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Feasibility study of waste heat recovery from laundry facility
Case study: Mr Washing Man Oy

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The purpose of this thesis was to study the feasibility of waste heat recovery from laundry facility of a company Mr Washing Man Oy. The usefulness of heat recovery was determined from wastewater leaving the washing machine at 60^{o}C and 0.11 kg/s and hot air exiting from dryer at a temperature of 90^{o}C and at a flow rate of 1.5 kg/s. Thesis project focused on the description of system, calculation of the energy savings, case studies of heat exchangers suitable for waste heat recovery system and pinch analysis of the system. Distance between recovery system and consumer, compatibility, accessibility, quality of heat source, upgrading requirement, flow rate and legislation were also studied for feasibility considerations.

The result of the thesis project suggests that a significant amount energy available in waste water and dryer exhaust air that can be harnessed, and this would save approximately €40,000 per year. Extracting 650 MWh of energy per year is a compelling benefit for climate and environment as well. In terms of maintaining minimum distance between recovery system and consumer, accessibility and legislation, the heat recovery is feasible with some necessity for further considerations in flow rate, quality of heat and compatibility because of their correlations.

Experimental observations within the process for parameters such as temperature, mass flow could lead to more reliable and accurate energy output and savings. For further research, study of heat pump in series in colder exhaust from heat exchanger to heat the water further is recommended. This integration of heat pump and heat exchanger might harness higher overall energy from the process compare than an individual system.

Keywords	dry cleaner, laundry, heat exchangers, heat recovery, energy saving, pinch analysis

Acknowledgement

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Contents

List of Abbreviations

CHP	Combined heat and power
GCC	Grand composite curve
HCC	Hot composite curve
CCC	Cold composite curve
HP	Heat pump
LMTD	Log mean temperature difference
NTU	Number of transfer units
ϵ	Effectiveness
EHHE	Ecowec hybrid heat exchanger
U	Overall heat transfer coefficient of heat exchanger
$T_{c,in}$	Inlet temperature of cold water
$T_{c,out}$	Outlet temperature of cold water
$T_{h,in}$	Inlet temperature of heat source
$T_{h,out}$	outlet temperature of heat source
C_p	Specific heat capacity
ΔT	Temperature difference
$\dot{Q}$	Rate of heat transfer
$\dot{m}$	mass flow rate
C_h	Heat capacity rate of heat source
C_c	Heat capacity rate of cooler source
HVAC	Heating ventilation and air conditioning

1. Introduction

This project aimed to study the feasibility of waste heat recovery from laundry facility. The focus was on the usefulness of heat recovery from waste water leaving washing machine and hot air exiting dryer at specific temperature and flow rates.

A significant amount of heat energy in residential buildings is released into atmosphere along with wastewater and dryer exhaust air. This process of discharging of heat to atmosphere does not seem to be slowing down. In Finland, on average, 155 litres of water is used per person per day, of which 13% is used by the laundry [1]. 15-30% of heat losses take place via waste hot water [1]. According to (Motiva, 2012) 7.1 TWh of energy is being flushed into the drain each year, and up to 4 TWh of this waste heat could be recovered and reused profitably each year. This amounts to the burning of more than 25% of coal for energy production. A considerable amount of fossil fuel is being burnt for generating energy for consumption in households, industries and organizations. This exploitation of traditional fuel causes CO_2 emissions leading to global warming. This impact on environment affects flora and fauna including human health.

Generally, heat is extracted either after water is treated at a treatment plant or in a heat recovery plant, by then, a considerable amount of heat is lost already. Sewage heat recovery technology has been practiced throughout the world in recent years with different capacity. Switzerland has been practicing it for a long time and also some other countries including Germany and the Netherlands. In Finland Helsinki Energy (HELEN) has been using sewage heat recovery as a supplement to its district heating and for a cooling plant in Katri Vala, Helsinki. In winter, the wastewater after treatment from Viikki wastewater treatment facilities is pumped to the heating and cooling plant where heat energy is extracted using a heat pump. Different inventions and approaches in wastewater heat recovery are also described in chapter 9.

The application of a waste heat recovery system can play a crucial role in saving heat loss, reduce adverse impact on environment and make profit for the companies at the same time. The energy harnessed can be utilized for different purposes such as hot water utilities, space heating and heating ventilation air. Implementation of waste heat recovery would contribute offsetting greenhouse emission in some proportion. Energy saving can be achieved not only by recovering heat as required instead but also by preheating the source. According to Helppolainen [1], when temperature of domestic water is preheated from 8ºC to 15ºC before the heating system, this will cut 30% of the energy required for domestic water heating.

2. Background

This thesis work was done for the company Mr Washing Man Oy, located in Käpylä district Helsinki (see Figure 1). The company was renamed to Mr Washing Man Oy from Pesula Vaahto and prior water used to be heated by wood burning. Now the company owns 1 industrial scale and 1 small scale dryers including 2 washing machines. Hotels and restaurants are the major customers of the company but the, company is not interested in personal clothes due to lack of space to store. The commercial facilities need the clothes as soon as possible, which is more convenient for Mr Washing Man Oy. The company offers a service of collecting the clothes from the site and as well as returning them after being washed and dried.
During 1952 Olympic games, the place was used as players' accommodation. Since then it has been prohibited to make any modifications in architecture of the building. But now the neighbourhood people are allowed to own houses and apartments.

The aim of this project was to recover heat from wastewater discharged from washing machine and from dryer exhaust air. Laundry uses electricity for washing purposes and ignites natural gas for drying purposes. The excess hot air is released into atmosphere and hot waste water is drained away in sewage. As stated above, this can have a significant effect on the carbon footprint. Washing machines and dryers operate 13 hours a day and 6 days a week. Laundry processes approximately 100 kg of clothes per day using 125 m^3 of cold and 28 m^3 of hot water is used per month.

A limited number of studies have been done in small-scale heat recovery either from wastewater or dryer exhaust. This thesis aimed to determine whether it would be feasible to recover heat for further utilization where dryer and washing machine operates certain hours a day. Further utilization of recovered heat by using air-air or air-water heat exchanger for water heating was investigated. Prospective commercial heat exchangers were studied as a case study. This study shed light on the possibilities of recovering heat from the water exiting washing machine and the hot and moist air exiting from the dryer in small scale. The amount of energy available in the exhaust will be calculated along with economic considerations. The additional data regarding parameters and their values for wastewater and dryer exhaust are explained in chapter 4 System description .

Figure 1 Google image of Laundry Site

3. Literature review

Pulat E.et.al. in [2] have done a thermodynamic and economic analysis of waste heat recovery potential in textile industry in Turkish textile industry. The study illustrates that with a heat transfer rate of 2020 kW, heat transfer area of 228.4 m^2 and a 0.92 effectiveness of shell-and tube heat exchanger, the payback period was less than 6 months. It was explained that parameters such as wastewater inlet temperature, flow rate, cooling water inlet pressure and dead state conditions are crucial factors that affect the performance of the system.

Liu L. et al. [3] have studied the application of exhaust heat recovery from public shower facilities via heat pump. They found that the application was beneficial in comparison with oil-fired, gas fired or even electric boilers in terms of energy consumption, pollution and operating cost. O. Culha et al.[4] have studied the application of heat exchangers in sewage heat recovery where researcher have classified different heat exchanger types according to different features including utilization and construction methodology applied. Noting the importance of heat exchanger in sewage heat recovery, authors have claimed that heat exchangers need to be designed according to requirements of transfer process, and at the same time, the design to overcome fouling, blocking and corrosion needs to be considered. Alnahhal S. and Spremberg E. [5] found in a separate experimental study that in-house wastewater energy is approved as a crucial source of energy that can be extracted providing a significant impact on hot water demand.

Another study on the laundry dryer exhaust heat recovery in the university dorm was done by students from Rochester University of Technology [6] found that harnessing dryer heat is feasible in terms of saving energy and water. Similar experimental study done by Baggett John et al. [7] concludes that dryer waste heat recovery systems are feasible for commercial establishment such as hotels, laundromats, and hospitals. The result suggests that service water at 4ºC was able to be heated up to 33ºC with a saving of $3.90 per day which does not seem significant, but still it is technically feasible and environmentally and socially beneficial.

A major concern in previous studies was about mass flow rate and temperature of exit water including the quality of waste water. The system can be designed according to the requirements and in some cases integration of heat exchangers and heat pumps was suggested to boost the energy available in wastewater.

Very few studies have been found on dryer heat recovery for the purposes of hot water utility, space heating or any other function. Meanwhile, studies have been done for capturing heat and releasing it within the premises using exhaust deflector, but in most cases air is dumped into atmosphere. In case of dryer exhaust heat recovery there are concerns over the source of dryer operation i.e. whether the dryer is electric powered or gas powered. Electric powered dryer emits less carbon monoxide into the atmosphere in comparison to gas-fired hence this factor has also been suggested as a factor to be taken into account while designing the system.

4. System description

The laundry premises operate 2 washing machines and 2 dryers. Introduction of each source system, their parameters, values and units will be explained in succeeding section.

4.1 Wastewater

Company situated in Käpylä district Helsinki operates the washing machines 13 hours a day and 6 days a week. The operation of the machine depends on the load, and the operating time is assumed to be fluctuating. The average operation time is considered to be 13 hours a day from 7 to 20. The machines use hot and cold water both for washing clothes where 125m^3 of cold water from is used from 7 to 20 per month, which is heated by natural gas whereas, 28m^3 of hot water is used, which is heated by the district heater heat exchanger.

Figure 2 shows the washing machines and dryers in the site and water exit pipings.

Figure 2. Washing machine and dryer's (a) and washing machine water exit (b)

In average 100kg of clothes items such as table cloth, bed sheets from restaurant and other commercial complexes are washed. Personal clothes are not washed in the laundry facilities due to lack of storage facilities. The exit temperature of waste water from washing machine is averaged to 60^{o}C. Without conducting an experiment, the flow rate of exit water was assumed on the basis of cold water used per month, which gives 0.11 kg/s. The wastewater values are summarized in Table 1.

Table 1 Summary of wastewater values

Parameters	Values	Units
Exit Temperature	60	^oC
Flow rate	0.11	kg/s
Specific heat capacity	4.8	kJ/kg.K
Cold water	125	m^3
Hot water	28	m^3
Operating time	13	hours/day
Washing machine	2	

4.2 Dryer exhaust

There are 2 dryers with separate exhaust in the premises: one large-scale, natural gas heated mangle dryer and other operates electrically. Like the washing machines, dryers are operated 13 hours a day and 6 days a week depending on the load. The mangle dryer operates by igniting natural gas. The mangle is a mechanical laundry aid consisting of two rollers in a sturdy frame, connected by cogs and, in its home version, powered by a hand crank or electrically (Figure 3), mangles are used to press or flatten sheets, tablecloths, kitchen towels, or clothing and other laundry [8].

Figure 3. Mangle dryer (a) and dryer exhaust (b)

As shown in the Figure 3, the dryer exhaust has different exit diameter throughout the section; therefore the differential diameter was excluded, and it was assumed that the mass flow was consistent throughout the exhaust. Due to the complexity of measurement, reasonable estimation was made for different parameters such as flow rate and temperatures. Flow rate of hot flue gases via the exhaust was assumed to be 1.5 kg/s with 90°C temperature and constant throughout the operation. It was assumed that most of the flue gases were hot air. Variation of moisture removed from cloth after drying was not taken into account.

Parameters, values and their units taken into considerations are listed in Table 2.

Table 2 Summary of dryer exhaust values

Parameters	Values	Units
Temperature	90	°C
Flow rate	1.5	kg/s
Density of air	1.225	kg/m^3
Specific heat of air	1.006	kJ/kg.K
Operating time	13	hours/day
No. of dryer	2	
Capacity factor	not considered	

In addition, the parameters for service water to be heated were considered and are given in Table 3.

Table 3 Summary of service water values

Parameters	Values	Unit
Inlet temperature	5	°C
Flow rate	0.5	kg/s
Specific heat	4.18	kJ/kg.K
Target temperature	39	°C

5 Review on heat exchangers

Different heat exchangers that have been used in waste heat recovery system are described below. To accomplish the objective of this project, the appropriate heat exchanger was studied based on different initial parameters. The heat exchanger can be defined as a device which helps to transfer heat from one media to another with different temperature levels. The media in heat exchanger could be, for example, liquid-liquid, air-liquid or air-air which flow either co-current or counter-current. The basic working principle of the heat exchanger is that transfer of heat takes place between a medium with high temperature and a medium with low temperature via conduction and convection. Application of heat exchangers in wastewater heat recovery can be classified according to the volume flow, temperature, and the place of heat extraction.

There are various heat exchangers in operation depending on the heat transfer process, materials, temperatures and the heat exchangers can also be classified depending on system requirements. The general classification is direct contact heat exchanger and indirect contact heat exchanger. In direct contact, two medium get mixed, and in case of indirect contact, heat transfer takes place via surface between hot and cold medium. The heat exchanger is mostly used either for cooling or heating purposes, so application of the heat exchanger varies depending on the requirements. Heat exchangers are used, for example, in the different sections of CHP power plants, in district heating systems, and in waste heat recovery in different process industries. A schematic illustration of co-current and counter current heat exchangers and their respective graphs are shown in Figure 4 and Figure 5 respectively.

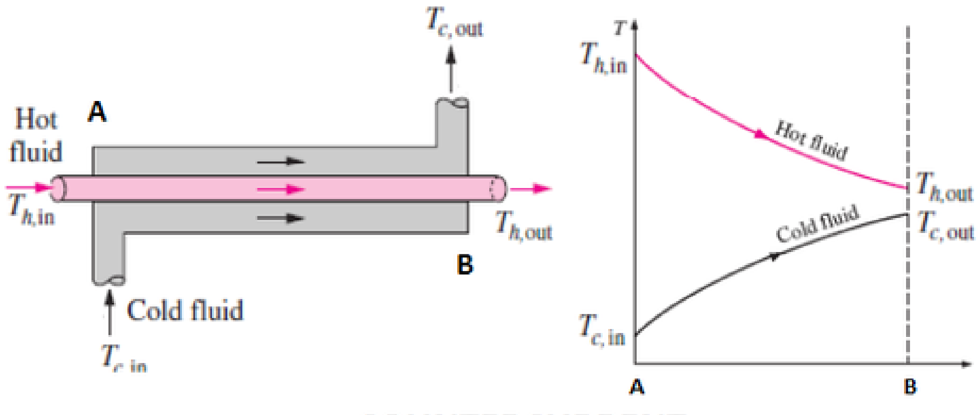

Figure 4 Co-current flow of fluid [9]

In co-current heat exchangers, two active fluid flows in the same direction and their respective temperature variation curve is shown on the right.

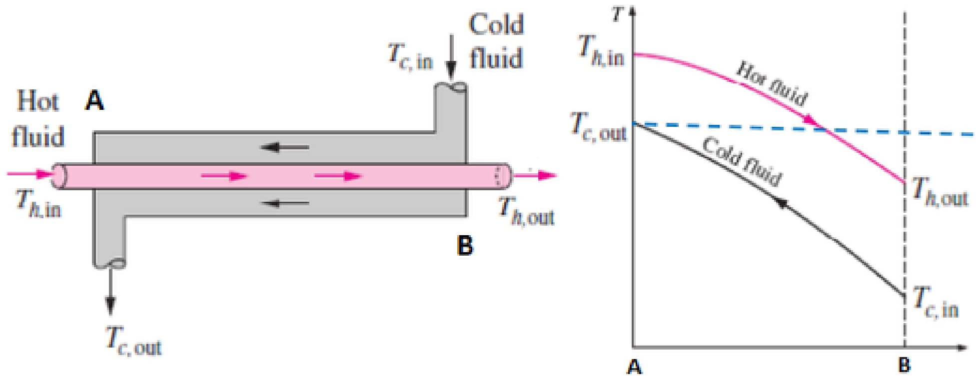

Figure 5 Counter-current flow [9]

Counter-current heat exchanger with flow of active fluid is shown in Figure 5. In this case outlet temperature of the cold fluid can also exceed then outlet temperature of the hot fluid [9] as shown in graph.

Some of the indirect heat exchangers that are mostly used in waste heat recovery, and their applications are be described in following sections.

5.1 Compact heat exchanger

Compact heat exchanger is generally used in gas-gas and gas-liquid medium where the fluid flow is perpendicular to each other making the flow as cross flow. The advantage of the compact heat exchanger is that it enables the large heat transfer area in small volume, which is also the design purpose of the compact heat exchanger. The ratio of the heat transfer surface area of the heat exchanger to its volume is called the area density, and represented by β. The heat exchanger with $\beta > 700\ m^2/m^3$ is classified as being compact [9]. The examples of the compact heat exchangers are car radiators (1000 m2/m3), glass ceramic gas turbine heat exchangers (6000 m2/m3), the regenerator of a Stirling engine (15,000 m2/m3), and the human lung (20,000 m2/m3) [9].

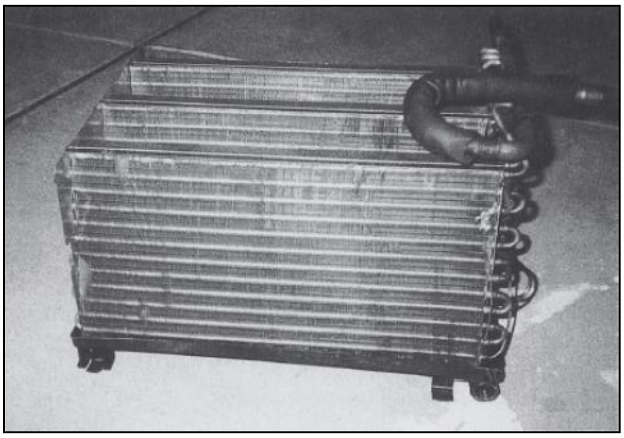

Figure 6 Compact heat exchanger [9]

5.2 Shell-and-tube heat exchanger

The shell-and-tube heat exchanger consists of large numbers of tubes packed inside the shell. One of the fluid flows inside the tube, while other flows outside. The shell-and-tube heat exchanger can be further classified depending on the number of shells and number of shell-passes it contains. These numbers of shell helps in the effectiveness of heat transfer. These heat exchangers are commonly used in industrial applications such as oil refineries and other chemical processes and are suitable for high pressure applications [9]. Meanwhile, due to the large size and weight, these heat exchangers are less suitable for automotive and aircraft applications [9].

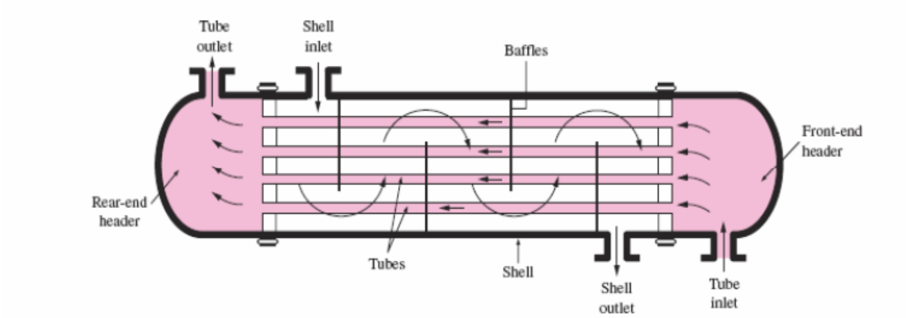

Figure 7 Shell-and-tube heat exchanger [9]

5.3 Finned tube heat exchanger

In finned tube heat exchanger, heat transfer takes place between the fluids by the conduction through the tube wall. Process liquid is pumped through one end of the tube (whether round or rectangular) which then absorbs or rejects heat to the air or gas depending on the application. The finned tube heat exchangers are employed when one fluid stream is at the higher pressure and/or has a significantly higher transfer coefficient than that of the other fluid stream [10].

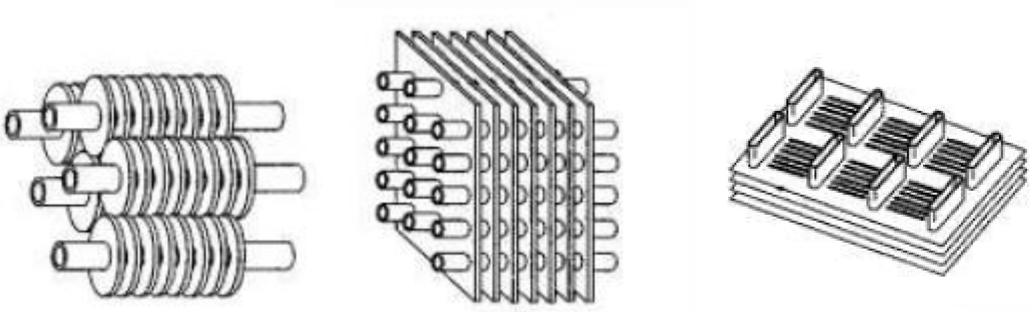

Figure 8 Circular finned tube (a), Plate finned tube (b) and Louvered plate fin flat tube (c) [11]

Three different types of the finned tube heat exchangers are shown in Figure 8. They differ in the design consideration and their application. Heat pipe, a specialized type of finned tube heat exchanger has been also used in wastewater heat recovery. The finned tube heat exchangers are mainly used in industrial and consumer product oriented waste heat recovery applications.

5.4 Plate heat exchanger

The plate heat exchanger consists of series of plates with corrugated flat flow passages. The hot and the cold fluid flows in alternative passages, where the cold fluid is surrounded by hot fluid making the heat transfer process more efficient. The size of heat exchanger can be made larger by simply adding number of plates. The plate heat exchangers best suits for liquid-liquid heat exchange applications provided that the hot and the cold fluids are in the same pressure [9].

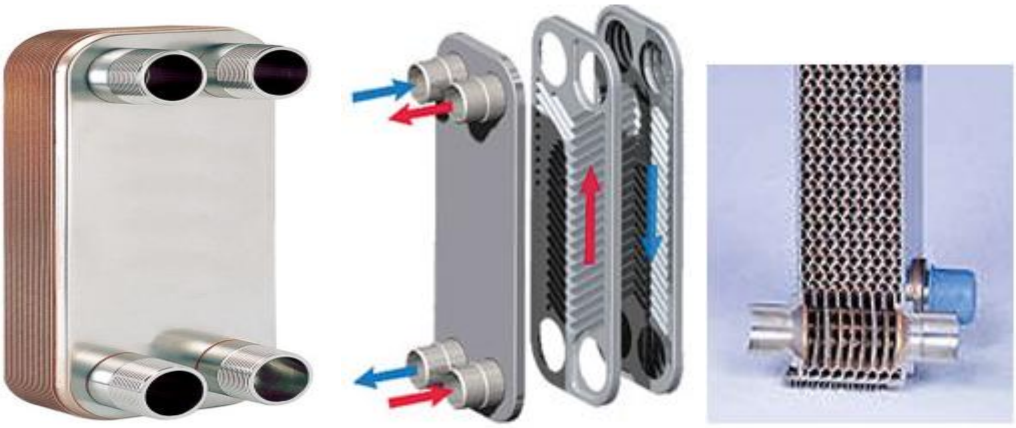

Figure 9. Plate heat exchanger, plates (b) and heat transfer surface(c) [12]

5.5 Gravity film

The gravity film heat exchanger is mostly used in domestic drainage systems where the flow and the temperatures are not consistent. This is a counter flow heat exchanger which is vertical in design and extracts heat from the wastewater to heat the water. The gravity film heat exchanger is installed around the particular section of the drainage pipe that carries warm water. The simple design, working principle, and little thermal mass of gravity film heat exchanger makes less effective in larger application. The sketch of gravity film heat exchanger is shown in Figure 10.

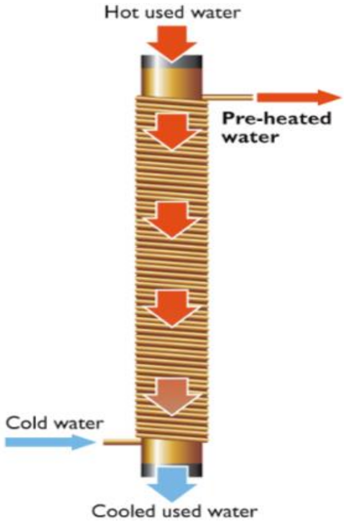

Figure 10 Gravity film heat exchanger [13]

5.6 Helical heat exchanger

The helical heat exchanger is best suited in the process industries such as gas processing, refining, petrochemical and chemical industries. Generally processes with high pressure, temperature, and low flow applications and also according to heat demand requirements helical heat exchangers are applied.

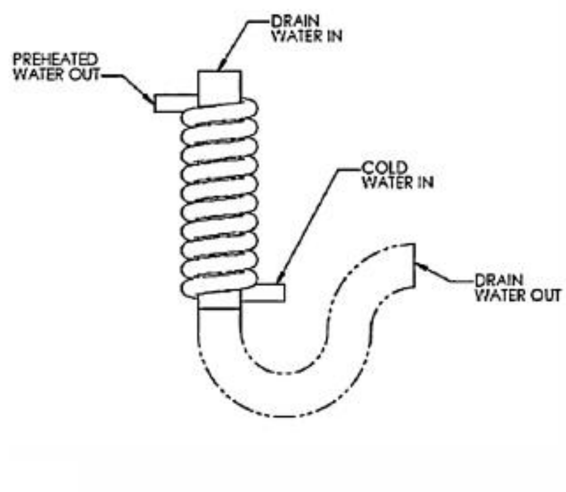

Figure 11 Helical heat exchanger [4]

Some of the heat exchangers used in sewage treatment depending on domestic, sewage and after treatment is classified in Table 4.

Table 4 Classification of heat exchangers [4]

Domestic	Sewage	After treatment
Gravity-film	External Type	Spray
Spiral/Helical	Integrated Type	Plate
Plate	Modular Type	Pressure Pipe
Shell-and-Tube	Special design	Helical

6 Heat exchangers application characteristics

The classification of different heat exchangers used in wastewater heat recovery on the basis of temperature, cross-contamination, and working fluids are listed in the Table 5.

Table 5 Operation and application characteristics of heat exchangers [14]

Specifications of Recovery unit	Temperature0-120°C	Temperature120-650°C	Temperatureabove 650°C	Recovers moisture	Large Temperature difference permitted	Can be retrofit	No Cross contamination	Gas-gas heat Exchanger	gas-Liquid Heat Exchanger	Liquid-Liquid Heat Exchanger

Heat Exchangers										
Shell-and-Tube Exchanger	√	√			√	√	√		√	√
Finned-tube Heat Exchanger	√	√			√	√	√		√	
Waste heat Boiler	√	√				√	√		√	
Spiral Heat Exchanger	√	√				√	√			√
Concentric Tube Heat Exchanger	√	√			√	√	√		√	√
Concentric Tube Heat Exchanger Recuperator		√	√		√	√	√	√		
Plate Heat Exchanger	√	√			√	√	√	√	√	√
Round around System	√	√			√	√	√	√	√	√
Heat Wheel Metallic	√	√				√	**	√		
Heat wheel hydroscopic	√			√		√	**	√		
Heat Wheel Ceramic		√	√		√	√		√		
Heat Pipe	√	√			*	√	√	√		

*Allowable temperature and temperature differential limited by the phase equilibrium of the internal fluid.

** Can be limited to <1% by mass

7 Heat exchanger analysis

General consideration should be made for the simplicity of analysis of the heat exchangers before performing calculations. These considerations are approximated in practice as well, which are mentioned below.

- The heat exchanger can be modelled as a steady device with no change in operating conditions [9],
- The outer surface of heat exchanger is completely insulated,
- The kinetic and potential energy change are negligible,
- The axial heat conduction along the tube is negligible,
- Specific heat of the fluid throughout the tube is constant,
- The individual and overall heat transfer coefficients are constant (Independent of temperature, time and position) [10]

While selecting heat exchanger, available factors and factors to be calculated need to analyse before. For practical considerations, effectiveness of heat exchanger is used instead of efficiency. The effectiveness, denoted by ϵ (epsilon) for the heat exchanger is formulated as

$$\epsilon = \frac{Thot,out - Thot,in}{Thot,in - Tcold,in} \quad 1$$

$$\epsilon = \frac{Actual\ heat\ transfer}{maximum\ possible\ heat\ transfer} \quad 2$$

Case 1;

When the inlet and the outlet temperature of both hot and cold fluids including the mass flow has been measured or available from previous study, then the heat exchanger type can be selected. In first case, we choose logarithmic mean temperature difference i.e. *LMTD method* to find the heat transfer surface area of the heat exchanger. In some cases this method is useful to calculate the heat transfer coefficient. Mathematically, LMTD is represented as following

$$\text{LMTD} = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T1}{\Delta T2})} \quad 3$$

Where ∆T1 represents temperature difference between the hot and the cold fluid at one end and ∆T2 represents the same at other end.

Further using the equation,

$$Q = U * A * LMTD \qquad 4$$

We can now calculate surface area (A) of the heat exchanger and also overall heat transfer coefficient (U) provided $\Delta T1$ and $\Delta T2$. It should be noted that the average temperature difference (LMTD) is dependent on flow arrangement and type of construction of heat exchangers [9]. Equations 3 and 4 are valid for any heat exchanger type given the temperature differences of end points in a parallel flow case.

Case 2;

When the heat exchanger type and size is known along with flow rates and inlet temperatures then outlet temperatures of two exiting fluids and the heat transfer rate can be figured out.

In this method, predefined heat transfer effectiveness of heat exchanger (ϵ) is used.

$$\epsilon = \frac{Q}{Qmax} \qquad 5$$

Where $\dot{Q}$ is actual heat transfer rate and can be determined by

$$\dot{Q} = C_c\,(T_{c,out} - T_{c,in}) = C_h(T_{h,in} - T_{h,out}) \qquad 6$$

Q_{max} represents the maximum possible heat transfer rate in a heat exchanger i.e. $Q_{max} = C_{min} * \Delta T_{max}$

C_c and C_h represents the heat capacity rate of the cold and the hot fluid respectively. In heat exchanger, the heat capacity rate and temperature change are inversely proportional i.e. fluid with higher heat capacity rates experiences lower temperature changes and vice versa.

Using equation 5 and equation 6 outlet temperatures can be calculated when mass flow rates and the specific heat capacities of the fluids are available.

8. Calculations

Values of the parameters obtained in the calculations are based on interview with laundry owner, unless otherwise stated. Considering a counter flow heat exchanger, amount of energy available in wastewater and hot air exhaust is as follows.

8.1 Wastewater case

Service water;

$T_{c,in}$ =5°C

Mass flow ($\dot{m}_c$) = 0.1112 kg/s

$C_{p,water}$ = 4.18 kJ/kg.K

Wastewater;

$T_{c,in}$ =60°C

Mass flow ($\dot{m}_h$) = 0.1112 kg/s

$C_{p,wastewater}$ = 4.18 kJ/kg.K

The number of transfer units (NTU) method was used depending on the available figures.

$C_h=\dot{m}_h*C_{p,wastewater}$ 7 [C_h ;heat capacity rate at hot side]

$C_c=\dot{m}_c*C_{p,water}$ 8 [C_c ;heat capacity rate at cold side]

The specific heat of both service and wastewater is assumed to be the same

C_h = 0.465189 kW/K

C_c= 0.465189 kW/K

C_{min}= C_h = C_h = 0.465189 kW/K heat capacity rate is same for both the hot and the cold streams.

Now the maximum heat transfer rate is determined by

Q_{max}= $C_{min}(T_{h,in}-T_{c,in})$= 0.465189*(60-5) i.e. [Cmin*∆max]

= 25.5 kW

Maximum possible heat transfer rate in this case is 25.5 kW. This can be referred to counter flow heat exchanger (*Figure 5 Counter-current flow [9]*), which means that the hot water cannot be cooled from 60°C to 5°C and the cold water cannot be heated higher than 60°C.

When the washing machine operates 13 hours per day and 6 days a week, than total energy available would be 25.5 kW *4,056h = 103 MWh per year

Now savings from heat recovered from wastewater can be obtained as saving = Q_{max} *€ /MWh.

Saving =103 MWh* 61.86 €/MWh

≈ 6,371 €/ year

The district heating price used is the winter price provided by Helen Finland [15].

The price used is for winter time and are subject to change throughout the year depending on the outside temperature.

8.2 Dryer exhaust case

Counter flow air-water heat exchanger is considered in this case.

Service water;

$T_{c,in}$ =5ºC

Mass flow ($\dot{m}_c$) = 0.5 kg/s

C_p = 4.18 kJ/kg.K

Hot air;

$T_{h,in}$ =90ºC

Mass flow ($\dot{m}_h$) = 1.5 kg/s

$C_{p,air}$ = 1.06 kJ/kg.K

The number of transfer units (NTU) method was used depending on the available figures

$C_h=\dot{m}_h*C_{p,air}$ [C_h ;heat capacity rate at hot side]

$C_c=\dot{m}_c*C_{p,water}$ [C_c ;heat capacity rate at cold side]

C_h = 1.59 kw/K

C_c= 2.09 kW/K

C_{min}= C_h =1.59 kW/K which is the lower of two heat capacity rates.

Now, the maximum heat transfer rate is determined by

$Q_{max}= C_{min}(T_{h,in}-T_{c,in})$= 1.59*(90-5) i.e. [$C_{min}*\Delta max$]

= 135 kW

This means maximum possible heat transfer rate in this case is 135 kW

When the mangle dryer operates 13 hours per day and 6 days a week than energy saving would be 135 kW *4,056h ≈ 547 MWh per year

Saving from recovered dryer heat can be obtained as saving = Q_{max} *€ /MWh. The district heating price used is the winter price provided by Helen Finland [15]

Saving =547 MWh* 61.86 €/MWh

= 33,837 €/ year

The available energy in wastewater can be used to heat water for hot water utilities. Meanwhile, uses for dryer exhaust can be pre-heating intake air for dryer, heating premises, and also heating water. Additional information is included in case study section, which comprises of utilization of waste heat in different form with the help of commercial heat exchangers and recovery units.

9. Case study

9.1 Wastewater

Finnish cleantech company *Wasenco,* established in 2014 is aimed to protect environment by different products and services. The Lahti based company focuses on reducing building's greenhouse gas emissions and the energy consumption. The company is committed to sustainable economic development, considering environmental values. The company is devoted in development, marketing and sales in one of its innovation called 'Ecowec hybrid heat exchanger' with limited carbon footprint over its 50-years' service life.

Ecowec hybrid heat exchanger (EHHE)

The EHHE recovers thermal energy from different sources including wastewater and dryer exhaust air. The system is ready to install during construction or renovation and it is suitable to use with various heating and cooling systems. The system is suitable in different places having large volume of wastewater such as launderettes, commercial buildings, hospitals, public pools, spa, hotels and even every block of flats.

The company claims that EHHE can process wastewater generated by up to 60 households and the capacity can be increased by arranging the system either in series or in parallel.

©Wasencco

Figure 12 Ecowec hybrid heat exchanger [16]

With no requirements of separate wastewater type, storage, cleaning, minimum maintenance, and remote monitoring system, company claims that the Ecowec system is cost-efficient also. Dimensions of EHHE are 155-208cm heigh and 55-95 cm wide and weigh 150-450kg when empty. The EHHE has an impact of 14 kWh/m^2 per year on the building's energy efficiency. Company further claims, Ecowec products with 30-70% efficiency annual level can save up to 30% energy with below 10 year of payback time.

Working principle

Heat transfer between wastewater and domestic water takes place via heat transfer surface. The materials and heat exchanging surfaces of EHHE meet the requirements of national building code of Finland. The heat source could be exhaust air, wastewater, vapour, and heat from refrigeration system, process water, solar heating and electricity. The application of recovered heat can be heat pump, domestic water, space heating and heating for air conditioning.

The wastewater from the source is directed to Ecowec unit where grey and black water flow through it all the way to bottom via spiral pipe. The heat contained in the wastewater is recovered and reused in the building. During this process the water does not accumulate in the tank rather after it is cooled it passes further immediately.

Resemblance with our requirement

This system seems to best fit in our situation, with ready-to-install. Firstly, the unit operates with both of the available energy sources in the laundry site; waste water and dryer exhaust hot air. Secondly, there are no moving parts and less energy consumption, which can be considered as overall benefit.

Most importantly the installation of device does not pose any risk to protected buildings which are prohibition for modifying; this complies with our desired situation. The device does not contain any moving parts, with no odours and noise with only requirement of $1m^2$ of space. The operation of the device is based on gravity, so system does not need electricity, although it is suitable for pressure sewers as well. It is a Finnish innovation and hence it satisfies Finnish legislative requirements.

Figure 13 EHHE connection with source and application [16]

9.2 Dryer exhaust

A significant amount of energy is lost from the exhaust of the mangle dryer in the form of heat. The amount of heat lost depends on the exhaust temperature and mass flow. The aim of the work was to extract this energy with practicing air-water counter-flow heat exchanger. Depending on the gas or electric dryer and the purpose of utilization of recovered heat, recovering techniques might different. Care is needed in case of gas dryer to avoid carbon monoxide releasing into room or building, if application is to heat ventilation air.

The efficient heat exchanger with a drain pump to remove condensed moisture from the dryer exhaust was assumed. The application of recovered heated air can have different form of application and end use; such as heating laundry premises, heat for hot water utilities, preheating the intake air of the dryer, which can be done whole year round.

There might be increment in need for separate outside air source as buildings have been designed with higher insulation. Paul bendt [17] suggests that it can also be possible to add a summer/winter selector so that in winter, recovered heat can be delivered to the building instead of releasing outside, this could reduce additional load on the HVAC system. But again this can trickier in case of gas dryer.

Commercial applications

The air/water heat exchanger would be suitable application to recover heat from dryer at temperature of 90°C. For this thesis air/water heat exchanger model *VLV 600* and *VLV 250* from Swedish company *Läckeby Products* were chosen. The company manufactures products for heat recovery and mechanical particle separation applications. The heat exchangers manufactured by the company has been used in Sweden is several wastewater treatment plants such as Käppala, Henriksdal, and also in abroad with air as the heat source. The company claims that the air/water heat exchanger can profitably utilise hot process air too. Furthermore, according to website of the company these units also recover heat for heating of ventilation air or tap water.

Working principle

Figure 14 Air/water heat exchanger [18]

Air/water heat exchangers are manufactured in stainless steel with cooper cooling tubes *[18]*. Water to be heated enters through one end of cooper loops and exits via another end (red arrow) after gaining heat from air as shown in Figure14. Air passes into heat exchanger parallel through the air pipe and being pressed against exchanger's wall and move further passing the wall of heat exchanger.

Resemblance with our requirement

Firstly, the unit is also being used in wastewater treatment plant for heat recovery with hot air as heat source. Secondly, the application of recovered heat from the unit is heating tap water which is similar to our requirement. Finally, the design parameters resemble approximately with our system description. Some of the parameters and their values available from Läckeby's website are mentioned in Table 6.

Table 6 Design parameters of model VLV 600 and 250 [18]

Parameters	Model VLV 600	Model VLV250
Air flow	15 000 Nm^3/h	2 250 Nm^3/h
Inflow air temperature	150°C	120°C
Outflow air temperature	59.3°C	44.6°C

Water flow	6 l/s	0.6 l/s
Inflow water temperature	10°C	10°C
Outflow water temperature	29.4°C	34.3°C
Power	489 kW	61kW
Air pressure loss	2	1.8

The air/water heat exchanger installed in wastewater treatment plant in sävsjö is shown in Figure 15

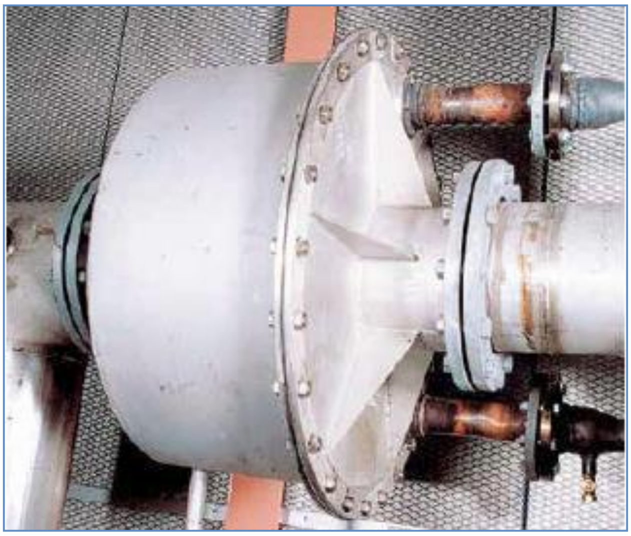

Figure 15 installed heat exchanger air/water VLV in sävsjö Sweden [18]

10. System placement

Several heat exchangers are available commercially, depending on different parameters such as temperature, flow rate, pressure drop and other design considerations. Heat exchangers can be applied at different sections of the sewage effluent depending on the source of sewage and its quality. The section to place exchanger systems can be considered depending on the piping cost and heat lost in transmission. Literature suggests 3 kinds of connections such as; internal, external and downstream, in practice. The 3 different types of placement of heat exchanger systems are shown in Figure 15. Internal connection here means the exchanger system exists inside the house or the facility. For e.g. hot wastewater discharge from kitchen, and sink shower, this system is suitable source which can have high temperature but fluctuations in flow.

The external exchanger system exists outside the sewage system with the pipe network. This could be close to heat source i.e. apartment building or the source facility. According to O. Chulha et al. [4], this system prevents bio-fouling and increase heat transfer efficiency from wastewater to fresh water. The plate or shell-tube heat exchangers are best fit for this system.

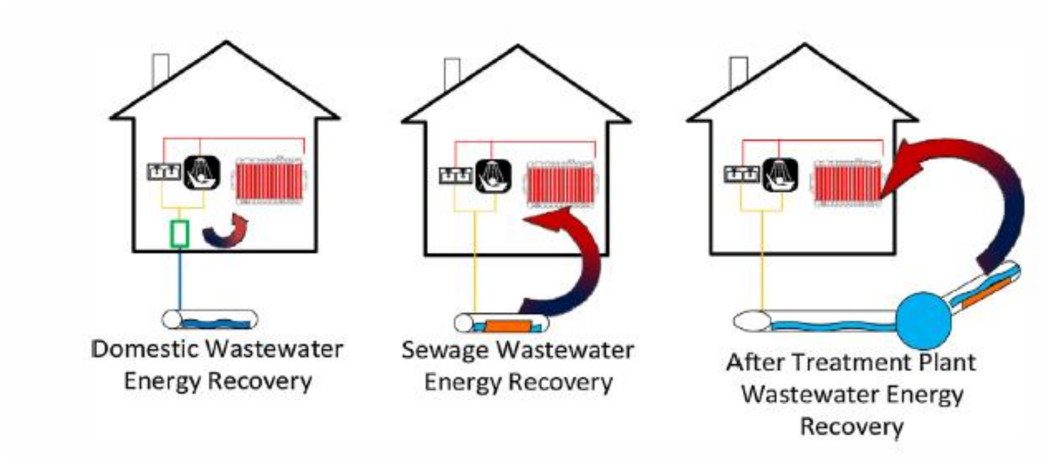

Figure 16 Heat recovery exchanger's installation locations [4]

The devices placed is not necessarily to be high efficient because devices with less efficiency can also have some advantages such as; smooth passage i.e. less pressure drop, easy maintenance. Different parameters can be used to model the available heat energy in the wastewater and optimization of the location to install the recovery system.

11. Feasibility considerations

Few considerations need to be made before installing the heat exchanger and designing the system. These considerations help for better efficiency, saving cost and time. According to (Department of Energy, ei pvm) and (Podobekova, 2013) the factors critical for designing of the heat recovery system are mentioned in following section.

I. Distance between consumer and heat recovery system

The distance between the source and demand is very critical. For the system to be efficient the distance needs to be maintained as short as possible. This reduced distance can reduce temperature loss and also is also cost efficient. Higher the distance more insulation work is needed which consequently increases the cost and time of the project.

Due to renovation restrictions within and proximity of the laundry facility site, the exchanger system needs to find space already available.

II. Accessibility

The heat available in the waste stream should be easily accessible. For example waste heat from CHP power plant is readily accessible. The accessibility in terms of availability and effort to extract heat is important.

In this thesis project the washing machine and the dryer operates 13 hours a day and the heat demand is within the facility or proximity of the facility so waste heat can be said accessible.

III. Flow rate of waste water and dryer exhaust

The mass flow in exhaust pipe from the washing machine and the dryer should be as high as possible in order to get rid of sediments or biofilm. The energy output is dependent on the mass flow.

The wastewater is expected to have less contaminant; responsible for clogging ducts and pipes in comparison to sewage water. The dryer exhaust carries considerable amount of vapour along with hot air. The condensation film or pipe should be installed at some point in exhaust vent. Considering Ecowec hybrid heat exchanger, which operates with variable ranges for air and water, the available flow rate is sufficient.

IV. Quality of heat source

The quality of heat source that flows in the effluent pipe before entering exchanger is extremely important. Fouling of the exchanger can hinder the project. Precautions need to be taken according to the level of contamination. In order to avoid corrosion of pipe network, and exchanger, accessing the quality of heat source is extremely important.

In comparison to sewage, laundry facilities contamination is relatively low and requires less clean-up of ducts and pipe.

V. Upgrading requirement

The upgrading need depends on the final use of recovered heat. One possible option for upgrading can be application of the heat pump as schematically described in Figure17. Some part of heat can be recovered by using heat exchanger for water heating then further heat pump can be used in series to recover heat where temperature could be approximately ≤ 10^{o}C.

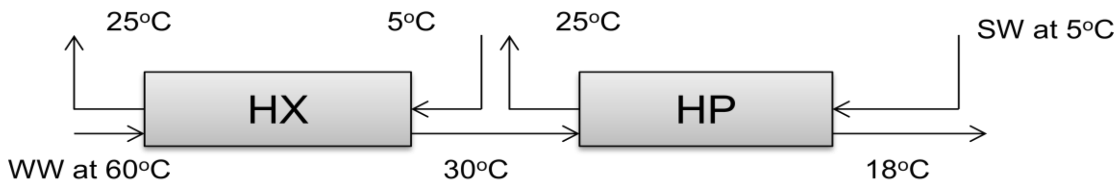

Figure 17 Upgrading possibilities using heat pump and heat exchanger

VI. Legislations

Considerations of requirement of environmental impact assessment or any other permit from the respective authority is crucial. Laundry which washes/dries about 100kg of clothes per day does not comply for need of environmental permit. Finnish land use and building act [19] article (57 a §) suggests that facilities within DH network territory are obliged to join the network. The connection is not mandatory if facility has another climate neutral heating system [20]. Hence the heat recovery project is feasible legally.

VII. Compatibility between source and demand [14]

The comparison between heat available and heat requirement can be done to define the range of heat application. The balance between source and demand is essential. If this is not the case, then energy storage needs to be taken into account. The compatibility is very much affected by operating schedule of the recovery system. The highest utilization factors, and therefore the most acceptable paybacks, are generally achieved for waste heat recovery projects integrated within a system [14].
The energy storage can be one solution to combat the fluctuation between supply and demand, which means storage of hot water for later use when heat is not available.

12. Financial feasibility

The financial feasibility analysis was done comparing conventional boiler with recovery system of 25-27 kW capacity. The assumptions were made such that conventional boiler uses natural gas for water heating whereas; electricity is used to operate sewage heat recovery system. Comparison of investment, operation and the maintenance cost for the sewage heat recovery by heat exchanger and traditional boiler was made. This comparison was done keeping the similar energy production, similar maintenance and the depreciation percentage.

Annual consumption of natural gas by household with an average of 3 members was taken as 2000m^3.This assumption is based on report by *Watercycle research Institute* [21]. This corresponds with total heat consumption of 25,600 kWh (1m^3= 12,8 kWh). The comparison of annual operating cost for the traditional gas boiler and the electricity operated heat recovery system is presented in Table 7.

Table 7 Cost comparison of gas boiler and sewage heat recovery

System description	Conventional boiler	Sewage heat recovery
Investment cost (25-27kW)	€2,500	€4,000
Life time	10 years	10 years
Gas price [29]	0.041 €/kWh*	-
Electricity price [15]	-	0,00574 €/kWh *
Depreciation	€62.5	€112.5
Electricity consumption	-	(5 kWx4,056)=20,280 kwh
Gas Consumption	25,600 kWh	-
Maintenance	€125	€225
Energy cost per year	€ 1,237	€454

In dryer exhaust heat recovery, the exhaust temperature and mass flow is higher than from washer, which increases operation and investment cost.

The cost analysis for feasibility study of sewage heat recovery can be estimated by equation 9 [22]

$$C+ W*C_{el} + L_{ds}*C_{ds}= H_R*C_u \qquad 9$$

Where C is the total cost, which includes investment, maintenance and operation cost
W is the electric power consumed by the sewage heat recovery system (kWh/y)
C_{el} is electricity cost (€/kWh.y)

C_{ds} is the distribution network cost (€/m)

L_{ds} is the length of distribution network (m)

H_R is recovered thermal energy (kWh/y)

C_u is the cost paid by the users (€/kWh.y

With the help of equation 9, the factors having significant impact on cost feasibility can be estimated. For example, third term on the left hand side, length of distribution network can have overall impact on the cost and the energy recovered. The shorter the length of network more the system is efficient in terms of cost and energy recovery. The cost of electricity to operate the sewage heat recovery system is also crucial. It is important to consider C_u factor too i.e. how we arrange this price, what are the variable need to be taken into account to mark the price.

Likewise, it is important to calculate net cash flow and benefits of projects for financial feasibility.

Economic benefit (B) = the mass flow rate of natural gas * price of natural gas

NPV is a powerful indicator of viability of the projects and can be determined from equation 10 obtained from [2]

$$\text{NPV} = \sum_{i=1}^{n} (\text{B} - \text{C})\text{i} * \text{ai} \qquad 10$$

Where NPV is net present value, B benefit, C is cost which includes cost of heat exchangers, installation and auxiliary equipment, cost of pumps, valves, pipes connections, test, regulations, and transportation and engineering services and a is discount rate which is obtained by equation 11.

$$a = \frac{1}{(1+i)^{\wedge}p} \qquad 11$$

; i is interest rate and p is period of month.

13. Pinch analysis

Pinch analysis is a procedure of optimizing heat energy transfer within the processes with minimum external heating or cooling utilities as possible. For example, power plant, process industries, pharmaceutical industries practice pinch analysis to optimize heating and cooling demand and harness waste heat. Pinch analysis utilizes energy targets, which are 'absolute thermodynamic targets, showing what the process is inherently capable of achieving if heat recovery, heating and cooling systems are correctly designed [23]. The minimum temperature (ΔT_{min}) difference between hot and cold composite curves affects the pinch temperature, the required external utilities and the size of heat exchangers [23]. The objective of pinch analysis is increasing efficiency with minimizing cost.

13.1 Pinch design method comprises of five concepts

I. Targets

The need of amount and size of utilities to be connected in the network are taken as targets.

II. The pinch

Pinch is a temperature, above which process needs external heating and below needs cooling. Pinch temperature gives overall idea about the place to locate utilities, how to recover heat from the processes.

III. More in, more out

An inefficient process requires more than minimum external heating and therefore more than minimum cooling [24].

IV. Freedom of choice

Within the boundaries of ‘heat sink and source are separate’ we design the plants lay-outs, control arrangements etc. But violating these limitations not necessarily fulfil the overall objective.

V. Trade-offs

Pinch analysis is done for optimization solution in maximum energy recovery. This target can be achieved by minimum number of utility requirement and also by minimizing the overall cost. The overall cost can be minimized by minimizing number and surface area of the heat exchanger. Assessing trade-offs can be a way for optimization. For example, trade-off between energy and surface area, equipment versus low products purity, more recycle costs versus increased feed use and increased waste, more heat recovery versus cheaper heat exchanger etc.

Some conditions to consider prior producing minimum utility design.

- Heat is not transferred across the pinch
- Cold utilities above the pinch and hot utilities below pinch are not allowed.

13.2 Design of heat exchangers

This process consists of 3 streams including 1 cold or service water, 1 hot air exhaust from dryer and a hot wastewater exiting washing machine. ΔT_{min} was chosen to be 10^{o}C as rule of thumb. Pinch Analysis was carried out using online tool [25].

Table 8 Cold and hot streams data

Stream No.	Stream Type	T_s (^{o}C)	T_t (^{o}C)	Mass flow($\dot{m}$) Kg/s	Cp/kJ/kg.k)	Heat load	Cp(kW/^{o}C)
1	Cold water	5	40	0.11	4.18	16.093	0.45
2	Hot air	90	34	1.5	1	84	1.5
3	Waste Water	60	20	0.11	4.18	18.39	0.45

In Table 8, T_s represent the source temperature and T_t represents target temperature of respective streams. Thermal capacity, represented by Cp, also known as heat capacity flow rate is temperature independent, which is mass flow time's specific heat capacity of the individual stream. Heat load represents the maximum amount of heat that is being transferred either to or from the system. Source temperatures are obtained on the basis of interview with laundry owner and target temperatures were chosen on the basis of heat exchangers explained in the case study chapter in this thesis work.

Streams cold water, hot air and wastewater are represented by stream number 1, 2 and 3 respectively. These streams flow in their respective network with temperature (T_s) and mass flow ($\dot{m}$). The aim here is to achieve the target temperature (T_t) by optimizing the heat energy transfer in the process, which include adding of cold or hot utilities in the network. Theoretically, pinch decomposition of the process would appear as shown schematically in Figure 18

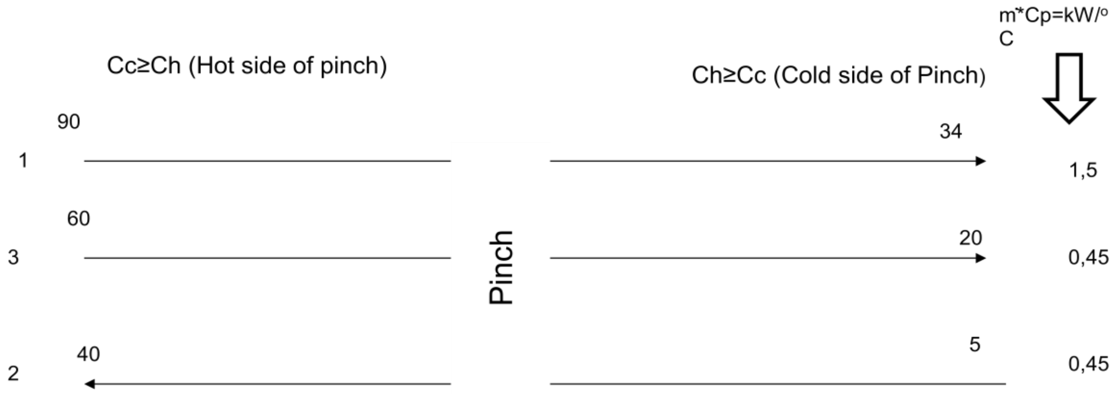

Figure 18 schematic of pinch decomposition

The target temperature assumptions are based on temperature performance of Ecowec Hybrid Heat exchanger which cools wastewater from 26 °C to 5 °C and preheats the cold water from 8 °C to 15°C [26]. Similarly, Läckeby air/water heat exchanger cools air from 120°C to 44.6 °C and heats up water from 10 °C to 34°C [18].

The hot exhaust air is cooled from 90 to 34°C [with reference to VLV heat exchanger, which cools hot air from 120°C to 44,6°C i.e. reduction approximation is done about 62%]. The wastewater is cooled from 60 °C to 15°C [with reference to EHHE explained in case studies cools wastewater from 26 to 5°C i.e. reduction approximation is done about 5 times]. In case of cold or service water, the approximation is done as requirement, assuming that hot water requirement is close to 40°C.

Figure 19 and Figure 20 represents the composite curve of cold and hot streams respectively. Table 9 and Table10 represent the enthalpy at respective temperatures obtained from cold and streams respectively. The cold water is heated from 5 °C to 40°C which gives 2 enthalpies represented by ΔH and can be calculated as $(\sum C_{p,hot}-\sum C_{p,cold})*(T_i-T_{i+1})$. Where $C_{p,hot}$ and $C_{p,cold}$ represents thermal capacities for hot and cold streams respectively in individual range of T_i and T_{i+1}. Likewise, enthalpies for hot streams are calculated in the temperature range cooled from 90-60-40-35 and 20°C.

Table 9 CCC data

Temperature (ºC)	Enthalpy (kW)
5,00	86,30
40,00	102,39

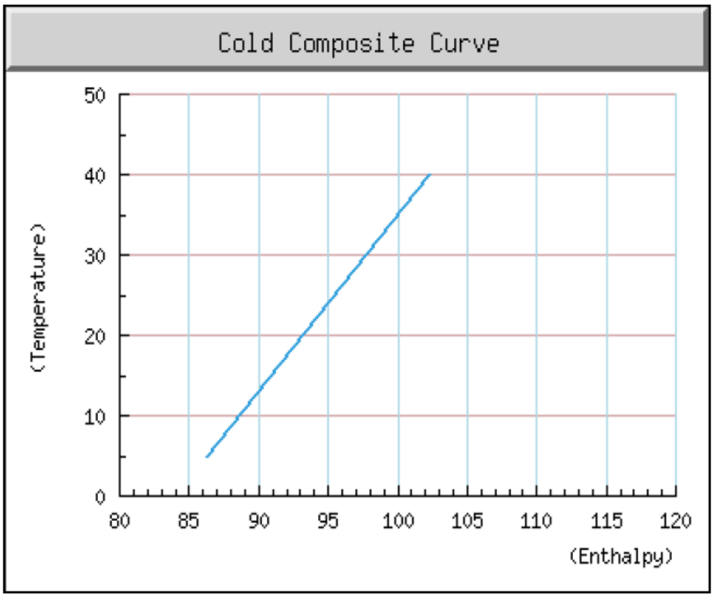

Figure 19 Cold composite curve (CCC)

Table 10 HCC data

Temperature (ºC)	Enthalpy(kW)
20,00	0,00
34,00	6,43
60,00	57,39
90,00	102,39

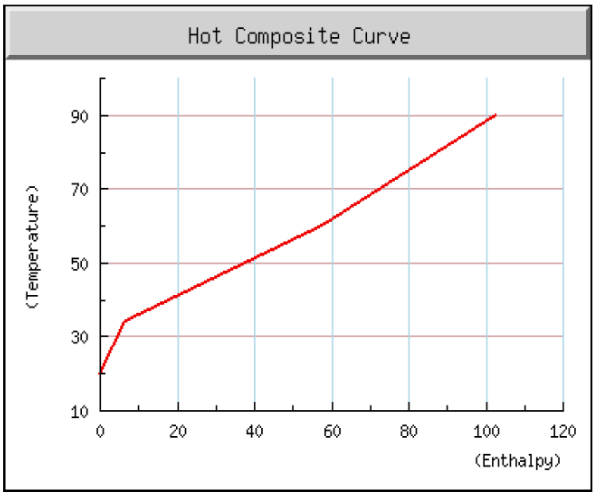

Figure 20 Hot Composite Curve (HCC)

Table 11 represents the output of pinch analysis obtained from online tool [25]. The result illustrates that pinch temperature is 90ºC and 86.3 kW of cooling utility is required to be placed on the hot stream.

Table 11 CCC curve

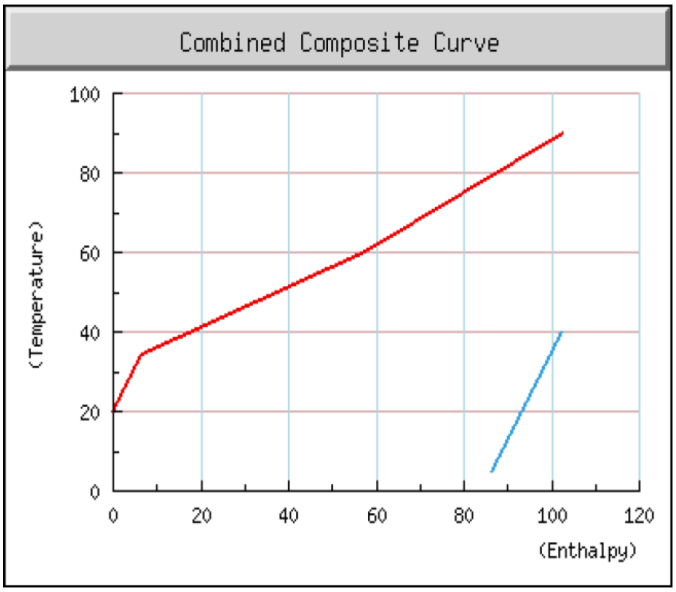

Figure 18 Combined Composite Curve (CCC)

DT_{min}	10ºC
Pinch Temperature	90ºC
Ideal Min. Cooling Required	86.3 (kW)
Ideal Min. Heating Required	0.00

Table 12 GCC data

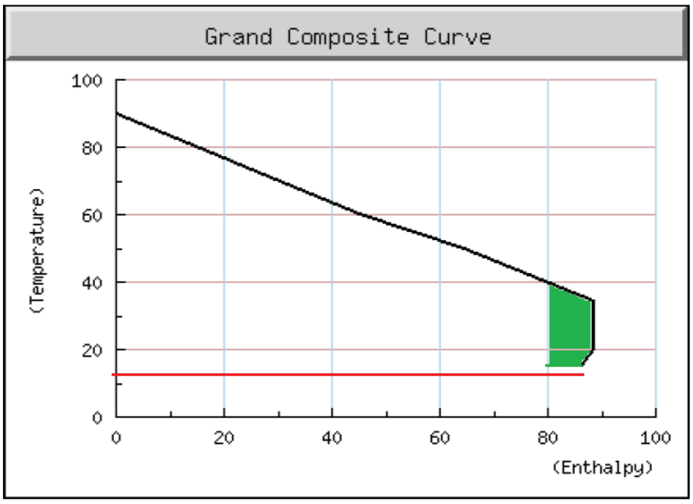

Figure 22 Grand Composite Curve (GCC)

Temperature(ºC)	Enthalpy(kW)
15.00	86.30
20.00	8.85E+1
34.00	8.85E+1
50.00	64.59
60.00	45.00
90.00	0.00

The grand composite curve (GCC) gives us the information about the pinch temperature, minimum heating and cooling utilities and process to process heat integration. Above the pinch is heat sink and below is the heat source. In this process all the region falls below the pinch, hence heat source is available lacking heat sink, which is the information obtained from GCC in Figure 22.

From Figure 22 intersection point of vertical axis and the curve is at 90°C, which is the pinch temperature. Since curve cannot be observed above the intersection point which illustrates that no hot utilities are needed. Observing at the bottom (marked by red line) of the curve, 86.30 kW of cooling utility needs to be added on hot streams, while no hot utility needs to be added. All the streams in process lie below the pinch. The area enclosed by green colour below the pinch is the process to process heat transfer. GCC for streams is summarized in Table 13.

Table 13 Streams availability in GCC

	Cold stream	Hot stream
Above Pinch	NA	NA
Below Pinch	A	A

NA-Not Available
A-Available

GCC for utilities is summarized in Table 14.

Table 14 Utilities above and below pinch in streams

	Cold utilities/hot utilities
Above Pinch	None of the streams are available above pinch.
Below Pinch	We can't add hot utilities below pinch but we can add cold utilities below pinch (on hot streams)

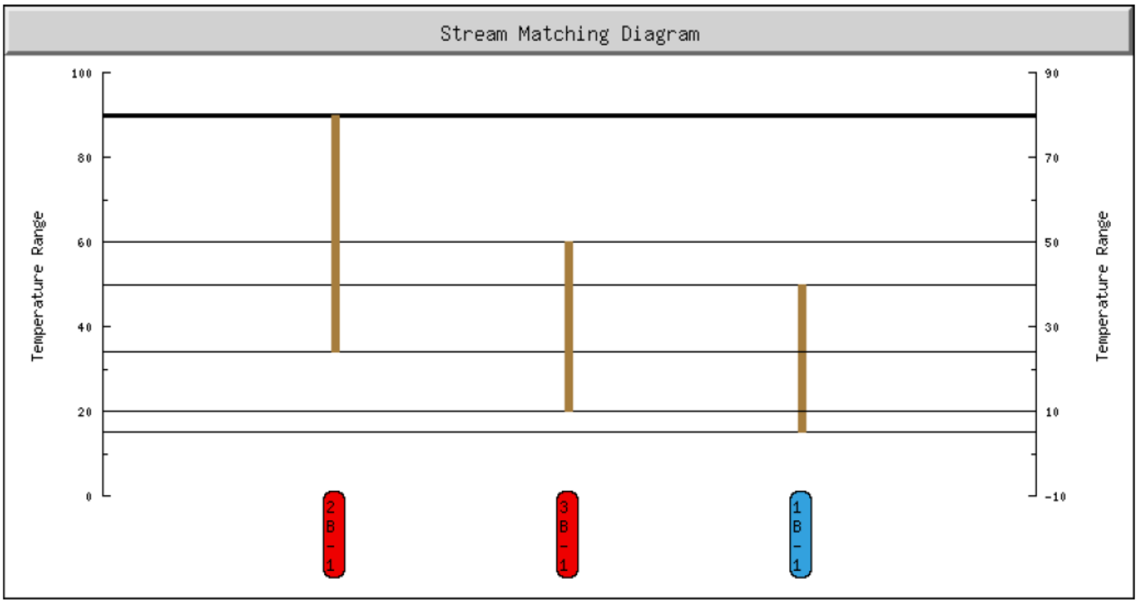

Figure 23 Stream matching

Figure 23 represents streams and their matching relationship with red colour as hot and blue one as cold stream

13.3 Drawbacks of the analysis

In the process, pinch temperature is 90^{0}C and cold stream doesn't fall in this range with only one hot stream in the range. Table *13* Streams availability in GCC suggests, none of the streams are available above pinch hence it is not possible to locate hot utilities above the pinch. Limitations are applied with only option to add cold utilities below pinch on hot streams.

14. Result

Feasibility study of waste heat recovery from wastewater exiting washing machines and dryer exhaust air in laundry facility was performed. The results of this thesis project from respective chapters are presented below.

Heat exchangers, their design parameters and applications were studied and summarized in Table 15. This study helps to select heat exchanger adhering to requirements of this project. Theoretically, shell-and-tube heat exchanger, finned tube heat exchanger, concentric tube heat exchanger and plate heat exchanger were considered suitable for heat recovery from laundry facility. These heat exchangers' best operate within temperature range from 0-120^{o}C. Most importantly these heat exchangers are suitable

for both gas-liquid and liquid-liquid working substances i.e. suitable for dryer exhaust and wastewater exiting washing machine.
Calculations for energy available in wastewater, dryer exhaust and saving by harnessing the energy, was performed from the available data. It was found that 103 and 547 MWh of energy is available in wastewater and dryer exhaust air per year respectively. Furthermore, calculation illustrates that tentatively 6,371 € from waste water and approximately 33,837 € from dryer exhaust can be saved per year.

For feasibility study, the distance between consumer and heat recovery system, accessibility, flow rate, quality of heat source, upgrading need, legislations and compatibility with demand were accessed. It was observed that distance between consumer and recovery system should be as minimum as possible. Approximately 1-5 m^2 of space is necessary to install the system with no allowed major renovation and modification in existing building. Flow rate, quality of heat source and compatibility are correlated, and have significant impact on energy output for both wastewater and dryer exhaust air.

Two commercially available heat exchangers Ecowec hybrid heat exchanger (EHHE) by *Wasenco* and air/water heat exchanger model *VLV* by *Läckeby* were analysed, one for wastewater and another for dryer exhaust. It was found that EHHE is suitable for both systems; wastewater and dryer exhaust, meanwhile, later one is suitable for dryer exhaust only with little variation in design parameters.

Comparison of investment, operation and maintenance cost for sewage heat recovery by heat exchanger and traditional boiler operating with natural gas was made. The result showed that, with the present values of natural gas and electricity price, annual operating cost for sewage heat recovery seems to be higher than conventional gas boiler for water heating purpose only.

Finally, pinch analysis was performed in order to optimize energy transfer within the process. Analysis showed that with both the hot and the cold streams available only below pinch temperature (90^{o}C), 86.3 kW of cooling utility needs to be added on hot streams, while no hot utility needs to be added.

The values used in calculations for different factors such as mass flow rates and inlet temperatures of service water were based on previous measurement and interview with laundry owner. These values and assumptions might cause deviation in energy output. Similarly, the annual operating cost for sewage heat recovery system and traditional natural gas boiler might vary depending on energy prices and investment cost.

15. Conclusions

The purpose of this thesis was to study the usefulness of waste heat drained away in wastewater and dryer exhaust. The feasibility study suggests that a significant amount of energy is available in wastewater and dryer exhaust air that can be harnessed. Tentatively 650 MWh of energy can be recovered from both wastewater and dryer exhaust air saving approximately € 40,000 per year. Harnessing this energy per year is a compelling benefit for climate and environment. With the current price of electricity and natural gas the annual operating cost for sewage heat recovery system is significantly less than traditional gas boiler. Models presented in this project for net cash flow and benefits and cost analysis in this thesis are useful for heat recovery from both wastewater and dryer exhaust air, when all the relevant figures such as distribution network length and cost, electricity price, recovered thermal energy are available.

In terms of maintaining minimum distance, accessibility and legislation, the project is feasible with further need for considerations in flow rate, quality of heat and compatibility because of their correlations.

Commercially available heat exchangers suitable for this project were presented. The case studies conferred in this thesis can provide guidance in selecting heat exchangers for small-scale recovery system. Furthermore, energy optimization within process needs intensive evaluation due to presence of unequal number of streams and approximated target temperature and flow rates.

The experimental observations within the process for parameters such as temperature, mass flow could lead to more reliable and accurate energy output and savings. The heat pump in series at colder exhaust of heat exchanger to heat the water further as shown in Figure 17 Upgrading possibilities using heat pump and heat exchanger is recommended for further research. This integration of heat pump and heat exchanger might harness more overall energy from the process than an individual system.

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