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Feasibility Analysis of Industrial Heat Pumps Application for Waste Heat Recovery

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The purpose of this Bachelor's thesis was to analyze the feasibility of using a heat pump to solve a problem of waste heat recovery in the industrial sector. Furthermore, the aim of the thesis was to provide the case company with practical instructions for checking the suitability of a heat pump at the early stages of any project.

For achieving the aim, the research included an investigation of the theoretical background of the topic, as well as two case studies. Additionally, invaluable information was given by experts familiar both with the topic, the study, and the case studies. Moreover, interviews with companies producing heat pumps were an essential part of the research.

The result of the thesis was an analysis determining the suitability of a heat pump application in different industrial factories. It can be applied in further research to solve waste heat recovery problems with the help of a heat pump.

Keywords	heat pump, industrial sector, waste heat, waste heat recovery.

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Contents

List of Abbreviations

COP	Coefficient of Performance
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning

1 Introduction

Sustainable development has become an essential factor in present days. Society has started to realize the actual meaning of sustainability and the positive impact of it. [1.] Already in 1987, a clear definition of sustainability was given by G. Brundtland. According to her, sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". [2, p. 169.]

Sustainable development is a complex system that includes three essential aspects: society, economy, and environment. The environment has to be fully functioning, and all possible harmful effects on the environment should be minimized. The society should focus on health, safety, opportunities, and other essential factors supporting a high quality of life. The economic factor includes cost and production efficiency with an appropriate use of resources. Figure 1 illustrates the connections between the factors. A proper collaboration of these aspects can help to move the society towards sustainable development. The figure below represents the importance of cooperation of the different aspects of sustainable development, none of which can be left out for improving sustainability. [1.]

Figure 1. Sustainable development [3, p. 5]

Sustainable development is an important factor influencing the implementation of new solutions in different fields, such as construction, technologies, and manufacture. These fields are a part of the industrial sector that includes the production of services. The industrial sector is the largest energy consumer. As a consequence, it is essential to improve the sustainability of the industrial sector mainly by implementing solutions to reduce the use of energy. By reducing energy consumption, the industrial sector can decrease its harmful effect on the environment from emissions, as well as improve the cost and energy efficiency of the sector. [4.]

A major problem in the industrial sector seems to be waste of heat released from industrial processes. This thesis explores and suggests a solution for the waste heat recovery problem in the industrial sector. The idea focuses on the possibility of using a heat pump in heating and cooling systems to decrease the release of waste heat and to improve the energy efficiency of the sector. The solution can develop the sustainability of the industrial sector.

This study concentrates on the feasibility of a heat pump application in different industries. The research includes two case studies that explore the different conditions of using a heat pump for improving waste heat recovery. Each case is an existing project of a case company in paper and food industries. Some information about the case studies is confidential, and, as a result, a detailed description of an industrial process may be absent in the research. The objective of this thesis is to provide Pöyry Finland Oy with practical instructions for a feasibility analysis of a heat pump application at the beginning of any industrial project. Pöyry Finland Oy is a consulting company in the engineering field focusing on the industrial sector. The final project is done for the Industrial Heating, Ventilation, and Air Conditioning (HVAC) department, which is searching for sustainable solutions in the industrial sector.

The thesis contains six chapters. The first chapter is an introduction to the importance of sustainability in the industrial sector, and also includes objectives of this research and briefly introduces Pöyry Finland Oy. The second chapter explains the connection between sustainability and energy consumption. Additionally, the second chapter describes the impact of waste heat on energy consumption. The third chapter demonstrates the heat pump as a solution for the problem of waste heat recovery that can also improve sustainability, Moreover, important features of the heat pump are also discussed in the chapter, including its advantages and disadvantages. The fourth chapter introduces a way to analyse the suitability of a heat pump application for a factory or a plant. It shows that a short analysis of heating and cooling demand gives a clear understanding about the options for heat pump implementation on a factory or a plant. The fifth chapter introduces a manufacturing company and two case studies. The manufacturing company introduced some products suitable for the industrial sector. These products were implemented in two case studies based on an analysis of heating and cooling demands. That last chapter is a conclusion to the research.

2 Industrial Waste Heat

2.1 Energy Consumption in the Industrial sector

The industrial sector accounts for 35% of the global energy consumption. Moreover, around 30% of the global greenhouse gas emissions are produced by industries such as paper, chemicals, and steel. Therefore, one of the main routs towards sustainability is energy efficiency. [4.]

Figure 2 below illustrates the energy consumption of various industries in European countries. Paper, steel, iron, chemical, and non-metallic mineral factories are the main energy consumers in the industrial sector. Energy saving solutions for these industries is highly important because of their high energy consumption. The energy saving have an influence not only on the reduction of energy consumption but also on the economic feasibility and the reduction of harmful impacts on the society and the environment. As a consequence, the industrial sector moves towards sustainability by improving energy efficiency. [5, pp. 52-55.]

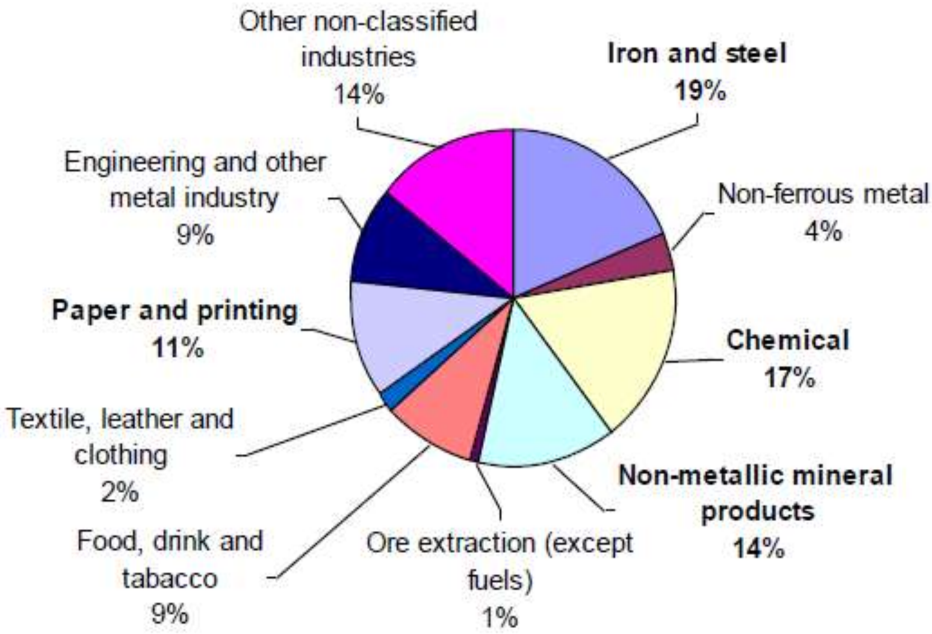

Figure 2. Energy consumption by industries in European countries [5, p. 55.]

Every country needs to concentrate on solutions which could decrease the amount of energy used by its main energy consumers. For example in Finland, around 140 TWh of energy was consumed by industries for products manufacture their products in 2015, and around 50 TWh of energy was lost. For comparison, around 65 TWh of energy was consumed by the residential sector in 2015, which almost equal to amount of wasted heat from industrial sector. [6.]

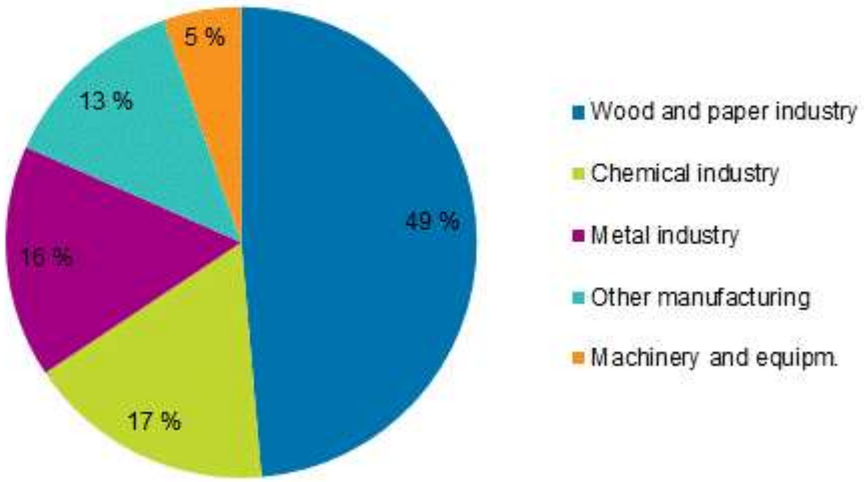

Figure 3. Energy consumption by industries in Finland 2015 [6].

In Finland, wood and paper industry has a leading position in the industrial sector. As shown in figure 3, it is responsible for half of the total energy consumed by the Finnish industrial sector. As a consequence, energy saving solutions for paper and wood industry have to be found in the first place because the overall effect is more noticeable. [6.]

2.2 Waste Heat and Waste Heat Recovery

The reduction of energy consumption is a complex process in the industrial sector. Reusing the energy released from industrial processes is one of the options for the reduction of energy used. Any process involving energy transfer losses heat as the second law of thermodynamics explains. In fact, the heat losses of the industrial sector vary from 20% to 50% of the total heat used by factories and plants. For example, data centres need energy for cooling computer systems. They consume an enormous amount of electricity. As a result, heat emitted from computers is generally released outside instead of reusing it. Heat released from an energy consuming processes into the environment is a waste heat. [4.]

Waste heat can be reused instead of emitting it to a body of water or the atmosphere. Waste heat recovery means the collection of waste heat for a purpose where the heat can be reutilized. Recovery of waste heat is an opportunity to improve energy efficiency and sustainability of the sector. Waste heat can encountered in various forms, depending on its temperature, such as hot gas, warm water, exhaust vapour, and others. Temperature is an essential factor in waste heat recovery solutions. Every industry has minimum and maximum temperature requirements for specific processes on a product plant. If the temperature of the waste heat is high enough, the heat can simply be transferred through a heat exchanger, a device that is usually used to transfer heat from a fluid to another one. For example, the waste heat recovery process of a paper machine comprises releasing of heat during the drying process and heating up the supply air with the waste heat from drying through a heat exchanger. [7.]

If the waste heat available does not meet the temperature requirements of a process and it cannot be used anywhere else, it is released outside. Therefore, a possible option for the reuse of low-temperature waste heat is to increase its temperature to the required one. The optimal solution for this situation is to use a heat pump. [8.]

3 Heat Pump

By definition, a heat pump is a device that transfers energy from one heat source to another. Heat pumps can be divided into three main types depending on the source of the heat. The first type is an air source heat pump where heat is absorbed from the air. The second type is a ground source heat pump that absorbs heat from the ground. The third type is a water source heat pump where heat is transferred from water. [9, pp 1-9.]

The operating principle of any heat pump involves four stages: compression, condensation, evaporation, and expansion. The processes involve a working fluid inside the heat pump. Four devices are included in the heat pump: evaporator, condenser, compressor, and expansion valve. The working fluid in the cycle inside a heat pump is called refrigerant. The refrigerant absorbs heat during the evaporation phase, and releases heat in the condensation phase. [9, pp 1-9.]

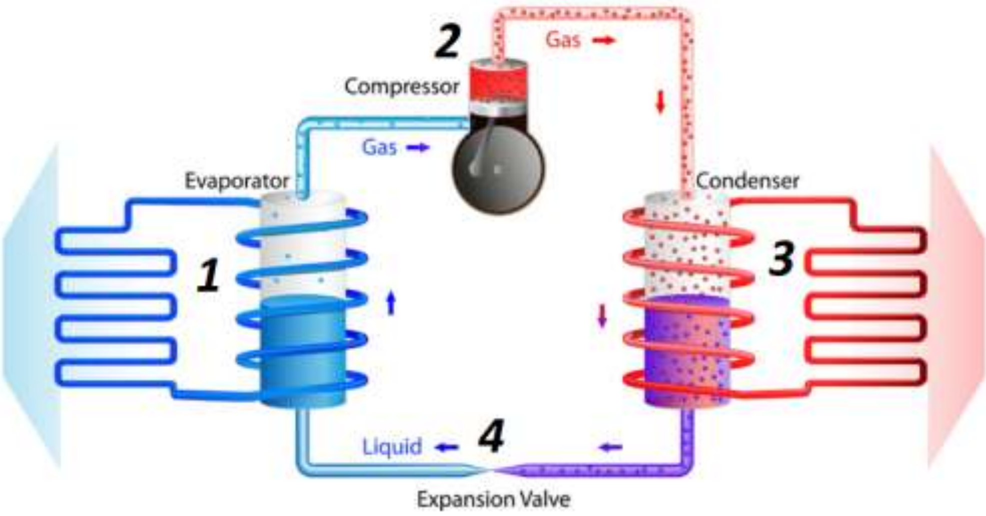

Figure 4. Working principle of a heat pump [10].

The basic operating principle of a heat pump is described in figure 4. The first stage is evaporation that occurs inside the evaporator, where the refrigerant is in a cold liquid state at low pressure. Heat from the outer source is transferred to the evaporator, where the heat is absorbed by the refrigerant. Due to heat absorption, the refrigerant changes its state from liquid to gas. The refrigerant is a cool low pressure gas. At the second stage, the refrigerant moves to the compressor. The role of the compressor is to increase the pressure of the refrigerant. As a result, the temperature rises and the refrigerant turns into a hot, highly pressurised gas. The third stage starts when the refrigerant moves to the condenser from the compressor. The condenser acts as heat exchanger and the refrigerant transfers heat to a heat distribution system. The refrigerant changes its state from gas to a warm highly pressurised liquid. Then, the refrigerant moves to an expansion valve, the last stage before repetition. The refrigerant changes temperature again, and is pressured to a cold liquid at low pressure. The cycle starts again. [9, pp. 1-9.]

This basic principle applies to all types of heat pumps. The standard cycle follows the direction illustrated in figure 4, the heating mode. Some heat pumps have a possibility to reverse the cycle from heating to cooling mode. In this cycle, the refrigerant moves from the condenser to the evaporator due to reversing valve in the heat pump. A reversing valve is a device that changes the flow of the refrigerant inside a heat pump. [9, pp. 14-16.]

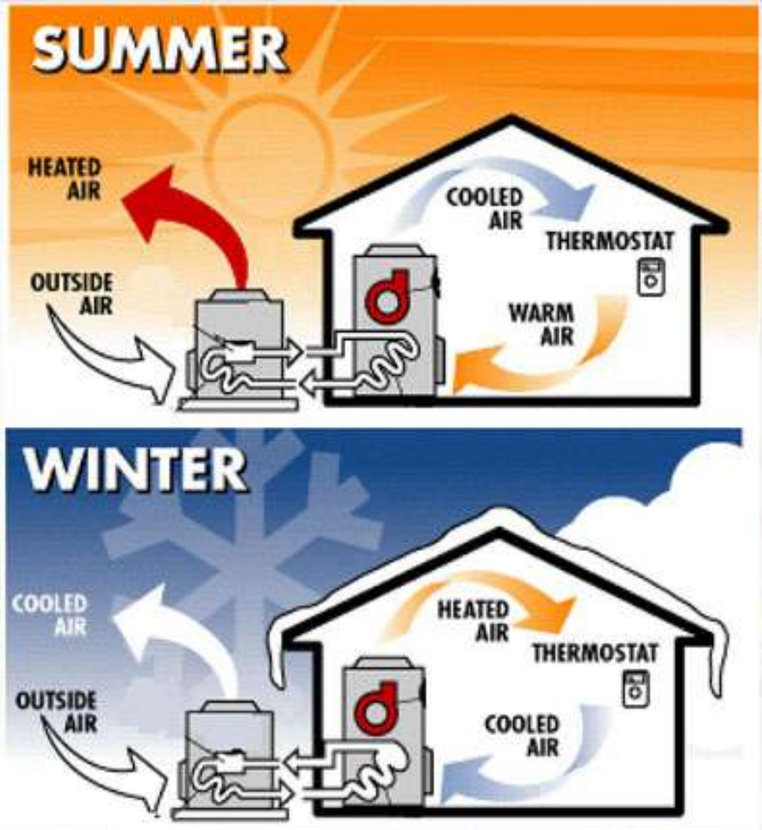

Figure 5. Reversible heat pump [11].

Figure 5 illustrates the example with air to air heat pump installed inside a small house. An air to air heat pump can be used for heating purposes in residential buildings during the winter and for cooling during the summer. It increases the efficiency of a heat pump because without a reversed cycle, it would be impossible to use the heat pump during the summer. [9, pp. 14-16.]

3.1 Combined Heating and Cooling

As mentioned above, a heat pump can fulfil one function at a time, where heating or cooling depending on the temperature of the heat source and the demand of the users. Combined heating and cooling solution is a suitable solution when the temperature of the source is changing as it is with the outside air example. On the other hand, industrial processes produce an almost constant temperature all year through. For example, pasteurization of milk needs a constant high temperature at around 100°C. To maintain it, a heating machine is used for pasteurization. After this process, milk products need to be cooled with a cooling mechanism, such as a chillier. Two separate machines have to be installed inside the same milk factory. However, the efficiency and technologies of the heat pumps are improving and some heat pumps can be used for both heating and cooling at the same time. [12.]

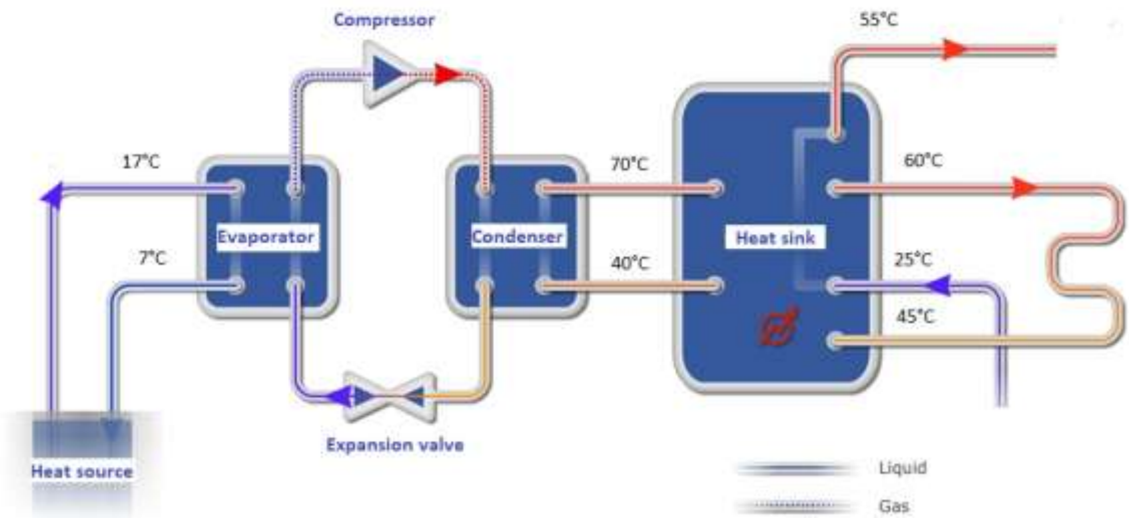

Figure 6. Complete process of a heat pump with heat source and users [13].

Figure 6 describes a possible combined heating and cooling system. It is assume that it is a water to water heat pump. The heat source on the left in the figure is a cooling process inside a factory. The refrigerant absorbs heat from the heat source. The water inside cools down from +17°C to +7°C due to the heat transfer to the refrigerant. The temperature of the water is now low enough to be reused in the cooling system. On the opposite side of figure 6 there is a heat sink connected to separate heating systems that need hot water for other processes. The heat from the refrigerant is transferred to water, and the temperature of the water rises from 40°C to 70°C. The hot water from the condenser moves to the heat sink where it can be distributed to various purposes at different temperatures. Consequently, a heat pump can provide multiple solutions suitable for heating, cooling, and their simultaneous use. [13.]

3.2 Industrial Heat Pump Application

Up to the present time, heat pumps have mostly been used in the residential sector for heating. As mentioned above, industrial processes have a more constant heating and cooling demand compared to the demand of residential buildings. A combined heating and cooling heat pump is the most feasible option for industrial sector. Figure 7 illustrates how a heat pump can combine heating and cooling systems. On the cooling side, the heat pump is used as a cooling machine to cool down a liquid for a cooling system, and the heat released from the cooling processes is used as a heat source for the heat pump. On the heating side, there is another process with another liquid with temperature of 50°C. This is too low temperature for the direct heat recovery option. Therefore, a heat pump is used to heat the liquid from 50°C to 75°C with the help of a cooling system to be reused. [5, pp. 1-3.]

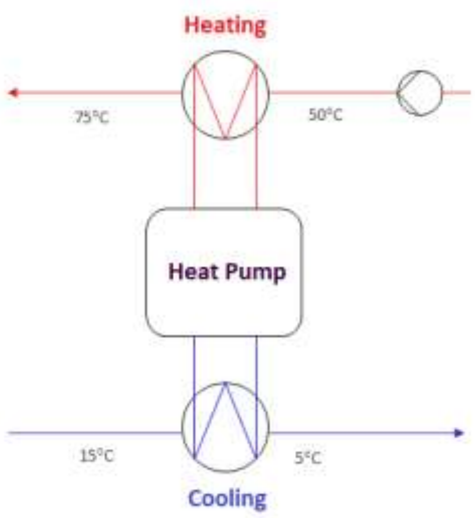

Figure 7. A heat pump that combines heating and cooling processes.

The main purpose of a heat pump in the industrial sector is to recover heat from processes using gas or liquid. It is also used to heat and cool buildings. An industrial heat pump is a medium or large heat pump specifically made for the industrial sector. It is used to recover heat from processes such as drying, washing, evaporation, cleaning, and others. Heat pump application depends on the type of industry, the process, and the temperature of the process. Figure 8 illustrates industries and typical processes where industrial heat pump is suitable. [5, pp. 1-3.]

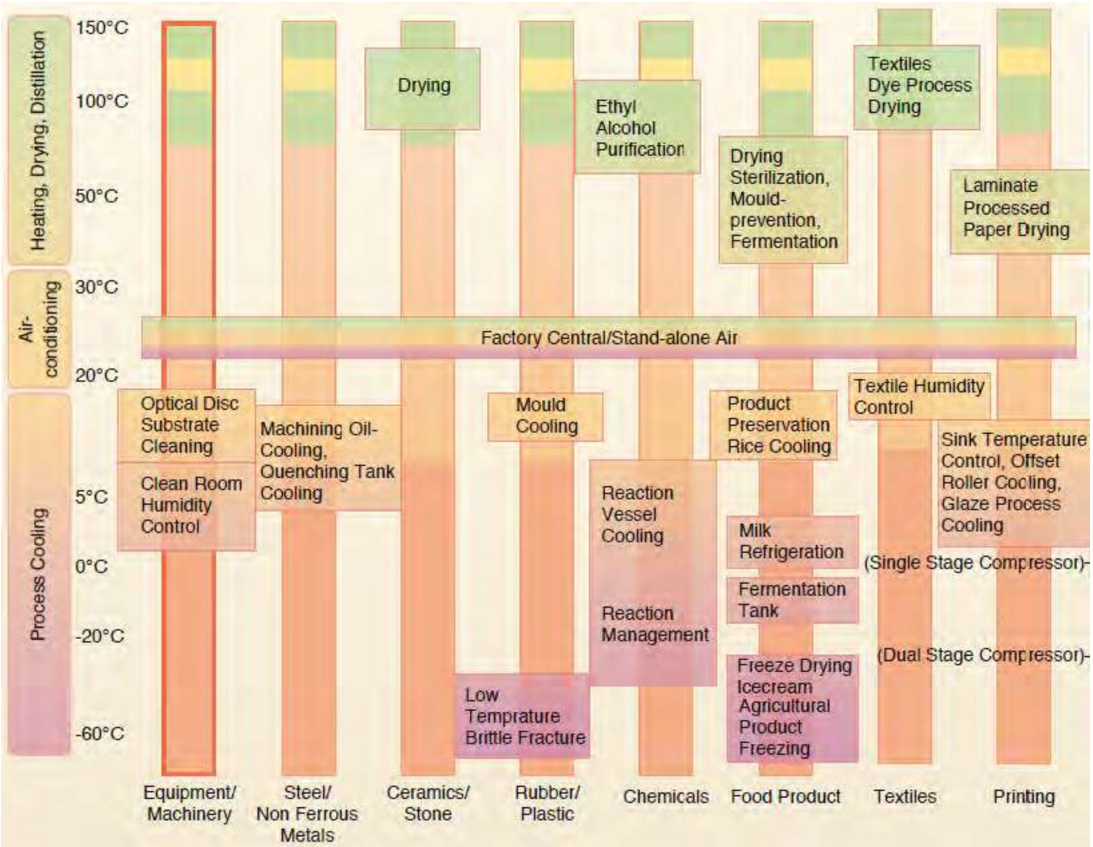

Figure 8. Industrial heat pump application [5, p. 1].

Figure 8 above shows that a heat pump can be used to recover heat from the drying process in a ceramics or stones factory. Drying is the most common industrial process where a heat pump can be used. Washing is the other widespread process suitable for a heat pump. [5, pp. 1-3.]

3.3 Coefficient of Performance

The coefficient of performance (COP) is a coefficient that describes the efficiency of a heat pump. It is the ratio of the heating capacity to the energy consumed for the operation of a heat pump. COP is a number that is generally equal to 2-5. Higher COP presents higher efficiency of a heat pump. A heat pump with COP=3 produces less work with more electricity consumed comparing with a same size heat pump with COP=4. However, heat pump technologies are improving, and their COP can rise up to 9 depending on the manufacturing company and its options. [9, p.331.] The characteristics of a heat pump can also include COPc. It is cooling coefficient of performance that is the ratio of the cooling capacity to the electricity consumed. A heat pump can be used for combined heating and cooling solution. In this solution, COPc describes the efficiency of the cooling mode of a heat pump, and COPh is used for specifying the efficiency of the heating mode. COPh is COP that means heating coefficient of performance. [14, p.23.]

One factor that strongly effects on the COP is the difference between temperatures of the condenser and compressor. The efficiency of a heat pump increases with a smaller temperature difference, and decreases with a higher temperature difference. There are other factors that have a smaller impact on the COP of a heat pump, such as the type of refrigerant, system control, efficiency of fans, and others. Consequently, all these factors have to be considered by the manufacturing company for identifying the correct COP. The manufacturing company selects the heat pump depending on its heating and cooling capacity, and temperature requirement. It also chooses the fan, refrigerant and other devices used in the heat pump. Under these circumstances, COP is identified. [9, p.331.]

3.4 Refrigerants

As mentioned above, refrigerant is a working fluid that is used in the cycle in a heat pump. Each refrigerant has a specific code starting with the letter R for refrigerant. An important factor with selecting a refrigerant is global warming potential (GWP). GWP is a coefficient that allows a comparison of the global warming impacts of various refrigerants. A refrigerant with higher GWP has higher impact on global warming. Nowadays, it is preferable to use refrigerants with low GWP. By selecting a heat pump with a low GWP refrigerant, the harmful impact on the environment is decreased. Consequently, heat pumps with a low GWP refrigerant support the sustainability of the industrial sector. [5, pp. 40-41.]

Table 1. List of suitable refrigerants for industrial heat pumps [5, pp. 41].

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3-CH2-CH2-CH2-CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

Table 1 illustrates suitable refrigerants for industrial heat pumps and the properties of these refrigerants. The third column represents the GWP of each refrigerant. For example, R134a is a widespread refrigerant used in medium-sized and large heat pumps. It is a non-flammable refrigerant and for this reason it has the highest safety class - A1. Unfortunately, R134a has the highest GWP compared to the other refrigerants listed in the table. On the other hand, a refrigerant with low GWP is R1234ze. Its GWP is 143 times lower than that of R134a. R1234ze has extremely low flammability, but it can still be dangerous in some applications. This is why its safety class is A2, lower than that of R134a. Flammability is an important factor for the selection because some industries have strict rules about flammable materials on a site due to a risk of a fire. A proper refrigerant has to be chosen with due diligence because an inapplicable refrigerant can be dangerous not only to the environment but to a factory as well. [5, pp. 40-41.]

3.5 Benefits and Limitations

A heat pump is a device with many advantages. First of all, it is an energy efficient solution because of its high COP, and it is a versatile solution that can be used for heating, cooling, and combined heating and cooling. Moreover, a heat pump can be used to recover heat and reduce energy consumption. The third benefit of a heat pump is its long lifespan, up to 35 years with minimum routine maintenance. Another advantage is short payback period based on the long lifespan and minimum maintenance. As shown above, a heat pump is a cost and energy efficient solution that mainly needs the initial investments. [7.]

Despite their benefits, the use of heat pump is not widespread as it could be. The first reason for that is the lack of knowledge about heat pumps. It is important to understand the working possibilities of a heat pump for industrial processes. The second reason is a lack of familiarity with industrial and HVAC processes in a factory or a plant. Unfortunately, it is also time consuming and costly to choose a suitable heat pump. As a consequence, most companies decline the use of a heat pump. The third obstacle is the relatively high investment cost of a heat pump, and it is an important factor for customers because of influence on the total expenses of the project. The fourth reason is the electricity consumption of a heat pump. A heat pump is powered by electricity and the system must have a constant access to electricity, but some customers would like to minimize the use of electricity. [13.]

To summarise, a heat pump is a profitable solution due to its energy and cost effective features. However, it has some disadvantages that have to be taken into account in a project planning stage, but they are minimal. As has been shown, a heat pump has a positive impact on the energy and cost reduction. Moreover, it has minimal harmful effects on the environment. These facts are a core part of the sustainability concept. Therefore, the heat pump has to be considered as a sustainable solution for both industrial and residential sectors. [13.]

4 Establishing the Feasibility of a Heat Pump - Theoretical case

The selection of a suitable heat pump for an industrial project is a complex process that has to take into account several important factors in the heating and cooling processes. If the owner of a project decides to consider a heat pump as the solution for waste heat recovery, the heating and cooling demands of a plant will have to be examined as the first step. This chapter introduces the steps that help to analyse the heating and cooling demand and, based on the analysis, to make decisions about the feasibility of a heat pump application for a production facility. This analysis was conducted with support from Pöyry Oy, and it is based on the knowledge of several project engineers, leading various projects.

4.1 Heating Demand

A heat pump is mostly used for heating processes, and an analysis of the heating demand has to be done first. Generally, industrial premises have heating processes that require set temperatures. Heat pumps have a maximum heating temperature of about 70-100°C. Processes with a temperature higher than this can be eliminated for heat pump application. A chart is a simple method to illustrate heating processes suitable for a heat pump. The schematic chart of figure 9 illustrates a theoretical case. The theoretical example is a production facility with six different heating processes. On the chart, these consumers are divided on the basics of the outlet temperature that is the desired temperature for all processes. The graph illustrates an increasing of temperature from T1 to T4. It is assumed that the maximum heating temperature of the heat pumps is lower than T3: **Th.p. < T3.** Processes 2 and 3, marked with a squared pattern in the chart, have too high a temperature, and that is why heat pump is an inapplicable solution for them.

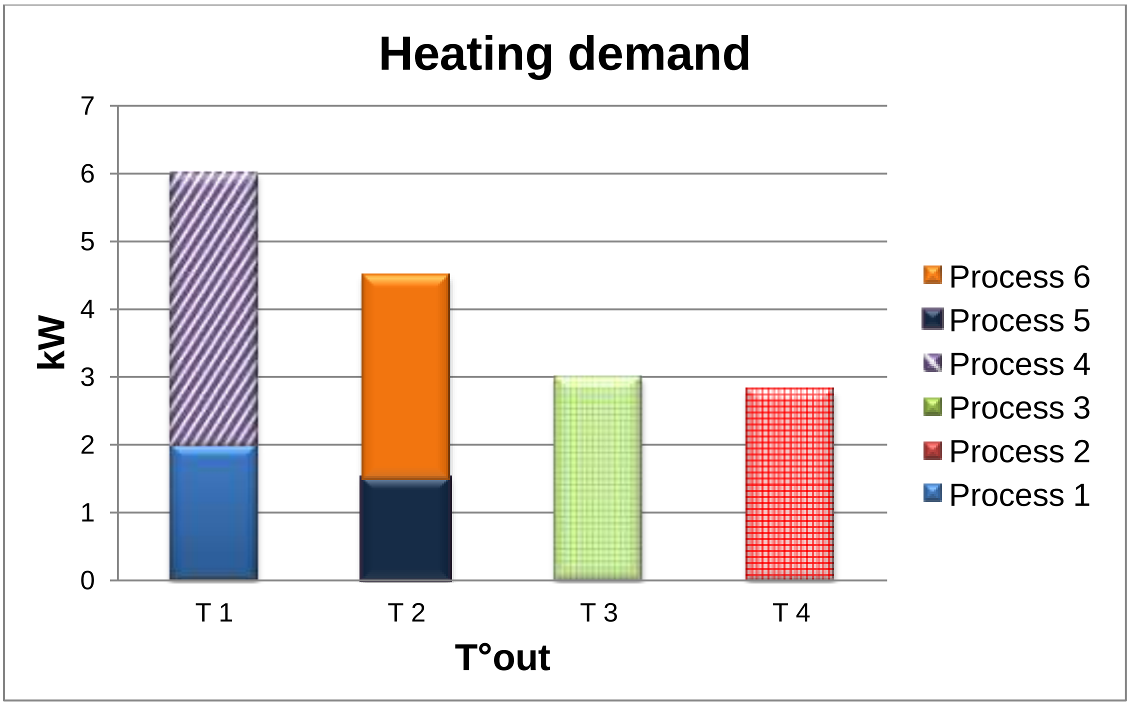

Figure 9. Heating demand based on the required temperature.

Process number 4 in the theoretical example, shown in purple, diagonal lines, has fluctuating heating demand during the year, meaning that heating is only needed during a specific period of a year. It is unprofitable to use a heat pump for fluctuating processes because they cause a low heating load on the heat pump and, thus, lower the efficiency of the pump. The optimal heat pump operation is around 70-100% of the total heating capacity of the heat pump to achieve high COP and a short payback time. That is why a fluctuating demand has to be marked on a chart to assess the feasibility of a heat pump solution.

Processes 1, 5, and 6 in the theoretical example are indicated in solid colour because a heat pump can be used for them. The temperature of these consumers is suitable for a heat pump application and they have a continuous daily annual demand. The heat pump can achieve high COP and a short payback period if used for processes 1, 5, and 6. The bar chart on figure 9 shows that a heat pump can be feasible for a non-fluctuating process that needs heat the whole year round, or at least during most of the year when the temperature of the process is lower than the maximum heating temperature of a heat pump.

Some industries have already implemented various waste heat recovery systems that must be taken into account if a heat pump is added. Most of the industrial recovery systems are direct heat recovery system with a heat exchanger. As mentioned above in chapter 2, direct heat recovery is used when the temperature of waste heat is high enough to be directly used in a process. For example, a ventilation recovery system is a widespread solution in the industrial sector where heat from exhaust air is used to preheat supply air through heat exchanger. As a result, less extra energy is used to heat supply air. A recovery system can cover a sufficient part of the heating demand of a production plant.

The heating demand that is covered by a recovery system has to be listed in the same chart analysing the heating demand to avoid taking it into account when analysing the need for a heat pump application. Figure 10 illustrates a theoretical case with the six heating processes from figure 9. It is assumed that this case also has a heat recovery system that can cover some of that demand. In the chart below, the recovery system covers the demand of the whole process 1 and 2/3 of the demand of process 5. Therefore, this recovery system hinders the use of a heat pump for process 1 and 5 on figure 10. In the case illustrated in figure 9, processes 1, 5, and 6 are the most feasible ones for a heat pump application, where as only process 6 and 1/3 of process 5 are feasible for a heat pump application in the case illustrated in figure 10 because of the heat recovery system.

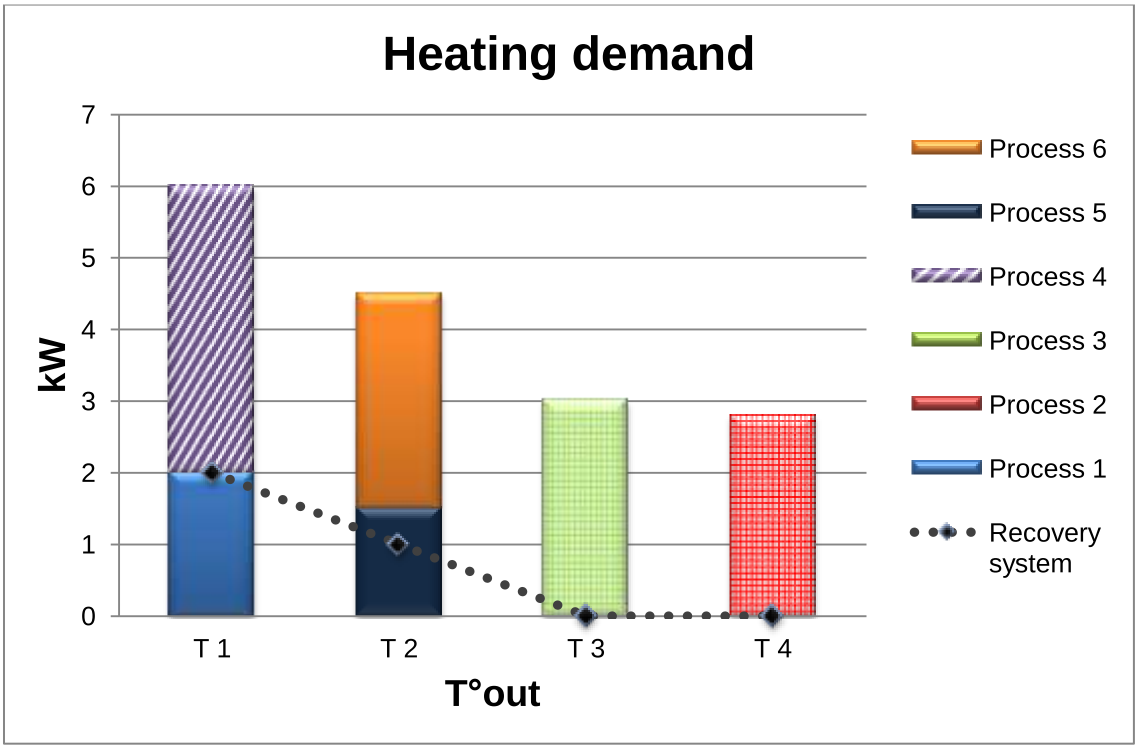

Figure 10. Heating demand and recovery system.

As indicated above, it is important to consider certain factors from the heating demand in a feasibility analysis of a heat pump application. They include:

- Heating process fluctuation
- Process temperature
- Additional heat recovery system

A non-fluctuation process that needs heat throughout the year, or at least a major part of the year, is more suitable for a heat pump application because it guarantee higher COP value and a shorter payback period. The process temperature has to be lower than maximum heating temperature of the heat pump to guarantee sufficient heat supply. The maximum heating temperature of heat pump varies usually between 60°C and 100°C, depending on the manufacturer. The use of an additional recovery system in a production plant has to be accounted what conducting a feasibility analysis for a heat pump system.

4.2 Cooling Demand

Once the analysis for the heating demand is conducted, it is important to analyse the cooling demand because it also effects the operation of a heat pump. Cooling demand has effect on the amount of heat that is transferred from the cooling side of a heat pump and to the amount of heat that can be produced on heating side. As a result, a higher cooling demand influence on increasing of the cooling capacity of a heat pump, and as a consequence, the heating capacity also increased. When analysing a cooling demand, a bar chart can illustrate cooling processes with process temperature suitable for a heat pump application. Figure 11 illustrates the same theoretical case of a production plant as described above with three cooling processes. In the figure, the cooling consumers are divided based on their process temperature. Temperature T1 in the figure is lower than T2.

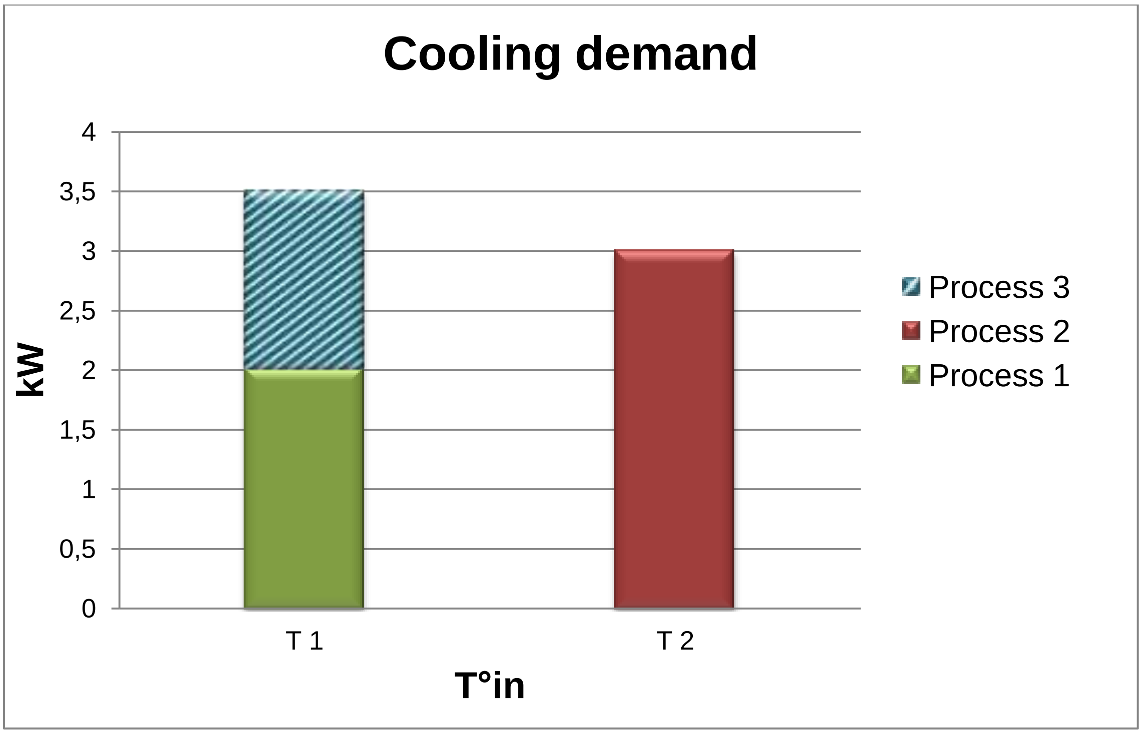

Figure 11. Cooling demand based on required temperature.

Process 3 marked with a linear pattern, has a fluctuating annual demand. The fluctuation in the demand means that this process has demand in cooling specific period of time. As mentioned above, a heat pump is unprofitable in fluctuating processes, because the processes has low load on a heat pump and decrease the efficiency of a pump. To maximize, the heat pump operation, it is more feasible for higher COP to consider processes with a continuous annual. Processes 1 and 2 are marked in a solid pattern because these consumers have a suitable temperature for a heat pump application and a continuous demand. A heat pump can be used as a cooling machine for these processes.

The temperatures of the processes 1 and 2 have to be compared with the maximum cooling temperature of the heat pump. If the temperatures are lower than maximum cooling temperature of the heat pump, the heat pump cannot be used for direct cooling of these consumers. In such a situation, it is preferable to use a chiller for cooling process water together with a heat pump. A chiller is a cooling machine, and the waste heat from a chiller can be used on the cooling side of a heat pump as shown on figure 12.

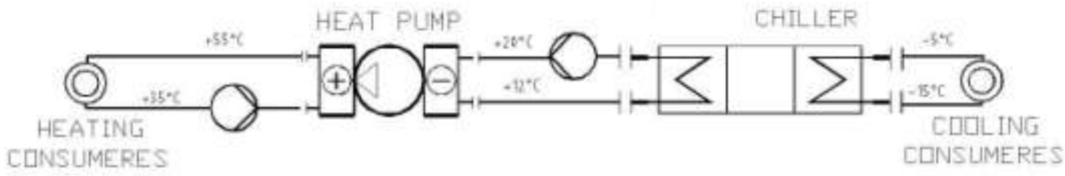

Figure 12. Direct connection of a heat pump to cooling system

If the temperature of the processes 1 and 2 is higher than the maximum cooling temperature, a chiller may not be needed as shown in figure 13. In such as situation, decision about a chiller has to be made by the project engineer based on a single aspect: the temperature difference between the heating and cooling processes. The COP of a heat pump rises with a lower difference in the temperatures of cooling and heating sides. If temperature difference is higher than 50 ºC, the heat pump will have very low COP with a long payback period. To improve the COP, it is preferable to add a chiller in the system. If high efficiency is not an important factor, it is possible to check the option for high temperature difference from the manufacturer.

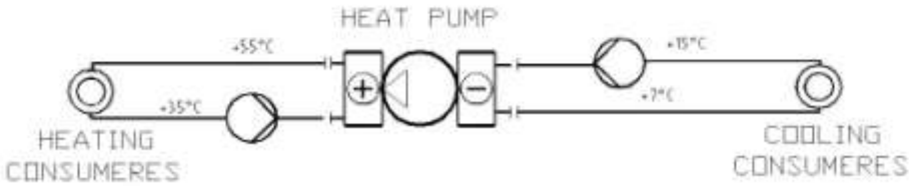

Figure 13. Connection of a heat pump to cooling system through a chiller.

As indicated above, it is important to consider certain factors from the cooling demand in a feasibility analysis of a heat pump application. They include:

- Cooling process fluctuation
- Temperature difference between heating and cooling demand

A fluctuating cooling process can minimize the heat pump operation during the period when the process needs no cooling. As a consequence, it is undesirable to take the fluctuating processes into account for a heat pump application because high COP and shorter payback period of the heat pump cannot be guarantee. A heat pump can be used for direct cooling of the cooling processes of in a production plant if the temperature difference between the heating and cooling consumers is lower than 50 ºC. In other cases, an option of chiller installation can be considered.

4.3 Heat Pump Feasibility

If an analysis of heating and cooling consumers demonstrates that a heat pump is a feasible solution for the project being analysed, the next step is to select a manufacturing company that, based on the demands, can suggest a heat pump. The manufacturing company can find a suitable product if the heating or cooling capacities of the desired heat pump are known. Also, the inlet and outlet temperatures of heating and cooling have to be known. From the above analysis of the theoretical case, the heating and cooling processes, selected for heat pump application, are used for the heating and cooling capacities. The cooling capacity can be calculated on the basis of the cooling demand. From the above analysis of cooling demand, cooling processes 2 and 3 from figure 11 are taken into account because of their non fluctuating demands. As mentioned above, cooling can be done directly with a heat pump or with an additional chiller.

If a heat pump is directly connected to cooling consumers as it is shown in figure 13, the cooling capacity of the heat pump is equal to the cooling demand of processes 2 and 3.
Heat pump cooling capacity = Cooling demand.

If a chiller is needed between the heat pump and cooling consumers as illustrated in figure 12, the cooling demand of processes 2 and 3 is equal to the cooling capacity of chiller.
Chiller cooling capacity = Cooling demand.

If a chiller is used, the electricity consumption of the chiller needs to be calculated in the cooling capacity of the heat pump. The electricity consumption can vary according to the device, but it is generally around 25% of the total cooling capacity.
Heat pump cooling capacity = Chiller cooling capacity + 25% * Chiller cooling capacity.

The preliminary heating capacity of the heat pump can be checked with a similar formula. The electricity consumption of a heat pump may also be assumed to be 25% of the total cooling capacity.
Heat pump heating capacity = Heat pump cooling capacity + 25% * Heat pump cooling capacity.

The heating capacity of a heat pump can be compared with the heating demand of suitable heating consumers from figure 10. If the heating demand is lower than the heating capacity of a heat pump, it is important to consider other options instead of a heat pump, or decrease the cooling capacity of the heat pump. If the heating demand is higher or equal to the capacity of the heat pump, information can be sent to a manufacturing company for further study. The information, presented in this chapter, is suited making a short feasibility check of a heat pump. It gives a clear understanding of the connections between heating demands, cooling demands, and capacities of a heat pump. The steps described guarantee that the heat pump selected for a production plant are optimal to operate with high COP, and decrease the waste heat released. The decrease in waste heat improves the efficiency of energy consumption and the sustainability of the industrial sector.

5 Establishing the Feasibility of a Heat Pump - Practical cases

To test feasibility analysis method discussed in chapter 4, a case in the food industry and pulp and paper industry respectively are looked into. Each industry is examined based on the existing project of Pöyry. The purpose of the feasibility analysis is to establish whether a heat pump is suitable for the cases. If there is enough heating and cooling demand for a heat pump, the suggestion of a manufacturing company is also demonstrated. To have clear understanding of heat pump properties, it is important to select a manufacturing company before analysing the two cases.

5.1 Manufacturing Company Selection

A growing number of heat pump companies concentrate on industrial heat pump applications. Several companies were been studied for the thesis, foe example Nibe, Oilon, and Gebwell. The manufacturing company must meet specific criteria of industrial applications. The company has to produce liquid to liquid heat pump because most industrial processes are based on liquids not gas. Another criterion is high temperature and capacity range. Industrial buildings have high heating and cooling demand and the temperature range has to be high to cover most of processes of a production plant. The most important criterion is the suitability of the heat pumps of the manufacturer for industrial purposes. [8.] Some manufacturers could not meet the requirements. For example, one of them produces heat pumps with a maximum temperature of 65°C, which too low for industrial use. One of the manufacturing companies, however, met all the requirements. As a result, it was used for the case studies.

The manufacturer that was selected is Oilon Oy, a Finnish company producing heat pumps for residential and industrial purposes. The company has a heat pump series called ChillHeat that can be used for heating, cooling or combined heating and cooling solutions. The products of the series can be used in industrial and large residential buildings. They are liquid to liquid heat pumps that cool one fluid and heat another fluid. There are three series of ChillHeat - RE, S, and P. The P series has the largest temperature range with the maximum heating temperature of 100ºC and minimum cooling temperature of -20ºC. [15.]

The ChillHeat products have several significant benefits. The main one is a possibility to the use heat pump for heating, cooling, and combined heating and cooling. Another benefit is a wide capacity range from 100 kW to 2 000 kW. Moreover, units can be connected in series to increase capacity up to several MW. The products are specifically made to meet the requirements of complex industrial processes. Moreover, the refrigerant can be chosen depending on the needs of a customer, including refrigerants with low harmful impact. [15.]

Figure 14. Mobile application of product [15].

An automatic control system is an important feature of the products. They have several running modes: heating, cooling, combined heating and cooling, passive cooling, and others. They are controlled with a special mobile application that is shown in figure 14. The system provides control of cooling in parallel with heating in the setting temperatures. Also, the size of the heat pumps is compact so they can be placed in small space. The height of the device is up to 2.5 meters and the width is up to 4.5 meters.[15.]

5.2 Food Manufacturing Plant

The feasibility analysis introduced in the chapter 4 was done for a food manufacturing plant in Northern Europe. The plant is an extension to an existing plant. Moreover, it is a greenfield project because the owner decided to build the plant on unused land. The plant produces mainly fermented products. The production processes have a high demand of both heating and cooling. Heating is primarily needed for heating ingredients and final products, but also for ventilation, space heating, domestic hot water, and freezing protection of some devices. Cooling is mainly needed for cooling ingredients and final products, but also used for cooling warehouses of ingredients and final products, and for the ventilation of electrical rooms and offices. The information was given by the project engineer.

The new plant is connected to the district heating system through the old plant. The owner has planned to implement a heat pump for combining heating and cooling systems from the beginning of the project. The idea was to use heat pumps and district heating as a hybrid system to minimize consumption through district heating and maximize heat pump operation and to achieve high efficiency of a heat pump with COP value of at least 5. The plant has a small ventilation heat recovery system that can be disregarded when selecting a heat pump. The aim of feasibility study is to select a heat pump that can help to reduce amount of heat that is wasted during a cooling processes.

5.2.1 Heating Demand

The heating demand of the plant is relatively high. As mentioned above, the main part of heating is used by ventilation, domestic hot water, space heating, freezing protection, heating of ingredients, and heating hot water for production. All required users and temperatures are listed in table 2 below. T°in is the inlet temperature, or the temperature of the incoming water from the outside. T°out is the outlet temperature, or the temperature for a process. Table 2 also illustrates the maximum heating demand for each heating consumer. The total maximum heating demand of the plant is 5, 630 kW.

Table 2. Maximum heating demand of different consumers.

Heating consumption	**Maximum heating demand**	**T°out**	**T°in**
Heating of ingredients	580 kW	50°C	30°C
Hot water for production	1,800 kW	115°C	90°C
Freezing protection	400 kW	35°C	20°C
Space heating	150 kW	50°C	30°C
Domestic hot water	500 kW	60°C	5°C
Ventilation	2,200 kW	50°C	30°C
Total	**5,630 kW**		

Two processes are mark in a different colour in the table. The hot water for production is marked in red because the temperature requirements are too high for a heat pump. ChillHeat products can heat up water with temperature up to 100°C, and desired temperature for the process is 115°C. As mentioned above, the plant is connected to the district heating, which can be used for this purpose. Domestic hot water is mark in orange because of the high temperature difference. Water for domestic use has to be heated to 55°C, and it can only partly be done with a heat pump due to the high temperature difference. The rest needs to be heated with district heating.

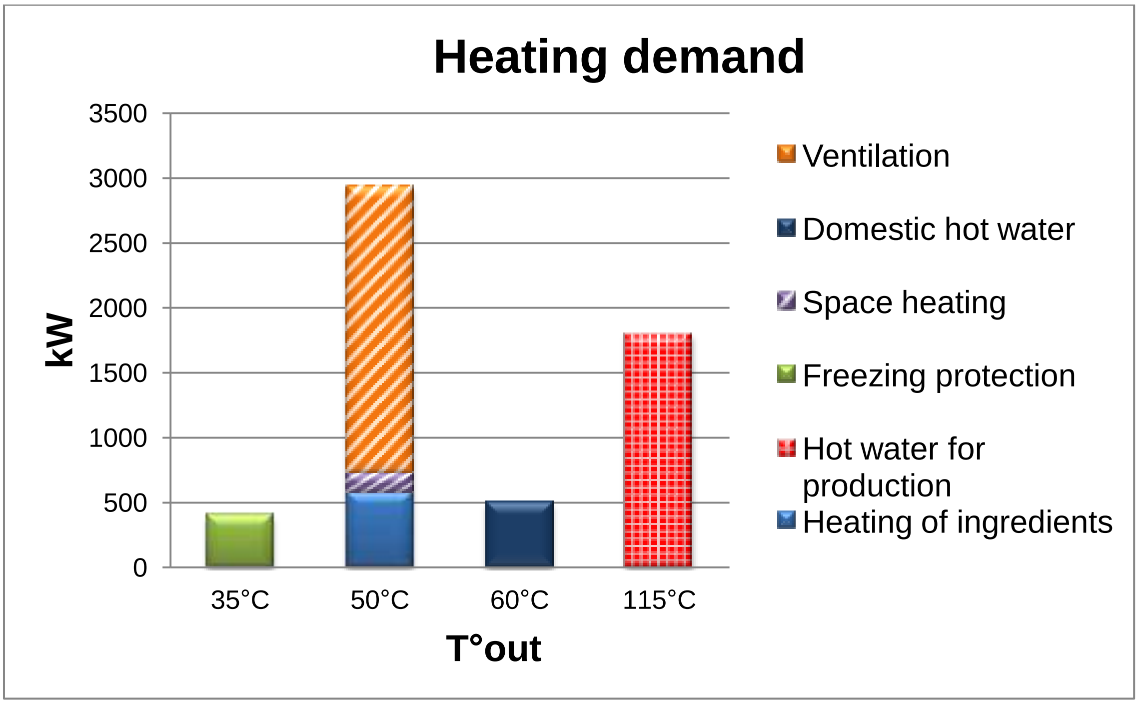

Figure 15. Heating demand based on required temperature.

Figure 15 illustrates the heating demand of all heating consumers, based on the desired temperature. Hot water for production is marked with red squared pattern to show that a heat pump is inapplicable for this process due to the high temperature. Ventilation and space heating are also marked with a pattern because the processes are not constant, but vary a lot depending on the outdoor temperature. In the summer, heating demand for these processes is almost zero. However, a heat pump can partly supply them in the winter when their heating demand is close to maximum. But there are processes that have a constant heating demand: heating of ingredients, freezing protection, and domestic hot water. Their total heating demand is 1130 kW, as can be calculated based on the information in table 2.

5.2.2 Cooling Demand

The main cooling consumers divided into two circulation cooling networks based on the demanded temperatures. Cooling network 1 requires water at temperature from 0°C and colder. It network consumers are the cold water for production, and cooling of warehouses. Cooling network 2 needs chilled water at temperatures of 7-10°C. It supplies following consumers: cooling of compressed air, chilled water for processes and the ventilation. Table 3 below illustrates the cooling consumers of both networks with their maximum cooling demands. The total maximum cooling demand of network 1 is 1700 kW, and the total maximum cooling demand of network 2 is 4, 150 kW. The total maximum cooling demand of the whole plant is 5, 850 kW. The temperature range can be seen in table 3. T°in is the desired temperature for the processes, similar to T°in in table 2 of heating demand, and T°out is the temperature of water leaving a process.

Table 3. Maximum cooling demand of different consumers

Cooling consumers	Maximum cooling demand	T°in	T°out
Process cold water	600 kW	-10°C	-4°C
Ingredients storage	300 kW	-10°C	-4°C
Products warehouse	800 kW	-10°C	-4°C
Total, Cooling Network 1	**1,700 kW**		
Process chilled water	1,250 kW	10°C	20°C
Ventilation	2300 kW	7°C	15°C
Compressed air cooling	600 kW	7°C	15°C
Total, Cooling Network 2	**4,150 kW**		

Figure 16 below illustrates the cooling demand of all cooling consumers based on temperature. Consumers for the cooling network 2 are marked in a linear pattern as was done in the theoretical case in chapter 4 due to a fluctuating process. Network 2 is not suitable for heat pump selection because the fluctuating demand reduces the annual heat pump operation. Network 1 has processes with almost constant annual needs of cooling and the processes are used in calculations of the heat pump selection. The total maximum cooling demand of network 1 is 1,700 kW as shown on table 1.

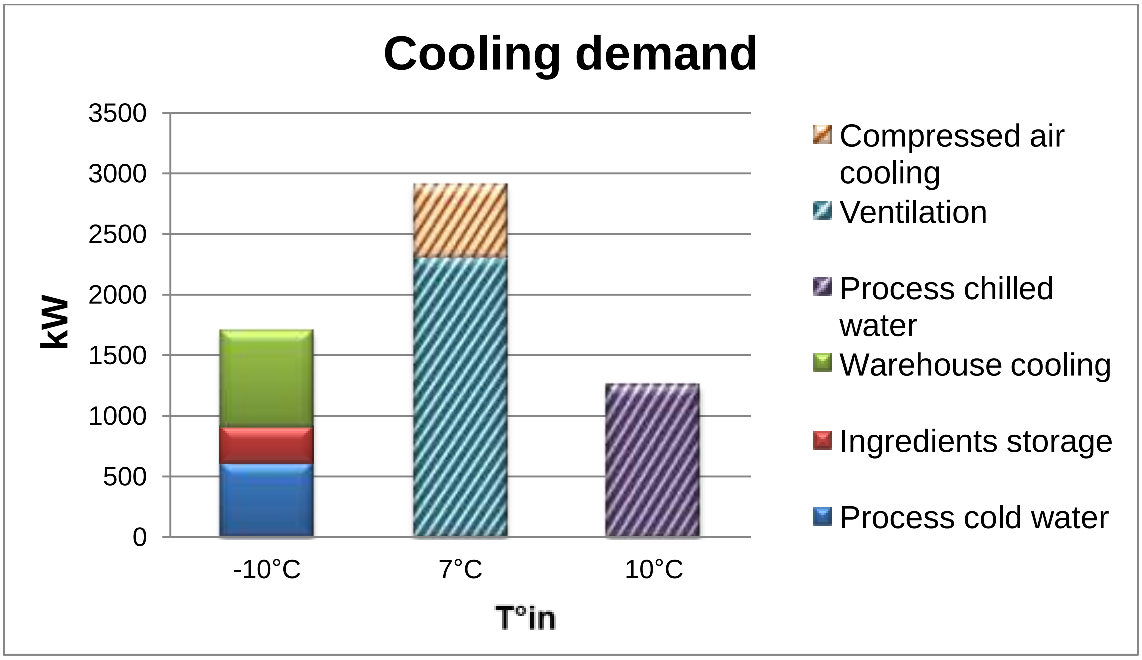

Figure 16. Cooling demand based on required temperature.

The total demand of both cooling networks is covered with water chillers and dry coolers because of information given by the project engineer. Dry coolers are used to release any waste heat into the ambient environment. It is impossible to replace water chillers with heat pumps for two reasons. First, the difference in the required temperatures in the cooling processes ranges from -10°C to +7°C, and the demand of network 2 fluctuates. Second, the temperature difference between the cooling and heating consumer is to high, over 50°C. The maximum desired temperature for heating consumers is +50°C and the minimum desired temperature for cooling consumers is -10°C. Therefore, direct connection of a heat pump to the cooling consumers is unacceptable.

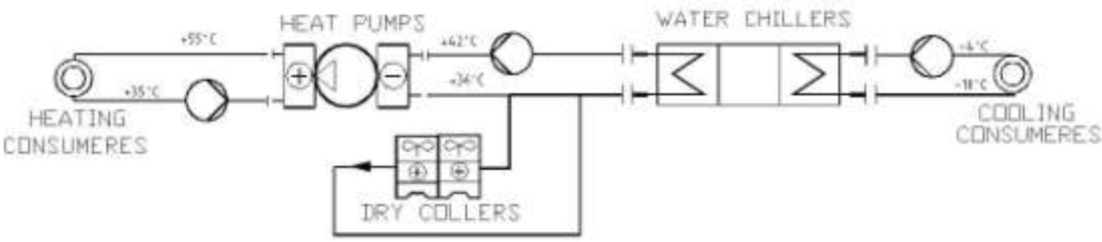

Figure 17. Schematic diagram with connection of cooling and heating consumer.

Figure 17 illustrates a schematic diagram of how the cooling network 1 is connected to a heat pump through water chillers. The outlet temperature of the water chillers is from 36 to 46°C, according to the project engineer.

5.2.3 Heat Pump Feasibility

In this case, heat pump can be a feasible option to recover waste heat from water chillers and minimize the use of dry coolers. The annual fluctuation of most heating and cooling consumers is minimal and the temperatures are suitable for a heat pump application. That is why a heat pump is a suitable solution for this case. The last stage of ensuring the feasibility of a heat pump is the selection of a heat pump from a manufacturing company. For this case, a heat pump with combined heating and cooling is a preferable option since the heating and cooling demands are high enough. The heat pump can be selected on the basis of the cooling demand, as discussed in chapter 4. The following steps, based on the calculations from chapter 4, were taken to choose a suitable heat pump:

1. The first step was to establish the processes with a constant demand for cooling. In this case, it included the cooling of process water and warehouses. The maximum cooling demand of these processes is 1,700 kW, and the standard cooling demand for the cooling processes can be calculated as a half of the maximum: **1,700 kW / 2 = 850 kW**. It is preferable to use standard demand for heat pump selection because it guarantees that the heat pump can operate almost 100% of the time.
2. The second step was to establish the cooling capacity of the water chillers which are part of the cooling system. The cooling demand is equal to the cooling capacity of a water chiller as shown in the formula presented in chapter 4: **cooling capacity of water chiller = 850 kW**. To calculate the cooling capacity of a heat pump, it is assumed that its electricity consumption is 25% of the total capacity of a water chiller. **Cooling capacity of heat pump = 850 kW + 850 kW * 0.25 = 1,063 kW.**
3. The third step in the process was the selection of a suitable heat pump based on the presented data: The cooling capacity of a heat pump has to be around 1,063 kW. The temperature required for heating is 55/35°C. The temperature required for cooling is 36/42°C. The COP has to be 5 or higher.
4. Finally, the heat pump manufacturing company selected two heat pumps for the food plant based on the previous steps. The selected heat pumps, both with COP=8, can be seen in figure 18.

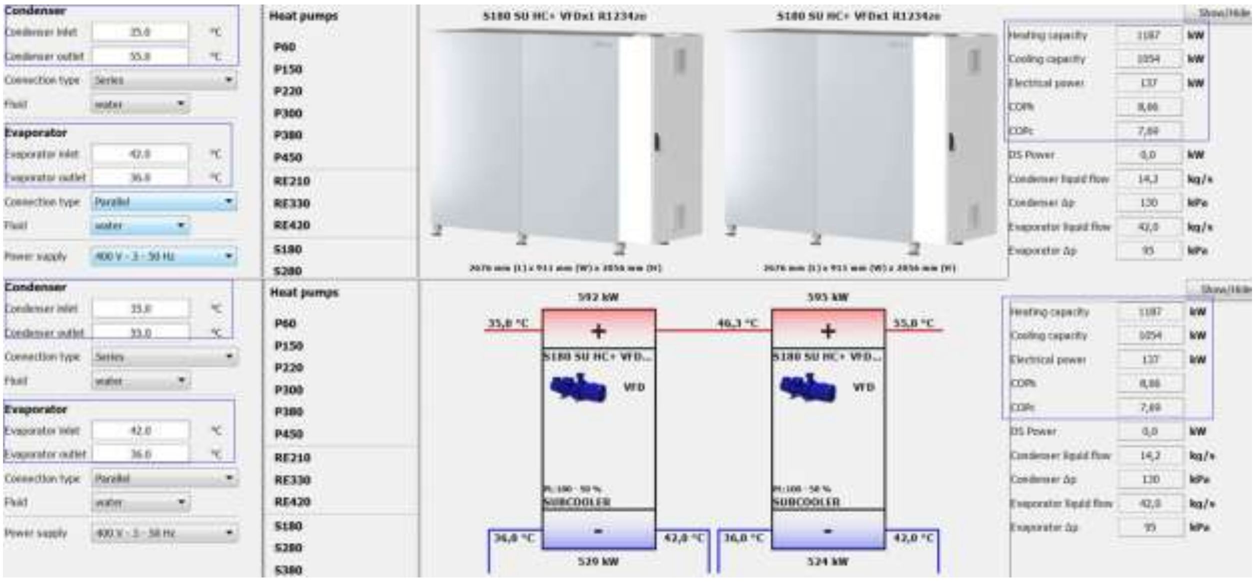

Figure 18. Heat pumps from manufacturing company.

Oilon Oy suggested two heat pumps in their S series with a low GWP refrigerant R1234ze. The cooling capacity of the pump is 1,054 kW, the heating capacity 1,187 kW. Due to a low temperature difference between cooling and heating, the COP is 8.66, which is higher than 5. The electricity consumption is only 137 kW because of the high COP. The price for these two units is 95, 000 EUR. A detailed connection of heating and cooling networks through these two heat pumps can be seen in the Appendix 1. The appendix illustrates the connections of water chillers, dry coolers, and heat pumps with required temperatures and capacities presented by the project engineer.

The feasibility analysis of the food production plant demonstrates that a heat pump can be suitable a solution for industrial premises that have sufficient heating and cooling demand. The heat source of the heat pump is an important factor for optimized work, and, in this case, it is the cooling demand that is constant during the year in the plant. Most heating and cooling demands that were used for the heat pump selection in the case are continuous the year round as it is preferable to take into account these processes for an optimal heat pump operation. As a result, it is guaranteed that only a minimum amount of heat is wasted from the heat pumps. The use of a heat pump in this plant reduces the amount of wasted heat.

5.3 Paperboard Factory

The second case in this thesis is a paperboard factory in Northern Europe. It specifies on the production of paperboard for various uses including the food industry. The heating and cooling systems of the factory are rather complicated and they serve an enormous amount of heating and cooling consumers with varying temperature requirements simultaneously. Heat is wasted in both heating and cooling process in the processes of the factory. That is why the aim of this study is to decrease the amount of heat released to outdoor, and to check the feasibility of a heat pump solution for waste heat recovery in the factory.

The main component of the board factory is a paperboard machine. The paper board machine is divided in three sections: forming, pressing, and drying. The form section forms a web out of pulp. The press section removes moisture out of the web. The dry section evaporates with steam all moisture left after the second stage. This section is covered with a closed hood to isolate the drying process from the machine hall. The hood prevents an overspreading of moisture, heat, and noise. [5]

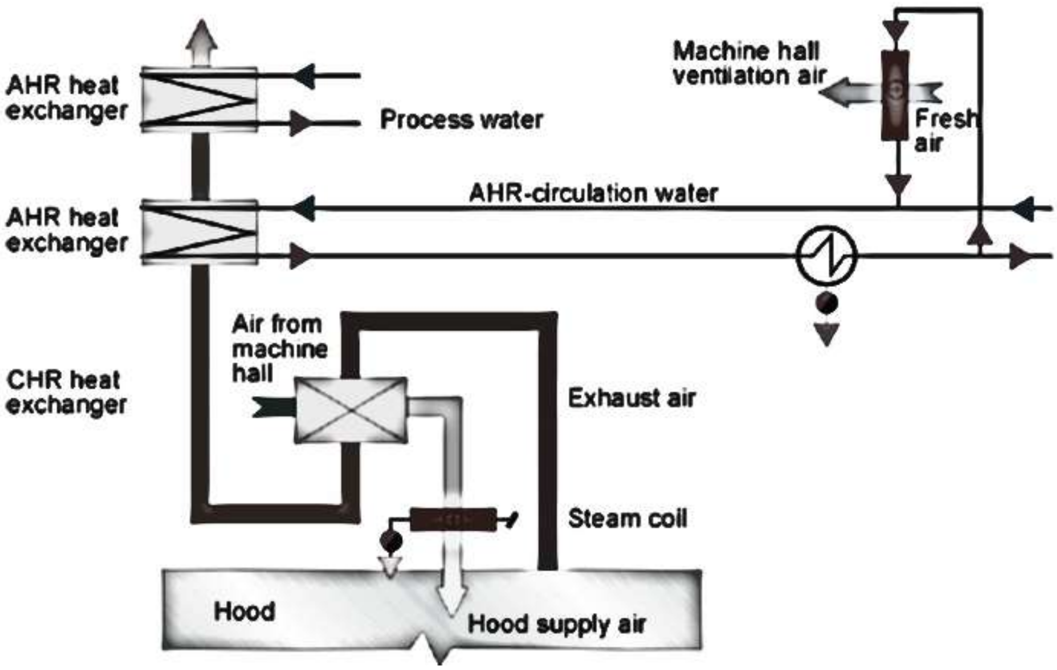

Figure 19. Heat recovery system of the hood of the paper and paperboard machines [5].

The drying section releases enormous amounts of heat during the process. Most of that heat is recovered by a heat recovery system illustrated in figure 19. As can be seen in the figure, heat released from the hood is used to heat the supply air for drying and to heat the circulation water used for ventilation, space heating, and domestic hot water. When necessary, process water is also heated by the heat recovery system. The heat recovery system covers a major part of the heating demand, but the exact amount of heat depends on the factory.

5.3.1 Heating Demand

As mentioned above, the heating demand in the factory comprises mainly ventilation, space heating, domestic hot water, and the heating of the false ceiling. Space heating and domestic hot water are mostly needed for offices. Ventilation includes the ventilation of the machine hall, offices, and electrical rooms. The false ceiling is a special part of the ceiling that is heated to prevent condensation. Process water needs a little in heating that can be disregarded because it is covered by a special recovery system. Table 4 illustrates the heating consumes that were taken into account in the analysis of the heating demand. T°in is the inlet temperature, or the temperature of incoming water from outside and T°out is the outlet temperature, or the temperature for a process.

Table 4 also illustrates the standard heating demand for each heating consumer. The total heating demand of the listed consumers is 33 900 kW. Domestic hot water is marked in orange to underline its high temperature difference, which is 50°C, and it can only be partly heated with a heat pump due to the high temperature. This factory has a backup system for cold weather conditions, shutdowns of the paperboard machine, and when heat provided by the standard system is not enough. A power plant next to the factory supplies it with a steam back up system. The steam system consists of two heat exchangers with a total capacity of 48, 000kW. The steam back up system is used for maximum heating demand. However, only the standard heating demands are listed in the table.

Table 4. Standard heating demand of different consumers.

Heating consumers	Standard heating demand	T°out	T°in
Hall ventilation	32,000 kW	55°C	25°C
Special rooms ventilation	2,200 kW	55°C	25°C
False ceiling	300 kW	60°C	45°C
Space heating	100 kW	55°C	25°C
Domestic hot water	200 kW	55°C	5°C
Total	**34,800 kW**		

As mentioned above, the paperboard factory has a heat recovery system with a high heating capacity. This heat recovery system has to be taken into account in the analysis. The factory has four heat recovery units with a total heating capacity of 46, 000 kW, where each unit has a capacity of 11, 500 kW. The heat recovery system only supplies the HVAC system in this factory, and heating demand with outlet temperature of 55°C and lower is covered by this system. As can be seen in table 4, the heat recovery system can easily cover all ventilation in the paperboard factory, and, for underline the processes, they are marked in purple. Since the heating of ventilation is covered by the recovery system, it can be deducted from the analysis of the heating demands: 46000kW - 32 000kW - 2 200kW = 11 800 kW. About 11 MW of heat produced by the heat recovery system can be used for heating other heating consumers listed in the table.

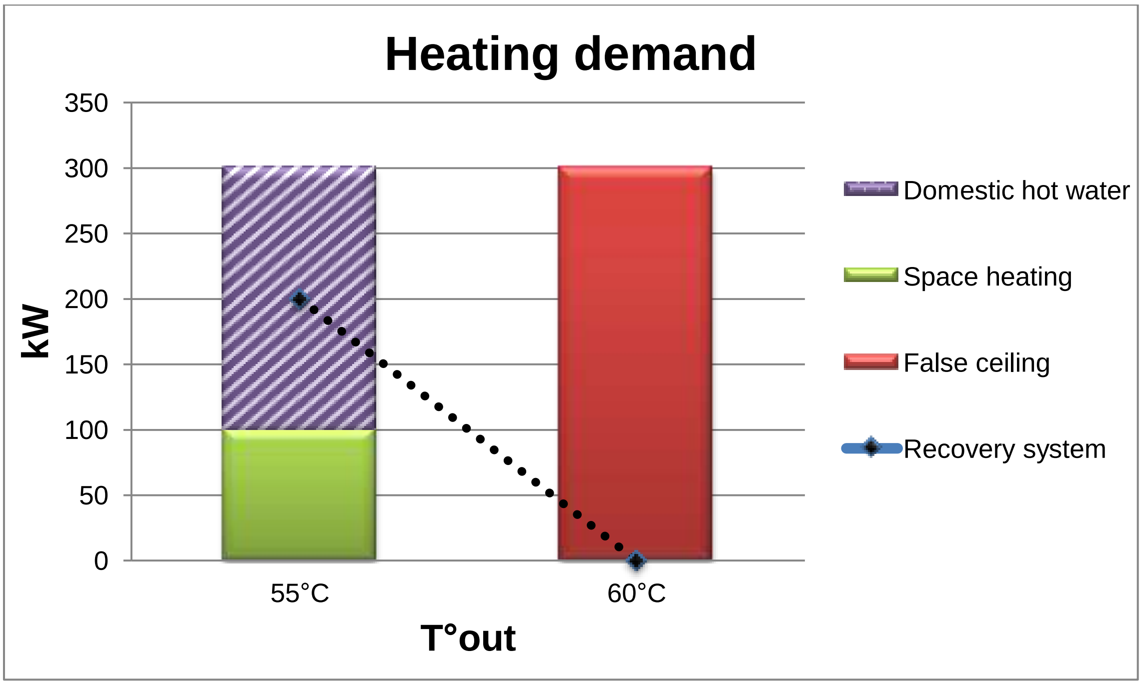

Figure 20. Heating demand based on required temperature.

Figure 20 illustrates the other heating consumers except for ventilation, and, as seen in the figure, the heating demand with outlet temperature 55°C is covered by the heat recovery system. However, domestic hot water can only be partly heated by the heat recovery system because the temperature difference of inlet and outlet temperatures is too high for a heat pump. Due to a higher temperature, the false ceiling cannot be covered with the recovery system. Therefore, the heat pump can only be applied for heating the false ceiling and partly heating the domestic hot. The total demand of the processes is about 400 kW, which too low a heating demand for a heat pump application. Additionally, a heat pump can be used for suppling space heating of the offices on higher outlet temperatures than the heat recovery system, and this change could help to decrease the size of radiators. Even taking into account the offices demands, the maximum heating demand for a heat pump is less than 500 kW. This means that it is unfeasible to use a heat pump as a waste heat recovery option inside the factory. The selection of a heat pump form the manufacturing company is inapplicable in this case because a heat pump is an infeasible solution.

5.3.2 Cooling Demand

According to heating analysis, a heat pump is an unfeasible solution for waste heat recovery in the paperboard factory. However, a lot of heat is released from cooling processes and HVAC system to the lake next to the factory. Around 18, 000 kW of heat with a temperature of 35°C is wasted from the factory. An alternative solution would be to use heat pumps to recover the heat and transfer it to a city or a town that is close to the paperboard factory.

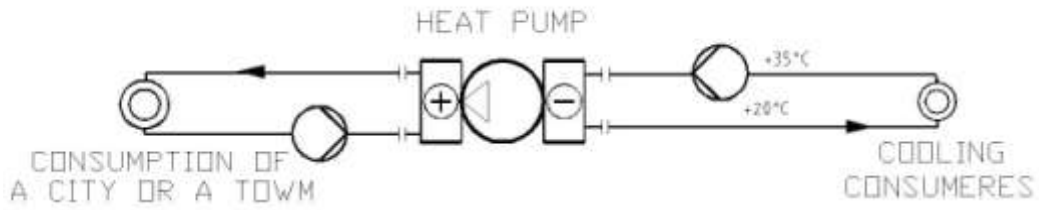

Figure 21. Possibility of connecting paper factory with a city or town.

Figure 21 demonstrates a schematic diagram of this solution. Around 22, 000 kW of heat could be provided to the city or town depending on the heat pump data. It could solve the problem with waste heat at any paper factory. Moreover, part of the heat could be used instead of steam for the factory purposes. The payback period of this alternative can be quite long depending on many factors, but it would improve the energy efficiency of paper industry and the sustainability of the sector.

5.3.3 Heat Pump Feasibility

As mentioned above, a heat pump is an unfeasible solution as a waste heat recovery option because of insufficient demands from heating consumers. Even taking into account that the cooling consumers have enormous heat losses, a heat pump is a useless option because the heat produced by a heat pump would be wasted without sufficient demand from the heating side. This paperboard factory has some difficulties with use of a heat pump for recovering waste heat. First, an existing recovery system has similar temperature requirements for heating consumers as heat pump. It is complicated to place an additional waste heat recovery system that produces heat at the same temperature level. The temperature is another factor in this case because the heating system has insufficient demand in temperatures suitable for a heat pump application. Most processes in the paperboard factory use steam for temperatures at over 100°C. The last factor is the fluctuating heating demands, which have an impact on long payback period and low operation time.

The reasons mentioned above lead to a conclusion that a heat pump is not a feasible solution to solve waste heat problem in this case. Sometimes, a heat pump may not be a better alternative for decreasing the amount of excess heat even when taking into account its sustainable features. As a result, other possibilities have to be considered for the waste heat recovery problem. An optional alternative for paper industry is selling the waste heat released from the cooling system. One possibility of selling the heat is described in this chapter, which includes the use of heat pumps, and future studies can look further into this possibility.

6 Conclusion

An industrial heat pump is a versatile solution that can be used not only to provide heating and cooling, but also to decrease the amount of heat that is wasted in the industrial sector. Waste heat is an essential problem for the sector especially when it comes to sustainability. A heat pump is a proper solution for recovering that heat due to the energy and cost efficiency features of it. Moreover, the heat pump minimizes the harmful effect that waste heat has on the environment because it was refrigerants with low GWP. As a result, all three main aspects of sustainability are incorporated in the heat pump.

The thesis concentrated on solving the waste heat recovery problem by using a heat pump and identifying how feasible a heat pump can be in different industries. From a waste heat recovery perspective, a heat pump is a promising solution, especially with a combined heating and cooling option. General instructions for checking the feasibility of an industrial heat pump is a complex process that has to take various factors into account. The thesis illustrates one way to analyze the feasibility of applying a heat pump to reduce waste heat. The analysis focused on the heating and cooling demands, and the temperature range of these demands. Based on the analysis of the demands, it is possible to rapidly determine how useful a heat pump can be for waste heat recovery in a specific industrial project. Moreover, preliminary heating and cooling capacities of a heat pump can be identified by means of the analysis presented in the thesis. The analysis, the main objective of the thesis, can be used as a practical instrument by Pöyry Oy in its future projects.

Two case studies were presented in the thesis to explore the use of a heat pump for waste heat recovery. The cases were completely different from each other and a conclusion of them was different as well. The first case from the food industry illustrated a perfect possibility for a heat pump application that can save about 1 MW of heat that otherwise would be released in the atmosphere. The second case from the paper industry demonstrated an alternative were a heat pump may not be a suitable option for waste heat recovery due to various barriers. The cases emphasize that the heating and cooling demands of a factory have to have minimum daily fluctuation for an optimal heat pump application in waste heat recovery. Moreover, there must be a sufficient demand for heating and cooling to use a heat pump as a combined heating and cooling solution. Also, other heat recovery systems have an enormous impact on the decisions about a heat pump application as was seen in the second case. An existing heat recovery system can minimize the need of a heat pump as a solution for waste heat recovery.

The results of the thesis can be applied for further study into the use of heat pump applications in waste heat recovery. Furthermore, following studies can concentrate on providing a solution for waste heat recovery problem in paper and pulp industry with the suggested solution in this thesis as a starting point.

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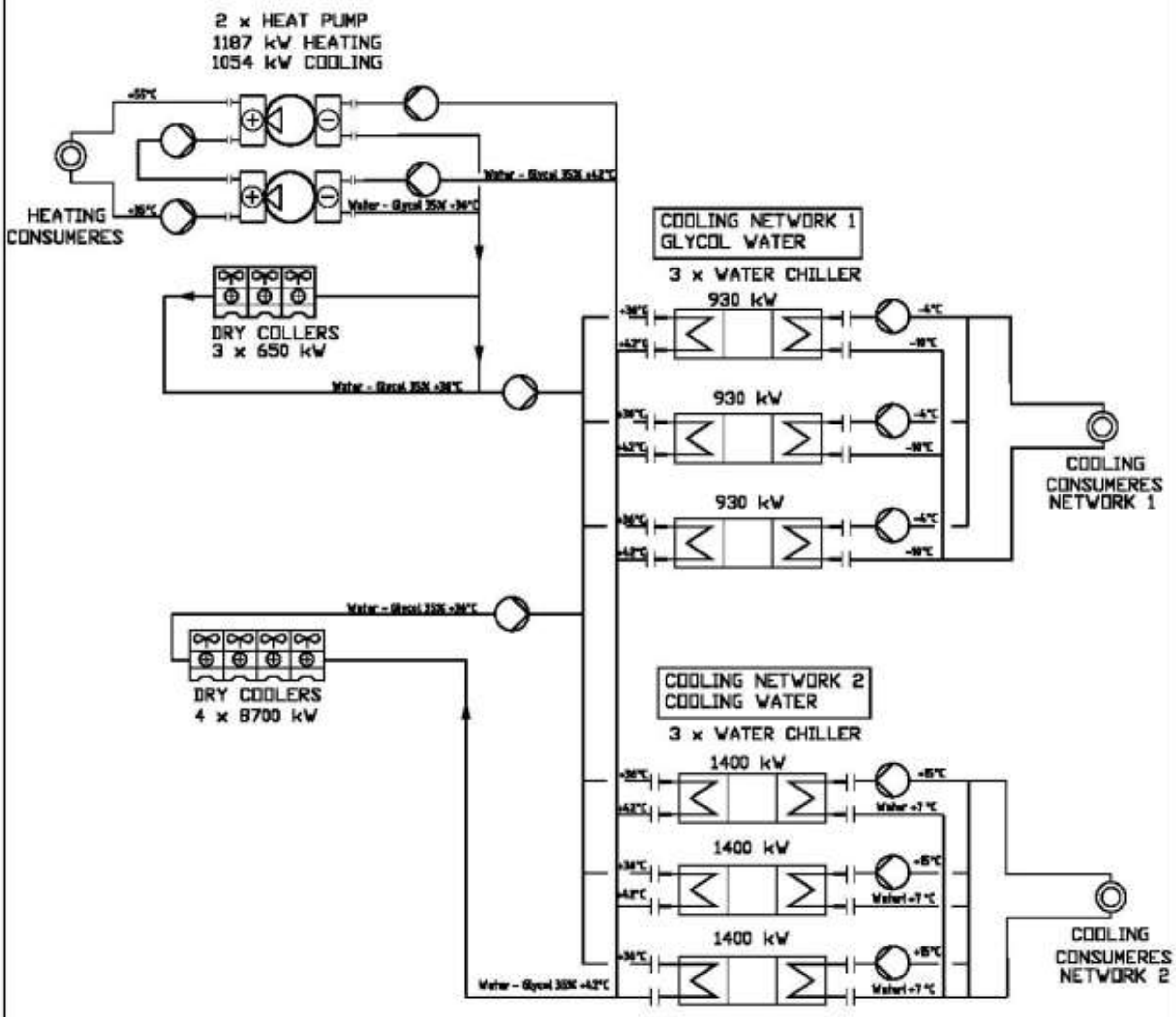
APPENDIX 1



CASE STUDY 1	PÖYRY	PRINCIPLE HEATING AND COOLING WATER DIAGRAM WITH HEAT PUMP