and high-temperature applications. R134a is a component in several refrigerant blends and it is used as a pure substance in many applications including automotive, industrial systems, and light air-conditioning. Because R134a is fluorocarbon it will be phased out in the EU at end of 2029. This refrigerant can be replaced with R1234yf and R513A. (Darment 2019.)

R407C is mix of three other refrigerants: 23% of R32 difluoromethane, 25% of pentaflouroethane R125, 52% of R134a 1,1,1,2 tetrafluoroethane. This mix is nontoxic and nonflammable, but it has a high GWP of 1774 and that is why it will be banned from new use in the 2020s. R407C is used to replace R22 and it is good for air-conditioning, freezers, and mid-temperature cooling applications. R407C was a good refrigerant as it has a low-pressure need and it is not harmful to the ozone layer. After bans come into play it will be replaced with R444B. (Darment 2019.)

R410A is a mixed refrigerant with a 1to1 blend of difluoromethane R32 and tetrafluoromethane R125. This refrigerant is a good fit for household air-conditioning applications. It can be also used in high-pressure applications like water freezing units. It is a nonflammable and nontoxic solution but needs high pressure and a degree of superheating. It has a relatively high GWP of 2088, but it will be banned from some applications. It can be replaced by R452B, R454B, and R455A. (Darment 2019.)

R1234ze 1,3,3,3 tetrafluoropropene is the main replacement for R134a which will be phased out because of high GWP. R1234ze has a low GWP of 7 and an ODP of zero, so is a good alternative for R134. This is a good wide usage refrigerant and can be used in many medium temperature applications like air-conditioning units and refrigerators in stores. It is nontoxic but has ow flammability. When transport and storage temperature stays under 30°C it is safe and can be considered non-flammable. Even though it is designed to replace R134a it is not a 1to1 fit because R1234ze has a higher boiling point and that is why it is not fit for all applications where R134a is used, or some changes need to be made to machinery. (Darment 2019.)

2.4.3 Natural substances

R744 carbon dioxide is one of the environmentally friendly refrigerants that are being studied for wider usage. R744 has a GWP of one and ODP is zero so it is more environmental than most other hydrocarbons. R744 is a nonflammable and nontoxic refrigerant. R744 is good in that it can be used to achieve temperatures down to -50°C. It is problematic in the sense that working pressure is high compared to other alternatives. Its advantage is that the piping can be smaller than with alternatives and that can make the whole system more compact. (Darment 2019.)

R290 Propane is a highly efficient refrigerant that has a low GWP of three and an ODP of zero. The biggest drawback of propane is its flammability. Because R290 is highly flammable it can not be used in large industrial systems. R290 has good thermodynamical properties for refrigerant and that it can be used in a wide range of applications. R290 is used to replace R22 and R502. The flammability of R290 prevents it from directly replacing fluorocarbons. (Darment 2019.)

R600a isobutane is a natural refrigerant that is widely used because it has a low environmental impact and good thermodynamical properties. Isobutane and butane R600 are both used as refrigerants. R600 is the same compound as R600a, but R600 is a straight chain, so every carbon atom is connected to one or two other carbon atoms. In the isobutanes R600a case, all three of four carbon atoms are connected to one atom, which is connected to three carbons. R600a is a well-known refrigerant for household appliances like fridges. R600a is also widely used in aerosols and petrochemistry. R600a is an extremely flammable and nontoxic compound with a GWP of three and an ODP of zero. (Darment 2019.)

R1270 propylene is a high-purity hydrocarbon that can be used in several applications like industrial and commercial air-conditioning and refrigeration. R1270 has good thermodynamical properties to be an efficient refrigerant. R1270 is environmentally friendly with a GWP of two and an ODP of zero. Similarly to other hydrocarbons R1270 is flammable and because of that need to be handled with care, and can not directly replace hydrofluoric. R1270 can be used to replace or substitute R600a and R290. (Linde 2020a.)

R717 ammonia is a refrigerant used widely in industry. This includes industrial heat pumps, refrigeration on transport, and centrifugal chillers. Ammonia is good environmentally friendly refrigerant because it has OPD of zero and GWP of zero. The environmental advantage comes with a price. R717 is a flammable and toxic substance so it can not be used to phase out hydrofluoric without some modifications to the system. Ammonia is used to replace R22 and R134a. (Linde 2020a.)

2.4.4 Properties of common refrigerants.

Every refrigerant has different properties to each other. It is important to know these differences when designing heat pump solutions, as the refrigerant determines possible operating conditions for the system. Some properties do not affect the operations but are important to know for other reasons like GWP and ODP. Figure 5 shows the main properties of refrigerant discussed in this work.

Aine	R134a	R407C	R410A	R1234ze	R744	R290	R1270	R600A	R717
Kylmäaine-luokka	HFC	HFC	HFC	HFO	Luonnolliset kylmäaineet	Luonnolliset kylmäaineet	Luonnolliset kylmäaineet	Luonnolliset kylmäaineet	Luonnolliset kylmäaineet
Kemiallinen nimi	1,1,1,2 - Tetrafluo-rietaani	R32/R125 /R134a	R32/R125	1,3,3,3-tetrafluoro-propeeni	Hiilidioksidi	Propaani	Propyleeni	Isobutaani	Ammoniakki
Kemiallinen koostumus	C2H2F4	Sekoitus	Sekoitus	C3H2F4	CO2	C3H8	C3H6	C4H10	NH3
Syttyvyys	Ei	Ei	Ei	Matala	Ei	Erittäin helposti	Erittäin helposti	Erittäin helposti	Kyllä
Myrkyllisyys	Ei	Ei	Ei	Ei	Ei	Ei	Kyllä	Ei	Kyllä
GWP	1430	1774	2088	7	1	3	2	3	0
ODP	0	0	0	0	0	0	0	0	0
Kiehumispiste (0 bar, g)	-26,3	-43,8	-51,6	-18,95	-78,5	-42,1	-51,7	-11,7	-33
Kriittinen lämpötila [°C]	101,6	86,05	74,7	109,4	31,04	96,7	78,1	135	132,4
Kriittinen paine [bar]	40,67	46,2	51,7	36,4	73,82	42,5	58,08	36,5	111,5

Figure 5 Properties of common refrigerants: Name, Classification, Chemical name, Chemical make, Flammability, Toxicity, GWP, ODP, Boiling point, Critical temperature, Critical pressure (source: (Kaksonen 2021))

2.5 Economics of heat pumps

Even though heat pumps are matured technology wide adoption is still plagued by high upfront investment costs and relatively long payback times. A study conducted by Paiho et al. concludes that ground source heat pumps are the most economical variant across heat pump technologies when heating for housing is studied. The study also found that all types of heat pumps are economically viable including in cases where energy prices rise. In situations where energy prices rise GSHP is even more advantageous compared to others. (Paiho, Pulakka et al. 2017) Across many other studies, it has been found that heat pumps are an economically beneficial investment.

Heat pumps are economical in a wider range of operations than just in buildings heating. Implementation of large-scale heat pumps in district heating systems suggests that the technology starts to be mature enough to be competitive against boilers. This competitiveness has its downside in impacting electricity prices. The viability and payback time is also somewhat tied to electricity price as it is the main operating cost of heat pumps. Historically fossil fuels have been a cheap way of heating with somewhat low upfront investment costs. This makes it hard to justify investing big sums of money in technology that offers small savings over a long period. Need for retrofitting old properties to fully utilize the potential of heat pumps is identified as one of the main barriers to wider utilization in the housing sector in the UK.

3 INVESTMENT CALCULATIONS

Investment calculations are part of management accounting with the main purpose to help determine the best course of action for the company. Management accounting provides information to decision-makers so they can pick the best option from different solutions for the problem. As the information era keeps moving forward the role of management accounting keeps growing and a new way to use accounting information can be found. In this work interest of accounting lies in investment calculations. Investment calculations are a way to evaluate different options for some projects, for example in this case option one could be a single large heat pump and the second option is three serial heat pumps. Investment calculations will decide which of these options is economically better (Neilimo, Uusi-Rauva 2005).

Investment calculations are a set of tested models that give a good estimate of how investment can perform. These methods differ from each other and every method is not suitable for every investment type. Because investments and calculation methods differ a lot from each other it is important to know many methods and how to use them (Neilimo, Uusi-Rauva 2005).

Investment calculations are used to evaluate different possibilities where money could be used in the best possible way to maximize the outcome of the investment. In many cases, it is not clear which is the best investment to go forward with without calculations. Investment calculations give value for future possibilities in an easily understandable way. Calculations are based on market situations, costs from the investment, and estimates of different things that are connected to the investment. The calculations give a deeper understanding of investment than just doing the investment because calculating possibilities give more information about the things that affect the outcome of the investment (Neilimo, Uusi-Rauva 2005).

Most of the time investments need a big amount of money, which increases the risk for the company and that is why in many cases well-made investment calculations help to medicate the risk. Investments are built from two blocks: basic acquisition cost (BAC), and running costs. Acquisition costs are most of the timeless volatile than running costs, because BAC is not in the far future, and fewer things can change. Running costs have more uncertainty as the costs are spread over a wider time frame. Running costs can be positive in way of running profits or negative as the costs. In many cases, profits from investments are hard to evaluate in unequivocally, as the market is not certain. For example, investing in a large marketing campaign BAC of the campaign is simple to calculate, but it is hard to know how much the campaign will increase the sales and in that way profits of the company (Neilimo, Uusi-Rauva 2005).

3.1 Rate of interest

Interest is the cost of money. In many cases, investments are paid with own and foreign capital (debt). When debt is used to pay investments, interest is the cost of this capital. In investments, calculation interest rate (i) is used to compare costs for different investment calculation interest rate can be used to get different costs of investment to a situation where the timing of cost doesn't affect the comparability of those costs is maintained. This is important in investment calculations as costs can come at different times. With interest, it is possible to calculate how much more costly something is in the future. This is done by discounting the money to some other timeframe. For discounting there are premade tables that tell the value of the money at some time in the future. Inflation is another big contributor to the cost of investment. Effect of inflation can be calculated by equation 5 (Neilimo, Uusi-Rauva 2005).

$$i_r = \frac{i-s}{1+s} \tag{5}$$

Where

i_r	Inflation-adjusted interest rate
i	Calculation interest rate
s	inflation rate

3.2 Net present value

When using the net present value method to evaluate investment all costs of the investment are discounted to the present moment by using the calculation interest rate. Investment is profitable when net present value calculations give a positive value as result. This means that investment net profits overweight the basic acquisition cost and running costs. In this case, net profits include the end value of the investment. The end value in investment is the value of the product at the end of its lifespan, this can be zero because the end value is in so far future that it can't be calculated in a good manner, or it can be negative as sometimes to get rid of some products some price needs to be paid. When calculating net present value with changing returns equation 6 is used. This equation discounts all returns to the present value (Neilimo, Uusi-Rauva 2005).

$$NPV = TC - \sum_{n=1}^{n} RE * \frac{(1+i)^n - 1}{i(1+i)^n} \tag{6}$$

Where

NPV	Net present value
RE	Return of investment in time period
TC	Investment total cost
n	Investment keeping time
i	Calculation interest rate
t	Time

If the net income of the investment can be simplified to be the same for every year in the future equation 8 can be used to measure the profitability of the investment. Using this simplification helps to get a grasp of the profitability of the investment, but more accurate results are achieved when not simplifying profits and costs. For this simplification, there are tables where values for the most common net present value discounting rate are calculated so the calculation of net present value from equation 8 is easier (Neilimo, Uusi-Rauva 2005).

$$NPVd = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{7}$$

Where

NPVd	Net present value discounting rate
n	Investment keeping time
i	Calculation interest rate

$$NPV = NPVd * RE - TC \qquad (8)$$

Where

NPV	Net present value
NPVd	Investment keeping time
RE	Return of investment in time period
TC	Investment total cost

3.2.1 Annuity method

The annuity method is like the net present value method reversed. In this method, basic acquisition costs are spread evenly to the useful time period of the investment. These parts are called annuities. Annuities are the product of depreciation and calculated interest rate. In this method, investment is profitable if the annuity is smaller or equal to net profits per year. When the annuity is calculated basic acquisition cost is multiplied by the annuity term. This term can be calculated by equation 9 or taken from the readymade table. When annuity factor is calculated it can be used to calculate annuity of the investment with equation 10 (Neilimo, Uusi-Rauva 2005).

$$ANF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (9)$$

Where

ANF	Annuity factor
n	Investment keeping time
i	Calculation interest rate

$$AN = RE - TC * ANF \qquad (10)$$

Where

AN	Annuity
ANF	Annuity factor
RE	Return of investment in the time period
TC	Investment’s total cost

3.2.2 Internal rate of return method

The internal rate of return method evaluates investment in the backward direction. In this method, the interest rate is what is calculated and this rate is compared to the company's target rate of investment return. This method calculates the point where investment costs are the same as the net profits for the investment. This method is like reversed net present value method. The IR number gotten from equation 11 can be used to find the rate of return percentage for investment from the NPV table. When the rate of return percentage is found it can be compared to the companies' internal minimum rate of return and if the calculated rate of return is larger than companies minimum requirement investment is profitable (Neilimo, Uusi-Rauva 2005).

$$IR = TC/RE \tag{11}$$

Where

IR	Internal rate of return point
TC	Investment's total cost
RE	Investment return in the time period

3.2.3 Return on investment method

Rate of return method is good method to evaluate investments that differ a lot. In many cases differences in investment type can make comparison hard, as the investment life span or other parameters. In many cases money is tight and it is not possible to go forward with all investment possibilities and therefore it is important to compare different type of investments in way that works if investments are widely different. Return on the investment can be calculated with equation 12 (Neilimo, Uusi-Rauva 2005).

$$ROI = 100 * (RE - \frac{TC - WO}{n})/TC \quad (12)$$

Where

ROI	Return on the investment
WO	Write-off
n	Investment keeping time
TC	Investment total cost
RE	Investment return in time period

3.3 Payback method

Payback method is probably the most intuitive of these investment calculations. In this method idea is to calculate how quickly net profits pay out basic acquisition costs. This method is simple to understand but does not give lot of information about how inflation or interest rate affect investment. Interest and inflation can be accounted in this method, but in that point it is as good to use other methods. Other problem for payback method is that it does not calculate how investment will succeed after the payback period. This method has also preference to investments where investment has low pay back which can mean that later stages of investment are not so profitable for example case where net profit from investment drops drastically after certain period when maintenance starts to play large part (Neilimo, Uusi-Rauva 2005).

3.4 Sensitivity analysis

Sensitivity analysis is one of the most important parts of any successful investment project. The main point of doing sensitivity analysis is to minimize the uncertainty of the future by making sure that investors have some leeway if some predictions go wrong, or prices fluctuate. Most of the time investment projects bind large amounts of money from other projects, and it is important to limit the risk of failure. Sensitivity analysis is used to limit these risks by acknowledging them. By acknowledging risky estimates, it is easier to evaluate how likely scenarios are and how the estimates can be changed to account for most of the scenarios.

The most common sensitivity analysis type is changing the cost of money and cash flows from the investment. This is because in most cases these two variables are the most influential to the whole investment. Sensitivity analysis is usually used by the management of the companies as it helps to relieve risk and risk management is important to make investments possible (Neilimo, Uusi-Rauva 2005).

4 WASTEWATER HEAT RECOVERY PLANTS IN FINLAND

The first investments in heat recovery from wastewater in Finland date back to the start of the 21st century. The first large-scale heat recovery plant is Helsingin Energia (Helen) build the Katri Valan recovery plant. This district heating plant was completed in 2006. After that Turku Energia build a similar plant to utilize heat energy from the wastewater treatment plant at Kakola. The last important large scale plant using wastewater is the 2015 operations started Fort um's plant at Espoo Suomenoja. Before these large-scale applications, similar technology have been utilized for smaller plants. (Valor Partners Oy 2016, 16.)

In 2019 Fortum started to plan on investing in new heat pump unit in Espoo suomenoja. This plan included a new heat pump to increase heat production from 40MW to 60 MW, but the increase in capacity is even bigger than expected from 46MW up to 70MW. This new plant uses wastewater as a heat source and in summer it is capable to use warm seawater also. This plant pushes Espoo district heating to more than 50% carbon neutral as the new heat pump uses source verified renewable electricity as the energy source. (Fortum 2021)

After these three large investments has been completed, many cities have started to look for investments in heat pumps for district heating. Large-scale heat pumps have increased in popularity and there are many reasons for this increase. The probably biggest single reason for the increase in popularity is uncertainty looming over the whole energy sector. As the uncertainty is growing in the energy sector it is clear that new energy systems need to be more flexible than in past. This need for flexibility is a due increase in an imbalance of production and usage of energy, this is amplified by energy sectors' movement more toward renewable electricity sources that are usually more unstable at production quantity than fossil fuel-based systems. Increased demand for district heating and cooling also plays major role in making investments in heat pumps more attractive. (Valor Partners Oy 2016, 16.)

4.1.1 Katri Vala Helsinki

Helen operated Katri Vala's heat pump district heating plant located in Sörnäinen Helsinki. This is the first operational large-scale wastewater heat recovery plant in Finland. Its operations started in 2006. This plant uses processed wastewater as a heat source in winter operations. In summer when the heating need is lower plant uses seawater and district cooling water as a heat source, providing up to half of the warm water needed of Helsinki. The whole facility is built underground below Katri Vala's park, that's where the name comes from. In 2006 when operations started at the site the facility housed five 18MW heat pumps, but nowadays heat pump count has increased to achieve even greater heating and cooling power. At the start maximum heating power from the plant was 90MW before the seventh heat pump installation it was 123MW and after the last heat pump becomes operational maximum power will be 155MW. (Valor Partners Oy 2016, 16; Helen Oy 2020a.)

Katri Vala's plant is one key to achieving Helen's ambition to become carbon neutral before 2035. To realize that goal, Helen needs toshut downn old coal operated power plants in Helsinki. Helen is transitioning the Hanasaari unit to backup operation in 2022-2023 and it will stop operation completely in 2024. These kinds of decisions are important when carbon neutrality is the goal. As the need for heating is not getting a lot lower investment must be flowing to projects like the seventh heat pump in Katri Vala. Heat and cold batteries in the system make the whole system more profitable and more adjustable to changing needs. This kind of heat plant has been a key part of lowering part load operations of large CHP power plants, as it can produce enough heating from heat batteries in fall and string when demand is too low for CHP plants to operate at full efficiency. (Helen Oy 2020b.)

Figure 6 shows an operational diagram of Katri Vala's heat pump plant in winter operations. The figure shows a simplified manner of how heat pumps are connected to different heat sources and where heat is flowing. First, the five heat pumps used in Katri Vala's power plant are Friotherm Unitop 50FY, these heat pumps use R134a as a refrigerant. In winter operations Heat energy is taken completely from wastewater as seawater is too cold to be useful. From the figure, it can be seen that wastewater comes to the first heat exchanger at a temperature of 12°C and leaves at 10°C. The 10°C water goes to the evaporator where the temperature drops to 4°C. Lastly water goes back to a heat exchanger where the temperature rises to 6°C. In condensing side district heating water comes at a temperature of 50°C and leaves at 60°C. Winter operations heat pumps are used to only preheat the water before it goes to some CHP plant to get heated to right temperature for district heating. (Foster et al. 2016, 4)

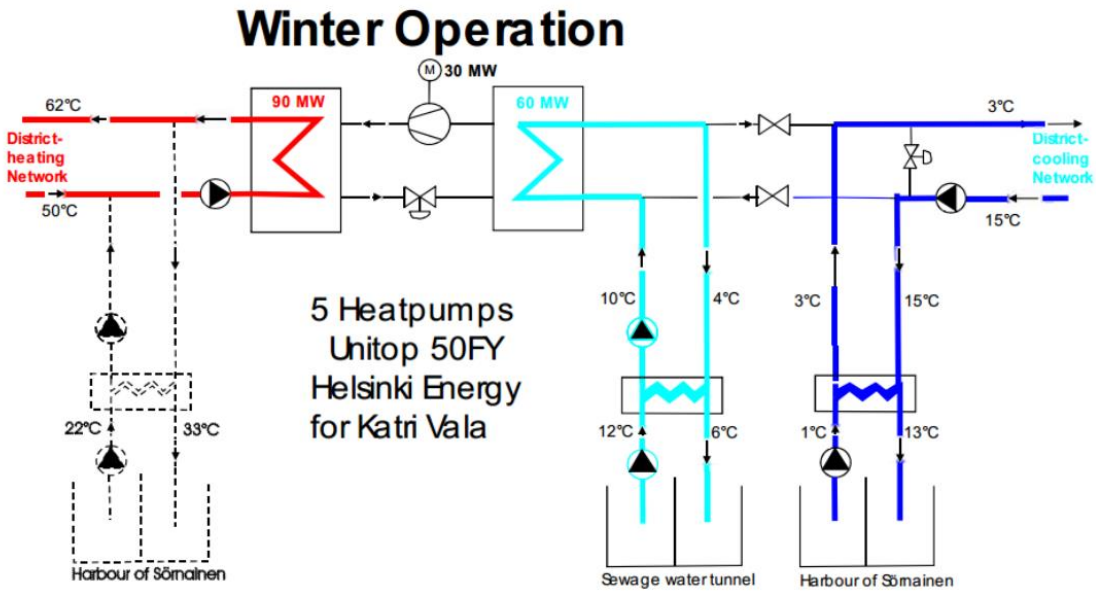

Figure 6 Katri Vala's heat plant in winter operations (source: (Foster et al. 2016, 4))

In summer operations heat pumps are used to provide mainly district cooling for citizens of Helsinki because in cooling operations heat is produced is used to provide hot water to Helen customers. In summer operations district cooling water comes in at temperature of 20°C and leaves at 4°C. This heat energy from cooling water is transferred to the district heating side. On heating side water comes in at a temperature of 45°C and leaves at 80°C. To keep heat balance right excess heat is transferred to the ocean. Summer operations are shown in Figure 7. (Foster et al. 2016, 4)

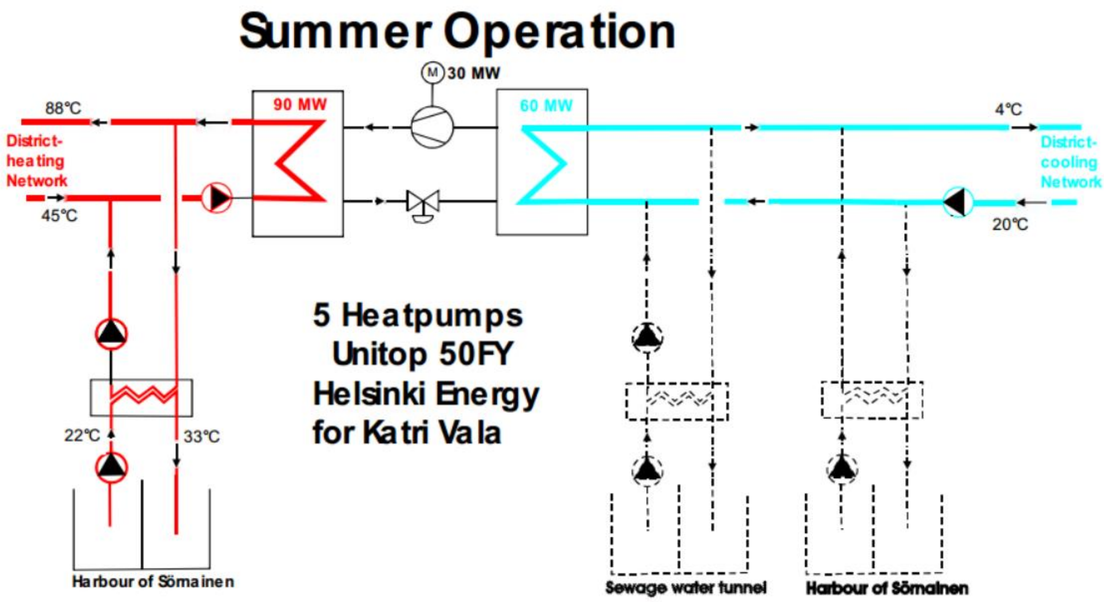

Figure 7 Katri Vala's heat plant in summer operations (source: (Foster et al. 2016, 4))

4.1.2 Kakola Turku

Heat recovery plant in Turku is very similar to Katri Vala in Helsinki. Heat pump plant in Turku is build in to same cave system that houses the waste water treatment center. Wastewater temperature used as heat source at Kakola changes a lot between seasons. At spring times water is about 7°C and in summer times temperature can rise to 20°C. Heat pumps are used to create 84°C water to use in district heating system, by dropping sources temperature down to 4°C. Kakola uses 15 000 m³ storage to store cold wastewater. Stored wastewater can be used in district cooling and after that it is released into sea. In similar manner as the Katri Vala, Kakola uses treated wastewater. Location for Kakola plant is great as it is close to district heating system where temperature is low enough that heated water from heat pumps can be directly used in that system. Location for Kakola is good also because the electricity grid in the area was sturdy, so upgrade for that was not needed.

Kakola heat recovery plant was build in 2009 using one heat pump with heating power of 21 MW and cooling power of 14.5 MW. Plant was quickly upgraded in 2013 to use two heat pumps. With these two heat pump Kakola plant can produce sufficient amount of heat to satisfy need for about 24 000 district heating customers.

Kuvan linkki) Shows simplified diagram how Kakola heatpump plant operates in normal situation. Cold battery in the diagram is drawn to be 17 000 m³, but according other sources it can be 15 000 m³ or 16 000 m³. Wastewater comes to evaporator at 14°C and leaves at 4°C to cold storage or to sea. 4°C water can be used in district cooling and released to sea at 14°C. Heat energy that is collected from wastewater is upgraded to be used in district heating. At condenser district heating water comes in at 43°C an leaves at 78°C. The exit temperature

4.1.3 Espoo Suomenoja

Fortum operated plant in Espoo suomenoja started the operations in 2015 by recovering around 300 000 MW of heat per year from cleaned wastewater. This is impactful amount of heat recovered as it can cover around 15% of Espoo's need for district heating. Whole project for this heat recovery plant went as planned and didn't have any accidents. Construction at this plant started in 2014 and finished early 2015. This kind of clean energy solutions are key part of realizing Fortum's vision of carbon neutral energy system in future.

Espoo heat plant differs bit from the two earlier examles in the sense that it uses seawater as heat source in summer times. This became possible in 2021 as the newest heat pump started operations. In 2015 Suomenoja plant used two 20 MW heat pumps but as the intent for clean heating grew Fortum invested in third heat pump. This latest heat pump is bigger that the predecessors at 25 MW of heating power. This new heat pump will increase Espoo clean district heating percentage to almost 50% all district heating.

Kuvan linkki) show working diagram how heat pump plant is operated. Suomenoaja gets its water in temperature in 8°C to 18°C depending on season. The water will exit to sea at temperature of 3°C-13°C. As it can be seen the temperature drop stays the same across the seasons. Water from district heating system comes to heat pumps at 40°C-50°C and goes back in temperature of 75°C-115°C. Lastly heat pump plant can provide district cooling where water comes to plant at 16°C and leaves at 8°C.

5 UTILIZATION OF HEAT ENERGY

5.1 Heat source

The heat source in this project is processed wastewater from a chemical industry factory. As the factory runs almost steadily thought out the year wastewater flow rate stays very constant. Wastewater flows through heat exchangers can be managed even more with wastewater where the stored amount of water can be changed up or down when production changes or when the factory has some maintenance is done and water production is a bit higher. Also, the temperature of the wastewater stays almost constant through the seasons, because most of the water used in the processes needs to be warmed up and at the moment heat is not collected after usage.

Wastewater flow from the factory is between 27m³/h and 37 m³/h at peaks. Temperature ranges from summer 32°C to winters lowest at 25°C. This temperature change is quite low when compared to temperatures of air in these two timing of the year, as the air temperature can be under -10°C and more than 30°C. This temperature fluctuation means that air temperature is not a big factor in water temperature. It can also be assumed that a temperature drop of 20°C is possible all year around.

The design flow rate for this case was decided by analyzing the duration curve of the volume flow-rate Figure 8. Figure 8 shows that most of the time volume flow rate exceeds the design value of 27 m³/h. Around 13% of the time daily average flow rate is under 27 m³/h this can be lowered more with the usage of a collection tank as a buffer. Data used in drawing Figure 8 is from 2020, and it skews the results a bit, as the factory was run on partial capacity. The small flow-rate is mostly in summer time when the need for heat is a bit lower and that way smaller flow rate is not too bad for total efficiency. Also in summer time temperature of wastewater is higher than in wintertime. This means that the difference in total heat energy that is possible to recover stays quite constant through out the year, the system needs to be operated a bit differently in summer and winter time. Energy stored on the water in normal design operations is 472 kW and in the summer conditions it is 525 kW, so heat pumps can run at full capacity even when the flow rate is a bit lower, as long as the heat exchangers are designed in a way that they can use this modified flow efficiently.

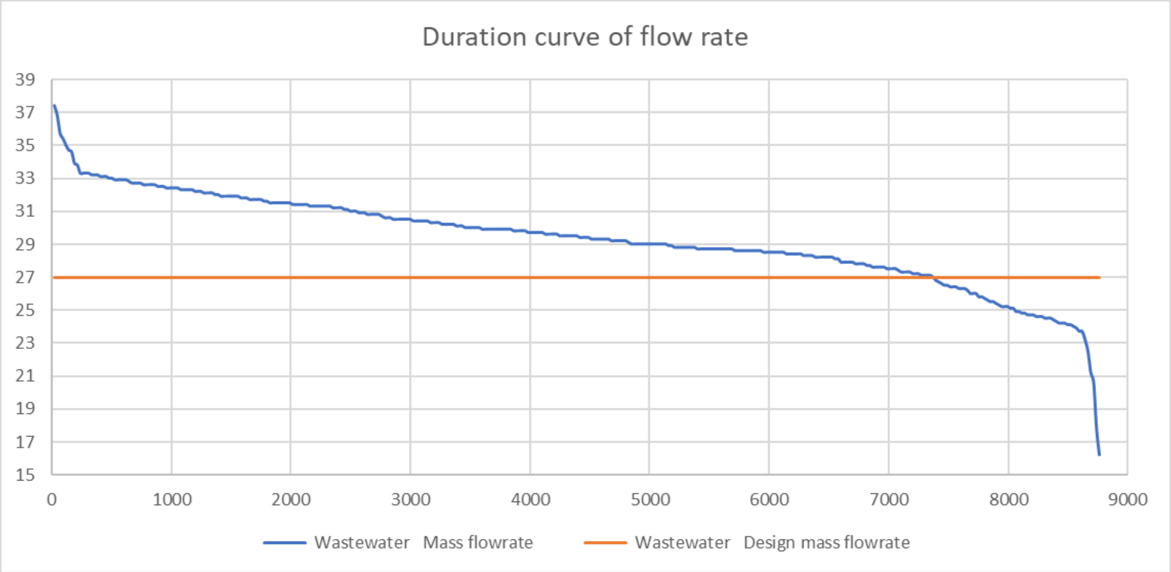

Figure 8 Duration curve of flow rate

The design temperature for the system is decided by using the duration curve shown at Figure 9. The real temperature is just 1.1% of the time under the design temperature of 25°C. This is very low compared to the flow rate, but daily fluctuation in temperature is higher than in flow rate so it needs to be compensated in this way. Using a good estimate of the temperate is also more important than the flow rate because the flow rate can be adjusted, but the temperature can not be. Also, design temperature is determined partly flow lower limit of the temperature, as out going water needs to be over the set value and that is limiting possibilities a bit.

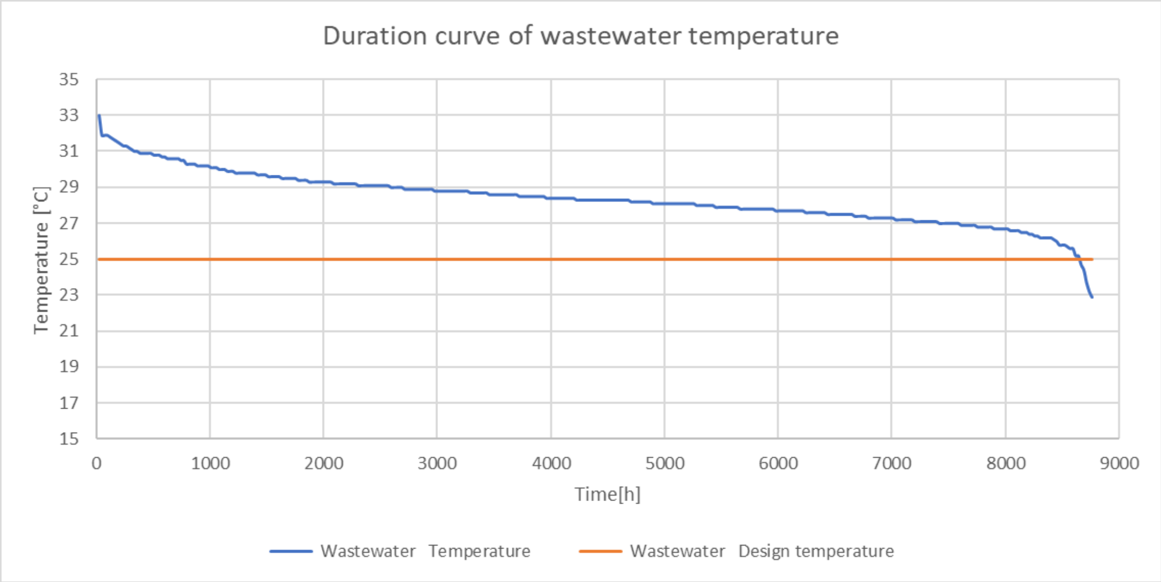

Figure 9 Duration curve of wastewater temperature

Currently, wastewater produced in the factory is pumped to the treatment center in Hanko. Because it is sent to the treatment center at this high temperature there is a lot of energy to be collected and reused. Wastewater cools because wastewater can cool down a lot before it reaches the treatment center in Hanko so the energy that is left in wastewater is lost to the environment. Recovering this heat from the wastewater could help to lower the heating bill at the factory. Investment towards heat recovery can help make the factory greener as less heat goes waste. Investment in environmental values is on the rise and can give more value in sales as the customers want to use producers that are interested in environmental values.

5.1.1 Challenges

Wastewater in this case work is dirty as it would be used before the treatment center. This can be challenging as the factory uses chemicals that make wastewater acidic. This makes material choices for heat exchangers more challenging than in cases where treated water is used as the heat source. Material choices can also make heat exchangers less efficient and that can lead to a bigger system to collect the same amount of heat energy from the flow.

Another challenge is the accumulation of solid matter in heat exchangers. This is because wastewater has some solids in it. This will make the decision of heat exchanger type a bit narrower and suitable heat exchangers are not the most efficient option in the market.

Accumulation of solids will also happen from chemical reactions happening in wastewater. This accumulation makes cleanability a very important quality, as fast cleaning improves up time for the whole system. Cleaning the heat exchangers is important also because fouling is one big factor in efficiency. The chemicals used in the factory can cause some sort of slimy material to form. This slime is quite easy to handle as it is a soft material and because of that can be cleaned simply by using brushes or airbrushing.

The wastewater has some salt in the water. These salts are mostly sodium sulfites from the acidic processes in use. Sodium sulfite will start to crystalize onto surfaces at low temperatures if the percentage of sulfates is too high. Figure 10 shows sodium sulfates solubility in temperature function. From the figure can be seen that a temperature of 10°C can have around 7 grams of sodium sulfate before it starts to clump up. This is more than twice as many sulfates that can be expected in wastewater in this case. Accumulation to surfaces should also be lower because the water in this case is flowing all the time. Before the construction of the heat recovery system starts it would be smart to conduct experiments for the wastewater and ensure that chosen design temperature is not too low that it would start the accumulation.

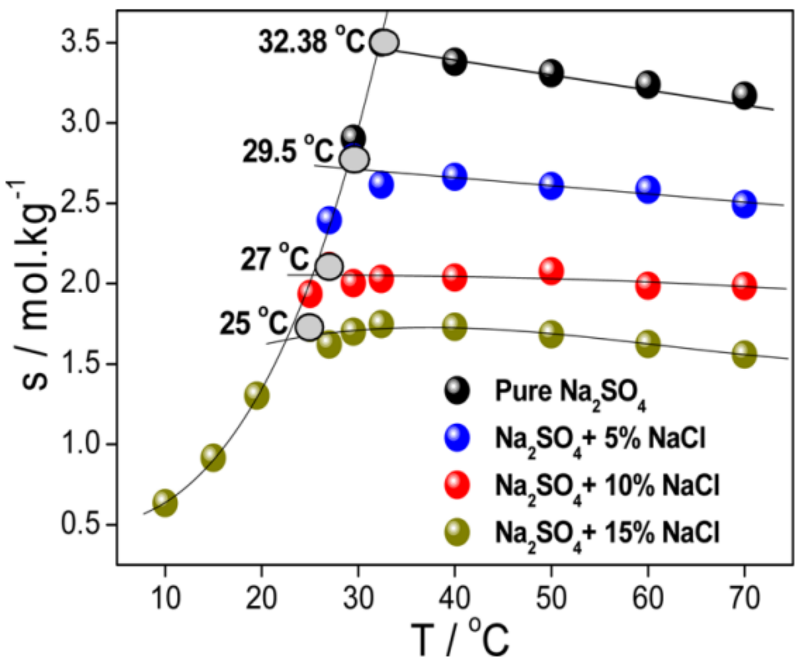

Figure 10 Solubility of Sodium (source: (Bharmoria, Gehlot et al. 2014))

5.2 Usages for the heat

Possible usages for heat are limited by the temperature that can be recovered effectively and the positioning of the recovery machinery. The most prominent plan is to use heat in chemical heating. This is because the heat used in that position is around 70°C and there is room close by where heat pumps can be housed. In this usage case return temperature is 60°C. Unfortunately, this mass flow is not currently being measured so the capacity of energy intake relies on estimates, but it is estimated that the flow is large enough to take up the whole energy load from the heat recovery.

Another possibility is to produce higher temperature heat, so a heat recovery system can be implemented in the main heating system of the factory. This would be the best possibility in the heat utilization sense as the heat load would be very stable over time. The biggest problem with this solution is that production of over 170°C heat is very expensive and the heat source of wastewater is relatively low temperature. This heat is returned to the heating plant at around 120°C and a pressure of 13 bars. Using heat energy in these high temperatures and pressures would most likely be not economically viable currently, so this use case is not pursued more as a possibility.

Heat recovered could be used by preheating water with the biological air purifier. At the air purifier water is used in two conditions: 80 m^3/d sprayed water at 28°C and 12m3 as steam. Both of these usages get the water at the temperature of 10°C and in that way can take around 75 kW of heat if energy from heat pumps is used to heat all spray water and preheat steamed water to 70°C. The whole of about 520 kW could be produced by heat pumps, but the temperature needed to make steam for use, in this case, is not very viable. The heating need in air purifiers is season dependent as the process needs less heating in the summertime than in wintertime. This would make designing a heat pump system more complicated as the system can not be used at design capacity around the year.

These few heat users are the main proposed solutions. There are also some other possibilities but those have more problems, like seasonality, temperature, or not heavy enough heat load to be profitable. For this work chemical heating is chosen to be heat user for simplicity's sake. A chemical heater doesn't have the capacity to take all the heat energy, but it would need specialized equipment to verify heat needs in possible heat users. Most likely this system would use a combination of a couple of heat users. The same methods shown in this work can be used to determine the cost-effectiveness of other similar projects in the future.

6 DIMENSIONING OF THE HEAT RECOVERY SYSTEM

To estimate the profitability of the heat recovery system it is important to make good assumptions about flow rates and temperatures. These assumptions are used in calculations to determine the sizing of the heat pumps and heat exchangers. In these calculations, variations in these variables should be considered, and calculation values should be values that can be achieved most of the time in operations. This means potential temperature change in heat exchangers should be calculated from the lowest point.

In this case, the flow rate can be removed from absolute minimums from the charts, because water is flown to the container that can hold more than 8 hours' worth of water from normal operations, so this container can be used as a buffer to largest fluctuations. As discussed in an earlier chapter flow rate for water can be assumed to be constant at 27 m^3/h, which translates to 7,5 kg/s. From the data, it can be seen that wastewater temperature stays over 25°C all year round, so this can be used as the temperature at whence the heat is taken. Another important temperature to decide is the outlet temperature for the wastewater heat exchanger. Because the factory doesn't have its own wastewater treatment center the temperature of exiting water needs to be in bit higher temperature than what would be optimal if water would flow into the environment after heat recovery. From a discussion with Hanko wastewater treatment center it has been decided that 10°C would not mess up their process. Wastewater from the plant loses around 15°C in summer operations before it reaches the treatment center and 20°C in winter conditions. These losses will be lower when the temperature of the water is lower at the exit of the factory. This is a bit more than 2°C that would be normal if heat recovery was using clean wastewater. The last know point is the temperature that needs to be achieved with the heat pumps to get the recovered heat back to usage.

In this case, heat is designed to heat up chemicals. Currently, chemical heating is done by using pressured water produced in a heat power plant close to the factory. This could be replaced with another heat exchanger, that has a flow cycle towards the condenser of the heat pump, or the condenser can be used as the heat exchanger of the system. Both of these systems have their own benefits and downfalls. Direct use is simpler than the system that has 4th heat exchanger added in and it has better energy efficiency as there are fewer heat exchangers that have temperature losses. The simplicity makes this system also a bit cheaper.

On the other hand, if 4th heat exchanger is added that cycle could use pure water as the heat transfer fluid. This is important as the case of leak contamination to chemicals heated could be devastating, but the usage of water as transfer fluid minimizes the harmful effect. This more complicated system is also more flexible for changes in load in long term as more heat pumps can be added more easily or heat can be supported with the steam flow. In this case, it is assumed that direct heating will be used, but additional cost for the additional heat cycle is calculated. The cost for the last cycle is assumed to be the same price for all heat pump providers.

With these assumptions, the system has six calculation points. These points are wastewater inlet (WW,in), waste water outlet (WW,out), evaporator inlet (E,in), evaporator outlet (E,out) condenser inlet (C,in), and condenser outlet. C,out. Heat transfer fluid in WW points is the wastewater. It can be assumed that temperatures in E points are the same as they are at the other side of the wastewater heat exchanger, or to be a bit more conservative some constant heat loss can be added in. Lastly, C points are common between condenser and heat users whether it is the chemical heater or bonus cycle.

Figure 11 shows a schematic of the system. In the system, warm wastewater is directed to the heat exchanger where the heat is transferred to the evaporator by using some icing-proof solution other than water-glycol mix. This is because the factory is in a groundwater area and usage of glycol solutions is prohibited in this kind of case, as the pipes run underground. Lastly in the figure is the heat pump that is used to move and upgrade heat from the heat transfer solution to the temperature that is useful in the system.

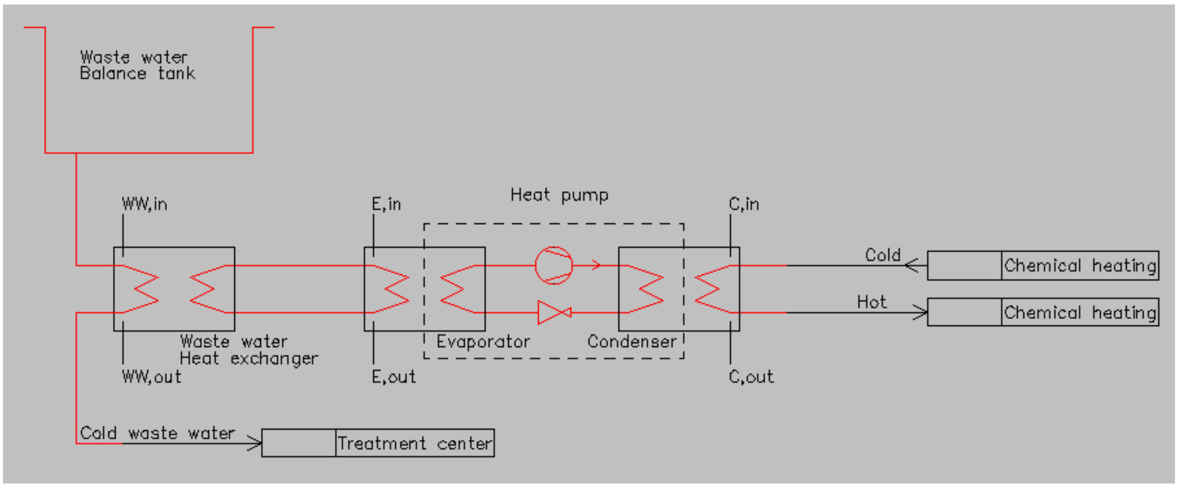

Figure 11 Simplified PI-chart of heat recovery system

Even though wastewater, in this case, is not pure water it is reasonable to simplify it to be so heat capacity (c_p) is 4,2 kJ/kgK. For the middle cycle, most likely fluid is a mixture of water and some alcohol to prevent icing in the system, so c_p of pure water can't be used, and it is easier to design flow speeds a bit too high and use a pump to correct that difference in real flow to designed flow than another way around. That is why in this case c_p of 3,5 kJ/kgK is used to calculate the flow rate for the cycle between the wastewater heat exchanger and evaporator of the heat pump.

In this case, it can be assumed that the terminal temperature difference of the wastewater heat exchanger is 1°C, which makes temperatures in the second cycle 1°C lower that designed, so those temperatures are 24°C and 4°C. In the evaporator and condenser terminal temperature difference is calculated to be 2°C, so the evaporation temperature of the working fluid needs to be 2°C and condensing temperature is 72°C. This larger terminal temperature difference is because there are phase changes present at these heat-exchanging surfaces. It is assumed that the heat pump houses 5°C superheating so the compression stays dry. This is important as small liquid droplets inside the compressor can cause large damage to the system. On the other side of the heat pump system, sub-cooling is done to ensure better efficiency at heat transfer. In this case, subcooling is assumed to be 3°C. For compressors, temperature losses are decided to be 5%, as it is a reasonable estimate in normal commercial machines.

6.1 Calculating operational points

With the chosen design values and some assumptions on the temperatures and temperature differences, the other important values can be calculated. Firstly, it is important to calculate the potential for heat recovery from the heat source. That gives an upper limit to the potential of the whole system. Heat transfer from wastewater can be calculated by using equation 13.

$$P = q_m * c_p(T_{in} - T_{out}) \tag{13}$$

$$P_{he} = q_{m,ww} * c_p(T_{ww,in} - T_{ww,out})$$

$$P_{he} = 7{,}5\frac{kg}{s} * 4{,}2\frac{kJ}{kg * k}(25°C - 5°C) = 630\ kW$$

Where

P	Power
he	Heat exchanger
q_m	Mass flow
ww	Wastewater
c_p	Heat capacity
T	Temperature

For this case refrigerant R1234ze is chosen, because it has good properties in the temperature range from -20°C to 100°C. In this temperature range, the pressure is reasonable for good operations. Figure 12 shows log p,h digram of the R1234ze refregerant. There is an approximate operational point for the heat pump in these conditions. From the Figure 12 pressure and enthalpy can be looked up for the operation points.

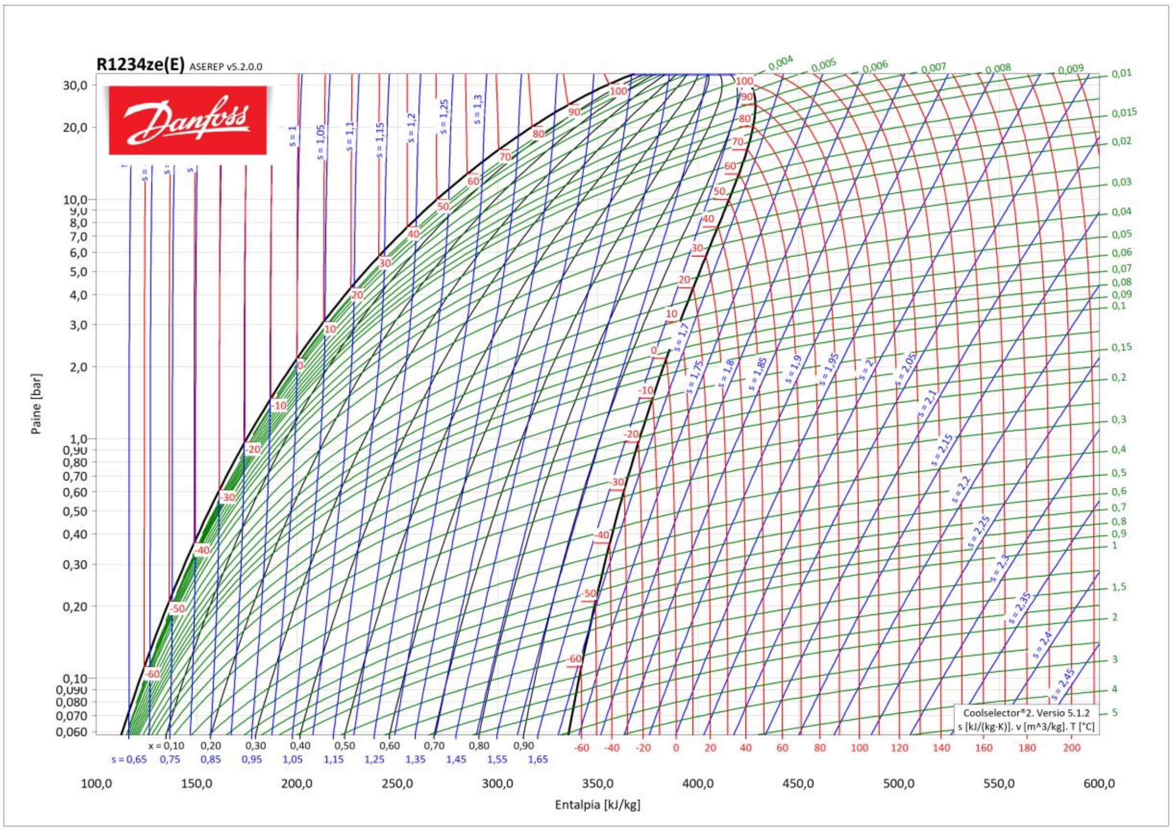

Figure 12 log p,h digram of the R1234ze refregerant (source: Danfoss coolselector 2 2022)

Finding all the values for the operational points take a bit of jumping around the h,s diagram, as some values are known and others can be derived from the known values. Every operational point can be locked in place by knowing the temperature and pressure at that point if the point is at the liquid or superheated vapor area of the diagram. At point 1 temperature is known and it is known that point one needs to be on the superheated side of the curve. Pressure for point one can be derived from point 4 as the temperature for point 4 is known and the point is inside of the curve, that way it has just one possible pressure for the design temperature. By knowing the temperature and pressure for point 1 enthalpy and entropy can be read from the diagram, that waypoint one is fully defined. Because point 4 is in transitioning area it needs one more variable to be fully defined. This can be achieved from point 3. For point 3 temperature before sub-cooling and the amount of sub-cooling are known. With these variables known point, 3 can be defined. This is done by getting pressure at that point from the knowledge that the temperature before sub-cooling is on the liquid-vapor curve. By using this pressure and applying sub-cooling point 3 is defined and enthalpy and entropy can be looked up. For point 4 enthalpy is the same as in point 3. Lastly by knowing points 1-, 3-, and 4-point 2s and point 2 can be defined. Point 2s is found at the same pressure as point 3 and the same entropy as point 1.

From point one to point two s pressure, temperature, and enthalpy are increased as the refrigerant goes through the compressor. Between these points entropy of the refrigerant stays constant. The pressure ratio, in this case, is about 6,57, and other values can be taken from the Figure 12. In this case for more accurate readings, Danfoss coolselector2 software is used.

Point 2s is the point that doesn't have physical losses calculated, so point 2 needs to be calculated. Point 2 can be calculated by using equation 14. For this casework, isentropic efficiency of 0.78 is chosen, as it is middle of the normal range of compressors efficiencies. The normal range for displacement compressors is 0,75 to 0,82 (Perry&green Kaksonen)

$$h_2 = \frac{h_{2s} - h_1}{\eta_s} + h_1 \tag{14}$$

$$h_2 = \frac{448{,}5\,\frac{kJ}{kg} - 409\,\frac{kJ}{kg}}{0{,}78} + 409\,\frac{kj}{kg} = 459{,}64\,\frac{kJ}{kg}$$

Where

h_2	Enthalpy at point 2
h_{2s}	Enthalpy at lossless point 2s
h_1	Enthalpy at point 1
η_s	Isentropic efficiency

From point 2 to point 3 refrigerant goes through the condenser. In this area, the refrigerant is handed over heat energy to the other system, in this case to the chemical heater. This is done under constant pressure. This process is called the isobaric process.

Between points 3 and 4 refrigerant flows through the expansion valve. At the expansion valve pressure of the refrigerant is lowered to the same pressure as point 1. The expansion between points 3 and 4 is presumed to be isenthalpic, so pressure and temperature are changing in this expansion, but enthalpy stays constant.

Lastly, the way from point 4 to point 1 is another isobaric temperature change. In this section heat energy from the heat source is collected into the refrigerant. With this added heat energy in the system, refrigerant is turned into vapor and superheated to design temperature. After this step, the cycle starts again.

From knowing operational points 1 and 4 mass flow needed in the heat pump can be calculated with equation 15. In this calculation, it is assumed that energy from the wastewater heat exchanger is transferred without any losses in the middle cycle. Losses can be taken into account if they are determined to be influential to results. By knowing the mass flow of the refrigerant and conditions at points 2 and 3 total capacity of the heat pump can be calculated with equation 16.

$$q_m = \frac{P}{\Delta h} \tag{15}$$

$$q_{mE} = \frac{P_{he}}{\Delta h_E} = \frac{P_{he}}{h_1 - h_4}$$

$$q_{mE} = \frac{630kW}{409\frac{kJ}{kg} - 299\frac{kJ}{kg}} = 5{,}73\frac{kg}{s}$$

Where

q_m	Mass flow
E	Evaporator
h_1	Enthalpy at point 1
h_4	Enthalpy at point 4
P	Power
he	Heat exchanger

$$P = q_m(\Delta h) \tag{16}$$

$$P_{hp} = q_{mE}(\Delta h_C)$$

$$P_{hp} = 5{,}73\,\frac{kg}{s}\left(459{,}64\,\frac{kJ}{kg} - 299\,\frac{kJ}{kg}\right) = 920kW$$

Where

q_m	Mass flow
E	Evaporator
P	Power
hp	heat pump
C	Condenser
h_3	Enthalpy at point 2
h_4	Enthalpy at point 3

With these values, calculated quotations can be asked from different heat pump providers. The most important values for the providers to make quotations are the temperatures and flow rate for the heat source and the temperature of the usage. In addition to these values, it is important to know what is terminal temperature difference at the heat exchangers. Calculations shown here are done just for these values provided here, if some value is changed the results for whole calculations will change.

7 COST OF THE HEAT PRODUCTION

7.1 Quotations

For this case, budget quotations were asked from five Finnish companies that have done this kind of project in past. All companies were given the same assignment and the same values are shown in Table 1. When asking for budget quotations Project in this case has been split into three parts. These parts are wastewater side heat exchangers and heat pumps, piping and digging at the yard, and lastly heat exchangers for the hot side of the heat pumps. This split is done because the variability of the costs is mostly on the cold side and in heat-pump systems. Another reason for splitting the project in this way is to make the differences between systems clearer.

Table 1 Values given to heat pump providers

Wastewater in	Wastewater out	Flowrate of waste water	Heat user hot	Heat user cold
25	10	27	70	60

In quotations, the existing temperature is 10°C and not 5°C as in the calculations. This is chosen because the cost of recovering the last few °C is higher than the first degree. It is also wiser to leave some energy to wastewater as it leaves the possibility to invest in more capacity in the future and smaller systems have lower upfront investment costs. Offers from companies vary a bit, and that is why offers are used in the calculations as a whole. For evaluating differences inside of the offers split of costs by percentages is used, this way offers that came without breakdown item by item can be evaluated to other offers, and offers that have cost breakdown are not treated unfairly. Offers are split 23% of costs are for heat exchangers, 63% for heat pumps, and the rest 14% to other expenses including but not limited to control electronics, pumps, heat transfer fluids, and refrigerants. All offers are shown in Table 2.

Table 2 Offers from different companies, with values that are used in every case

		Company A	Company B,a	Company B,b	Company B,c	Company C	Company D
Design temperatures	°C	27/10	25/10	25/10	25/10	25/13	25/10
Volume flow rate	m³/h	30	27	27	27	30	27
Cooling power	kW	500	470	480	400	411	470
COP	-	2.71	2.7	2.9	3	2.66	3.20
Heating power	kW	792.4	746.5	732.6	600.0	659.0	685.0
Electrical power	kW	292.4	276.5	252.6	200.0	248.0	215.0
Price per kW heat	€/kW_heat	455.71	355.00	327.59	308.33	220.03	753.28
Heat exchanger (s)	€	83053	60950	55200	42550	33350	118680
Number	-	3	1	3	2	2	
Heatpump (s)	€	227493	166950	151200	116550	91350	325080
Number	-	6	1	3	2	1	
Other expences	€	50554	37100	33600	25900	20300	72240
Total variable costs		361100.00	265000.00	240000	185000.00	145000.00	516000.00

7.1.1 Company A

Offer from company A is built from several smaller heat pumps in series connection. These 6-pump series have a cooling power of 500kW. Heat exchangers in this case are three industrial-grade tube-type heat exchangers made out of AISI 316L alloy. This alloy should handle our wastewater well. Representatives of company A have addressed concerns about corrosion and fouling in an email conversation and company A knowhow from cases like this in past. Heat exchangers in this case are a closed system and can not be cleaned easily by brushes or other kinds of mechanical cleaning methods. The offer from company A has leeway in design power, it can be modified by adding or removing heat pumps from the system. Leeway in capacity is good at the start of the design phase as the optimal capacity can vary a bit at a closer look at the situation. Offer by the company is calculated by bit differing design values as the offer came before the writing of this work. After discussion with the representative of company A prices were updated to the current level, but machinery and design stayed the same, as the power is in range for the new parameters.

7.1.2 Company B

The offer from company B is one heat pump with one pipe-type heat exchanger. The cooling capacity on company B's offer is 470kW with a COP of 2.7. In this offer heat exchanger capacity is designed to be 130% of the heat exchange needed with given temperature values. The heat exchanger that company B is recommending for this case is easy to clean even mechanically although it is a pipe type of heat exchanger. Company B has experience in dealing with uncleaned wastewater as in this case. Company B is specialized in providing its customers with a custom solution for this kind of investment and that is why the offer is not split object by object but is one large solution.

Company B gave two more offers. To avoid confusion offers from company B are reported with ,a ,b ,c. Offer B has three heat exchangers with a total capacity of 135% of the theoretical minimum need. The total cooling capacity of the three heat pumps in offer b is 480kW with COP of 2,9. Offer c has two heat exchangers with a total capacity of 130% of the total heat transfer needed. This offer has two heat pumps with a cooling capacity of 400kW with COP of 3,0. Offers b and c from company B use the same machinery, but offer c has one less heat exchanger and heat pump. This makes offer c cheaper than other offers, but at the same time, heat saving potential is lower. Similarly, company A offering this possibility to upgrade the system might be beneficial as it leaves potential at a later time quite easily. Company B,c offer has the lowest electricity usage of all the offers. This makes green transitioning the lowest, but at same time the offer is lest affected by changes in electricity prices.

7.1.3 Company C

Offer from company C includes 2 heat exchangers for the evaporator side (wastewater) and one heat pump. These one heat pump systems rises concern that electricity connections currently present at the factory. A representative from company C confirmed that they can provide smooth start systems that lower the peak power needed at star. Company C offers a heat pump with a heating power of 659 kW and electricity power of 248 kW making cooling power 411 kW. COP of the heat pump is 2,66. The heat pump of company C uses a screw compressor and refrigerant R1234ze. Company C is done this kind of system in past and is confident that they can provide the right solution for this case. The brochure from company C has a lot of technical details that are important when projects like this go forward.

7.1.4 Company D

Offer from company D differs from other offers quite a lot, as the offer is for complete sett-up with building and other accessories provided by them. This makes the comparison between other offers harder and can skew evaluation. Company D can provide a custom system also, but the offer received for is for this case is plug in and play type solution. The solution has a heat pump with a cooling power of 470 kW and a heating power of 685 kW. With these values COP of the system is 3,2 and the electrical power is 215 kW. COP in this system is the highest of all the offers provided for the case. Company D's offer includes some filters and a 3m3 hot water tank. For closer comparison with other offers in later calculations offer of Company, D is reduced by 100 000€. This reduction is done after talking with the company D representative, but the real comparable price is very hard to know at this point. Without reducing some elements from offer D it would be much more expensive than others, but most of the increased costs come from differences in offer type and what is included. Like the other companies in this paper, company D has a lot of experience in doing heat recovery projects. Some of the experience is from heat recovery from industrial wastewater, so people at company D know the difficulties when working with uncleaned wastewater.

7.2 Non variable costs

Costs, in this case, can be split into two categories, variable and non-variable. Variable costs in this kind of project include all things mentioned in the quotations from the companies. Non-variable costs are costs that can be taught to be the same for every different set of variable costs. This is not completely true, as the pipe diameter, pump size, or some other parameters can change as the other systems change. To simplify things and compare what is the best setup of heat pumps and exchangers it is reasonable to assume some costs to be non-variable.In this case, non-variable costs are shown in Table 3. The secondary cycle is based on the piping costs of the primary cycle and an estimate from the heat exchanger selling company on how much heat exchangers for this kind of case would cost. Piping costs; digging and piping; installation and management costs are taken from the company A quotation that has these things included. Electrical work costs are taken from a conversation with the electrical manager at ViskoTeepak.

Table 3 Non variable costs in euros

Instalation and management	Piping	Digging and piping	Secondary heat exchangers	Secondary piping	Electrical work	Total non varible cost
70000	35000	55000	15000	35000	35000	245000

7.3 Enegy cost

The cost of heat and electricity is one of the biggest factor profitability of this kind of energy production project. Heat and electricity prices fluctuate a lot throughout seasons and years. This can make evaluating energy investments hard, as the profits are tied-up on market fluctuations going in the good direction. Fluctuations in prices make predicting profitability hard and most of the time number of different scenarios need to be evaluated to be certain enough about the future that a large amount of money can be tied up in investments. Energy prices are hard to predict in the far future because they are affected by policies and as the political landscape is always changing it is hard to know how the future is going to look.

In this case, heat is used internally, so the investment doesn't need to compete in selling heat to outside customers. In this case, the heating price is calculated to be similar to factory customers in the district heating system. Another way would be to compare heat produced in this way to wood chips or other fuels used in the energy sector. Comparison to fuel prices makes sense in cases where heat is produced to be sold to district heating or somewhere else, but in energy-saving cases, it makes more sense to compare to the current cost of heat bought from the market. In the evaluation of heat price data from Fortum is used Figure 13, and for finding how the price is changing internal data from ViskoTeepak is used to draw trend lines. To protect company data only the trend line is shown in this work Figure 14.

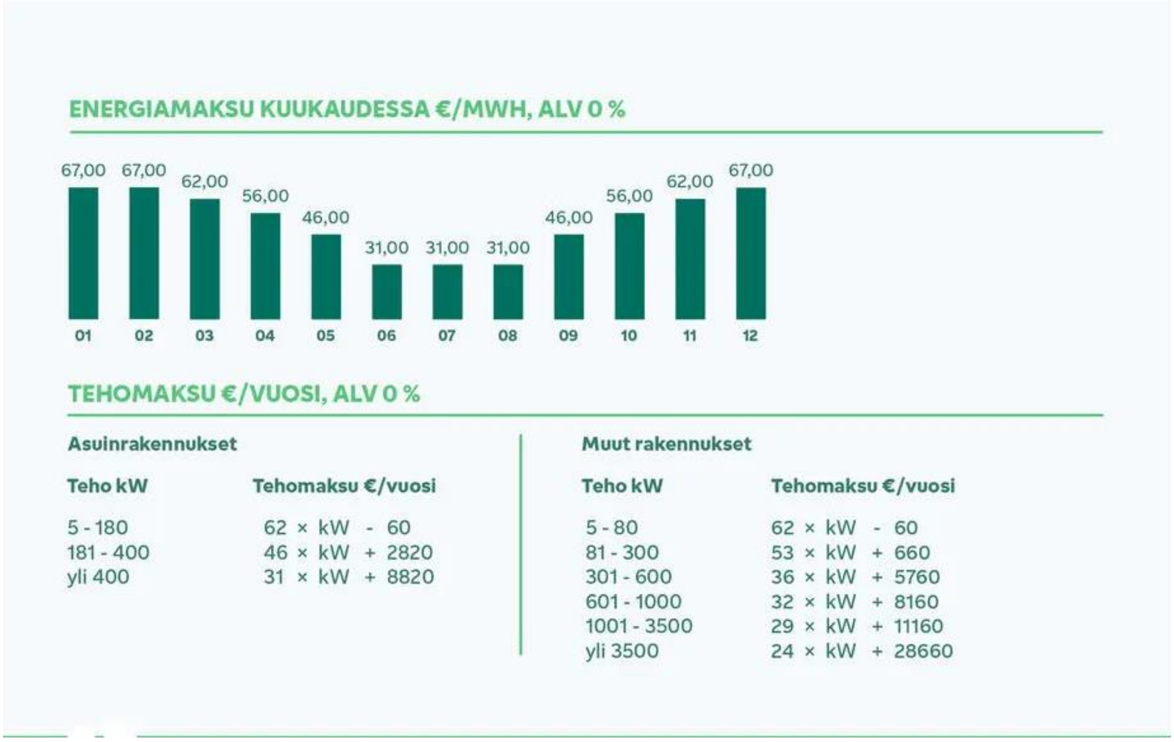

Figure 13 Price of heat in €/MW in 2021 from Fortum (source: Fortum 2022)

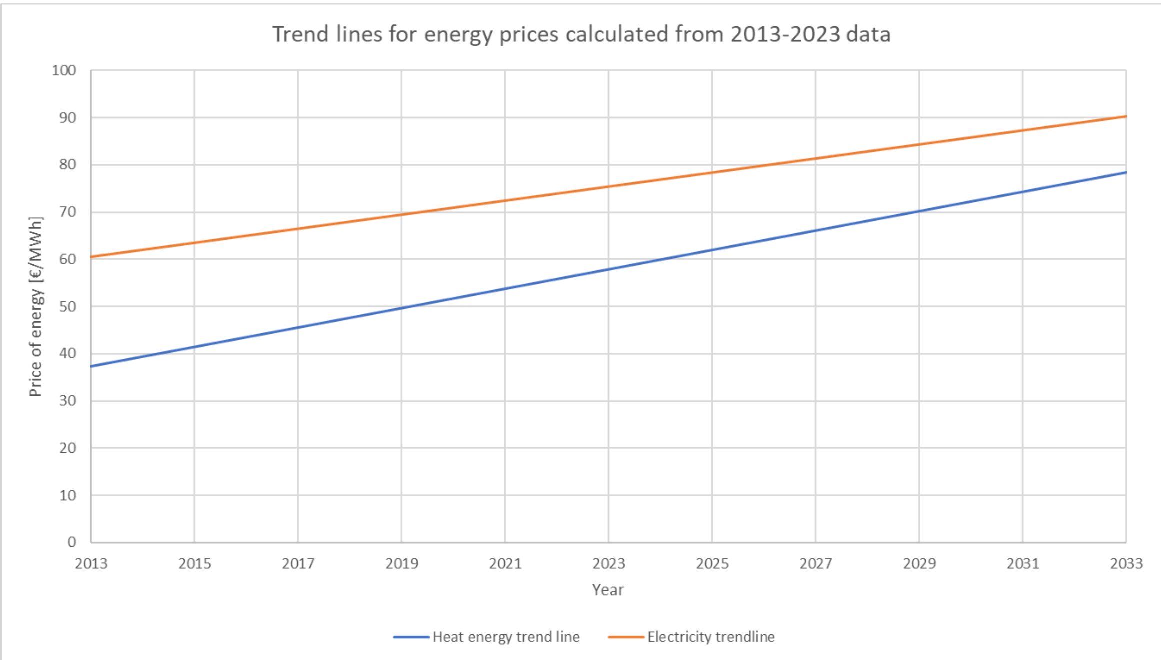

Figure 14 Energy prices trendlines calculated from 2013-2021 data.

Electricity price is another major influencer in how profitable heat pump-produced heating is. The price of electricity in the companion of heat pump investment cost and COP defines the price for heat produced. Electricity price in this case is taken from Nordpool data (Nordpool. 2022.), shown in Figure 15 and internal data shown in Figure 14. Similarly to heat price only trend lines are shown here from internal data.

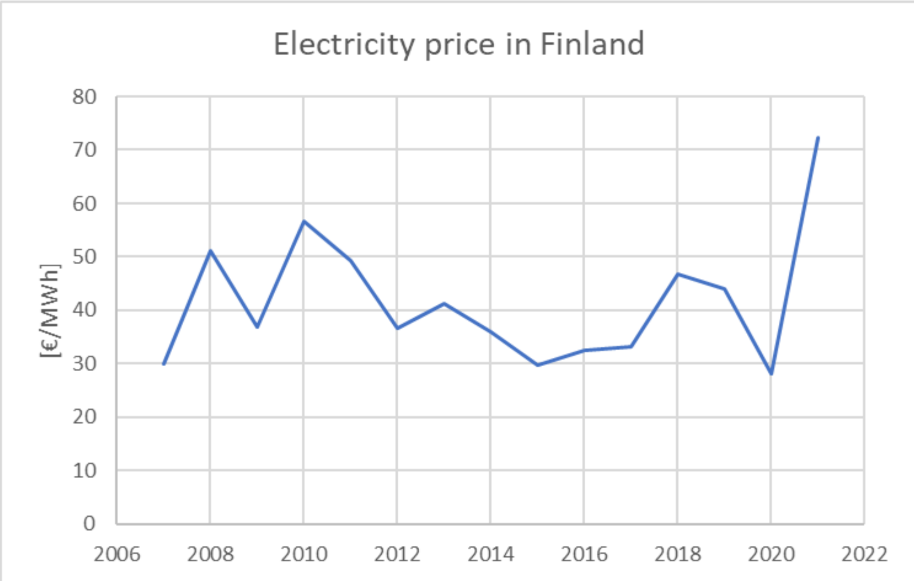

Figure 15 Electricity price (source: Nordpool. 2022.)

7.4 Calculating heat cost

Heat power for the heat pumps in the case can be calculated by using COP and cooling power. For calculating the heating power design flow rate and temperature are used because design values are chosen in a way that more than 90% is covered by full power usage. This can be seen from the duration curves shown in 6.1. Calculating the cooling load with equation 13 for a couple of days, for example, 4.12.2021, where temperature 24.7°C is under the design limit of 25°C and the flow rate is 31.4m3/h. Another example date is 7.8.2021, where the flow rate of 24.5m3/h is under the design value of 27m/h but in change temperature, 28.5°C is over the design value. In both, these example cases cooling power is higher than with the design value of 472,5 kW.

$$P_{cooling,1} = 8{,}72\frac{kg}{s} * 4{,}2\frac{kJ}{kg * k}(24{,}7°C - 10°C) = 538\ kW$$

$$P_{cooling,2} = 6{,}81\frac{kg}{s} * 4{,}2\frac{kJ}{kg * k}(28{,}5°C - 10°C) = 529\ kW$$

$$P_{cooling,normal} = 7{,}5\frac{kg}{s} * 4{,}2\frac{kJ}{kg * k}(27°C - 10°C) = 472{,}5\ kW$$

It needs to be noticed that in the summer of 2021 factory was run at a lower capacity which affected the water usage. In normal operation conditions flow rate should not be this low for longer times than repairs. In summertime have also the possibility to run out going water to a bit lower temperature, as the lowering of temperature doesn’t affect water treatment center operations at Hanko, as they can run the process at winter temperatures that are lower than lower design limit of 5°C. For example heat pump system provided by company A.

The cost for heat production can be calculated from COP and given cooling power equation 17. The cost of production is based on investment cost and the cost of electricity used to produce the heat. Electrical power can be calculated from the COP and cooling power or the difference between the heating and cooling power of the system equation 18. In this case profits for the system are also derived from the heating power and electrical power of the system equation 19. In this case, energy for the process is needed no matter what and wastewater is produced at a certain temperature. If it is possible to take some energy from the wastewater back to process at a lower cost than it is bought at the moment factory will save some money. This saving can be viewed as profit because it will lower the operating costs of the factory by the amount of the saving.

$$P_h = \frac{COP * P_c}{COP - 1} \quad (17)$$

$$P_{el} = \frac{P_h}{COP} = P_h - P_c \quad (18)$$

$$RE = (C_h * P_h - C_e * P_e) * t \quad (19)$$

Where

P_h	Heating power
P_c	Cooling power
P_e	Electrical power
C_h	Cost of heat
C_e	Cost of electricity
RE	Return on investment
t_o	Time in hours

By calculating the return on investment in this way different solutions from different providers can be evaluated against each other. Time in return calculations should be operation time in a year. In this case, uptime for the system is assumed to be 8750, so 10 hours of maintenance per year can be done without it effects on the viability of the investment.

8 VIABILITY OF THE SYSTEM

This chapter is about the viability of the system. To determine the viability of the system it is important to calculate how different things can affect viability. Viability is not simply one solution that fits every situation. Viability criteria can change between different projects or investments. Also, the political situation can move the goalpost for viability, as some policies can make some monetarily bad investments necessary in the future, for example, emission-lowering technologies are expensive, but not following the regulations can be even more costly. Also, that kind of regulated technologies can increase in price as the regulations come necessary.

8.1 Calculating viability

Viability for the investment, in this case, can be calculated by using the following equation 20 and 21. These equations take into account changes in energy prices in the useful life time of the system. Using these equations different scenarios for the future can be evaluated and in that way, some uncertainty about the viability can be eliminated.

$$RE_n = \sum_{n=1}^{n} \begin{pmatrix} (P_h * C_h * (100\% + i_h)^{(n-1)} \\ -P_e * C_e * (100\% + i_e)^{(n-1)} \end{pmatrix} * t_o * \frac{1}{(1+i)^n}) \tag{20}$$

$$NPV = RE_n - TC * (C_{inc} + 100\%) \tag{21}$$

Where

P_c	Cooling power
P_e	Electrical power
C_h	Cost of heat
C_e	Cost of electricity
i_h	Inflation of heat price
i_e	Inflation of electricity price
n	Lifespan
RE_n	Return on investment for lifespan
t_o	Time in hours
NPV	Net present value
TC	Total investment cost
C_{inc}	Increase in investment price

In this example calculation values are for one-year operations with the company A offer as the powers, and energy prices are taken from the historical data from Finland shown in 7.3. In this calculation, the heat and electricity price is without any inflation as the inflation terms are 0%. 8750 h/a is assumed to be a good estimation of operating time per year in normal conditions. This can be achieved because the flow rate and temperature range are calculated with maximizing operation time in mind, also heat exchangers for this case are selected minimizing maintenance needs in mind. In this example calculation, it can be seen that this investment with one-year operational lifespan would not be profitable as the result is negative.

$$RE_n = \sum_{n=1}^{1} \begin{pmatrix} 792kW * 0{,}052\frac{€}{kW} * (100\% + 0\%)^{(1-1)} \\ -292kW * 0{,}042\frac{€}{kW} * (100\% + 0\%)^{(1-1)} \end{pmatrix} * 8750h/a * \frac{1}{(100\% + 7\%)^{1}}) = 235415€$$

$$NPV = 235415€ - 606100€ * (0\% + 100\%) = -370685€$$

Net present value is chosen as the main investment profitability indicator, as it is easiest to incorporate inflation and other variables. Because net present value can have a lot of different variables calculated in, it can give good estimations of how profitably changes in different scenarios.

8.2 Sensitivity analysis

Currently, energy markets are on transitioning from fossil fuels to cleaner fuels. This transition makes estimating future energy prices very hard. As established earlier the energy price is one big factor in how profitable energy production is. Because of the large effect on profitability, a big part of the sensitivity analysis part is based on different energy price scenarios.

In this sensitivity analysis, the main factor for profitability is evaluated by calculating net present values with one changing variable. Effect on profitability is calculated as percentage change from the smallest variable if not stated otherwise. This way it is possible to get a grasp on how changing multiple variables simultaneously will affect. The calculation method is the same as in 9.1 with other variables, other than the one studied, as same as in 9.1. Figures in sensitivity analysis are produced from company A data and the same results are shown in the tables for other offers.

8.2.1 Effect of operating time

The effect of operating time is calculated with 20h steps. This step is chosen as it is close to one operating day and it can be viewed as two and a half maintenance breaks of eight hours each. For this review, zero point is full operating hours of 8760 h/a. Figure 16 shows that changes in operations makes linear change in profitability.

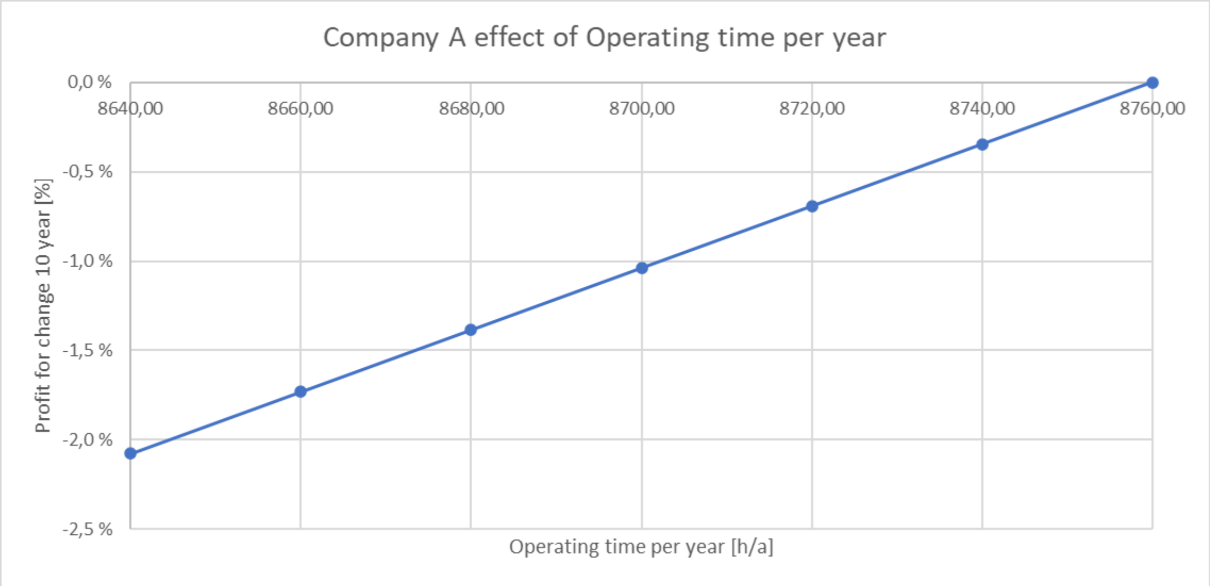

Figure 16 Effect of operating time to profitability

Table 4 shows that the effect over the life time of the system is relatively small around two percent or 20 to 25 thousand euros. This effect is a bit larger than maybe expected as the change of 120 hours of operating time is 1,4% but the change in profitability is around 2 percent. It is hard to conclude why there are differences between the companies. One reason for company D is the higher upfront investment cost, but for the others is difficult to give defined simple reasons. Table 5 shows that company B's offer b is the most profitable even if it would be operated 120 hours less per year than other options.

Table 4 Effect of operating time on profitability in euros

Operating time per year	8760	8740	8720	8700	8680	8660	8640	Change
Company A NPV	1172,24	1168,18	1164,12	1160,06	1156,00	1151,94	1147,88	-24,36
Company B,a NPV	1162,66	1158,84	1155,02	1151,20	1147,38	1143,56	1139,74	-22,91
Company B,b NPV	1204,56	1200,71	1196,85	1192,99	1189,13	1185,28	1181,42	-23,14
Company B,c NPV	971,35	968,15	964,95	961,76	958,56	955,36	952,16	-19,20
Company C NPV	1076,6	1073,3	1069,9	1066,6	1063,2	1059,9	1056,5	-20,09
Company D NPV	873,02	869,29	865,56	861,83	858,10	854,37	850,64	-22,38

Table 5 Effect of operating time on profitability percentage

Operating time per year	8760	8740	8720	8700	8680	8660	8640	Change
Company A NPV	0,0 %	-0,35 %	-0,69 %	-1,04 %	-1,39 %	-1,73 %	-2,08 %	-2,1 %
Company B,a NPV	0,0 %	-0,33 %	-0,66 %	-0,99 %	-1,31 %	-1,64 %	-1,97 %	-2,0 %
Company B,b NPV	0,0 %	-0,32 %	-0,64 %	-0,96 %	-1,28 %	-1,60 %	-1,92 %	-1,9 %
Company B,c NPV	0,0 %	-0,33 %	-0,66 %	-0,99 %	-1,32 %	-1,65 %	-1,98 %	-2,0 %
Company C NPV	0,0 %	-0,31 %	-0,62 %	-0,93 %	-1,24 %	-1,56 %	-1,87 %	-1,9 %
Company D NPV	0,0 %	-0,43 %	-0,85 %	-1,28 %	-1,71 %	-2,14 %	-2,56 %	-2,6 %

8.2.2 Energy costs

Heat and electricity prices are one of the biggest factors in any heat recovery project. In a heat pump system electricity is used to produce heat, so the ratio of heat price to electricity price, starting prices, and how the prices change over time. Historically heat to electricity ratio has been about 0,7 when the electricity tax and other expenses are taken into account, but in the baseline scenario, the ratio is 1,23. This can skew the results a bit when reviewing different starting values for prices. Figure 17 shows how the heat and electricity price ratio affects profitability. Without inflation, every offer is unprofitable if electricity is twice as expensive as heat. Currently global energy market is in a situation where it is possible that electricity could be twice the price of heat, but this calculation assumes that the price ratio is the same for the whole lifespan of the system. Table 6 shows the monetary values for every offer and can be used to interpolate a better estimate of the profitability breakpoint than the Figure 17.

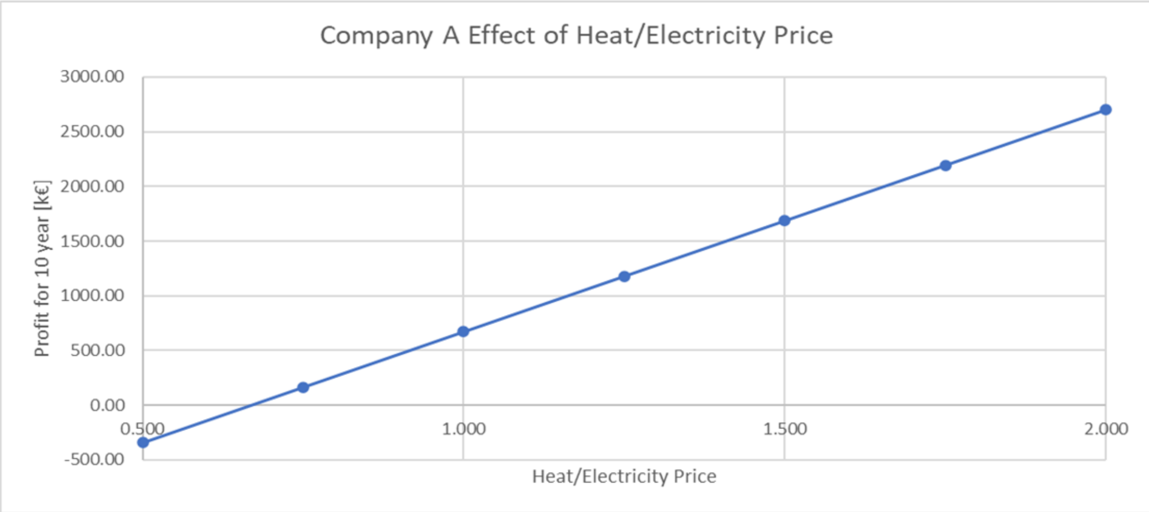

Figure 17 Effect of heat to electricity ratio on profitability

Table 6 Effect of heat to electricity ratio on profitability in euros

Heat/Electricity Price	0.50	0.75	1.00	1.25	1.50	1.75	2.00	Change
Company A NPV	-340.61	166.07	672.74	1179.42	1686.10	2192.78	2699.45	3040.06
Company B,a NPV	-262.51	214.80	692.11	1169.42	1646.73	2124.04	2601.35	2863.86
Company B,b NPV	-194.23	274.23	742.69	1211.15	1679.61	2148.07	2616.54	2810.77
Company B,c NPV	-174.23	209.42	593.08	976.73	1360.38	1744.04	2127.69	2301.92
Company C NPV	-181.5	239.8	661.2	1082.6	1504.0	1925.3	2346.7	2528.28
Company D NPV	-434.89	3.11	441.11	879.12	1317.12	1755.13	2193.13	2628.03

Price increases or price inflation can affect the viability of long-term investments as the changes from inflation are small in short term but compound in long-term situations. Figure 18 shows that changes in electricity inflation linearly change the profitability. Changes in inflation have a bigger effect on profitability than a similar-size change in operating time, so it is more important to get electricity inflation estimation right than operational time. Electricity prices have historically been very volatile and it is hard to find a clear trend in the price. For the last 10 years, electricity prices have increased by around 2%.

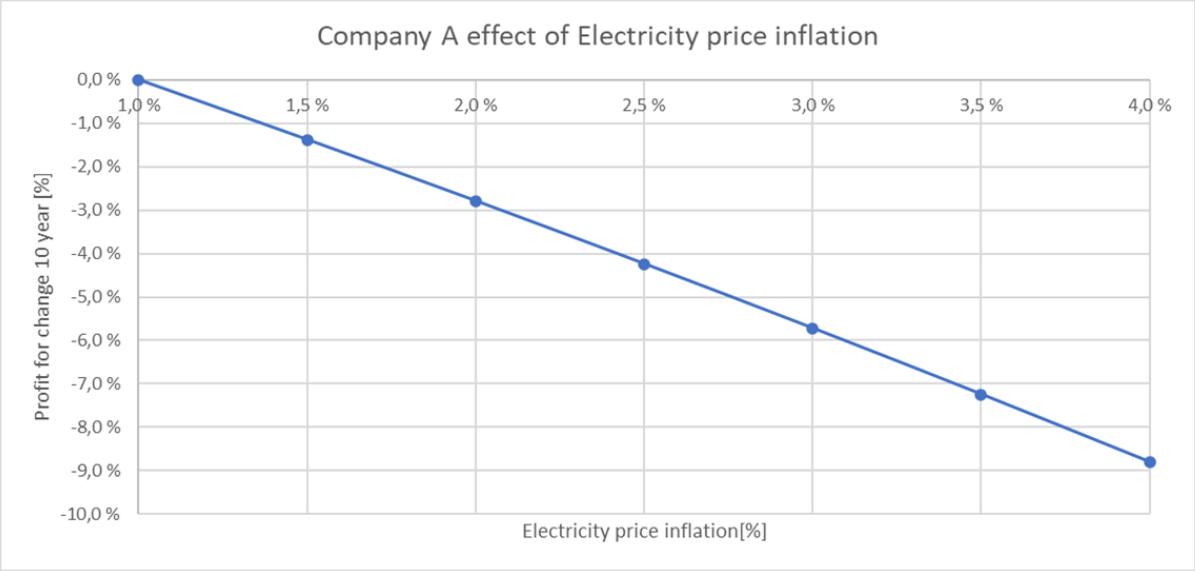

Figure 18 Effect of electricity price inflation on profitability

Tables 7 and 8 show that a 3% change in the inflation rate of electricity can lower the profitability up to 8.8% or 100 000€. In this review difference between the least and most affected offers is 1,57%. This difference is more than the effect of a 0,5% change in the inflation rate. In this review company, B's offer b is the second least affected and is the most profitable throughout the review. As the effect of this offer is less than to second most profitable company A offer the difference between these two offers increases when the inflation rate raises. Company A offer is the most affected by changes in the electricity inflation rate. A big factor in how electricity price change affects different offers is the COP and electrical power. Because Company A offer has the biggest electrical power and relatively low COP it is affected a lot. Company B offer b and company C offers have similar electrical power, but the COP difference explains the difference in the result.

Table 7 Effect of electricity price inflation on profitability in euros

Electricity price inflation	1.0 %	1.5 %	2.0 %	2.5 %	3.0 %	3.5 %	4.0 %	Change
Company A NPV	1139.95	1124.24	1108.14	1091.63	1074.70	1057.35	1039.56	-100.39
Company B,a NPV	1132.13	1117.28	1102.06	1086.45	1070.44	1054.03	1037.21	-94.93
Company B,b NPV	1176.49	1162.92	1149.01	1134.74	1120.12	1105.12	1089.75	-86.74
Company B,c NPV	949.06	938.31	927.30	916.01	904.43	892.56	880.39	-68.67
Company C NPV	1049.3	1035.9	1022.3	1008.3	993.9	979.2	964.1	-85.15
Company D NPV	848.91	837.36	825.52	813.38	800.93	788.17	775.08	-73.82

Table 8 Effect of electricity price inflation on profitability in percentage

Electricity price inflation	1,0 %	1,5 %	2,0 %	2,5 %	3,0 %	3,5 %	4,0 %	Change
Company A NPV	0,0 %	-1,38 %	-2,79 %	-4,24 %	-5,72 %	-7,24 %	-8,80 %	-8,8 %
Company B,a NPV	0,0 %	-1,31 %	-2,66 %	-4,03 %	-5,45 %	-6,90 %	-8,38 %	-8,4 %
Company B,b NPV	0,0 %	-1,15 %	-2,33 %	-3,55 %	-4,79 %	-6,06 %	-7,37 %	-7,4 %
Company B,c NPV	0,0 %	-1,13 %	-2,29 %	-3,48 %	-4,70 %	-5,95 %	-7,23 %	-7,2 %
Company C NPV	0,0 %	-1,27 %	-2,57 %	-3,90 %	-5,27 %	-6,67 %	-8,11 %	-8,1 %
Company D NPV	0,0 %	-1,36 %	-2,75 %	-4,18 %	-5,65 %	-7,15 %	-8,69 %	-8,7 %

Similarly to electricity price inflation, heat price inflation is hard to predict. According to (Tilastokeskus 2022) price of wood chips has been very constant throughout the 2010's so the price increases come from heat production. This makes estimating future prices hard because there is not of data on where to conclude as the price is negotiated case by case bases between the user and supplier. From trend-line data an 8.3 estimation of 4.5% average price increase can be calculated, this is higher than the normal inflation rate of 2%. Because normal inflation is around 2% viewed range, in this case, is from 1% to 4%. Similarly to electricity increase in the inflation rate affects the profitability linearly, so other scenarios are simple to calculate. Increases in heat price make the investment more profitable as the saving are greater. This effect is shown in Figure 19.

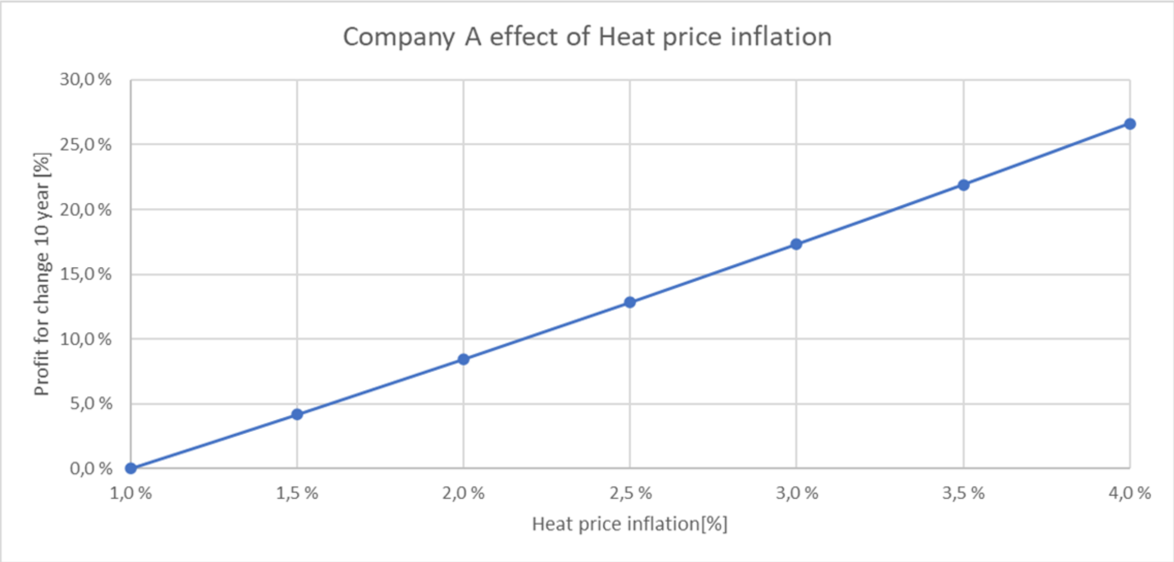

Figure 19 Effect of heat price inflation on profitability

Table 9 and table 10 show that a 3% change in heat price inflation changes profitability between 250 000€ to 338 000€ or 24% to 31%. The largest percentage change is on company D's offer. Even if the percentage change is large the largest euro change is in the company A offer. When heat inflation is the only variable that changes Company A offer the best if the inflation rate is 4% or more. In this situation correlation between heat power and increases in profitability can be drawn as companies A and B offer have large heat powers and higher change than company C or company B offer c.

Table 9 Effect of heat price inflation on profitability in euros

Heat price inflation	1.0 %	1.5 %	2.0 %	2.5 %	3.0 %	3.5 %	4.0 %	Change
Company A NPV	1272.34	1325.35	1379.70	1435.43	1492.56	1551.14	1611.19	338.85
Company B,a NPV	1256.96	1306.90	1358.10	1410.59	1464.41	1519.59	1576.17	319.21
Company B,b NPV	1297.06	1346.08	1396.33	1447.85	1500.67	1554.83	1610.36	313.29
Company B,c NPV	1047.09	1087.23	1128.38	1170.57	1213.84	1258.19	1303.66	256.58
Company C NPV	1159.9	1204.0	1249.2	1295.5	1343.0	1391.7	1441.7	281.81
Company D NPV	959.45	1005.27	1052.25	1100.43	1149.81	1200.45	1252.37	292.92

Table 10 Effect of heat price inflation on profitability in percentage

Heat price inflation	1,0 %	1,5 %	2,0 %	2,5 %	3,0 %	3,5 %	4,0 %	Change
Company A NPV	0,0 %	4,16 %	8,43 %	12,81 %	17,30 %	21,90 %	26,62 %	26,6 %
Company B,a NPV	0,0 %	3,97 %	8,04 %	12,22 %	16,50 %	20,88 %	25,38 %	25,4 %
Company B,b NPV	0,0 %	3,78 %	7,65 %	11,62 %	15,69 %	19,86 %	24,14 %	24,1 %
Company B,c NPV	0,0 %	3,83 %	7,76 %	11,79 %	15,92 %	20,15 %	24,49 %	24,5 %
Company C NPV	0,0 %	3,80 %	7,70 %	11,69 %	15,78 %	19,98 %	24,29 %	24,3 %
Company D NPV	0,0 %	4,77 %	9,66 %	14,68 %	19,82 %	25,10 %	30,50 %	30,5 %

8.2.3 Effect of changes in internal interest rate

Interest rate plays a big role in investment calculations as small changes make large differences in profits. Although the effect of a 1% change in interest rate has less effect than a 1% change in heat inflation it is more likely that interest rate changes in large amounts than average inflation changes. Figure 20 shows that changes in interest rates do not have a linear result. The change from 5% to 6% has an impact of 6,79% but the change from 10% to 11% has the result of 4,79%. Internal interest rate is most of the time constant for a long time, but uncertainty in investment markets or investment that is considered to be risky can affect the calculated interest rate.

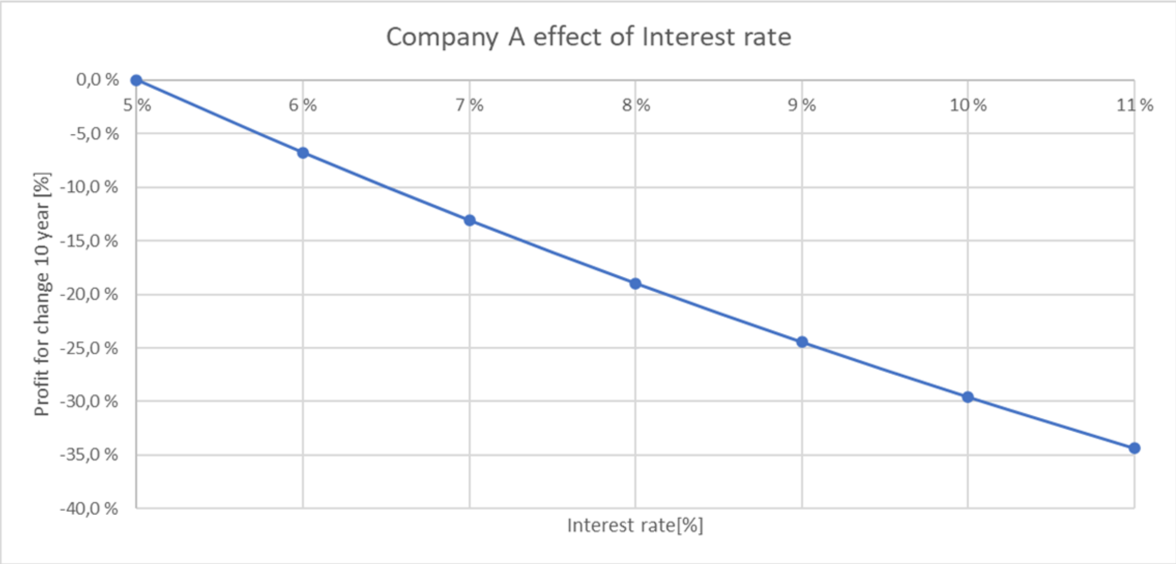

Figure 20 Effect of internal interest rate on profitability

Table 11 and Table 12 show that a 6% change in interest rate has an effect ranging from 365 000€ to 463 000€ or 31,3% to 41,2%. Company c has the lowest percentage change between the best and the worst case, it also has the second lowest euro change of all the offers. Company A has the highest euro change and company D has the largest percentage change. Company B's offer b is the most profitable throughout the calculation. Company b offer a is more profitable than company A offer when the interest rate is 10% or higher. Increases in the interest rate seem to affect offers that have the highest upfront cost the most, as offers C and B,c are the cheapest and have the lowest change in the other hand offers A and D are the most expensive ones and have the highest chance.

Table 11 Effect of internal interest rate on profitability in euros

Interest rate	5 %	6 %	7 %	8 %	9 %	10 %	11 %	Change
Company A NPV	1346.78	1255.31	1170.21	1090.92	1016.97	947.90	883.33	-463.45
Company B,a NPV	1326.82	1240.79	1160.75	1086.17	1016.61	951.65	890.91	-435.91
Company B,b NPV	1370.39	1283.49	1202.64	1127.31	1057.04	991.42	930.07	-440.32
Company B,c NPV	1108.89	1036.82	969.75	907.28	849.00	794.57	743.69	-365.21
Company C NPV	1220.5	1145.1	1074.9	1009.5	948.5	891.6	838.3	-382.21
Company D NPV	1033.39	949.35	871.16	798.30	730.35	666.89	607.55	-425.84

Table 12 Effect of internal interest rate on profitability in percentage

Interest rate	5 %	6 %	7 %	8 %	9 %	10 %	11 %	Change
Company A NPV	0,00 %	-6,79 %	-13,11 %	-19,00 %	-24,49 %	-29,62 %	-34,41 %	-34,4 %
Company B,a NPV	0,00 %	-6,48 %	-12,52 %	-18,14 %	-23,38 %	-28,28 %	-32,85 %	-32,9 %
Company B,b NPV	0,00 %	-6,34 %	-12,24 %	-17,74 %	-22,87 %	-27,65 %	-32,13 %	-32,1 %
Company B,c NPV	0,00 %	-6,50 %	-12,55 %	-18,18 %	-23,44 %	-28,35 %	-32,93 %	-32,9 %
Company C NPV	0,00 %	-6,18 %	-11,93 %	-17,29 %	-22,28 %	-26,95 %	-31,31 %	-31,3 %
Company D NPV	0,00 %	-8,13 %	-15,70 %	-22,75 %	-29,33 %	-35,47 %	-41,21 %	-41,2 %

8.3 Energy scenarios

As the future in the energy sector is hard to predict, some scenarios are shown here so it is easier to make informed decisions if the risk in the project is manageable. The scenarios shown in Table 13 are constructed from the baseline values that are used in the sensitivity analysis and also from the energy prices from ViskoTeepak. Scenarios are calculated using the net present value method, with a ten-year useful lifetime. Inflation rates are estimations around the most likely case that are possible.

For the baseline scenario inflation rates are estimated to be similar to overall inflation in long term. In the baseline scenario, the operational time is 8750 to accommodate ten hours of maintenance per year. According to all the system suppliers, this operating time should be possible. The interest rate is 7% in this scenario because it is the normal calculation interest rate for this kind of investment.

In the most likely scenario inflation rates are the same as the average inflation rate at energy prices at ViskoTeepak in the 2010s. In this scenario, energy prices for the first year are the same as the real prices in 2021. The internal interest rate has been 6,5% can be estimated as the calculation show good potential for this kind of investment and interest in green investments are on the rise. Currently, system suppliers predict that the investment prices will increase next year from 10% to 20%. For this scenario lower estimate of 10% is used as it seems more likely than the higher estimate. A more conservative estimation of operating time is smart as it includes other possible timing for maintenance or some other unexpected stoppage, although the effect of lowering operating time is quite small as established in 8.2.1.

Scenario very good is constructed by moving all the parameters a bit in the good direction. This scenario should be possible, but unlikelier than the most likely scenario. In this scenario, the heating price is the same as in the other scenarios, because it is very stable apart from the source. Electricity price is a bit lower than in other cases as 2020's electricity price has been higher than before and can be lower in the future. The interest rate is lower two percent lower than in the baseline scenario as the interest rate can be a bit lower for some investments if the investment is viewed to be safe. Inflation rates are pushed around 1,5% towards profitability. This is done because electricity price inflation can lower in the future if the market stabilizes. Heat price inflation can go higher than historically it has been if, for example, taxation of heat from burning has risen. In this scenario, investment price is lowered by 5%, because market prices in 2022 have been very high and when global situations stabilize, prices can return to more normal levels. A 5% percentage price reduction is a conservative estimate as some prices have increased more than 15% in 2022 alone.

A very bad scenario is the opposite of a very good scenario. In this scenario main idea is to move every parameter a bit to lower profitability direction. The changes in this scenario are modest and possible. The interest rate of 8% is a bit higher than normal but is possible if the investment is considered to be risky, as the interest rate is affected by how risky the lender thinks the investment is. Electricity price inflation is considered to be 5% in this scenario. This is high inflation, but possible as the world is moving more towards clean electricity, mostly from wind and solar, making the market more volatile. Heat inflation is 1%, which is low, but the price of wood chips is very stable, so it is possible that heat prices can also stay close to stable. In this scenario investment prices increase by 15%, as stated earlier this is possible in near future, as the market is unstable. Operating time in this scenario is lower than in others. The operating time for this scenario is chosen in a way that there is a bit more room for maintenance. Fouling of the heat exchangers is a concern in this case and it needs to be taken into account and easiest way is to calculate more maintenance time.

With the last scenario named a bit bad the parameters are changed a bit towards lesser profits. This scenario should be more likely than the very bad scenario, but less likely than the most likely case. In this case, the heat starting price is kept as same as in previous scenarios, because the heating price is quite stable. Energy inflations are in the between baseline and a bad scenario. For his scenario investment price increase is 10%, because it is likely to happen and it is also between baseline and bad scenario, same explanation is for the operating time in this scenario.

Table 13 Energy scenarios

Case		Baseline	Most likely	Very Good	Very Bad case	A bit bad
Eletricity price	€/kW	0,042	0,072	0,062	0,095	0,075
Heat price	€/kW	0,052	0,054	0,054	0,054	0,052
Disconting	%	7,0 %	6,5 %	5,0 %	8,0 %	7,0 %
electricity inflation	%	2,0 %	2,2 %	1,0 %	5,0 %	3,0 %
Heat inflation	%	2,0 %	4,5 %	6,0 %	1,5 %	3,0 %
Investment price increase	%	0,0 %	10,0 %	-5,0 %	15,0 %	10,0 %
Operating time	h/a	8750	8740	8755	8720	8730
Case		Baseline	Most likely	Very Good	Very Bad case	A bit bad
Company A NPV	k€	1318	1097	1859	-34	657
Company B,a NPV	k€	1299	1095	1805	31	681
Company B,b NPV	k€	1343	1185	1868	175	782
Company B,c NPV	k€	1086	969	1528	153	640
Company C NPV	k€	1197	1014	1633	70	647
Company D NPV	k€	1007	875	1547	-46	503
Change to baseline	%					
Company A NPV	%	0,0 %	-16,7 %	41,1 %	-102,6 %	-50,1 %
Company B,a NPV	%	0,0 %	-15,7 %	38,9 %	-97,6 %	-47,6 %
Company B,b NPV	%	0,0 %	-11,7 %	39,1 %	-86,9 %	-41,7 %
Company B,c NPV	%	0,0 %	-10,8 %	40,8 %	-85,9 %	-41,0 %
Company C NPV	%	0,0 %	-15,3 %	36,5 %	-94,1 %	-45,9 %
Company D NPV	%	0,0 %	-13,0 %	53,6 %	-104,6 %	-50,0 %

9 RESULTS

The main finding, in this case, is that the project is profitable with the assumptions made here and by using the calculation values provided in this text. Results may change in the future, as more knowledge about the case can be collected. Results apply only to these values provided in this text.

Table 14 shows a few different calculation methods to give an idea about the profitability of the system. These results are calculated by using values of the previously mentioned most likely scenario with 8750 h/a operating times and zero percent increase in investment cost. Using these values gives the best estimate of how the investment will perform.

Table 14 Results on investment calculations

		Company A	Company B,a	Company B,b	Company B,c	Company C	Company D
Design temperatures	°C	27/10	25/10	25/10	25/10	25/13	25/10
Volume flow rate	m³/h	30	27	27	27	30	27
Cooling power	kW	500	470	480	400	411	470
COP	-	2,71	2,7	2,9	3	2,66	3,20
Heating power	kW	792,4	746,5	732,6	600,0	659,0	685,0
Electrical power	kW	292,4	276,5	252,6	200,0	248,0	215,0
Price per kW heat	€/kW_heat	455,71	355,00	327,59	308,33	220,03	753,28
Total variable costs	k€	361,1	265	240	185	145	516
Total non varible cost	k€	245	245	245	245	245	245
Total	k€	606,1	510	485	430	390	761
NPV simple 7,0236	k€	1054,00	1051,45	1092,23	878,18	979,09	764,38
NPV	k€	1159,61	1148,30	1235,73	1013,56	1054,4	953,45
Payback periode	a	3,44	3,08	2,79	2,94	2,71	4,35
AN 0,1424	€/a	90,00	92,86	104,49	85,01	88,22	66,53
Rate of return	%	19,09	22,45	25,78	24,01	26,86	12,98
Average rate of return	%	38,17	44,89	51,56	48,01	53,72	25,96
NPV per kW cooling	k€/kWh	2,32	2,44	2,57	2,53	2,57	2,03
NPV per kW heating	k€/kWh	1,46	1,54	1,69	1,69	1,60	1,39
NPV per kW Electrical	k€/kWh	3,97	4,15	4,89	5,07	4,25	4,43
Operational time	Investment price increace	Electricity price	Heat price	Electricity infla	Heat inflation	Keep time	Interest rate
8750 h/a	0 %	0,072 €/kWh	0,054€/kWh	2,2 %	4,5 %	10 year	6,5 %

Table 14 shows that offers company B,b, company B,c, and company C performs fairly equally when looking rate of return or payback period. This gives the knowledge that these three investment possibilities are of similar value when profits are valued against investment costs. This is a good way to evaluate investment if the main point is to make the most efficient use of invested money. Another way to evaluate different systems is to calculate the net present value per energy capacity. This way the previously mentioned three are the best option. Company B offers c the best value per kW of electrical power. When looking results from the cashflow-based results, it shows that company B offer b performs the best, so if the most important thing in the investment is absolute cashflow company B offer b is the best.

9.1 Sensitivity analysis results

Sensitivity analysis shows that the effect of operating time per year is not very large for the total profitability of the case. This lowers the risk of fouling in heat exchangers as cleaning more often doesn’t make the investment unprofitable very easily. As the operational time is not the most impactful for total the investment, so estimate how much time needs to be accounted don’t need to be the most accurate one.

Changes in interest rates can affect profitability by large amounts. This makes getting this assumption more important than the operating time assumption. Fortunately, the internal interest rate is quite stable for longer periods and can be considered as a helper for the calculations and that way is not so connected to market situations. The risk of changing the interest rate is also predictable because interest rates don’t change very quickly even when global situations are in change.

Inflation is one of the hardest to predict. This is because energy prices have historically been volatile with the changes. Fortunately, inflation in heat price is about three times as effective per percentages of change. A change of a few percent is possible for both energies, but a change of two percent won't make the investment non-profitable. Predicting inflation is hard because it is linked to global situations. It is hard to predict also because the inflation rate is always changing, so calculating with the model that assumes the inflation to stay constant over long periods can and will have some errors.

Sensitivity analysis shows that company B offer b performs excellently in different situations. This offer is affected quite little by changes that hurt the viability of the investment. This makes company B's offer safer than competing offers that have greater changes in the same scenarios. Percentage changes in some cases are better for other offers, but when calculating euros company B's offer b performs the best. Offers companies A and B,b are also performing well in the sensitivity analysis. Company B offer c and company C offer are also performing well, but are worse than previously mentioned ones. From the options shown in this text, with the values, in this case, the offer b from company B can be recommended as the main solution for this case.

9.2 Results from the energy scenarios

The results from this study are shown in Table 13. The results are shown monetarily and in percentage change to the baseline scenario. Monetary results are color coded for ease of use. In this case, the results show that monetarily company B's offer b is the most profitable over the ten years. The offer from company A and the offer from company B are quite close, the difference is about 50 000 euros or about 3% for lifespan, in value for scenarios baseline and very good. In the most likely scenario, the difference is a bit clearer about 100 000€ or 8%. In a very bad scenario company, A offers and company D's offers are not profitable.

Percentage change for company B offer c is the best in all scenarios apart from the very good scenario, where company D offer increases most, meaning the change is largest when profitability increases and lowest when profitability decreases. Changes between company B offers b and c are very closely matched. Company A offer and company D offers have the largest bad changes, but also the largest change towards higher profitability.

From the energy scenarios conclusion can be drawn that company B offer b is the best-performing one. This offer is very stable throughout the scenarios and makes a good profit. An important point learned from this scenario study is that company B's offer b is profitable when the scenario is bad and some other offers are not profitable. Company C's offer is also very good and performs well in the study, but it is not quite as effective as company B's offer B. Company C's offer is cheaper than company B's offers should be considered.

10 CONCUSION

The energy sector in Finland is currently going through great change, as the environmental legislation is tightening, and companies need to lower emissions. This new direction needs some new investments in clean energy and one good way to lower the losses that happen in the process. This thesis is based on the idea of minimizing heat losses from wastewater.

Theory in this case is about heat pump technology currently in similar situations. The focus on heat pump theory is at a higher temperature range, as the most probable heat usage in the factory is at around 70°C. In this theory part, different types of heat pumps are discussed. The second theory part goes through similar systems in Finland currently. Comparison to other similar systems is hard as all known systems, as the other facilities are larger and use cleaned wastewater. The third theory part is about investment calculation. This is an important theory, which makes it easier to understand the later chapters and how the profitability is calculated.

The case part is about a possible heat recovery system at the ViskoTeepak Hanko factory. This system is restricted by heat in the wastewater and how much can be recovered without hurting the wastewater treatment center in Hanko. With the usage of duration curves and knowledge from the wastewater treatment center, it was decided that 15°C is the largest amount of heat that can be recovered from the water constantly over the seasons. The flow rate of the wastewater is around $30 m^3/h$, system is designed at a bit lower point of $27 m^3/h$ as seasonal variation can lower the flow rate to this level.

To make a comparison and evaluation as accurate as possible quotation from four Finnish companies was asked. These quotations were asked with the same values given to all companies, but there was some variation between the offers. The cooling power of these offers ranged from 400 kW to 500 kW. Costs, in this case, are divided into two categories: variable costs which include heat pumps, wastewater heat exchanges, and components needed to operate these parts, and non-variable costs which can be used for all the systems for simplicity. These cost account for piping, project management, groundwork, and electrical work. By calculating different scenarios for the future it is determined that in normal scenarios all of the offers are profitable, but in a situation where a lot of things go badly some offers are not profitable and the rest of the offers are a little bit profitable. With sensitivity analysis and the energy scenario analysis company B offer b is the best offer. Before this project can go forward it is important to refine some assumptions for the example end user for the heat is not clear and can bring some extra non-variable costs. The possibility for a smaller heat recovery system should also be studied as other energy-saving projects can affect the wastewater temperature of mass flow and those will affect the total amount recoverable heat, so in long term, it might be more profitable to invest in a smaller system that can operate on full power in the future.

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