Tampereen yliopisto

Timo Loiva

UPGRADING WASTE HEAT FROM RENDERING PROCESSES UTILISING STEAM GENERATION HEAT PUMP

Techno-economic-environmental analysis

Diploma thesis
Faculty of Engineering and Natural Sciences
Examiner 1: University Lecturer Henrik Tolvanen
Examiner 2: University Lecturer Hannele Auvinen
January 2024

ABSTRACT

Timo Loiva: Upgrading waste heat from rendering processes utilising steam generation heat
pump: techno-economic-environmental analysis
Master's Thesis
Tampere University
Master's Programme in Environmental and Energy Engineering
January 2024

Industrial heating is a significant energy user globally, and a large share of process heating is provided by steam heating systems powered by fuel boilers. Nearly half of the industrial energy demand is lost as waste heat of different forms. Heat recovery and utilisation has potential to decrease the energy use and energy-related emissions significantly, but heat recovery potential is often limited by too low temperatures of waste heat, which makes it difficult to find a reasonable use for the waste heat.

High-temperature heat pumps (HTHPs) offer a solution for upgrading waste heat to utilisable temperature levels for industrial use. They can supply hot water, air, or steam by using moderate amounts of electricity to upgrade the temperature. Steam generation heat pumps (SGHPs) have high potential in process industry with heat demand at temperature band 100-200 °C. They can use waste heat at 50-100 °C for generating steam up to 200 °C. The lower the temperature lift, the better the efficiency.

Rendering industry, which takes care of circular economy of animal by-products, is a good example of a field that could take advantage of SGHPs. This study investigates SGHP integration into a low-temperature wet rendering (LTWR) plant that is planned to be built. Providing significant amount of waste heat at close to 100 °C in form of process vapour from drying processes, relatively low temperature lift at the SGHP is required for generation of 2 $\mathrm{bar_g}$ (134 °C) steam, which can be utilised by most equipment in the process.

Three commercial SGHP solutions were identified and compared in techno-economic-environmental analysis (TEEA) to find out the most beneficial solution for case plant. Solution S1 based on MVR technology showed the best overall results in technical, economic, and environmental performance, however, it had the highest investment costs. Results of solutions S2 and S3 based on CCHP technology were close to each other and offered a good option to S1 with lower investment costs. Total price for steam was estimated to be in range of 19-24 €/MWh, providing significant savings in energy costs compared to fuel boilers and electric boilers. Payback period for all the solutions were relatively long, around 8 years at rate of 5.5 %, but economic benefits after payment period were estimated to be significant. Main parameters identified to affect the feasibility of SGHPs were COP, electricity price, boiler steam price, waste heat load, and carbon price, if the plant is subject to emissions trading.

Integration of SGHP into rendering plant would also have a strong positive impact on environmental performance. The CO_2 emissions of steam produced by SGHP were about 98 % lower than steam produced by boiler using peat as a fuel, providing a carbon handprint of around 500 kg CO_2e/MWh steam. When it comes to energy efficiency of the case plant, a saving of 118-135 kWh per ton raw material could be achieved with SGHP, resulting in specific energy consumption of around 250-270 kWh per ton raw material.

This study shows that SGHP integrations have potential to decrease energy related costs and emissions significantly with reasonable payback periods at rendering plants and similar industrial processes. The results suggest that SGHP technologies are becoming more widespread in industry in near future, as they can provide steam at lower cost than current steam generation methods such as fuel boilers and electric boilers.

Keywords: steam generation heat pump, high-temperature heat pump, heat recovery, rendering, energy-efficiency, waste heat, LTWR

TIIVISTELMÄ

Timo Loiva: Renderöintiprosessissa syntyvän hukkalämmön jalostaminen
höyrylämpöpumpun avulla: teknistaloudellinen ja ympäristöanalyysi
Diplomityö
Tampereen yliopisto
Ympäristö- ja energiatekniikan DI-ohjelma
Tammikuu 2024

Teollisuuden lämmitys on maailmanlaajuisesti merkittävä energian kuluttaja, ja suuri osa prosessien lämmityksestä on toteutettu polttoainekattilaan perustuvalla höyryjärjestelmällä. Lähes puolet teollisuuden energiantarpeesta menetetään hukkalämpönä eri muodoissa. Lämmön talteenotolla ja hyödyntämisellä on potentiaalia vähentää energian kulutusta ja energiantuotantoon liittyviä päästöjä merkittävästi, mutta hukkalämmön hyödyntämismahdollisuuksia rajoittaa usein hukkalämmön liian matala lämpötila, mikä vaikeuttaa järkevän käyttökohteen löytämistä hukkalämmölle.

Korkealämpötilalämpöpumput (HTHPs) tarjoavat ratkaisun hukkalämmön jalostamiseen teolliseen käyttöön sopiville lämpötilatasoille. Ne voivat tuottaa kuumaa vettä, ilmaa tai höyryä kuluttaen kohtuullisen määrän sähköä lämpötilatason nostamiseen. Höyrylämpöpumpuilla (SGHPs) on merkittävä potentiaali teollisuuden lämmitystarkoituksissa 100–200 °C lämpötila-alueella. Ne voivat hyödyntää 50–100 °C hukkalämpöä jopa 200 °C höyryn tuottamiseen. Mitä matalampi lämpötilan nosto on, sitä parempi on höyrylämpöpumpun tehokkuus.

Renderöinti, joka vastaa eläinperäisten sivutuotteiden kiertotaloudesta, on hyvä esimerkki teollisuudenalasta, joka voisi hyödyntää höyrylämpöpumpputekniikkaa. Tämä työ tutkii höyrylämpöpumpun integroimista suunnitteilla olevaan LTWR-tuotantolaitokseen. Laitoksella syntyy merkittävästi lähes 100 °C asteista prosessihönkää, mikä mahdollistaa 2 $\mathrm{bar_g}$ matalapainehöyryn tuottamisen höyrylämpöpumpulla kohtuullisella lämpötilan nostolla, tarjoten höyryä useimpiin laitoksen prosesseihin.

Kolme kaupallista höyrylämpöpumppuratkaisua tunnistettiin soveltuvaksi esimerkkilaitokselle, ja niitä vertailtiin teknistaloudellisessa ja ympäristöanalyysissa (TEEA) tarkoituksena löytää edukkain ratkaisu kyseiselle laitokselle. MVR tekniikkaan perustuva ratkaisu S1 osoitti kokonaisuudessaan parasta suorituskykyä teknisestä-, taloudellisesta- ja ympäristön näkökulmasta, mutta oli investointikustannuksiltaan kallein. CCHP tekniikkaan perustuvien ratkaisujen S2 ja S3 tulokset olivat lähellä toisiaan, ja tarjosivat hyvän vaihtoehdon ratkaisulle S1 pienemmillä investointikustannuksilla. Tuotetun höyryn kokonaishinta höyrylämpöpumpuilla asettui välille 19–24 €/MWh, mikä tarjoaa suuria kustannussäästöjä verrattuna muihin höyryntuotantotapoihin. Kaikkien ratkaisujen takaisinmaksuajat olivat noin 8 vuotta 5.5 % korolla laskettuna, mikä on kohtuullisen pitkä aika, mutta takaisinmaksun jälkeen saatavat taloudelliset hyödyt arvioitiin suuriksi. Tärkeimmiksi kannattavuuteen vaikuttaviksi tekijöiksi havaittiin COP, sähkön hinta, kattilahöyryn hinta, hukkalämmön saatavuus ja hiilidioksidin hinta, mikäli laitos on päästökaupan piirissä.

Höyrylämpöpumpun integroinnilla renderöintilaitokseen olisi myös suuret positiiviset vaikutukset ympäristön kannalta. Höyrylämpöpumpulla tuotetun höyryn päästöt olivat noin 98 % matalammat kuin turvetta käyttävällä kattilalla tuotetun höyryn päästöt, mikä tarkoittaa noin 500 kg CO_2e/MWh hiilikädenjälkeä tuotetulle höyrylle. Esimerkkilaitoksen energiatehokkuudelle höyrylämpöpumppuratkaisut mahdollistaisivat 118–135 kWh energiansäästön per raaka-ainetonni, jolloin energian ominaiskulutus raaka-ainetonnia kohden olisi vain noin 250–270 kWh.

Tutkimus osoittaa, että höyrylämpöpumppuintegraatioilla on potentiaalia vähentää energiaan liittyviä kustannuksia ja päästöjä merkittävästi renderöintilaitoksilla ja muissa vastaavissa prosesseissa. Tulokset viittaavat siihen, että höyrylämpöpumpputeknologiat tulevat yleistymään teollisuuden parissa lähitulevaisuudessa, sillä niiden avulla voidaan tuottaa höyryä edullisemmin kuin nykyisillä höyryntuotantomenetelmillä, kuten polttoainekattiloilla ja sähkökattiloilla.

Avainsanat: höyryä tuottava lämpöpumppu, korkealämpötilalämpöpumppu, lämmön talteenotto, renderöinti, energiatehokkuus, hukkalämpö, LTWR

FOREWORDS

This techno-economic-environmental analysis was conducted as an assignment for GMM Finland Ltd, which is a consulting, industrial engineering, and development company specialised in the processing of food industry by-products. It has been a pleasure to investigate such a concrete topic, and I hope that the results will help in the implementation of a SGHP system as the work continues. I would like to thank my GMM supervisors Mika Kierikka and Matti Lehtinen for encouraging and supporting me throughout the process. Many thanks to all the colleagues who have been helping me in this work, providing support on for example data collection and technical questions.

I would also like to give warm thank you to Henrik Tolvanen and Hannele Auvinen, who have been the supervisors and examiners from Tampere University side. Thanks for the great cooperation and support during the process. To my dear fellow students, thank you for all the funniest and also the toughest study sessions at the Uni. Thank you for being a part of the journey. Thank you for the loved ones for the support every day.

In Oulu, 29 January 2024

Timo Loiva

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ABBREVIATIONS AND SYMBOLS

ABP	animal by-product
bar_a	absolute pressure in bar
bar_g	gauge pressure in bar
BAT	best available technology
BREF	BAT reference document
CAPEX	capital expenses
CCHP	closed-cycle heat pump
COP	coefficient of performance
CR	compression ratio
DPP	discounted payback period
GHG	greenhouse gas
GWP	global warming potential
HTHP	high temperature heat pump
IHX	internal heat exchanger
LCA	life cycle assessment
LTWR	low-temperature wet rendering
MVR	mechanical vapour recompression
ODP	ozone depletion potential
OPEX	operational expenses
ROI	return on investment
SGHP	steam generation heat pump
TEEA	techno-economic-environmental analysis

C_{CO_2}	carbon costs	€/a
C_{el}	cost of electricity	€/a
C_f	fuel costs	€/a
C_m	maintenance costs	€/a
C_t	total investment costs	€
c_p	specific heat capacity	kJ/(kg °C)
E_s	operational revenue	€/a
h	enthalpy	kJ/kg
h_f	liquid enthalpy	kJ/kg
h_{fg}	enthalpy of evaporation, latent heat	kJ/kg
h_g	total enthalpy of gas	kJ/kg
$\dot{m}$	mass flow	kg/s
p	pressure	bar
P_{el}	electric power	kW
$\dot{Q}$	heat content of a stream	kW
r	interest rate	%
T	temperature	°C
w	moisture content	kg/kg

1. INTRODUCTION

Climate change is a major threat to the globe and society, most significantly affected by the greenhouse gas (GHG) emissions from the use of fossil fuels. Industry is one of the largest contributors to global warming, causing around 24 % of global GHG emission (IPCC, 2023). A predominant share of industrial energy demand is process heating, accounting for 66% of total industrial energy demand in Europe, of which 26% is in range of 100-200°C (de Boer et al., 2020). Conventional solution for process heating at this temperature range is a steam heating system with fuel-driven boiler. Steam has a vital role in industry due to its excellent heat transfer properties, safety, and ease of control.

It is important to note that approximately half of the energy produced for industrial purposes is lost as waste heat in form of hot off gases, vapours, water, air, or other losses such as radiation, friction, etc. (Forman et al., 2016). Waste heat is well available, but the temperature levels of waste heat sources are typically lower than the temperature requirements of process heating. However, lately efforts on high temperature heat pumps (HTHPs) show that waste heat sources 50-100 °C can be upgraded to 100-200 °C or even higher temperatures. (Saini et al., 2023) HTHP technology is noted to have significant potential for waste heat recovery in several industrial applications such as drying, sterilization, evaporation, papermaking, and food processing (Arpagaus et al., 2018)

Animal by-products processing, also referred to as rendering, takes care of circular economy of animal by-products from food industry. Value is created by processing animal by-products into valuable products that can be utilised in other purposes. Typical products from rendering industries include protein meals for pet food and feed industry, fat products for animal feed and biofuel production, and biofertilisers for nutrient supply in agricultural applications. Rendering industry aims ensure that animal by-products are utilised in a resource efficient and environmentally friendly manner, providing the best possible value for each stream.

Rendering plants require significant process heat, which is typically provided by a steam system with a fuel-driven steam boiler. Waste heat can be collected in different forms, but utilising recovered heat for main processes is limited, as the temperature of waste heat is lower than required for process heating. One potential option for tackling this problem is to implement HTHP technology in steam generation from waste heat. Steam generation heat pumps (SGHPs) could have a significant contribution to improving heat recovery as they can upgrade waste heat to steam with relatively low electric power. This could decrease the energy related costs and emissions significantly due to the saved fuel. SGHPs could provide a sustainable technology alternative for adding steam capacity.

SGHPs are a novel field of study and most of the studies are from recent years. Commercial scale installations are few, as well as empirical scientific literature. Research activity in latest years has been high, and industrial scale projects are on the increase. SGHPs are one type of HTHPs having steam as a heat sink. Arpagaus et al. (2018) reviewed the available HTHP technologies in the market and described the research status of the field. Bless et al. (2017) studied different options for generating 3 bar_a steam, including SGHPs. Kang et al. (2019) and Liu et al. (2022) made experimental studies about SGHPs. A list of HTHP and SGHP suppliers and demonstration projects is maintained on Annex 58 webpage, which is an important information source in such a novel research area (Annex 58, 2023). It seems that in rendering industry there are not yet SGHP applications nor scientific literature related to the integration of SGHP technology. This work will gather and discuss useful information on adaptation of SGHP technology in rendering plants or similar industrial processes.

The objective of this work is to discover the potential SGHP solutions for rendering case plant and compare the alternatives in terms of technical, economic, and environmental performance to find out the most beneficial solution. Methodology of this work comprises literature research, gathering case plant data, contacting technology suppliers, and making the calculations for techno-economic-environmental analysis.

The research questions of the study are:

1. What are the drivers of utilising waste heat from rendering processes?
2. What kind of SGHP systems would be applicable for the case plant?
3. How much low-pressure process steam can be produced with chosen SGHP systems from waste heat and utilised in studied processes at case plant?
4. How economically feasible are the chosen SGHP systems in the case plant?
5. How large savings in energy consumption and CO_2-emissions can be achieved with the chosen SGHP systems in the case plant?

This work consists of 7 chapters. Following this introduction, theory chapters 2-4 aim to describe the framework for SGHP applications in rendering industry. Chapter 2 discusses waste heat recovery in rendering industry, presenting conventional waste heat recovery systems and discussing the heat pump option, with a bit of steam theory as support. Chapter 3 introduces SGHP technology and heat pump theory, focusing on potential options for steam generation. Chapter 4 describes what affects the economic feasibility of steam generation by heat pumps and the environmental performance of the system. Chapter 5 describes the research methodology and initial data. Chapter 6 presents the results of the study and discusses them from different viewpoints. Chapter 7 summarises the study.

2. WASTE HEAT IN RENDERING INDUSTRY

Thermal treatment is in the core of rendering processes. One task of heating is to inactivate micro-organisms from the feedstock. Heating also enables the modification of feedstock structure and separation of materials. Some rendering processes also use pressure to decompose the structure of the material. Steam can be used for both heating and pressurizing. As an energy carrier steam is efficient, easy to control, and safe to use. Hence, rendering processes rely on steam in process heating systems.

Heated industrial processes produce waste heat in form or another. Recovering waste heat is one of the most important ways of improving energy efficiency and thus, saving energy costs and reducing energy related emissions. This chapter explains the context where SGHP is considered as well as supporting steam theory.

2.1 Rendering plant

The term rendering can be used for processing animal by-products (ABP) from food industry into value added products. Multiple types of processes are employed in rendering, including mechanical processes, thermal treatment, separation technology, drying, and sieving. Rendering plants can have feedstocks in different categories that in EU are defined in the Animal by-products Regulation (EC 1069/2009). Feedstocks to rendering plants originate from slaughterhouses, meat processing plants, livestock rearing centres, supermarkets etc. (EIPPCB, 2005).

Animal by-product categories reflect the risk level of the materials to public and animal health. Category 1 comprises different types of risk materials that are prohibited for use as feed or fertiliser in EU. Category 3 comprises different types of animal by-products that are not for human consumption but suitable for animal consumption. Category 2 feedstocks comprise those animal by-products that are not categorized to categories 1 or 3, and they can be processed to e.g. biofertilizers, biofuels or fur animal feed. EU regulation sets conditions for processing of each category 1-3 animal by-products, including requirements for e.g. temperature, processing time, particle size, and/or applied pressure. (EC 1069/2009) Seven standard processing methods for rendering are described in the EU regulation 142/2011 and collected into table 1.

Table 1. *Standard processing methods for animal by-products according to ABP regulation (142/2011)*

Processing method	Particle size (mm)	Time (min)	Temperature (°C)	Pressure (bar)	Notes	Used for
1	< 50		> 133	3 bar	Batch/Continuous	
2	< 150	125 120 50	> 100 > 110 > 120	No requirement	Batch	
3	< 30	95 55 13	> 100 > 110 > 120	No requirement	Batch/Continuous	
4	< 30	16 13 8 3	> 100 > 110 > 120 > 120	No requirement	Batch/Continuous With added fat	
5	< 20	120 60	> 80 > 100	No requirement	Batch/Continuous	
6	< 50 < 30	60 60	> 90 > 70	No requirement	Batch/Continuous Formic acid treatment (24h, pH <4)	Aquatic origin category 3
7	Any validated processing method authorized by authority. Microbiological quality proved at sampling period of 30 production days					

The case plant of this work is a category 3 poultry plant with low-temperature wet rendering (LTWR). The process consists of pretreatment, preheating, fat, solids, and water separation, drying, milling, sieving, and bagging. The feedstock of the plant is raw poultry by-product from slaughterhouses. Final products of the plant are poultry protein meal for pet food and animal feed industry and liquid fat for biofuel production, pet food and animal feed industry.

The rendering process has multiple stages that are in general similar, though the configurations may vary in different plants depending on the feedstock, end products, and processing method. In the beginning of all solid rendering process lines there is a size reduction unit process, which is required in ABP regulation to make sure all the material is under maximum regulated particle size. Particle size requirement varies between 20-150 mm, depending on the used processing method. Size reduction has benefits the processing as well, such as higher weight capacity and lower heating energy demand. (EIPPCB, 2005). On the other hand, the energy consumption increases if size reduction is done to smaller maximum particle size. In the case plant, the particle size is reduced to maximum 20 mm with pre-breaker and fine grinder, which makes the material suitable for pumping to the further processing.

Cooking or preheating is a thermal process in which the material is treated in certain pressure and temperature for a certain time, and it has a vital role in all kinds of rendering lines. It can be implemented as a continuous or a batch process. The main tasks of cooking are to deactivate micro-organisms and to melt fat so that it can be separated from protein and bones. (Meeker, 2006) A part of moisture is also removed in cooking. In the case plant, cooking is a continuous process, heating the material to about 90 °C.

Rendering process aims to separate fat, solids, and moisture. This is done after cooking by pressing and/or centrifugation (EIPPCB, 2005). In the case plant, separation is implemented by a twin-screw press and a three-phase decanter centrifuge (tricanter) and as a result, three streams are formed: fat, solids, and stick water. Fat is further cleaned in separators and stick water is concentrated in evaporators.

Solid fraction still contains significant amount of moisture after separation process. Processing of solids fraction into protein meal includes drying, milling and screening. Several types of dryers can be used in rendering processes: ring dryer, disc dryer, steam-tube dryer, spray dryer and rotary dryer (Meeker, 2006). A continuous disc dryer is employed for drying the solids in the case plant. Drying in disc dryer is based on contact of the material with hot rotating discs and jacket heated with indirect steam. Hot surfaces of discs and jacket evaporate water from the product stream, and process vapour is then removed based on slight vacuum pressure created by an off-gas fan.

Grinding reduces the particle size of dried product into desired range. The selection of grinding equipment depends on the input properties and requirements of the final product. There are many options for grinding equipment such as hammer mill, ball mill, cage mill, roller mill (Meeker, 2006; Ockerman and Hansen, 1988). Screening takes place after grinding and makes sure that too large or foreign particles do not end up in the final product. Oversize material is recirculated back to the mill to get grinded and screener again (Ockerman and Hansen, 1988). A hammer mill and a multi-stage vibrating screen are used in the case plant for protein meal particle size control.

Process heating in rendering plants is commonly implemented by a steam heating system. Steam can be used directly in some processes and indirectly in other. Direct use means that steam gets in direct contact with the feedstock, releasing heat and adding water to the material. (Roberts et al., 2017). An example of direct steam use can be found in processing method 1, pressure sterilisation (table 1), in which > 3 bar_a steam is applied to the material to raise temperature and pressure simultaneously. Indirect use does not involve contact with the feedstock, only latent heat of the steam is transferred to the process (Roberts et al., 2017). For example, a disc dryer uses indirect steam to heat the contact surfaces. In indirect steam use, the steam is condensed when it releases its latent heat to the steam user, and the condensate is returned to steam generation (Spirax Sarco, 2023).

The heat consumption in a typical rendering process can be around 800 kWh per ton raw material, but with optimisations far lower values can be achieved. For example, using decanter system in drying is reported to cut energy consumption of drying in half. (EIPPCB, 2005) In an existing LTWR poultry plant in Honkajoki, the measured value for heat consumption was around 344 kWh per ton raw material and total energy consumption including electricity around 387 kWh per ton raw material in 2023. In addition to process energy demand, these values also include space heating, so the cold climate in Finland causes an increase to the heat consumption.

Conventionally steam is generated at fuel driven boiler plant and transferred to process plant with transfer lines. Boiler plant generates higher pressure steam than what is needed in the processes to cover the pressure losses in pipelines and to allow the controllability of steam supply to users (Roberts et al., 2017). As an example from rendering industry, the most of the energy consumption for processing of 162,897 tonnes raw material at Honkajoki rendering plant in 2022 was thermal energy (95.9 GWh), followed by electricity (13.7 GWh) consumed by process equipment for mechanical work (Honkajoki Oy, 2022). Energy consumption can be seen as the largest environmental impact of rendering industry.

Odour emissions are one of the potential environmental issues of rendering plants – therefore effective odour management systems must be implemented (EIPPCB, 2005). Odour management include collection and treatment systems for process vapours and ventilation systems. Many kinds of odour treatment processes can be used: wet scrubbing, bioscrubber, chemical scrubber, biofilter, and activated carbon filter. Rendering processes create effluents as well, containing e.g. organic matter, and nutrients. All effluents need to be treated before release to water bodies, and the treatment can be implemented either in internal or external treatment plant. At Honkajoki Oy, there are separate treatment lines for process effluents and process vapour condensates high in ammonia.

2.2 Sources of waste heat

There are many kinds of waste heat sources in rendering plant. Characteristics of waste heat streams must be found out when considering heat recovery and utilisation. Waste heat source can be in form of hot air, water, or water vapour, or as a mixture of them.

The heat capacity of the flow depends highly on the phase of heat source. Waste heat sources occur in different temperature levels. Then there is quality criterium: waste heat source can be clean or unclean – basically meaning whether it has been in contact with treated material. The magnitude of heat available in a stream depends on mass flow and the thermodynamic properties of the stream. The heat that can be recovered from a liquid waste heat source can be calculated by

$$\dot{Q} = \dot{m}c_p(T_1 - T_2), \tag{1}$$

where $\dot{Q}$ [kW] stands for heat content of the stream, $\dot{m}$ for mass flow [kg/s], c_p for specific heat capacity of the stream [kJ/kg°C], and superscripts 1 and 2 are the initial and final state. Heat content can also be calculated directly from specific enthalpies [kJ/kg] as in equation 2, which works also when phase is changed. Using steam tables, this is very convenient way to calculate heat content of streams.

$$\dot{Q} = \dot{m}(h_1 - h_2) \tag{2}$$

where $\dot{Q}$ [kW] is the heat content of the stream, $\dot{m}$ the mass flow [kg/s] of the stream and h [kJ/kg] is the specific enthalpy of the stream at certain state.

The availability of waste heat varies during the process due to the varying heating requirements of different process phases. There are heat losses in all thermal processes in form or another. After applying heat to a process, the waste heat becomes available sooner or later. For example, in drying process waste heat occurs rather simultaneously with applying heat, as water from product stream starts to evaporate quickly. Controversially, if there would be heated batch process where the feedstock come in cold, it would take some time to heat up before the material heats up and waste heat becomes available. Figure 1 visualises the waste heat sources and main steam users at the case plant LTWR process described in chapter 2.1.

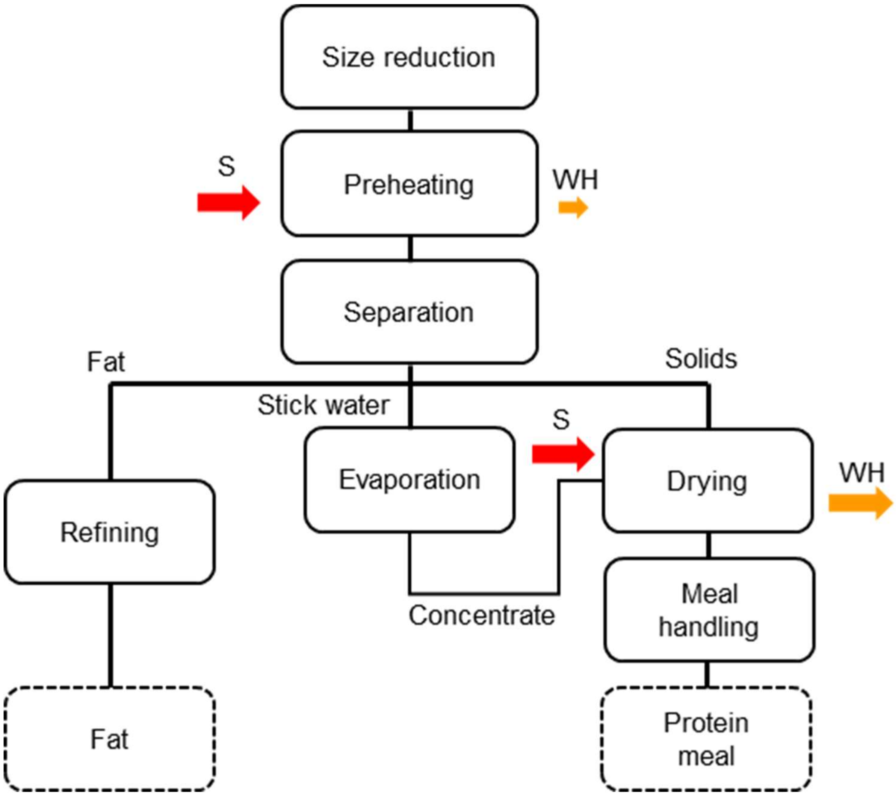

Figure 1. *Basic LTWR process with steam use points and heat sources highlighted.*

Drying processes use typically most of the total energy consumption of rendering process, taking up around 2/3 of the total energy. Thus energy-related emissions from drying processes are also one of key environmental issues for rendering plants. (EIPPCB, 2005) Dryers are major source of waste heat as well. The moisture from feedstock is removed in form of water vapours and due to the high latent heat of steam, this stream contains a significant amount of heat. Drying vapours are an unclean source of waste heat as they originate from feedstock which sets challenges to heat recovery design. Unclean heat sources can cause accumulation of impurities on heat transfer surfaces, which decreases the heat transfer efficiency. Additionally, the risk of corrosion must be considered in material choices if heat source includes impurities.

Disc dryers are commonly used technology for drying rendering products. They are typically large, horizontally lying vessels with rotating discs that are in contact with material. Drying is based on evaporation of water from the product stream. Evaporation of product moisture occurs at contact area of the discs, which are heated by saturated steam. Saturated steam condenses into water after releasing the latent heat to heat the contact surfaces (Zhang et al., 2021). At the case plant, drying is done by two disc dryers. As all the removed moisture from the product goes into the process vapour, the amount of waste heat in the process vapour from dryers can be estimated from the mass flow of the evaporated water and its specific enthalpy. As most of the energy content of steam is latent heat and it is quickly transferred in condensation, the latent heat (condensation of saturated steam into saturated liquid at constant temperature) is used when estimating the amount of waste heat. Derived from mass balance of the dryer and equation 2, the heat content of process vapour can be calculated from product mass flows and moisture contents in and out as in the equation 3.

$$\dot{Q}_{PV} = h_{\mathrm{fg}}(w_{\mathrm{in}}\dot{m}_{\mathrm{in}} - w_{\mathrm{out}}\dot{m}_{\mathrm{out}}) \quad (3)$$

where $\dot{Q}_{PV}$ [kW] is the heat content of process vapour, h_{fg} [kJ/kg] is the enthalpy of evaporation (latent heat) of steam at certain temperature, w [kg water/kg product] is the moisture content of product and $\dot{m}$ [kg/s] the mass flow of product.

Process vapour must be condensed and cooled before it goes to further treatment. This is the point where waste heat is plentifully available and recoverable. Recovering waste heat from process vapour not only offers energy to other use, but also saves energy that would need to be used for cooling. Process vapour must be first condensed and then the temperature must be cooled down. This gives the opportunity to recover at first the latent heat of the process vapour when it condenses, and if wanted, additionally the heat from cooling down the process vapour condensate to lower temperature.

In addition to the dryers, which are the largest waste heat sources, there are other smaller sources of waste heat. Preheater, which is in the process after size reduction to warm up the raw material, also produces some unclean vapour. This amount is way smaller than dryers, as the temperature goal of preheater is under 100 °C, so water does not evaporate to large extent. Collecting this vapour for heat recovery would probably not pay off due to its lower temperature level and energy content. Adding collection lines adds costs and makes the system more complex. Hence, preheater is left out of the heat recovery scope.

Waste heat from other smaller process equipment could be recovered with heat exchangers to a liquid heat recovery cycle. The form of waste heat in those units is something else than vapours, so it would be a totally different system, and that will not be further studied in this work. Thus, only the dryers of the case plant are considered into the heat recovery scope in this case study.

Flash steam in is unavoidably formed steam heating systems, but its energy content is often wasted by releasing it to atmosphere. Flash steam is generated when pressure of water allowed to drop. This happens because the enthalpy of liquid water at higher pressure is greater than at a lower pressure. This difference in enthalpy between these pressure states makes a part of the water to evaporate. (Roberts et al., 2017) Flash steam is clean since it is from boiler quality water and has no contact with product streams. Therefore, it can be utilised as heat source when just the temperature levels match. The flash steam generated per 1 kg water can be calculated from liquid enthalpies of initial and reduced pressure (Spirax-Sarco Limited, 2008).

$$\text{Proportion of flash steam} = \frac{(\mathrm{h_f\ at\ P_1}) - (\mathrm{h_f\ at\ P_2})}{(\mathrm{h_{fg}\ at\ P_2})} \tag{4}$$

where $\mathrm{h_f}$ [kJ/kg] is liquid enthalpy (sensible heat) and $\mathrm{h_{fg}}$ [kJ/kg] enthalpy of evaporation (latent heat). (Spirax-Sarco Limited, 2008). Flash steam is formed after all the indirectly steam heated equipment, when the pressure of hot condensate is lowered by a steam trap before condensate return line that takes the condensate to steam generation. To maximise energy efficiency, flash steam should be separated from condensate and utilised at any suitable low-pressure application. All the flash steam that can be utilised in heating purposes decreases the use of boiler steam, thus saving costs and emissions. (Spirax Sarco, 2023)

2.3 Waste heat recovery and utilisation

Heat exchangers can be used to transfer heat from a stream to another, keeping the streams separate without any contact to each other. Hot stream releases heat to cold stream and cools down whereas temperature of the cold stream rises. Waste heat from rendering processes has been reported to be recovered by heat exchanger systems in several rendering installations in different countries for example for heating boiler feed water, fat, cleaning water or district heating water (EIPPCB, 2023). Examples of reported heat recovery installations are given in table 2, and it can be noted that waste heat from process vapour is already utilised at many rendering installations. Heat exchangers are important in cooling purposes as well. Condensation of waste vapours is often carried out by indirect cooling with heat exchanger, where water or air flows in cold side (EIPPCB, 2023). Heat recovery from hot source to colder sink can be done by just one heat exchanger where there is cold side and hot side. Another option is to have separate circulation that cools one or several heat sources by heat exchanger and transfers the heat to one or more heat exchangers where the heat is used for heating another stream.

Table 2. *Examples of heat recovery systems in rendering plants in EU (EIPPCB, 2023)*

Heat source	Purpose of recovery	Location
Process vapour from cooking/drying processes	Hot water for cleaning, scalding or district heating system	Austria, Belgium, Germany, Finland
Condensate from steam circuit	Hot water for cleaning	Spain, France, Italy
Dryer, evaporator of a fish rendering plant	Heating of raw material, evaporator, district heating	Denmark, Norway

A typical solution for heat recovery in a case plant would be that waste heat from process vapours and other heat sources is recovered to water-glycol circulation by heat exchangers. Heat recovery circulation is then used to provide heat to in-plant heating purposes and/or external heat users such as greenhouses nearby. This kind of heat recovery system reduces the total energy use by utilising the waste heat of main energy users to smaller energy users. However, the energy consumption of main energy users, drying and cooking, cannot be reduced by only heat exchangers. When recovering heat with only heat exchangers, heat sink cannot be higher temperature than heat source since heat only transfers from higher to lower temperature.

To have potential for heat recovery, the need and supply of heat must (be made to) match (Salonen, 2020). In other words, there must be a user for available waste heat, otherwise waste heat cannot be recovered. If the demand of heat occurs later, heat can be stored way or another, but it is always an extra expense to store heat. Hence, the best case is that heat demand goes hand in hand with available waste heat i.e. it is needed at same time and can utilise as much waste heat as available. Also, the distance between heat source and heat sink should not be too long since long transfer lines add costs and lead to heat losses.

2.4 Upgrading waste heat using heat pump

Whereas in heat recovery systems based on heat exchangers the heat source must be at higher temperature than at heat sink where the heat is utilised, with a heat pump the situation is opposite. Heat source of a heat pump is a colder stream, and the heat sink is of higher temperature. The temperature difference between heat sink and heat source is referred as temperature lift (Zühlsdorf, 2019). The basic principle (figure 2) is that heat pump uses electrical power to upgrade the heat to higher temperature – the temperature of the heat sink. The advantage of producing heat by heat pump, compared to fuel driven or electric boilers, is that most of the thermal output originates from waste heat, and smaller part, such as 25 % (depending on system properties) comes from electrical power of compressor.

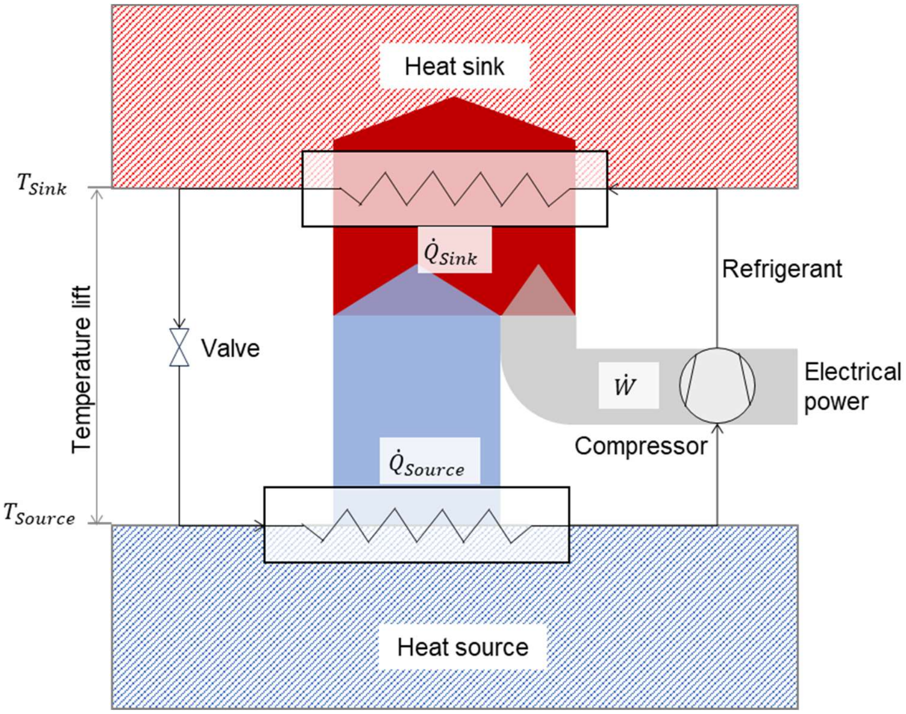

Figure 2. *Cycle layout and energy flows of basic closed-cycle vapour compression heat pump. Based on (Zühlsdorf, 2019)*

Heat pump technology has been developing quickly and now it is already mentioned in the final draft of upcoming rendering BAT reference document (BREF) that "heat pumps upgrade the heat in relatively cold streams so that it can perform more useful work than could be achieved at its present temperature" (EIPPCB, 2023). In current BREF from 2005, there are no mentions of heat pumps in heat recovery, as heat pump technology wasn't developed enough for high temperature uses, and heat recovery was altogether less considered that time (EIPPCB, 2005).

Kosmadakis (2019) conducted a study about EU potential of HTHP based industrial heat recovery. The study aimed to match the heat consumption and upgraded heat. It was noted that many commonly used processes in food, chemical and paper industries, such as drying, evaporating and distillation, require significant amounts of low-temperature heat < 150°C. Within temperature range of 100-150°C, annual consumption of heat in

EU is 192 TWh/year, of which food industry represents the largest share (35 %). Several today’s commercial heat pumps can provide heat of that temperature (HPTTCP, 2023).

Rendering processes could have a significant benefit of heat pump technology. Rendering plants produce waste heat with high energy content and consume a significant amount of heat energy in form of steam. The role of heat pump technology would be to upgrade the waste heat to a usable form, steam. Temperature levels of available SGHP systems, up to 150 °C or even higher, are high enough for rendering purposes, and so integration of SGHP technology into rendering plants is only question of proper system design.

There are several ways how heat recovery system with SGHP can be organized, and the design is case specific. System design needs to consider the time-profile of heat sources and steam users, with target of matching the available heat source and the need of heat. SGHP can be integrated into an industry plant as parallel steam generation system with a boiler (Saini et al., 2023). In this option the SGHP produces steam into central steam delivery system from centralized waste heat collection. Boilers often create steam with higher pressure and temperature for efficient delivery. This means that to match the boiler pressure, a SGHP would need to have a very high temperature supply and large temperature lift. (Saini et al., 2023) Temperature lift is defined as the temperature difference between heat sink outlet and heat source inlet (Kosmadakis et al., 2020).

Another option is to integrate a SGHP to a process so that it uses the waste heat of the process and upgrades it to steam to be utilised by the process. In that option, the temperature lifts are typically smaller than in generating heat to central steam system. Heat pump systems with lower temperature lift offer higher coefficient of performance (COP) values than those with higher. This would advocate integrating SGHP into a process level rather than for central steam system with higher pressure and temperature levels and decreased COP. (Saini et al., 2023)

Drying processes have been mentioned in several articles to have a significant potential when it comes to integration of SGHP systems (Arpagaus et al., 2018; Saini et al., 2023). This potential is based on that drying processes have high energy consumption due to the high evaporation enthalpy of water, they are often based on fossil fuel combustion, and waste heat recovery is typically limited. Drying processes produce a lot of waste heat of high enthalpy vapour, and in addition, the temperature levels suit well to SGHP implementation. The scale of industrial drying is large, being estimated to cover 12-15% of industrial energy consumption in developed countries. (Wilk et al., 2022) Thus, wide implementation of SGHP technology would have significant role in improving energy efficiency and reducing GHG emissions.

Conventionally disc dryers, which are largest steam users and waste heat sources in the case plant, have been driven with higher pressure steam (up to 8 bar_g). However, steam pressure and temperature could also be lower, and so easily and efficiently achievable by a SGHP. Saturated 2 bar_g steam (134°C) would be a good compromise for the case plant: high enough to reach sufficient temperature levels but low enough to be reached by a SGHP efficiently. In disc dryers, using low pressure steam (2 bar_g) seems to require larger contact area and/or longer residence time to achieve the same drying result. Thus, the size and price of the dryer would be higher. Similarly to disc dryer, preheaters could use low pressure steam, but this might require larger contact area and/or longer residence time.

In the case plant, the SGHP integration could be something between centralised and unit process integrated steam delivery. The heat recovery would occur from two largest waste heat sources, the disc dryers, and the produced steam would be delivered to the dryers, preheater, and some smaller users that can utilise low pressure steam. Thus, the system would be close to process-integrated system, with only addition of some smaller steam consumers. On the other hand, as in parallel steam generation system described by Saini et al. (2023), a steam boiler would be connected to the steam delivery as a back-up for moments when the SGHP cannot fulfil all the steam demand of the process.

This kind of integration system would have the advantage that waste heat follows steam consumption. This helps to match the supply of waste heat with the steam demand as waste heat is available at the same time when the same machine uses steam. Whereas conventional steam system has the challenge, where extra steam boiler capacity is required to cover the peak loads, leading to inefficiencies, extra costs and emissions, this kind of SGHP system would match the demand and supply of steam better.

2.5 Steam as energy carrier in industrial heating

Water can exist as a solid (ice), a liquid (water) and a gas (steam). Steam and water, and the phase transitions between them, are important for rendering processes and in this study since both steam heating and heat recovery from process vapour is based on phase transitions between liquid and vapour. Steam properties, such as enthalpy, heat capacity, and density depend on pressure and temperature, and they are commonly presented in steam tables, which are based on experimental data. Relationship between temperature and enthalpy at different pressure levels can also be visualised in steam phase diagram (Figure 3). (Spirax-Sarco Limited, 2008).

The transitions in steam generation can be explained in the phase diagram as follows. When heat is brought to water, the temperature and enthalpy rises along saturation curve until the saturation temperature at the current pressure is reached (A - B). Saturation curve is a phase boundary between liquid and gaseous form that shows the states of temperature and pressure at which water exists as saturated water or saturated steam. If heating is continued when saturation point is reached, saturated water can’t receive more energy but starts to boil and form saturated steam. Adding heat doesn’t affect the temperature if the pressure is constant, but the heat is transferred to the steam that is formed. In state between saturated water and saturated steam, water is in the form of wet steam, which is a mixture of water droplets and steam. Dryness factor χ describes the proportion of dry steam in the mixture. (Spirax-Sarco Limited, 2008) At point C, there is no more water droplets along steam, and hence saturated steam is also referred as dry saturated steam (Roberts et al., 2017). The heat that is needed to evaporate saturated water into saturated steam (B – C) is called enthalpy of evaporation or latent heat. If heating is continued after reaching saturation curve, saturated steam turns into superheat steam (dotted line). (Spirax-Sarco Limited, 2008) In this work, steam is assumed to be in the saturated stated unless otherwise specified.

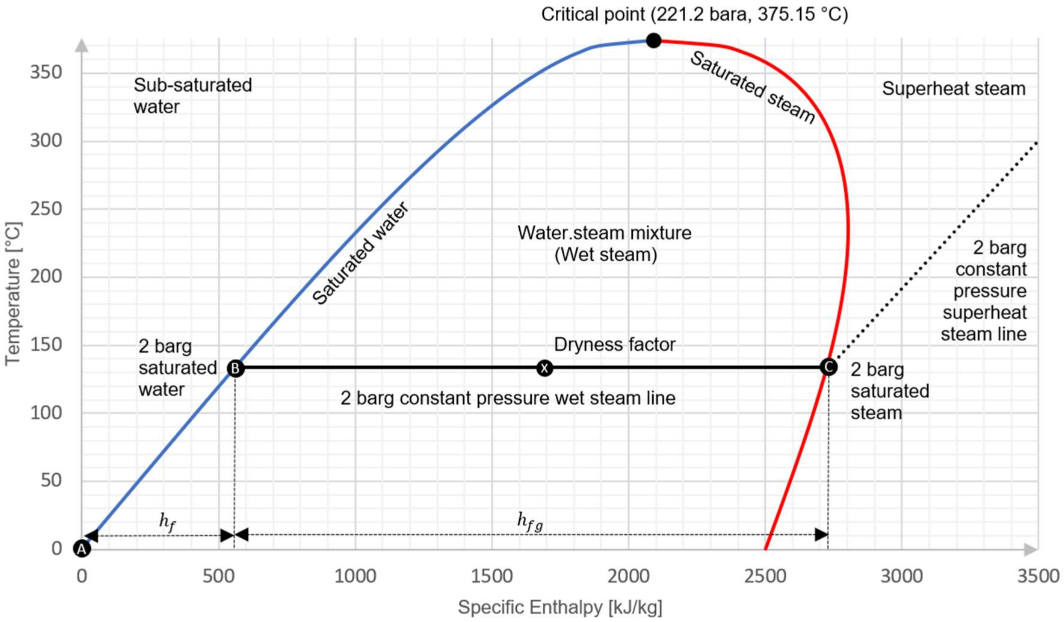

Figure 3. *T-h phase diagram of water with 2 bar$_g$ constant pressure line. Based on (Roberts et al., 2017; Spirax-Sarco Limited, 2008)*

Total enthalpy of saturated steam consists of liquid enthalpy and enthalpy of evaporation. (Merritt, 2015) As can be seen from phase diagram, most of the total energy content of steam is enthalpy of evaporation (also referred as latent heat) (2675 kJ/kg at 1 bar and 100), whereas liquid enthalpy is smaller part (419 kJ/kg at 1 bar and 100 °C). The reverse process of evaporation is condensation, where saturated steam transforms into saturated water. In condensation the enthalpy of evaporation is released, and this can happen quickly. A large and rapid energy release of phase transition into liquid with the ability to drive steam through processes makes it a highly effective medium for heat transfer. (Roberts et al., 2017) High energy content of steam allows relatively small heat transfer areas compared to other heat transfer media (Spirax-Sarco Limited, 2008).

There are also various other reasons that make steam useful for industrial processes. One of the advantages of steam is the ease of delivery and control. Steam heating does not need pumping since the pressure of steam makes it fill any space and flow in the pipes to the users. Steam delivers the heat at the saturation temperature, and so the temperature is uniform at the heat transfer areas. (Spirax-Sarco Limited, 2008) The direct relationship between temperature and pressure of saturated steam makes it easy to control both the pressure by only controlling the steam pressure. The mass flow of steam is another parameter to control, defining the energy input of heat. Automated control systems in steam delivery using pressure-reducing valves and flow control valves offer precise and rapid control of steam heating. (Merritt, 2015) Steam is safe to use. It does not contain chemical hazards and causes no fire risk (Roberts et al., 2017). Steam is also sterile, which makes it very useful for e.g. food and pharmaceutical industries (Spirax-Sarco Limited, 2008).

3. STEAM GENERATION HEAT PUMPS

The excellent capabilities of steam as a heat transfer medium and for other uses will be needed in future industry as before. Whereas fossil fuel powered steam boilers have been the major technology for steam generation, new alternatives for steam generation in transition towards fossil-free economy are highly needed. Heat pumps show a lot of potential in decarbonising steam generation as they can be used to upgrade waste heat into steam utilising electric power. This chapter will describe SGHP technology, starting with basic heat pump theory and focusing on potential SGHP types for rendering industry.

3.1 Heat pump cycle and operation parameters

The basic vapour compression HP cycle and working principle of a heat pump was visualised in figure 2. Four main components are evaporator, compressor, condenser, and expansion valve. Pipeline connects the components, and refrigerant, also referred as working media, circulates the cycle. Evaporator is a heat exchanger, where heat from heat source is brought to refrigerant, which makes it to evaporate. Evaporated refrigerant continues to the compressor, where it is compressed to higher pressure and temperature. Compressor is the component that consumes electrical power to upgrade the heat to higher pressure and temperature. Considering the performance of heat pump, the compression ratio (CR) of the compressor is an important factor. It is defined as ratio of pressure after compressor and pressure before compressor (equation 5), and the compression of a single compressor is limited by maximum CR.

$$CR = \frac{p_{out}}{p_{in}} \tag{5}$$

The other heat exchanger is condenser. In the condenser, compressed refrigerant vapour releases its heat to the heat sink and condenses into liquid. After condenser the refrigerant goes through pressure relief valve, which decreases the pressure to a level at which the refrigerant can once again evaporate at the evaporator.

Main indicator of heat pump system performance is COP, which is determined as ratio of supplied heat to the used electrical power (equation 6). If there are multiple heat supplies and/or compression stages, the values are summed up for calculating the system COP. (Zühlsdorf, 2019)

$$\mathrm{COP} = \frac{\sum \dot{Q}_{Sink}}{\sum \dot{W}} \tag{6}$$

The efficiency of a heat pump is highly affected by temperature lift. The maximum possible COP of a heat pump can be calculated theoretically from the temperature levels of heat sink and heat source. Theoretical COPs for heat pumps are commonly derived from Carnot and Lorenz cycles. According to Zühlsdorf (2019), $\mathrm{COP}_{\mathrm{Lor}}$ (equation 7) can be used for calculating theoretical COP of a heat pump, when the heat source and heat sink experience a temperature glide. Temperature glide refers to the difference in inlet and outlet temperature of a stream that is being heated or cooled. Therefore, it should be more suitable to real life heat pumps since there is typically some temperature glide in heat source and heat sink.

$$\mathrm{COP}_{\mathrm{Lor}} = \frac{\bar{T}_{Sink}}{\bar{T}_{Sink}-\bar{T}_{Source}} \tag{7}$$

This equation assumes that heat transfer occurs at the thermodynamic average temperature of heat sink $\bar{T}_{Sink}$and heat source $\bar{T}_{Source}$. The thermodynamic average temperature is defined as $\bar{T} = \Delta h/\Delta s$, but logarithmic mean temperature of streams $\bar{T}_{lm} = (T_1 - T_2)/\ln{(T_1/T_2)}$ can be used as an approximation. (Zühlsdorf, 2019)

Theoretical COPs, whether Carnot or Lorenz, are far from achievable in practice. Carnot efficiency η_{Car} or Lorenz efficiency η_{Lor} is determined as a relation of measured COP (equation 6) and $\mathrm{COP}_{\mathrm{Car}}$ or $\mathrm{COP}_{\mathrm{Lor}}$, which indicates how close to theoretical maximum performance a heat pump can perform (Zühlsdorf, 2019). Arpagaus et al. (2018) gathered COPs of available HTHPs into a graph as a function of temperature lift, curves of theoretical $\mathrm{COP}_{\mathrm{Carnot}}$ on the background. It showed that most HTHPs achieve η_{Car} at range 40-60%, some of them a bit less and few a bit more. It can be noted that $\eta_{Car} = 50\ \%$ is a good guess for HTHP efficiency, but obviously there are differences in efficiencies, depending on properties such as refrigerant, compressor, cycle, and how well the system is optimized.

3.2 Classification of high temperature heat pumps

HTHPs are a new field of study, and those used for steam generation even more novel. Hence, the terms and classifications of different types are not fully unified, but different terms can be found in the literature for same things. This sub-chapter will present a brief overview of different types of HTHP systems based on previous research.

There are many types of HTHPs, and to get a broad understanding of diversity of different technologies, they can be classified by technical options and properties (Figure 4) There are several different cycles that heat pumps can be based on, and only the most potential ones for the case plant are being described in this work. Cycles can be upgraded with optimization technologies, and some of them are discussed later. Other important thing is the media of heat sink and heat source. SGHPs are one type of HTHP technology, with steam as the heat sink, other options being hot water or hot air. Heat source can be in different forms such as process vapours, wastewater, or flue gas. Different refrigerants and compressor types are discussed later. Then of course, heat pumps are designed for different temperature levels of heat sink and source, having different temperature lifts. Industrial HTHPs are scalable and come in different scale applications, e.g. from heating capacity of 30 kW to 70 MW (Annex 58, 2023).

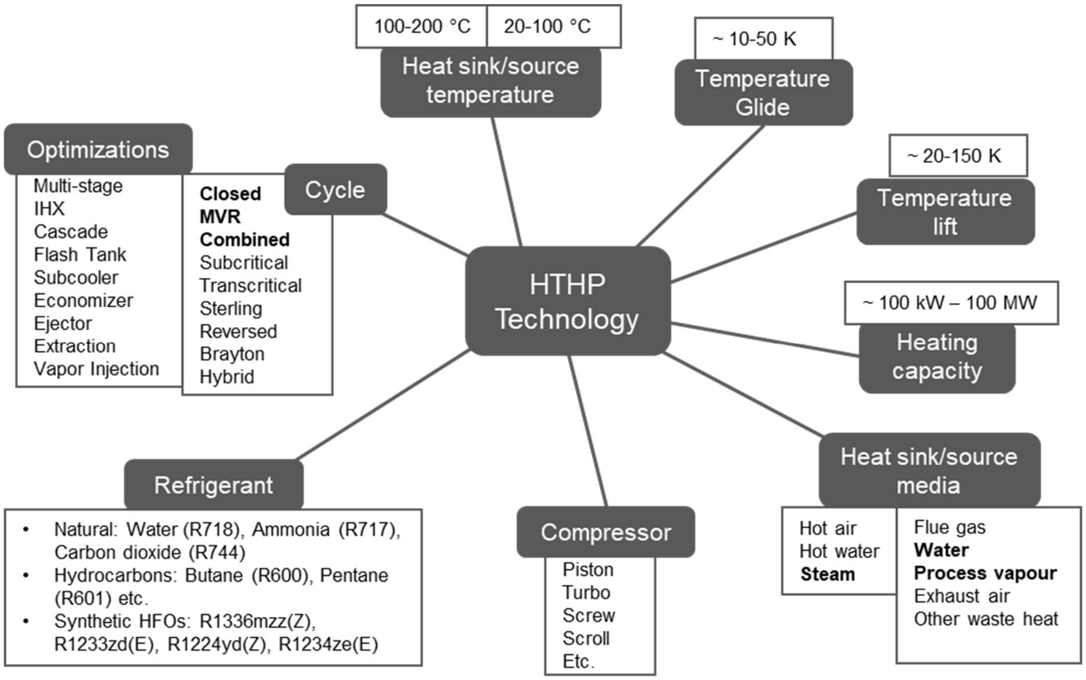

Figure 4. *Overview of HTHP technology, based on Arpagaus et al. (2018) and A2EP (2023)*

In this work the focus is on heat pump systems where heat source is waste heat in form of hot water or directly from process vapours and heat sink is steam at 2 bar(g). Closed, MVR and combination of them are the cycles to be further described in this work. When it comes to temperature levels, even high lifts as 150 K are possible, but then feasibility comes into question, since COP is lower than with smaller lifts. The scale of heating capacity in this case study is 3-5 MW, which is medium size within potential HTHP systems, but large within existing HTHP installations.

Literature shows many kinds of optimizations to HP cycles. They can be additional equipment to the basic cycle or ways to organize the cycle. An internal heat exchanger (IHX) is one of the equipment that can added to HP cycle to recover heat from condenser outlet for preheating the inlet flow of compressor (Zhao et al., 2021). IHX seems to have become a standard part of closed-cycle HTHPs, as it improves the cycle performance and helps to reach higher temperatures (Kosmadakis, 2019).

Mateu-Royo et al. (2021) described and compared eight advanced HP cycle configurations found in the literature. Different configurations used different cycle optimizations to improve the system efficiency, such as ejector, flash-tank, economizer, parallel compressors and/or extra heat exchangers. Also Jiang et al. (2022) described several optimizations systems and cycles based on them. When COPs of different cycles were compared for different temperature lifts, it was shown that some configurations perform well at low temperature lifts but worse at high lifts, and other cycles vice versa. A single-stage cycle optimized with economizer and parallel compression was most efficient at lower lifts (< 55 K) and a two-stage cascade cycle performed best at higher lifts (60-80 K). (Mateu-Royo et al., 2021) A cascade system has two separate cycles with different refrigerant. The heat sink of low-temperature cycle works as a heat source for high-temperature cycle, hence allowing higher temperature lifts.

3.3 Steam generation heat pump alternatives

Numerous cycle configurations are found in the literature, but most available HTHP systems can be categorized into three types: closed-cycle, mechanical vapour recompression (MVR) and combined-cycle (figure 5). When it comes to steam generation, all the cycle types can be utilised, when only the temperature levels are high enough generating steam at goal temperature. Since the aim of the study is to investigate and compare the potential SGHP technologies for real life application in near future, the focus is on the potential SGHP technologies that were identified based on the list of commercial HTHP technologies (HPTTCP, 2023) and literature review.

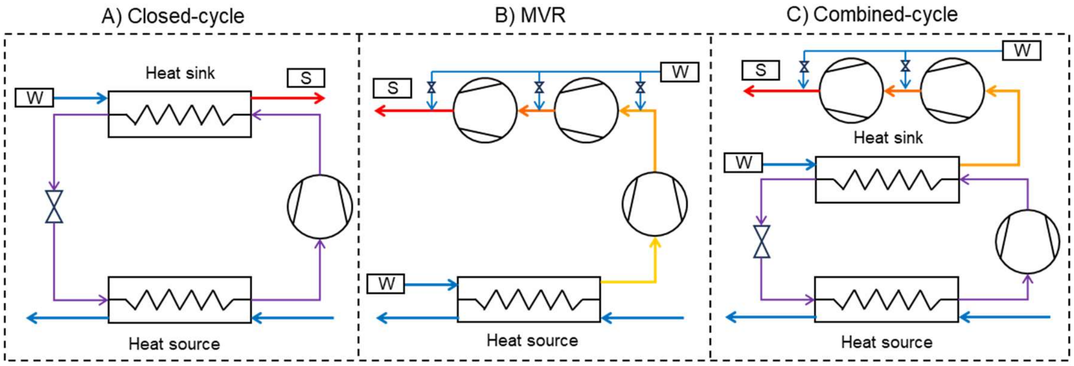

Figure 5. *Basic diagram of three main types of SGHPs: A) closed-cycle heat pump B) MVR heat pump C) combined-cycle heat pump*

A closed-cycle heat pump (CCHP) (figure 5a) is based on closed refrigerant cycle presented in the chapter 3.1, without contact with produced steam. Heat is transferred from heat source to heat sink via refrigerant circulation and heat exchangers at heat source (evaporator) and heat sink (condenser). Steam generation in case of closed-cycle SGHP can be done directly at the condenser of HP, as in the model of Dusek et al. (2021) or via flash tank as in the system of Kaida et al. (2015). If steam generation occurs at the condenser, the heat exchanger type must be water/steam. Also demonstrated in BAMBOO project, steam generation using flash tank works so that HTHP heats up hot pressurized water at the condenser, and then flash valve expands water and makes it evaporate. The flash tank itself is a vertical separator, which allows the separation of flash steam to the user and unevaporated water to recirculation. (Zeilerbauer et al., 2023)

Many different compressor types can be used in CCHPs: piston (or reciprocating), screw, scroll, and centrifugal (or turbo) compressors are reported to be utilised. In piston compressor, which can be compared to an engine, the compression takes place in cylinder where piston first sucks the refrigerant through a valve and then compresses it when moving back. Screw and scroll compressors are based on rotating structure that compress the refrigerant by two counter-rotating screws or two spirals moving into each other, respectively. In centrifugal compressor, the energy of rapidly rotating impeller is transferred to the medium in form of pressure. (HPTTCP, 2023) It should be noted that depending on compressor technology, heating capacity of single closed cycle can be relatively low, and so in larger systems there might be need for multiple units or parallel compression cycles.

The importance of refrigerants for closed-cycle HPs is high, as their thermodynamic properties define the applicable temperature range and the achievable COP depend on the refrigerant properties (Dusek et al., 2021). Research has been active with HTHP refrigerants, with objective to discover safe, low GWP and ODP refrigerants that are usable to higher heat sink temperatures. Due to environmental reasons, conventional refrigerants such as 134a and R245fa are to become outdated in near future due to their higher global warming potential (GWP) and/or ozone depletion potential (ODP) (Arpagaus et al., 2018). The critical temperature and pressure are important factors in refrigerant selection since the temperature limit for subcritical operation is limited by them. Heat pumps commonly rely on subcritical operation, but also transcritical cycles can are implemented with some refrigerants (Mateu-Royo et al., 2021). Arpagaus et al. (2018) compiled the selection criteria for refrigerants. They include thermal suitability (critical temperature/pressure), environmental compatibility (zero ODP, GWP<10), safety (nontoxic, no/low flammability), efficiency (high COP and volumetric heating capacity VHC), availability and price, and mechanical properties.

If required temperature lift is high, there might be need for a cascade HTHP. In cascade HTHP, heat sink of the lower temperature cycle acts as the heat source for the higher temperature cycle. Mateu-Royo et al. (2021) studied 8 different systems, of which a two-stage cascade cycle showed the best COP at high temperature lifts 60 K and above. Cascade HPs can use different refrigerants for low-temperature cycle and high-temperature cycle to have the optimised use of refrigerants' thermodynamic properties (Arpagaus et al., 2018).

In MVR HP system (figure 5b), there is no separate refrigerant circulation, but the working medium is water and steam. The basic system configuration is simple, having only two main equipment, evaporator and compressors (Bless et al., 2021). As in closed-cycle HP, evaporator is used to transfer heat from heat source to the working medium. In MVR HP system, the other stream through the evaporator is the feedwater, of which steam is generated. In evaporator, the heat of the heat source makes the feedwater to evaporate.

In atmospheric pressure the boiling point of water is 100°C, and according to second law of thermodynamics, heat does not move from colder medium to warmer. Therefore, waste heat under 100°C cannot be used for evaporation of water in atmospheric pressure. However, the evaporation temperature of water decreases when the pressure decreases, which makes it possible to use lower temperature waste heat to evaporate water to generate steam (Bless et al., 2017). If the heat source in MVR HP system is lower than 100 °C, a vacuum pressure is maintained in the evaporator to enable evaporation of water. The evaporation temperatures of water at certain pressure follows the saturation curve of water. For example, water at 60 °C evaporates at 0,2 bar(a) and 80 °C at 0,5 bar(a).

After water is evaporated at the evaporator to a low-pressure steam, MVR compressors are then used to lift the pressure and temperature of the steam. Maintaining the vacuum at the evaporator is another task for the compressors, if heat source is lower than 100 °C. The pressure lift of one steam compressor is limited to maximum pressure ratio, which means that multiple compression stages are required when aiming for higher temperature lifts (Bergamini et al., 2019). Maximum compression ratio (CR) for one MVR compression stage is noted to be around 4 (Bless et al., 2017). To optimise the performance, low compression ratio per stage is typically preferred. (HPTTCP, 2023) The number of MVR stages is defined by the required temperature lift and the optimal CR of the used compressor type.

MVR systems have proven to perform high efficiencies compared to CCHPs. When several HTHP demonstration cases were analysed, the Lorenz efficiencies of MVR systems varied between 0.45 and 0.91 whereas Lorenz efficiencies of CCHP systems ranged between 0.35 and 0.59. The difference in efficiencies can be explained by that less heat exchangers are needed. In open operation mode there is not evaporator nor condenser, and in a semi-open operation mode only evaporator is needed. Heat exchangers always have some temperature drop from hot side to cold side, which causes more work for the compressor(s) to reach a certain temperature and thus weakens the efficiency. (HPTTCP, 2023)

Combined-cycle HP (figure 5c) is an option that combines closed-cycle HP and MVR technology. Basic idea is that a number of MVR compressors is added after the closed-cycle HP to increase the steam pressure efficiently. If the range of closed-cycle SGHP cannot reach the goal supply temperature or the COP decreases drastically, combined-cycle configuration can offer a reasonable option (Saini et al., 2023). In combined cycle SGHP system, closed-cycle HP is often referred to as bottom cycle, recovering energy from lower temperatures, lifting the temperature up with refrigerant loop, and generating steam at low temperature. MVR section can be referred as top cycle, and its role is to upgrade the generated steam to a goal pressure level efficiently. (HPTTCP, 2023)

Even if it would be possible for closed cycle SGHP to supply steam at the goal temperature, high temperature lift and thus high compression ratio causes low compression efficiency and low COP (Lu et al., 2022). Combined-cycle HP can be implemented to improve the COP if the temperature lift is high. For example, Bless et al. (2017) showed that combined cycle performs significantly better COP upgrading 80 °C heat source to 150 °C steam than closed heat pump cycle, respective COP values being around 4.0 and 2.7.

Table 3. *Comparison of three main types of SGHPs (HPTTCP, 2023)*

	Closed-cycle HP	MVR HP	Combined-cycle HP
Working fluid	Synthetic HFOs Hydrocarbons Natural	Water	Synthetic HFOs Hydrocarbons Natural Water (Top cycle)
Compressor(s)	Piston Screw Scroll	Turbo/centrifugal compressors in series	Piston Screw Scroll Turbo/centrifugal
Availability and technology readyness	In commercial production and few installations in industrial use	In commercial production and industrial use	Commercial in Japan Demo projects in Europe

Bless et al. (2021) analysed and compared 5 different types of HP cycles for 150 °C (4.8 bar(a)) steam generation from 80 °C waste heat. Closed-cycle, MVR and combined cycle HPs were top 3 cycles in terms of COP and total costs steam generation. MVR heat pump, which was called an open loop water HP, had the lowest long-term costs and similar COP with combined cycle systems. Closed-cycle HP could not achieve COP as high as at temperature levels 80 → 150 °C. (Bless et al., 2021)

When it comes to applying SGHP technology in industrial scale in the near future, the availability of combined-cycle SGHPs is worse than of closed-cycle and MVR systems. Any suppliers don't offer combined-cycle solutions as a total delivery in Europe at high technology readiness (HPTTCP, 2023). To build a combined-cycle SGHP to an industrial plant, it would probably require cooperation with more than one supplier and more responsibility of system design should be taken by the purchaser, compared to a turnkey solution. It seems that combined-cycle solutions are upcoming, for example Aneo Industry has a project of 1.5 MW combined-cycle SGHP using ammonia in bottom cycle (CCHP) and water in the top cycle (MVR) (Aneo Industry, 2024).

4. HEAT RECOVERY FEASIBILITY AND ENVIRONMENTAL ANALYSIS

Previous chapters discussed the technical applicability of SGHP to the rendering context. Potential technical solutions based on commercialised SGHP products were identified. For investments in industry, techno-economic analyses (TEA) are necessary to get understanding whether considered technical solution is economically viable. The costs of SGHP implementation are highly case specific, and feasibility of the system must be assessed for every case individually. Especially, since SGHPs are novel technology and industrial implementations are few, assessing feasibility for a plant requires more effort than with well-established technologies. As there is less empirical data about SGHP performance in industrial plants, the feasibility analysis must rely largely on estimations and supplier data. Economic feasibility comprises capital costs (CAPEX), operational costs (OPEX), revenues and subsidies.

Especially when making a significant investment for improving energy-efficiency, it is important to analyse the total environmental impact of the investment – to get a comprehensive understanding of the total benefits of the investment. Techno-economic-environmental analyses (TEEA) have become more common in recent years, as environmental aspects have become an integrated aspect in decision making. On ScienceDirect database, search term “techno-economic-environmental” showed 2,685 results published in 2023, which is more than ever before. In TEEA, the system of TEA is extended with an environmental analysis, for example based on LCA framework. This chapter will give background information for TEEA in case of estimating the total benefits of integrating a SGHP system into rendering plant.

4.1 Operational costs and revenues

The feasibility of a HTHP system is highly dependent on the performance of the system, i.e. the COP (Lu et al., 2022). Waste heat can often be considered free, and so the electricity is the part of which the operator needs to pay. Higher COP means that larger share of heating capacity is waste heat, which saves more money. Kosmadakis et al. (2020) conducted a techno-economic analysis of a heat pump and the economic part of this TEEA is largely based on their framework, with adjustments to this case.

As heat pumps consume electricity and replace use of fuel, it is clear that cost of electricity and fuel affects the feasibility significantly. In techno-economic consideration, electricity to gas price ratio (in countries where gas is the main industrial energy source) is often discussed (Kosmadakis et al., 2020). If fossil fuels are too inexpensive compared to electricity, it might not make sense economically to apply a heat pump system. This is seen as one of the major barriers to adoption of HTHP technology. (Arpagaus et al., 2018) Good availability and cheap price of renewable electricity, on the other hand, is a significant driver for implementing HTHP systems. Finland and other Nordic countries are identified as attractive area for HTHPs due to relatively inexpensive electricity in several studies. For example, Kosmadakis et al. (2020) identified Finland as the most attractive European country for HTHP applications, since it has the lowest electricity to gas ratio. On the other hand, in countries where electricity to gas ratio is high, it acts as one of the main barriers for implementing HTHP systems (Arpagaus et al., 2018).

Depending on the complexity of the HTHP systems, there is always some operational and maintenance costs. Operation of the HTHP systems is automated but requires supervision. Maintenance of the equipment also requires labour costs and the costs of spare parts. Annual operation and maintenance costs of a HTHP system were estimated to be 4% of the capital cost (Kosmadakis et al., 2020). This depends on the chosen technology as some systems may require more maintenance works than others. For more detailed estimations of maintenance costs, the technology suppliers are the right source.

The cash flow of a HTHP investment is based on saved fuel costs. When it comes to SGHPs, the savings can either be saved fuels cost, if steam boiler is at owned and operated by the production plant itself, or saved price for bought steam, if steam is bought as a service. Increasing price of carbon emissions (carbon tax) is another thing that has a role on the revenues and total feasibility of a HTHP implementation. As HTHP technology can save a significant amount of carbon emissions, it lowers the amount of carbon tax that the company needs to pay. Levels of carbon taxes vary by time and between countries, but significant carbon taxes are found for example in Switzerland and Liechtenstein (120.16 €/tCO_2), Sweden (115.34 €/tCO_2), Norway (83.47 €/tCO_2), and Finland (76.92 €/tCO_2) (Mengden, 2023). Operational cost and savings can be summed up to operational revenue, as in equation (8)

$$E_s = C_f + C_{CO_2} - C_{el} - C_m \tag{8}$$

Where C_f is the cost of saved fuel, C_{CO_2} the cost of saved CO_2 emissions, C_{el} the cost of electricity, and C_m the maintenance costs.

4.2 Investment costs and payback period

Investment cost is simple when the whole technology package is from same supplier. In a typical situation it might not be as straightforward, if a turn-key delivery is not available or it is too expensive. Equipment costs can be split into smaller groups. Large contributors to total equipment costs are the compressors, heat exchangers, automation and instrumentation, and piping and tanks. If the system uses a refrigerant else than water as working fluid, it also adds costs. A typical/average price for refrigerants in large volumes are around 50 €/kg, so this addition to equipment costs has a minor role (Kosmadakis et al., 2020).

Though HTHP and SGHP products, applications and demonstrations are relatively few, the literature gives some information on the capital costs. Annex 58 (HPTTCP, 2023) presents price range per kW heating capacity for commercial HTHP products, offered by the suppliers. This specific investment costs varies between 200-1200 €/kWh, and there are large differences in different manufacturers' price estimates. Generally, HTHPs with high temperature lift have higher specific investments costs than those with lower temperature lift. High maximum supply temperatures correlates to higher specific investment cost as well.

When it comes to total project costs of a HTHP/SGHP project, there are many other expenses than just the equipment cost. Investigations, engineering, and feasibility studies must be carried out before advancing to investment proposal and decision. The waste heat sources must be characterised for specific data about available waste heat. In addition to gathering data from existing measurements, this might require organising sampling or additional measurements. This data must be compared to the energy demand. This design work is to find out the theoretical potential. When it is proven, the design of actual heat recovery systems must be done. This might be complex, especially in a retrofit project, where there might be other existing heat recovery systems and the whole systems must be reconsidered. In a greenfield project it should be simpler since the total system can be designed to have a HTHP/SGHP as a part of it. Yet in both cases by and large all the design areas must be involved: process design, structural and layout design, piping, automation, and electrical design.

In addition to the design costs, there are costs associated with construction, transportation, start-up period, management, and supervision. Estimating these costs is another task that requires resource planning and more specific cost data. Total project costs (C_t) can be estimated based on experimental factors, for example Kosmadakis used multiplication factor 4.16 of the equipment cost for estimating total project costs. (2020) This kind of estimation can offer a rough initial estimate, but for a real-life case, more specific calculations must be done.

Public investment subsidies for new low-carbon technology might also help in HTHP projects. For example, in Finland, the government usually has a budget for these subsidies, and companies can apply for a subsidy, and most potential and advantageous projects are then funded in accordance with the budget.

The overall feasibility of a project comprises investment costs and operational revenues obtained during the use. The discounted payback period (equation 9)(Kosmadakis et al., 2020) describes the time during which the revenues from operation exceed the investment costs, considering also the rate for foreign capital.

$$DPP = \frac{ln\left(\frac{1}{1-\frac{C_t r}{E_S}}\right)}{ln(1+r)} \tag{9}$$

where C_t is total investment cost, r is interest rate, and E_s is annual operational revenue. Another indicator for evaluating the overall feasibility is return on investment (ROI), which is defined as ratio of net profit to capital employed, can be calculated in different ways depending on the object of calculation (Suomala et al., 2011). In this kind of case, ROI can be calculated by dividing the net profit of typical year by the average capital employed (equation 10)

$$\text{ROI} = \frac{\text{Net profit}}{\text{average capital employed}} \cdot 100\% \tag{10}$$

In the investment calculation of SGHP, besides the investment cost, the interest rate affects greatly the yearly instalments and total capital costs. Years of payment impact does also have an impact on both. If payment period is longer, the yearly instalments are smaller, but the total capital costs are larger due to the impact of the rate.

4.3 Environmental aspects and carbon handprint

Environmental performance of a SGHP system goes hand in hand with the economic feasibility by many measures. Both are strongly dependent on COP of the system. Steady and high-capacity operation of the SGHP system benefit both economic and environmental performance. Saving the fuel combusted in the boiler is the basis of economic and environmental performance of a SGHP system.

Whereas in economic analysis, the electricity price is very important factor to total feasibility of a SGHP, in environmental analysis the emission factor of electricity has very high effect on the environmental performance. Emission factor (or emission coefficient or carbon intensity) of electricity [gCO_2/kWh] describes the GHG emissions from the production of a unit of electricity in CO_2-equivalent and it is highly affected by the source of electricity (Fingrid, 2023). This can be used in GHG calculations if the electricity source of the studied object is specifically known. If the source of electricity is not specified, the emission factor of grid mix can be used, which describes the average GHG emissions of electricity in the grid at specific time and area. Grid mix is commonly presented country level, and emission factors of country mixes can be found on the internet. Emission factor of grid mix in 2022 of different countries ranged between around 20 – 800 gCO_2e/kWh (Ember, 2023). In Finland, the grid operator Fingrid updates the emission factor of the grid live, and history data from specific time can be found in the database. The emission factor of Finnish grid mix have been decreasing rapidly since 2018, from 120 gCO_2e/kWh down to 60 gCO_2e/kWh in 2022. (Fingrid, 2023).

In a steam boiler system, the GHG emissions originate from combustion of the fuel and the production chain of the fuel. GHG emissions of the combustion can be simply calculated based on fuel specific emission factors. Statistics Finland updates a fuel classification list yearly, including CO_2 emission factors for different fuels, and these emission factors are commonly used in CO_2 calculations (Tilastokeskus, 2023). These emission factors, however, include only the CO_2 emission from the combustion, not other emission compounds or emissions from fuel production. For a full understanding of the total emissions of energy production by fuel, it would be good to assess the emissions from the fuel production chain as well.

Holmgren et al. (2006) summarises the results of a Swedish and a Finnish LCA study of energy use of peat, offering more information of the lifecycle emissions. Emissions from peat harvesting working machines were estimated to be 1 gCO_2/MJ peat. Peat field air emissions were estimated to be 8.321 gCO_2/MJ peat. Emissions were also estimated for peat field drainage period and restoration phase, but they were presented per field area, not produced peat, and their importance was small or there were uncertainties in the results. Compared to the peat combustion air emissions 107.6 gCO_2/MJ (Tilastokeskus, 2023), the emissions from production chain are small but not negligible. CH_4 emissions of peat combustion are small (0.0085 gCH_4/MJ equals 0.238 gCO_2e/MJ) but N_2O emissions of 0.0128 g N_2O/MJ does have an impact on the emission factor as the GWP value is 265 (Myhre et al., 2013), leading to value of 3.39 gCO_2e/MJ (Holmgren et al., 2006). Combining these values together, the GHG emission factor for production chain and combustion of peat would be 120.5 gCO_2e/MJ, which equals to 510.6 gCO_2e/MWh.

There are different frameworks for estimating environmental impacts of activities and products. One of the widely used methods is Life Cycle Assessment (LCA), which is a standardised method for estimating environmental impacts (SFS-EN 14040:2006). LCA framework is a versatile tool, and it can be applied to many kinds of objects with different system boundaries. A LCA study consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (SFS-EN 14040:2006). ISO 14000 standard series for environmental management also has narrower methods for GHG emissions calculations: ISO 14064 for corporate carbon footprint and ISO 14067 for carbon footprint at product level (SFS, 2023).

Grönman et al. (2019) presents an approach for assessing and communicating positive climate impacts of improved solutions. The idea is that if a product or solution decreases the carbon footprint of customer, it has a carbon handprint. As described by Grönman et al. (2019), “Reduced carbon footprint is equal to the created carbon handprint” (equation 11). This framework can be used to describe the positive climate impact gained by integrating a SGHP system into industrial production. SGHP integration decreases the climate impact of the product and thus the customer can decrease their carbon footprint. The environmental part of this case study uses basic four-phase structure of an LCA, but the idea of carbon handprint described by Grönman et al. (2019) is used in interpretation. This idea of presenting the values is closely related to the calculation of operational revenue according to equation 8, but operational costs are changed to operational CO_2 emissions.

$$Carbon\ handprint = Carbon\ footprint_{Baseline} - Carbon\ footprint_{Modified} \tag{11}$$

Where modified practice is producing steam using SGHP and baseline practice is producing steam using a fuel boiler. To open the calculation to GHG source level, the carbon handprint from SGHP system can be calculated as in equation 12:

$$Carbon\ handprint = GHG_{fuel} - GHG_{electricity} \tag{12}$$

where GHG_{fuel} stands for GHG emissions from generating certain amount of steam with fuel boiler and $GHG_{electricity}$ for the GHG emissions of the electricity used by a SGHP to produce the same amount of steam.

Zeilerbauer et al. (2023) conducted a cradle-to-gate LCA study of steam generated by a SGHP. Studied system was the SGHP system of the BAMBOO project, a closed cycle HP with a flash tank for generation. The LCA system included phases from manufacturing the heat pump system to use phase. End-of-life was excluded from the scope. All the impact categories were included in the analysis, which is important regarding the refrigerants especially. The study found that the environmental impacts of the refrigerant were relatively low, even though a higher GWP and ODP refrigerant was chosen for the analysis. Assessing the environmental impacts of refrigerants was noted to be challenging since there are not yet environmental data available from new, low GWP and ODP, refrigerants in databases. As the significance of refrigerant is low and due to the lack of environmental data of new refrigerants, it is justified to exclude the refrigerants from the environmental analysis of this case study. As the refrigerants suggested are zero-to-low GDP and ODP, their environmental impacts are assumed to be minor.

It would also be possible to estimate the GHG emissions from manufacturing the SGHP equipment. Building the SGHP equipment with > 10 t steel and stainless steel does have a significant GHG emissions. However, the manufacturing GHG emissions are expected to be small in relation to GHG emissions from operation phase, as the lifetime of SGHP system is assumed to be 20 years, and the operational hours are 5 days a week through the year.

5. MATERIALS AND METHODS

5.1 Research strategy

The methodology of the study is summarised in figure 6, visualising the background of the study, research for the solutions, and comparison of solutions. Main data sources are described as well as three parts of comparative TEEA, and how the research questions (RG) are related to the methodology.

Gathering initial data from the case plant was one of initial tasks since all calculations and discussions must be done in accordance with the plant data. Gathering data started from determining what data needs to be collected, followed by the actual collection of data. Initial data is presented in chapters 5.2 to 5.5. Data sources regarding the case plant include in-house mass and energy balances and plant diagrams, measured data from existing production line with similar process equipment, and personal communication with process designers. A lot of cross-checking was done to prove the reliability of plant data.

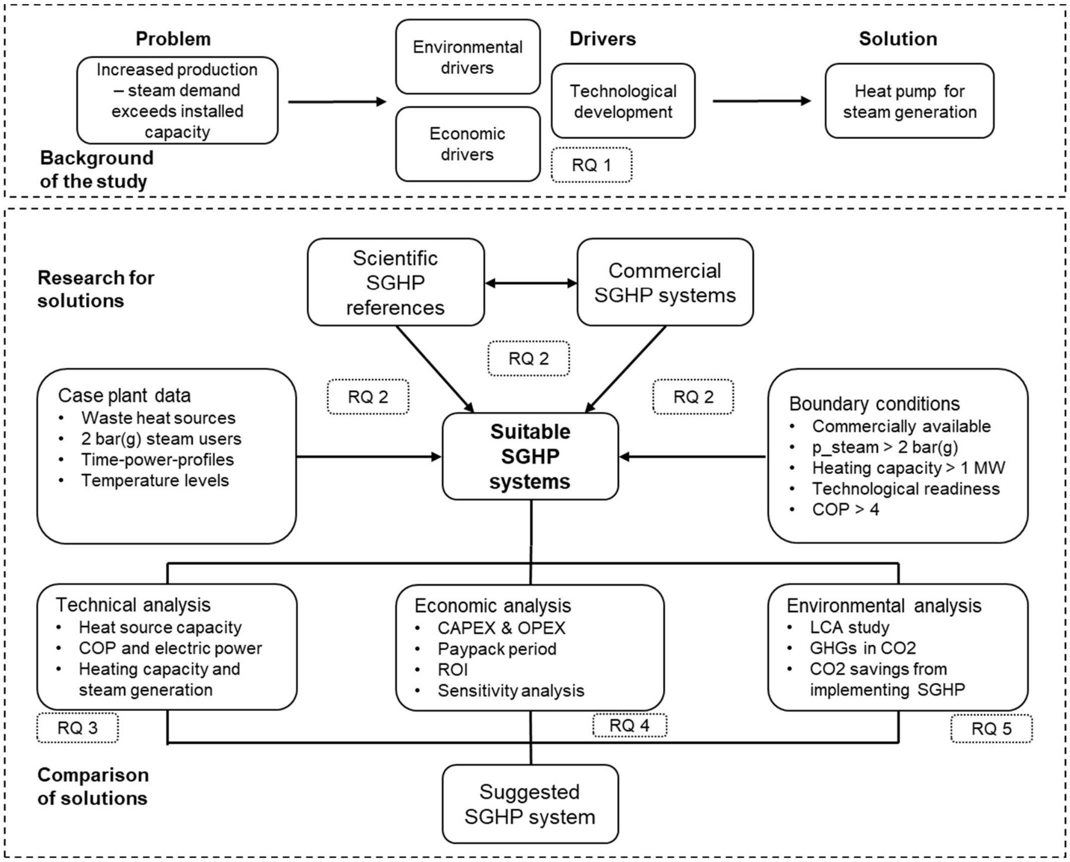

Figure 6. *Visualisation of research strategy*

Another fundamental task was to identify applicable heat pump technologies for steam generation. This was done by thorough literature review on field of HTHPs and SGHPs. Commercial products, pilots and reference plants, and theoretical research of HTHP and SGHP systems were reviewed from scientific articles, conference papers, academic theses, webinars, and websites of technology providers. Scientific research data was compared with information of commercial SGHP manufacturers to gain comprehensive understanding of available technology. Research articles of HTHP and SGHP technology were searched from scientific databases and search engines such as Science Direct, Scopus, Google Scholar and Andor. Search phrases such as “steam AND “heat pump”” and “steam generat* AND heat pump” gave relevant results.

Data from commercial products was used to estimate the real-life costs and performance of the SGHP system. Annex 58 project of the Technology Collaboration Programme on Heat Pumping Technologies By IEA (HPTTCP, 2023) compiles information of available commercial heat pump technologies, which helps to discover and review the technological solutions that are available on the market and proven to work in demonstration cases or industrial plants. Another important information source about commercial SGHP products were discussions with companies that supply SGHP technology. Most of the technical performance data and economic data of alternative solutions were received from technology suppliers and used in the study on their permission.

Along the research, the suitability of different solutions to the case plant was assessed, mirroring to the boundary conditions of the case plant (figure 6). Technologies that didn’t have potential to meet the boundary conditions were neglected, whereas the focus was on the technologies that could be applicable to the case plant. As described in figure 7, when SGHP systems with most potential was identified, a comparison between potential systems must be done to gain understanding on which of the potential technologies is the most favourable solution for the case plant. The potential SGHP systems were explored thoroughly and compared in a techno-economic-environmental analysis (TEEA). This included comparative calculations from technical, economic, and environmental point of view. In practice, the calculations were conducted on one Excel sheet with technical, economic, and environmental parts. All the needed information of the solutions (S1-S4) was calculated and presented on the columns side by side to allow easy comparison. Alternative solutions are described in chapter 5.3.

In the end, the results of the TEEA were used for finding a suggestion for the most beneficial SGHP solution to the case plant. The results were investigated from different viewpoints to find justification for why other solution is more beneficial than other. An economic sensitivity analysis was made for better understanding of how solutions compare when some parameters of the TEEA is changed. Sensitivity analysis was conducted in the same Excel sheet by changing one of the parameters at the time and reporting how the results change. After comparing the results of TEEA and sensitivity analysis, the suggested option was the solution that seemed to have most benefits to the case plant. The assessment process for identifying the potential and non-potential solutions is also visualised in figure 7.

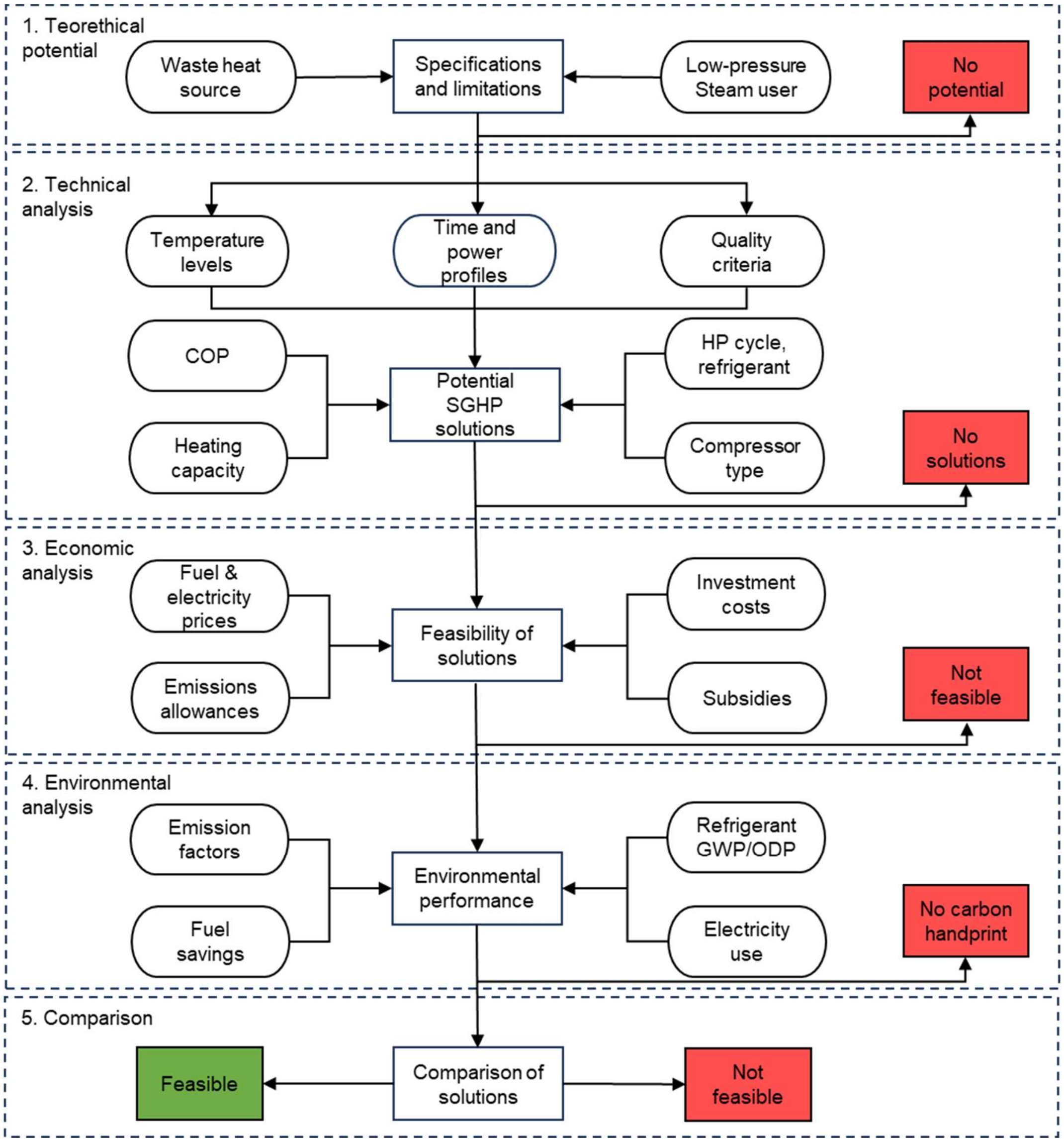

Figure 7. *Decision diagram for SGHP integration into a rendering plant or similar industrial application, based on (Salonen, 2020)*

This decision diagram starts all the way from identifying the theoretical potential for waste heat recovery with SGHP system in the case plant. Technical analysis is the part where potential SGHP technologies are identified, and their technical details are gathered. Decision diagram continues to economic and environmental analysis where the performance of potential SGHP systems is analysed. In the end of the decision diagram is the comparison between potential technologies. Each phase of decision diagram can either confirm or disprove the potential of each solution. Using this decision chain, it can be that there is no feasible solution at all, there is one solution that shows potential, or there are multiple solutions that must be evaluated to choose the best solution. The decision diagram can be used as a support in similar case studies to find out the best solutions for the case.

5.2 Case description

A new LTWR plant is planned to be built at Honkajoki site in Finland, which increases the total production capacity of the site significantly. The new plant sets a challenge to central steam supply system since the total steam demand would exceed the maximum capacity of the existing boiler plant. Required steam capacity must be covered in a way or another, in an economic and environmentally friendly manner. Investing in a decarbonised solution would be preferable for environmental reasons and to offer technological competitiveness towards future. Adding a fuel-based boiler is noted to be an infeasible solution whereas a solution that saves the use of primary energy and improves energy-efficiency could significantly lower the energy-related costs in long run.

A SGHP is planned to be integrated into LTWR rendering plant described in chapter 2.1. Waste heat from two largest waste heat sources is collected to be upgraded to low-pressure steam by the SGHP. These waste heat sources are the disc dryers that use indirect steam for drying i.e. evaporating water from the product stream. The dryers produce significant amount of process vapour at approximately 98 °C, as evaporated water from product is collected from top of the dryers. Process vapour does include some particles, air, and non-condensable gases, but as it is mostly evaporated water from the product stream, thermodynamic properties of water should give a good approximation. This assumption was made due to the lack of more specific data about the process vapour, and to simplify the calculations.

The main users for produced low-pressure steam at 2 bar_g are preheater and two disc dryers (table 4). They use steam indirectly, so the condensate is be returned to steam generation via condensate tank. Some water can be lost from the circulation in steam system in points where condensate from steam traps cannot be collected or if the steam traps are not working optimally and release some of the steam. In addition, there are smaller low-pressure steam users, such as heated tanks, and their steam consumption in total is presented in the table 4 as “Others”.

Table 4. *Heat sources and low-pressure steam users in the case plant*

	Waste heat load	Max steam demand	
Parameter	Q_{WH}	m_S	Q_{WH}
Machine	kW	kg/s	kW
Preheater		0.79	1,713
Dryers	900-2,800	1.65	3,577
Other		0.34	733
Total	900-2,800	2.78	6,024

It can be seen from the table 4 that the maximum steam demand of low-pressure steam users is much higher than what is available from the heat source. Even though the SGHP system brings electrical power into the system to produce steam, it surely cannot cover all the consumption of the 2 bar_g steam users. Therefore, there must be back-up steam in the system to cover the steam consumption that the SGHP cannot generate. Back-up steam system is visualised in system diagrams figure 8 and 9. The principle is that back-up system is automatically maintaining the pressure level by injecting steam when the pressure of steam manifold would otherwise drop.

Based on literature research and decision chain described in chapter 5.1, two alternative potential SGHP technologies for the case plant were identified. These are MVR heat pump and CCHP. Combined cycle heat pump that combines these two technologies was close to being potential, but as mentioned in chapter 3.3, combined cycle heat pump is noted to be feasible with higher temperature lifts than what is needed at the case plant. Additionally, combined cycle heat pumps are not yet commercially available at industrial scale in Europe, and so in case of combining CCHP and MVR, much more engineering and risks would need to be managed by the investor. Combined cycle would become more complex system with more uncertainties, and the investment costs would most likely be higher, which obviously advocates choosing one of the other options.

One option for SGHP system is a closed cycle heat pump (CCHP) that has a separate refrigerant cycle. Solutions S2 by Heaten AS and S3 by SPH (Sustainable Process Heat GmbH) are CCHP type systems. Heat recovery system with CCHP is described in figure 8. Heat pump cycle itself simplified in the diagram, because the commercial SGHPs are more complex and may use different cycle configurations with multiple compressors and heat exchangers, and optimisation techniques.

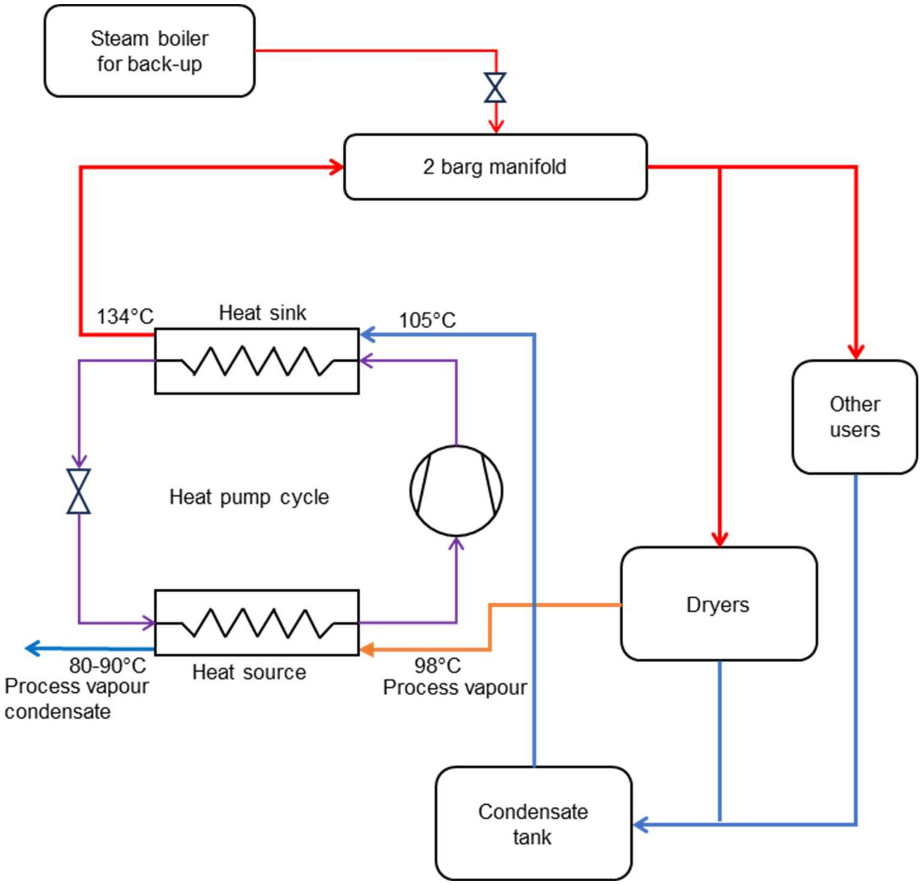

Figure 8. *Conceptual diagram of closed-cycle SGHP integration into LTWR process*

Another option is MVR heat pump system (figure 9), and solution S1 by EPCON Evaporation Technology AS represents this type of SGHP system. In MVR HP, the steam generation takes place at the evaporator, where the process vapour releases its latent heat to the feedwater, making it to evaporate, and condenses. Certain number of MVR compressors (depending on the temperature lift) upgrade the pressure and temperature stage by stage, reaching the goal state at the last compressor. Number of compressors in figure 9 is an example, not the actual number of compressors in solution S1. Subcooling, also known as desuperheating, is done after every compression stage to return the steam into saturated state by injecting water to superheated steam. Additionally, flash steam that is formed at the condensate collection due to pressure reduction at the steam users, can be brought to MVR compressor of suitable pressure level directly for upgrading the pressure to goal pressure. This is a beneficial possibility that MVR HP in contrary to CCHP, as the energy of flash steam can be recovered to the process itself. In case of CCHP integration, the flash steam can be utilised in other heating purposes.

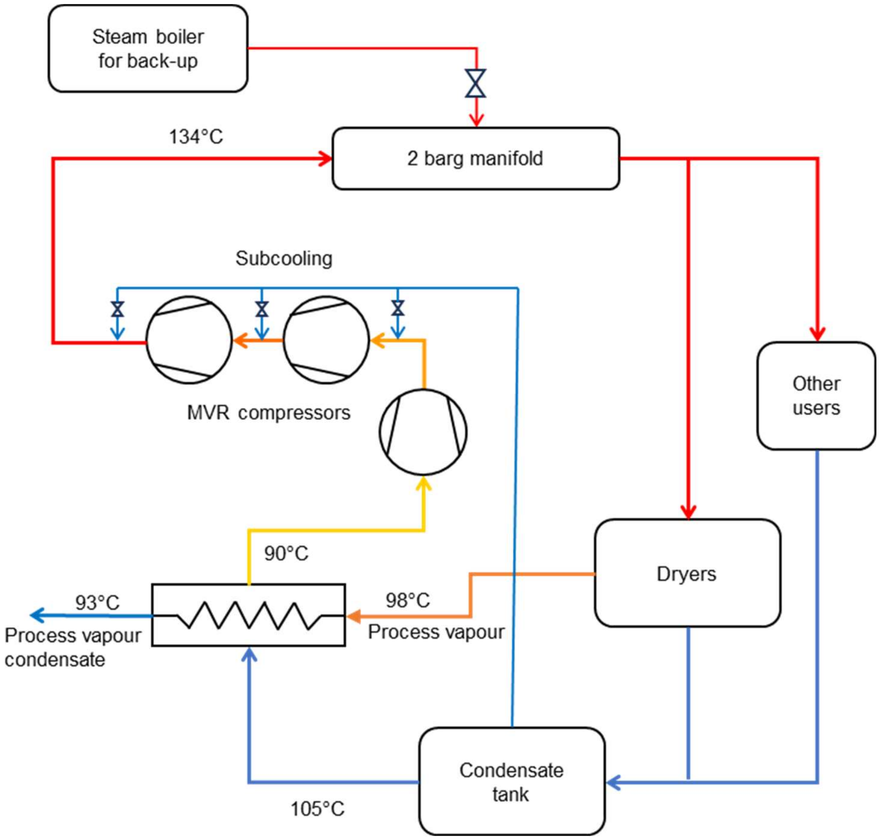

Figure 9. *Conceptual diagram of MVR SGHP integration into LTWR process*

To compare SGHP technologies to a simpler option with cheaper investment cost, an electric boiler is taken into comparison as solution S4. The S4 solution represents a generic electric steam boiler, without any technical details. Idea in this comparison is to see the difference in economic feasibility between electric boilers and SGHPs. In solution S4, the waste heat is not utilised in steam generation, so the steam energy originates 100% from electric power of the electric boiler.

The goal of the SGHP system is to generate as much 2 bar_g steam as possible, with best possible COP, yet having an opportunity to adjust the steam generation flexibly following the waste heat demand. The COP of the SGHP system is a high priority, as it has a large effect on economic feasibility and environmental performance. In addition, an option to adjust the steam pressure to 3 bar_g to offer flexibility in the steam heating system is held on to.

As the location of case plant is in Finland, the features of operational environment (weather conditions, legislation, pricing, and taxes etc.) are taken into account. When comparing this study to cases in other countries, local conditions must be considered. A positive thing from this point of view is that outside temperature does not have a significant impact on this kind of SGHP system, as the waste heat is utilised in processing itself, where the steam demand remains relatively constant regardless of the outside temperature. On the contrary, if waste heat would be used for space heating for example, there would be significant differences in heat demand depending on outside temperature.

5.3 Technical analysis

Technical analysis in this work refers to data collection and calculations related to SGHP integration to the LTWR process at the case plant from technical point of view. Data collection can be roughly divided into case plant data and SGHP data. Figure 10 describes the workflow of the technical analysis.

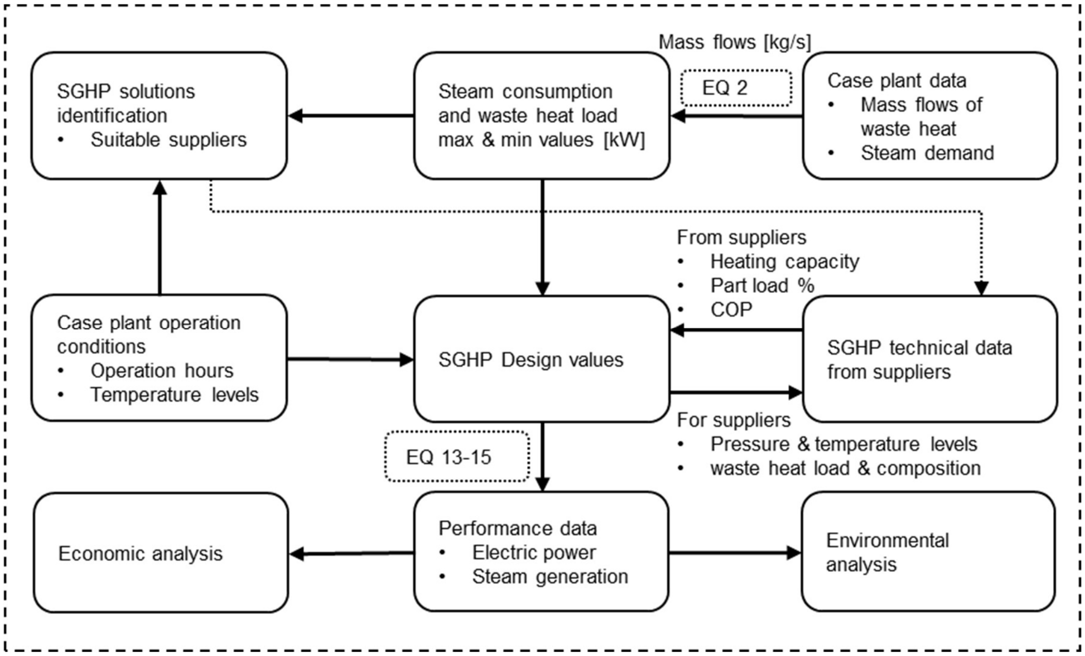

Figure 10. *Data collection and calculation workflow of technical analysis*

Starting with case plant data (table 5), the mass and energy flow data related to case plant LTWR process were collected and calculated based on in-house calculations. The first task was to determine, which mass and energy flow data is needed in this case study and in which units. Basically, the waste heat generated and the steam demand data of LTWR equipment was provided in unit kg/s or kg/h per hour water/steam. These mass flows were used to calculate the energy flows in kW using equation 2 and X steam tables for MS Excel (X-eng, n.d.). All the water and steam mass flows were assumed to be pure and in saturated state to simplify calculations and for being able to use X steam tables.

Dimensioning of SGHP system was done based on available waste heat. Availability of waste heat is the basis for SGHP operation and steam generation can start only if there is enough waste heat available for the SGHP. A design value for waste heat load was decided, so that comparable analyses of alternative solutions could be conducted based on same dimensioning. Design value for waste heat load (cooling power of SGHP) was a compromise that can utilise most of waste heat on maximum waste heat load, and still operate on minimum waste heat load. Part load range (%) of a SGHP system is an important factor in dimensioning of the system, and large rangeability gives flexibility to the system and allows to design larger maximum capacity. If part load range is low, the maximum capacity must be lower, so that operation is possible with smaller waste heat loads. Though the LTWR process is continuous for 5 days a week, the availability of waste heat does have some variation, and the SGHP system should be able to handle to operate in all process conditions. For example, in start-up, the waste heat is less available, but it is an advantage if the SGHP can despite start soon after start-up of dryers. Also, the waste heat load is dependent on feedstock input of the production line.

Table 5. *Case plant data for design basis*

Operation hours	6,240	h/a
Lifetime	20	a
Steam pressure	2	bar$_g$
Steam temperature	134	°C
Waste heat load	2,000	kW
Heat source temperature	98	°C
Flash steam available	300	kW
Feedwater temperature	105	°C

Then another main part of data collection was collecting the data of the potential SGHP solutions. List of commercial solutions (HPTTCP, 2023) was gone through by checking the suitability to the case plant data and boundary conditions, which rejected many of the solutions available. Common reasons why technological solutions did not show potential to this case included: too low output temperature, too small heating capacity, too low COP, too low technology readiness, or that the supplier does not offer the total technology package for the SGHP. SGHP systems by EPCON, Heaten and SPH showed most potential to the case plant and therefore they were identified as alternative solutions S1-S3, respectively. Details of these solutions were obtained through personal communication with the suppliers, and general technical information of the solutions are presented in table 6. For example, estimation of COP using other case studies with different working environment, cycle configuration and working environment would probably not give an accurate estimate of system performance, and thus the best way to get an estimate of COP was to request a supplier to calculate it for a specific case.

Table 6. *General technical data of solutions*

parameter	unit	**S1**	**S2**	**S3**	**S4**
Technology		MVR HP	CCHP	CCHP	Electric boiler
COP	-	6.9[a]	4.9	4.9	1.0
Part load range	%	60-100[b]	30-100	11-100	0-100[c]
Compressors		centrifugal	piston	piston	-
Refrigerant		water	R1233zd	R1233zd	-

a) Utilisation of flash steam increases COP, without flash steam utilisation it would be a bit less
b) Part load range can be extended, but that will decrease COP
c) Assumption that the electric boiler power can be adjusted without limits

As visualised in figure 10, the design values are based on case plant data (table 5) and SGHP data (table 6). Values for steam consumption and waste heat load as well as operation hours and temperature levels are needed from case plant data. SGHP technical data were given by suppliers based on case plant data, and used as initial values for further technical, economic, and environmental calculations. Electric power at design waste heat load was calculated by equation 13

$$P_{el} = \frac{\dot{Q}_{source}}{COP-1} \tag{13}$$

where P_{el} [kW] is electric power and $\dot{Q}_{source}$ [kW] the waste heat load at source. Electric power is then used for calculating the heating capacity at design point. Heating capacity of the SGHP $\dot{Q}_{sink}$ [kW] is calculated by summing the energy flows of heat source and electric power of the heat pump by equation 14.

$$\dot{Q}_{sink} = \dot{Q}_{source} + P_{el} \tag{14}$$

To convert this heating capacity of heat pump into mass flow of generated steam, the enthalpy difference [kJ/kg] from feed water liquid enthalpy $h_{f,feedwater}$ to steam total enthalpy $h_{g,steam}$ was taken into account. Based on equation 2, the steam mass flow [kg/s] was calculated by equation 15.

$$\dot{m}_{sink} = \frac{\dot{Q}_{sink}}{h_{g,steam} - h_{f,feedwater}} \tag{15}$$

Yearly electricity consumption and steam production were calculated for operation time 5 days of 24 h operation per week, which makes 6240 h/a. The lifetime of SGHP system was assumed to be 20 years. Heat losses are not considered in the calculations. Waste heat load is assumed to be constant 2000 kW to simplify calculation and because it was difficult to estimate the dynamic waste heat load. The production of steam was calculated for each solution based on equations 13-15 to harmonise the calculation methods, and the results were compared to those obtained from suppliers to check that calculated results are close to produce estimates given by the suppliers. Small differences in calculated values compared to supplier's values were accepted due to the uncertainties in the calculations.

Another strategic option would have been to use the produce and performance values given by the suppliers and not calculating them from COP and waste heat load. This would, however, limit the possibility of changing parameters in the calculations since some of the valuables would have been locked to suppliers' design values. Locking the produce values would have made it difficult to conduct a sensitivity analysis where some of the parameters are changed.

5.4 Economic analysis

Economic analysis comprises calculations of operational costs and revenues, investment calculations, and sensitivity analysis. The workflow of the economic analysis is visualised in figure 11. Full analysis was conducted for SGHP solutions S1-S3. Electric boiler S4 was analysed as a side case because the focus is on the SGHP technology, and of some parts the results are not that comparable.

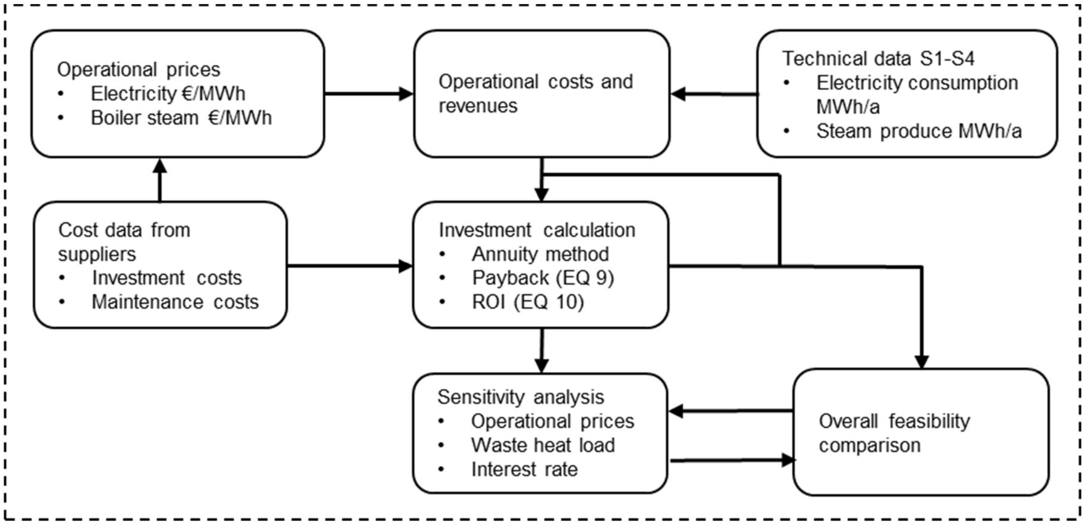

Figure 11. *Workflow of economic analysis*

As described in chapter 4.1, operational costs of SGHP are strongly dependent on fuel and electricity prices. The hourly price of electricity (Day-ahead Price) in Finland in 2023 was analysed to show the current price level in Finnish electricity market and to investigate how using stock exchange electricity would affect the feasibility of an SGHP system. Electricity price data was downloaded from ENTSO-E transparency platform (ENTSO-E, 2023) and analysed in Excel. The price data was divided into categories and their frequencies and cumulative percentages were presented in a histogram (figure 12).

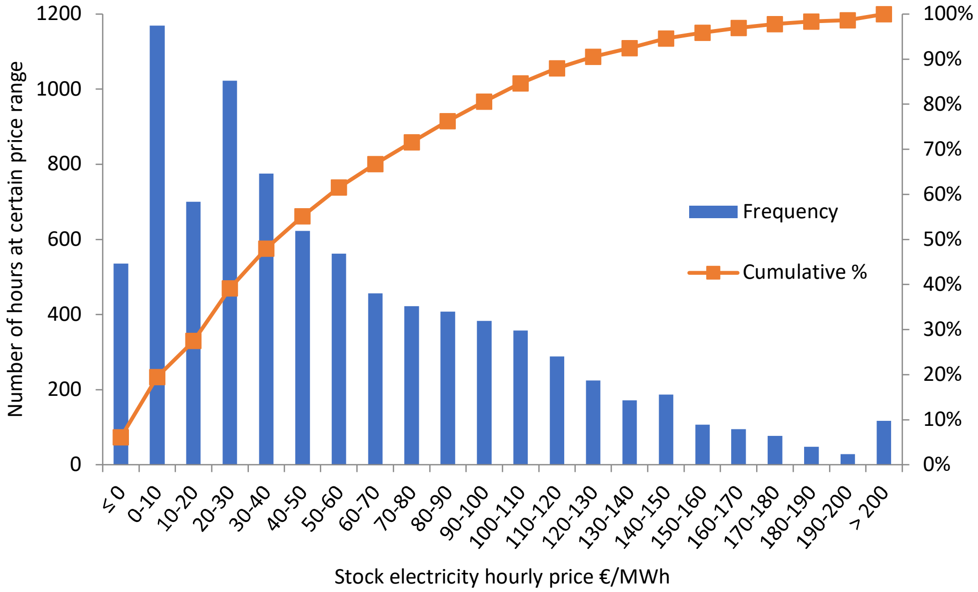

Figure 12. *Analysis of hourly prices of electricity from stock exchange, Finland 2023*

The analysis shows that the hourly electricity prices in stock exchange are variating a lot. Bars in the diagram describe the number of hours at certain price range. Most common price range was between 0-10 €/MWh, followed by 30-40 €/MWh. The average hourly price of electricity was 56.47 €/MWh, median being 42.80 €/MWh. In total, electricity prices ranged between -500-780 €/MWh. The share of negative hourly prices and positive prices above 200 €/MWh were 6.1 % and 1.9 %, respectively. The curve “cumulative %” describes how large percentage of hours are cheaper than the range maximum price. For example, 55 % of hours in 2023 had lower prices than 50 €/MWh, which is close to used value in the economic calculation, when transfer fee and taxes are added to the price.

Initial data for economic analysis is presented in the table 7. Electricity price in the calculations was set to 70 €/MWh, which can be seen as a typical value for fixed price electricity contract for industrial users for Finland, including the transfer fee and taxes (around 20 €/MWh). The price for boiler steam energy was set to 32 €/MWh. Currently, the case plant would not be under emissions trade, and thus the cost for CO_2 was set to zero. However, it was included in the economic calculations so that impact of emissions trade can be easily checked by just setting a price for CO_2-allowance.

Table 7. *Initial data for economic analysis*

Electricity price	70	€/MWh
Boiler steam price	32	€/MWh
Interest rate	5.5	%
S1 investment cost	2,150,000	€
S2 investment cost	1,380,000	€
S3 investment cost	1,350,000	€
S1 maintenance cost	1	% of CAPEX
S2 maintenance cost	4	% of CAPEX
S3 maintenance cost	5	% of CAPEX

The economic analysis was conducted based on the results of technical analysis in the same Excel sheet. Annual steam production MWh/a and annual electricity consumption of the SGHP system are the main initial technical data for economic calculations, and they are presented in table 9. The main revenue of the SGHP system is saving in steam energy cost, which was calculated based on boiler steam price and annual steam production of SGHP which replaces the same amount of boiler steam. Main operational cost is the annual price of electricity, which was simply calculated of electricity price and annual steam production. Annual maintenance costs (% of CAPEX) were based on supplier estimate and it should cover the cost of equipment services and technical support. Adding the operational cost and savings together, the operational net revenue was calculated by equation 8.

The investment calculations were conducted based on the budgetary prices (table 7) for case specific system given by the suppliers. Generally, the prices for SGHP systems are greatly affected by several factors as systems are designed and tailored to each case and its requirements. The prices were rounded up estimates of investment costs of equipment and commissioning. Additional costs are involved regarding to purchaser's design of integration, additional housing of equipment if needed, installation and piping, and transportation. These were not included in this economic analysis and can be estimated to be in the same range regardless of the choice of the solution.

The investment calculation was made for 20 a lifetime, and the investment cost was divided into equal depreciations for first 10 years. Interest rate was set to 5.5 % as it is a typical rate currently. The annual net profits were calculated by deducting the annual depreciations and interests from annual operational revenues. The cumulative net profits were plotted in diagram to illustrate cash flows over the life cycle. The discounted payback period was calculated by equation 9. ROI was calculated according to equation 10 separately for 10 first years during which depreciations and interests are paid and for 20 years which is the design lifetime in this study.

An economic sensitivity analysis was conducted in order to discover the impacts of several parameters that might deviate from the assumed values in the original calculation. Understanding these cause-and-effect relationships is helpful for decision making. Sensitivity analysis was conducted in the same Excel sheet as TEEA, only changing one parameter at the time and saving the changed results for comparison. Parameters to be changed in the sensitivity analysis were waste heat load, electricity price, boiler steam price, and interest rate. Diagrams of total cost of steam and the discounted payback period were plotted to visualise the impact of changing the parameters to solutions S1-S3.

5.5 Environmental analysis

Environmental analysis was conducted according to the structure of LCA, consisting of goal and scope definition and inventory analysis in this chapter and impact assessment and interpretation in chapter 6.4. The process of the environmental analysis is presented in the figure 13. The goal in this environmental analysis was to compare the CO_2 emissions of different steam generation solutions. The inventory analysis and calculations for impact assessment and interpretation were conducted in Excel. Studied impact category was GHG emissions as CO_2-equivalent and functional unit was 1 MWh produced steam. This environmental analysis was made to help decision makers to evaluate the total benefits of implementing SGHP technology in the case plant.

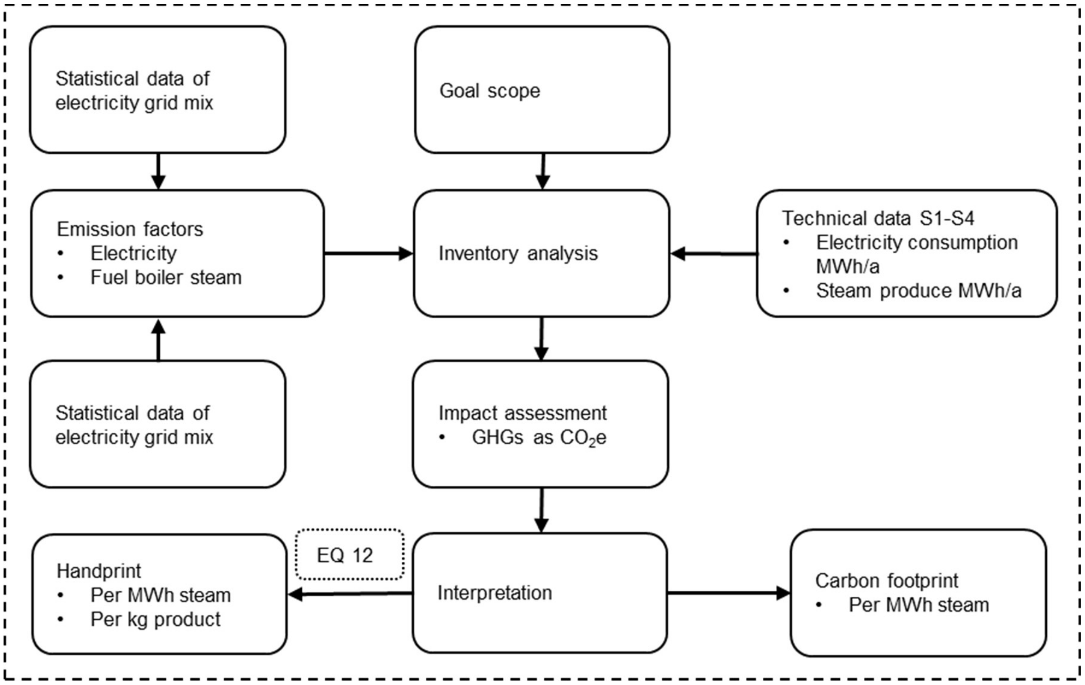

Figure 13. *Workflow of the environmental analysis*

There are two sources of GHG emissions in the system scope (figure 14): steam boiler using peat as a fuel and the production of electricity. GHG emissions from peat driven steam boiler include the emissions from production chain of peat (peat cutting machines and peat field air emissions) and peat combustion at the steam boiler with thermal efficiency of 85%. Emissions from electricity include the direct emissions of electricity production, not life-cycle emissions for example manufacturing of the power plants (Fingrid, 2023). Green arrow describes the saved GHG emissions when a certain amount of boiler steam is replaced by the steam produced by a SGHP. Manufacturing of SGHP system is not included in the scope of this environmental analysis.

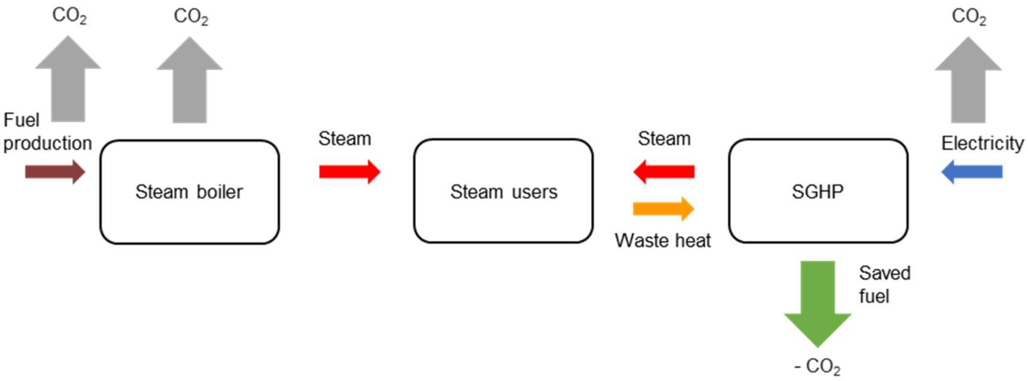

Figure 14. *CO2-emissions in a SGHP-system with boiler back-up*

The emission factor of peat production chain and combustion was divided by thermal efficiency to obtain the emission factor for the boiler steam. Emission factor for electricity used by the SGHP was calculated from statistical data of Fingrid as an average of monthly average emission factors of electricity grid mix in Finland in 2022 (Fingrid, 2023). Obtained emission factors are presented in the inventory analysis (table 8).

Table 8. *Inventory data and emission factors*

Emission source	**S1** MWh/a	**S2** MWh/a	**S3** MWh/a	**S4** MWh/a	Emission factor	Unit
Electricity consumption	2,115	3,192	3,200	15,676	60[a]	kg CO_2e/MWh
Saved boiler steam	16,467	15,672	15,680	15,676	511[b]	kg CO_2e/MWh

a) (Fingrid, 2023)
b) CO_2 emissions of combustion (Tilastokeskus, 2023), other data (Holmgren et al., 2006)

GHG emissions i.e. carbon footprint per MWh steam was calculated based on inventory data and emission factors gathered in table 8. In addition, carbon handprint was calculated by equation 12 to describe the saved CO_2 emissions when a certain amount of steam produced by the SGHP replaces the same amount of steam that would otherwise be produced by the steam boiler. Carbon handprint was also calculated per ton of poultry protein meal, the main product of the LTWR process, to show the environmental benefit of SGHP integration from the end-product point of view.

6. RESULTS AND DISCUSSION

6.1 Technical performance

The results of technical analysis are presented in the table 9. Solutions S2 and S3 have exactly same results in technical performance, and this is due to the same COP value, which was another main initial value besides waste heat load. Due to higher COP, the electric power of S1 at the same waste heat load is significantly lower than of S2 and S3. At the same time the steam power and mass flow are higher than of S2 and S3, and this is explained by the utilisation of flash steam, which adds steam output by 300 kW. Values for boiler steam is calculated for same amount of steam production with S2 and S3, and the difference is that all the needed energy for steam generated steam is electricity.

Table 9. *Technical performance results*

		S1	S2	S3	S4
		MVR	CCHP	CCHP	Electric boiler
Electric power	kW	339	513	513	2,513
Steam power	kW	2,639	2,513	2,513	2,513
Steam mass flow	kg/h	4,157	3,958	3,958	3,958
Steam production	MWh/a	16,467	15,680	15,680	15,680
Electricity consumption	MWh/a	2,115	3,200	3,200	15,680
Saved energy per feedstock	kWh/t	135	118	118	0

Yearly steam production of SGHP solutions would be around 16 GWh, if the waste heat load would be constant 2 MW and SGHP system would operate 6240 h through the year. Waste heat load, however, is one of the largest uncertainties of this study. As a continuous process, the time-power profile of the waste heat load is expected to be relatively flat, but there can be variation due to various reasons. As the case plant is at design phase, it is not possible to obtain precise data of waste heat and steam demand. This uncertainty is taken into account by investigating its impacts on the sensitivity analysis. Electricity consumption for this amount of steam produce would be around 2.1 GWh with MVR HP or 3.2 GWh with CCHP solutions.

Considering the specific energy consumption per treated raw material, as much as 135 kWh/t and 118 kWh/t of energy could be saved at the case plant with S1 and S2-S3, respectively. This value considers both heat and electricity, and the energy saving is based utilisation of waste heat. By integrating a SGHP into LTWR process, the specific energy consumption of the case plant could possibly be reduced to around 250-270 kWh per ton raw material, when the base value of 387 kWh/t from operating LTWR plant in Honkajoki is used. Electric boiler S4 does not save energy of steam production in principle, only replaces the fuel energy with electricity. In practice, some energy saving occurs due to higher efficiency of electric boiler compared to fuel boiler.

Figure 15 visualises how heating capacity of each solution S1-S4 is formed of different energy sources. SGHP solutions utilise the same amount of waste heat whereas electric power is dependent on the COP. The role of flash steam in the S1 can be noticed clearly, as while the electricity consumption is lower than of solutions S2-S3, the heating capacity of S1 is still higher. This is a significant advantage for the solution S1, but it must be recalled that in case of other solutions, some other use for flash steam can be discovered.

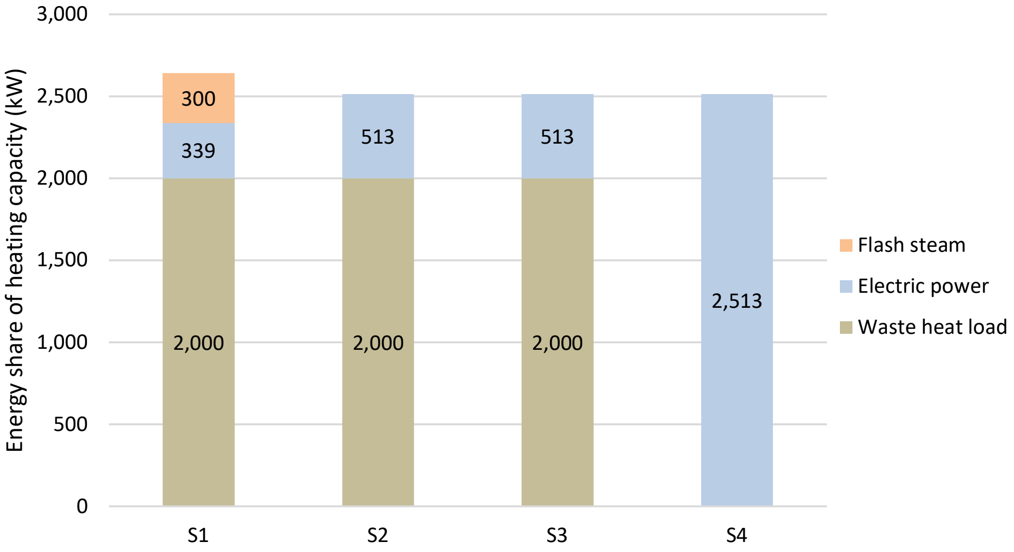

Figure 15. *Visualisation of how the heating capacity of different solutions comprises different energy sources.*

The amount of steam that a SGHP can produce in the case plant is much less than the maximum steam demand of processes using low-pressure steam (table 4). The steam generation of SGHP solutions at these design values could cover around 40 % of maximum low-pressure steam demand or 70% of the steam demand of the dryers. In typical operation, probably more than 40 % of low-pressure steam demand can be covered by SGHP, as the consumption is probably less than maximum values.

6.2 Economic performance

Operational costs are in important role in total feasibility of a SGHP system. COP and electricity price has the largest impact on operational costs, and higher COP means lower electricity costs and better feasibility. The results regarding the operational costs are presented in table 10. The CO_2 saving [€/a] is in the table with cost of zero due to the CO_2 set to zero. However, it is presented there for the sake of clarity, while operational saving is the sum of CO_2 saving and boiler steam saving. Operational revenue, which is the difference between savings and costs, is one of the key results and an important initial data for the investment calculations.

Table 10. *Operational costs and revenues of solutions S1-S4.*

		S1	**S2**	**S3**	**S4**
Electricity cost	€/a	148,068	224,000	224,000	1,097,600
Maintenance cost	% of Capex	1.00%	4.00%	5.00%	0.50%
Operational costs	€/a	169,568	279,200	291,500	1,099,850
CO_2 saving[a]	€/a	0	0	0	0
Boiler steam saving	€/a	525,035	499,935	499,935	499,935
Operational saving	€/a	525,035	499,935	499,935	499,935
Operational revenue	€/a	355,467	220,735	208,435	-599,915
Cost of steam OPEX	€/MWh	10	18	19	70

a) price of CO_2 is set to 0 €/t CO_2 as case plant is not involved in emissions trade. To see the impact of CO_2 price, see figure 22 in chapter 6.3.

Operational revenue shows significant differences between solutions. Firstly, the operational “revenue” of electric boiler in constant use is greatly negative, due to the massive electricity costs. This already shows that all the SGHP options outperform the electric boiler clearly when it comes to feasibility. Difference in operational revenue between S1 and S2-S3 is clear, and it is based on the higher COP, larger steam produce, and lower maintenance cost. Once again, S2 and S3 are close in the results, and the small difference is based on the difference in estimated maintenance cost. Cost of steam OPEX sums up the operational costs per MWh of produced steam, in which the cost of electricity is the biggest factor. Cost of steam OPEX only considers operational costs, not savings, and it can be used in comparison to fuel steam boiler costs.

In the investment calculation, the total feasibility consists of both operational revenues and investment costs. The results of investment calculation are presented in the table 11 and figures 16-17. As the investment cost of S1 is significantly higher than of other solutions, the depreciations and interests during the 10-year payment period are larger than for other solutions. With solutions S2 and S3, the depreciations and interests are far lower than for S1. Total cost of steam (figure 16) is a good indicator of total feasibility, as it includes both operational and capital costs.

Table 11. *Results of investment calculation*

		S1	S2	S3	S4
Investment cost	€	2,150,000	1,380,000	1,350,000	450,000
Annual depreciations	€/a	215,000	138,000	135,000	45,000
Total interests	€	532,125	341,550	334,125	111,375
Total cost of steam	€/MWh	19	24	24	72
Payback period	a	7.55	7.87	8.23	-
ROI 10 a	%	8.1	7.0	5.9	-
ROI 20 a	%	37.4	36.5	33.5	-

The discounted payback periods for solutions S1-S3 are actually very similar, close to eight years. Solution S1 has the shortest payback period with just a small margin to solutions S2 and S3, respectively. The payback period was not calculated for electric boiler S4, while the operational revenue was negative and thus it would never pay the investment back. Considering only the payback period, the differences between SGHP solutions are small, but payback period only describes when the investment costs are covered by the revenues, not the feasibility after the payback period. Also results for ROI are relatively similar to solutions S1-S3. ROI values for 10 first years, during which the investment is being paid back, are low, but for the design lifetime 20 years, the ROI values for all SGHPs indicate a good investment.

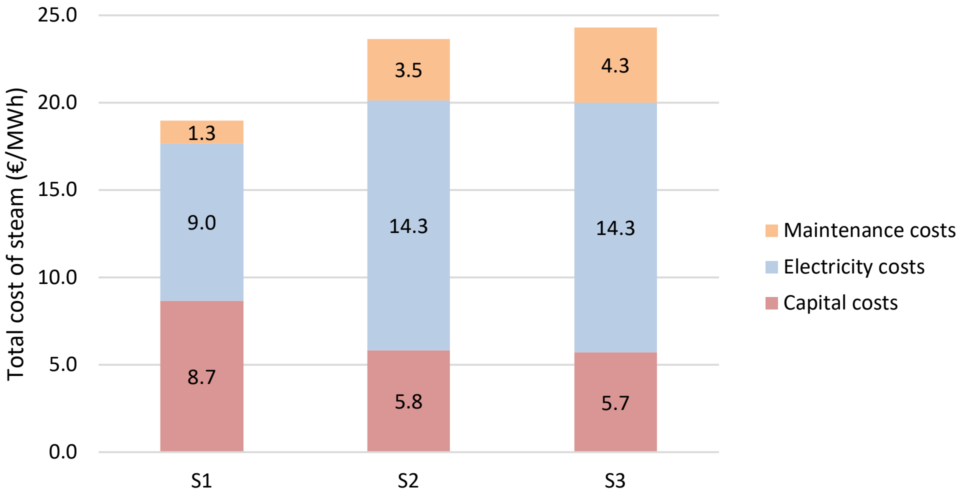

Figure 16. *Cost breakdown for total cost of produced steam by S1-S3*

Figure 16 visualises the cost breakdown for total cost of steam of solutions S1-S3. Electricity consumption involves the largest costs for every SGHP solution, followed by capital and maintenance costs. The cost breakdown shows large differences in the structure of steam price. Regardless of highest capital costs, the solution S1 has the lowest total cost for steam due to the significantly lower operational costs. Results for solutions S2-S3 are close to one another, both having lower capital costs than S1 but higher total cost for produced steam due to higher electricity and maintenance costs. The higher electricity costs of S2-S3 compared to S1 are caused by the lower COP value, and the larger maintenance costs of S2-S3 can be explained by the higher need of services regarding the piston compressor technology. The electric boiler S4 is clearly the cheapest option of capital costs, but the total cost of steam, around 72 €/MWh, was in the different scale due to the high operational costs, and thus it was left out of the diagram.

Figure 17 presents the cumulative profit of solutions S1-S3, which describes the difference between gained revenue and invested money by the time. The diagram shows that all the SGHP solutions make profit every year with these design values and assumptions. Long period of payment keeps the annual instalments moderate, and the revenues from replacing more expensive boiler steam stay larger than the capital costs. During the first years, the net profits are low, because the interests take a notable share of the operational revenue. As over the years the investment is paid back, the operational net profits start growing.

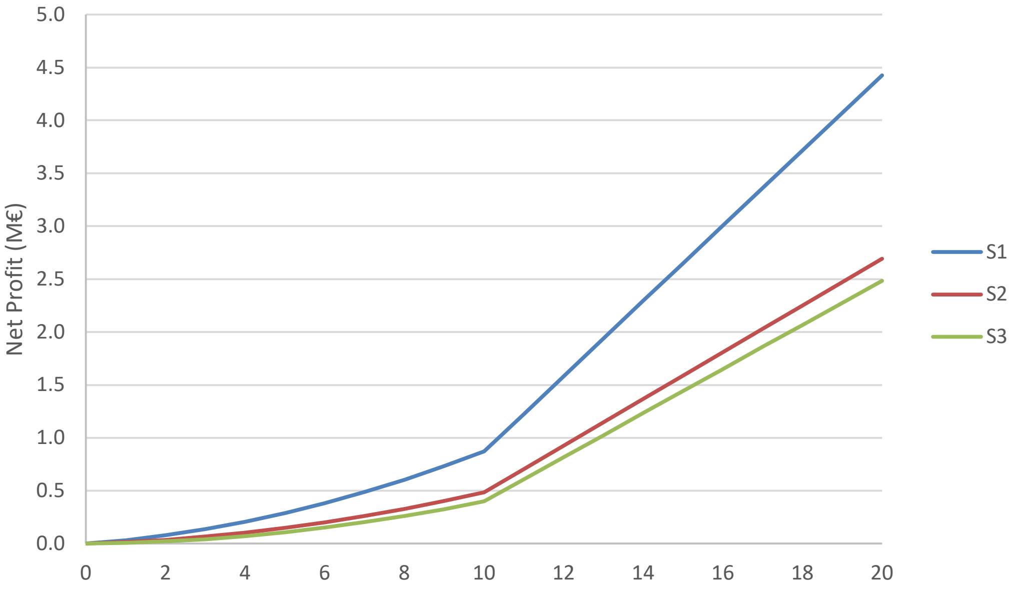

Figure 17. *Cumulative profit of SGHP solutions S1-S3*

When annual depreciations and interests end after payment period of ten years, the curve of cumulative profit accelerates, and the differences in profit can be seen more clearly. Solution S1 provides the largest operational revenues, which can be seen as a large difference to solutions S2-S3 in cumulative net profit of the investment. Solutions S2 and S3 have a small difference in the gain of net profit, S2 showing slightly higher result.

6.3 Sensitivity analysis

If the electricity price would be something else than 70 €/MWh, the indicators of feasibility would get different results. As can be seen in the figure 18a, the total cost of steam increases along the increase of electricity price. One critical value for electricity price is at around 100 €/MWh, since at that point the total costs of steam (solutions S2-S3) become larger than the price for boiler steam, and thus the investment is infeasible. Looking at figure 18b, the discounted payback period (S2-S3) starts to increase rapidly to long payback periods when price of electricity is above 80 €/MWh. S1 is less sensitive to the electricity price due to higher COP.

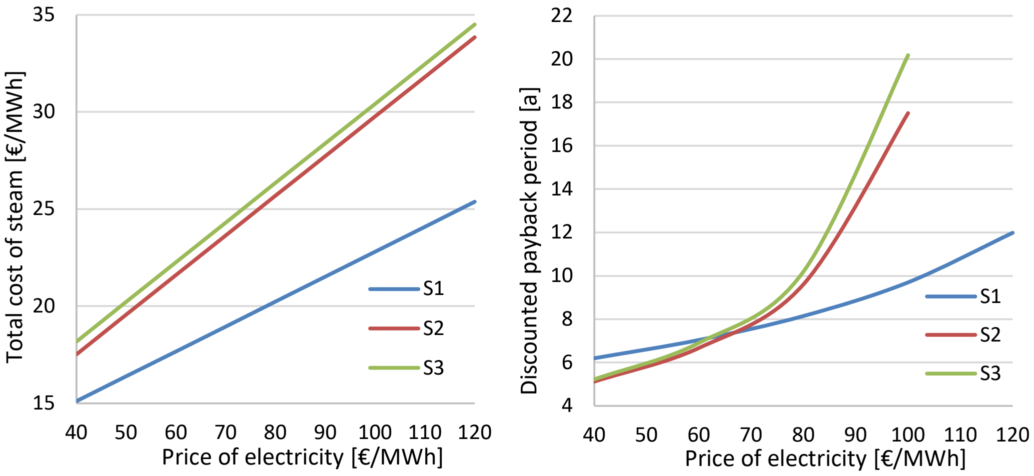

Figure 18. *Impact of electricity price to the a) total cost of steam and b) discounted payback period.*

The price of boiler steam does not influence the cost of steam produced by SGHP. However, its impact on the revenues and thus also the discounted payback period (figure 19) of a SGHP system is clear. If the price for boiler steam is higher, the operational savings are higher, and revenues increase significantly. Figure 19 shows that if boiler steam would be more expensive, the SGHP systems could reach very short payback periods, such as three years at steam price of 60 €/MWh (S1) or 2 years at steam price of around 65% (S2-S3).

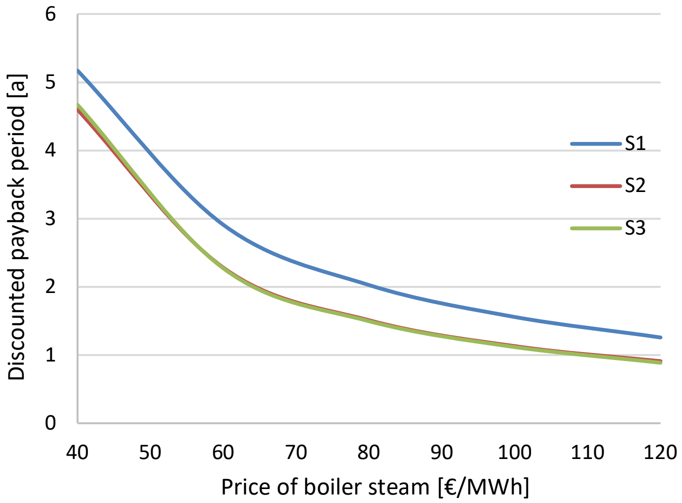

Figure 19. *Influence of boiler steam price to the discounted payback period.*

As mentioned, waste heat load is one of the biggest uncertainties of this case study. Hence, the impact of lower waste heat loads to the feasibility of SGHP systems is calculated. Total costs of steam (figure 20a) are relatively safe at waste heat load range 1200-2000 kW, not overlapping the price of boiler steam in any case. Discounted payback period (figure 20b) is much more sensitive to lower waste heat loads. Reason to this is that if waste heat is less available, the steam production and savings from replacing boiler steam are lower. Considering solutions S2-S3, the payback period becomes very long if average waste heat load is lower than 1500 kW. Payback time of S1 is less sensitive to lower waste heat load, but it can be noted that with waste heat load less than around 1600 kW, the payback period becomes over 10 years, which means negative profit for first 10 years (payment period). For S2-S3 the similar limit would be at around 1700-1800 kW. In general, operating close as possible to full capacity is most feasible option. The results show that lower waste heat load should be considered as an economic risk.

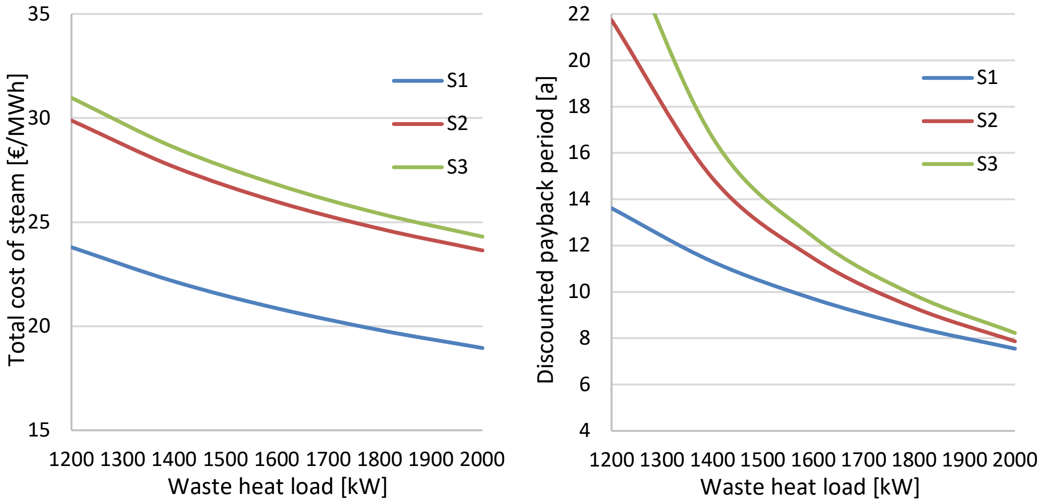

Figure 20. *Impact of different waste heat loads to a) total costs of steam and b) discounted payback period.*

The interest rate is an important factor in the investment calculations. An increase of interest rate increases the total cost of steam (figure 21a) steadily with moderately low increments. Having larger investment cost, S1 is more sensitive to the interest rate than other solutions, as the curve of total cost of steam is steeper. Discounted payback period (figure 21b) is significantly influenced by the interest rate, and accelerating growth can be noticed at larger values of interest rate. Also, the differences between payback periods of solutions appear more clearly of the graph at higher interest rates.

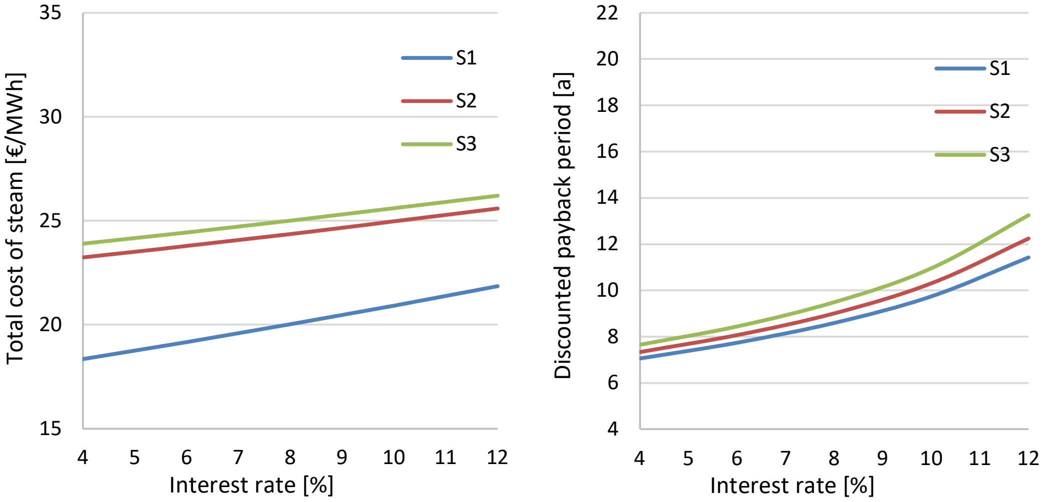

Figure 21. *Influence of interest rate to the a) total cost of steam and b) discounted payback period.*

If the case plant would become a subject to emissions trading in the future, the feasibility of the SGHP system would experience a significant boost. As in this case plant, the SGHP systems would cut about 98% of the GHG emissions compared to fuel steam boiler, saving of those emission allowances would increase the revenues notably. Even with carbon price of 20 €/t CO_2e, the payback period shortens to less than 5 years for all the solutions (figure 22). Increasing the carbon price to more than 100 €/t CO_2e, payback periods for all the solutions become less than 2 years. The influence of increasing a carbon price is very similar to increasing boiler steam price (figure 19), since in both cases the savings increase, which leads to higher revenues and shorter payback periods. Noteworthy, in both figures the result for S1 is less advantageous than for S2-S3, whereas basically in all other results S1 seems more advantageous.

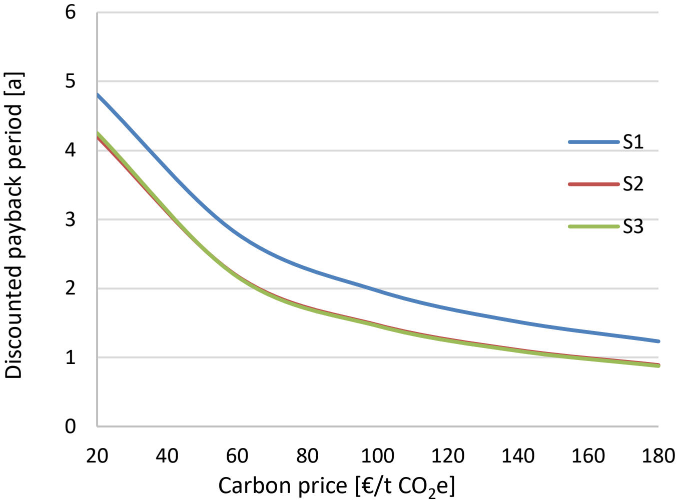

Figure 22. *Impact of carbon price on the discounted payback period*

To conclude the results of sensitivity analysis, the main findings are presented in table 12. Column “effect of increase” describes the main influence of increasing the following parameter and column “critical value” presents values above which the feasibility is threatened.

Table 12. *Summary of sensitivity analysis results*

Parameter	Effect of increase	Critical value
Electricity price [€/MWh]	Total cost of steam increases significantly. Payback period increases steeply (S2-S3). S1 less sensitive	For S2-S3, 80–90 €/MWh For S1, 100–110 €/MWh
Boiler steam price [€/MWh]	Payback period drops quickly, down to 1–2 years, if boiler steam price exceeds 80 €/MWh	positive change, no critical value
Waste heat load [kW]	Increase improves feasibility. Decrease increases total cost of steam and payback period.	For S2-S3 1700–1800 kW For S1, 1500–1600 kW
Interest rate [%]	Increases total cost of steam and lengthens payback period. S1 more sensitive	If rate > 9-10 %, payback period > 10 a
Carbon price [€/tCO$_2$e]	Payback period drops quickly, down to 1–2 years if carbon price exceeds 100 €/t CO$_2$e	positive change, no critical value

Sensitivity analysis shows both positive and negative impacts on the feasibility of SGHP systems. The results of sensitivity analysis should be considered in decision making with the results of economic analysis at basic case. Additionally, the results of sensitivity analysis can be used to optimise the design values to direction where the best feasibility is achieved. Sensitivity analysis does not show the influences of changing several parameters at the same time, so that is something to be assessed based on given results.

6.4 Environmental performance

One key point of the environmental analysis is to show how much GHG emissions can be saved by integrating an SGHP system into the case plant. The results (table 13) show that all the SGHP solutions produce drastically less GHG emissions than a peat fuel boiler. GHG emissions from consumed electricity by the SGHP solutions are around 98% less than GHG emissions from producing the same amount of steam using peat driven steam boiler. Around 7,800-8,300 t of CO$_2$e/a could be saved by integrating a SGHP system. The role of COP is clear for environmental performance when electricity CO$_2$ emissions of S1-S3 are compared since lower electricity consumption means less GHG emissions from electricity use. However, in the big picture the difference between SGHP solutions is negligible, considering that all the solutions cut the emissions as much as around 98 %.

Table 13. *Results of environmental analysis*

		S1	S2	S3	S4
electricity CO_2	t CO_2e/a	127	192	192	941
100% boiler steam CO_2	t CO_2e/a	8,408	8,006	8,006	8,006
saved CO_2	t CO_2e/a	8,281	7,814	7,814	7,065
cut of steam CO_2	%	98.5	97.6	97.6	88.2
saved fuel energy	MWh/a	19,373	18,447	18,447	18,447
saved fuel mass	t/a	6,905	6,575	6,575	6,575
steam footprint	kg CO_2e/MWh	7.7	12.2	12.2	60.0
steam handprint	kg CO_2e/MWh	503	498	498	451
handprint per product	kg CO_2e/t	377	356	356	322

Overall energy efficiency increases when a SGHP is integrated for steam generation. Annually, around 18-19 GWh of fuel energy can be saved with only 2-3 MWh of electricity. The amount of saved fuel energy corresponds to 6,500-7,000 t of peat.

Carbon footprint of produced steam in the case plant is 7.7 kg CO_2e/MWh for solution S1 and 12.2 for solutions S2-S3. For the electric boiler S4, carbon footprint is 60 kg CO_2e/MWh, which is the same value as the electricity emission factor since electric boiler steam comprises 100 % electricity. For boiler steam the carbon footprint is 511 kg CO_2e/MWh (table 8).

When it comes to carbon handprint [kgCO_2e/MWh], the results for produced steam are 503 kgCO_2e/MWh for S1, 498 kgCO_2e/MWh for S2-S3 and 451 kgCO_2e/MWh for S4. In other words, each megawatt hour of produced steam saves that amount of CO_2 emissions compared steam produced by the fuel boiler using peat. What is also interesting from the case plant production point of view, the carbon handprint per ton of protein meal [kg CO_2e/t product] is as much as 377, 356, and 322 for S1, S2-S3 and S4, respectively.

6.5 Discussion

The TEEA and sensibility analysis gave both expected and unexpected results. The role of COP was as important for the feasibility of SGHP system as expected. The advantage of better COP of solution S1 can be seen from basically all the economic and environmental results. Only in sensitivity analysis, when the boiler steam price or carbon price was increased, leading to gain of operational revenues, S1 shower worse result than S2-S3 in payback period. MVR being more feasible than CCHP is also in line with the study of Bless et al. (2021) where MVR was the most cost-efficient steam generation method.

One unexpected result was that payback period of S1 with highest investment cost was shortest, even with higher interest rates. The effect of interest rate to S1 feasibility was not as large as expected since even with higher interest rate (12 %) at 10-year payment period, larger operational revenues of S1 keeps it more feasible than S2-S3. The importance of waste heat load to the feasibility of surprisingly high, as payback periods and total costs of steam increase rapidly, if the average waste heat load is less than the design value.

The results of total cost of steam showed that SGHP systems in general are very competitive technology for steam generation compared to electric boiler or fuel boiler. The total cost of steam by SGHPs (19-24 €/MWh) is down to 74% less than by electric boiler (72 €/MWh) at continuous operation at electricity price of 70 €/MWh in this case plant. Due to low investment costs and flexible operation, electric boiler is a good option for reserve capacity or for use at times of low electricity cost. A SGHP system in contrary performs best at stable operation close to the design capacity of the system.

Operation at lower part load decreases the feasibility significantly and lengthens payback time of a SGHP. Hence, it is very important to choose the design value for the SGHP capacity wisely. If the design value for waste heat would be chosen as maximum value of waste heat load, the maximum steam production would be higher as well. With design waste heat load of 2800 kW, the maximum heating capacity of SGHP could be around 3500 kW, which would be close to the steam demand of dryers. However, this would involve higher investment costs, since it would require larger heat pump equipment. Additionally, the risk of having too low waste heat load in some operational circumstances would be higher if the design value was higher.

Arpagaus et al. (2018) points out long payback periods as one of main barriers for HTHP integration to industrial plants. Payback periods for the studied systems at the case plant are surprisingly long, around 8 years at design values. Sensitivity analysis shows that depending on several parameters, the payback periods can be either longer or shorter. For example, inexpensive steam energy in this case study gives conservative results on the economic feasibility of SGHP. According to the results of sensitivity analysis, higher boiler steam cost would lead to significantly larger operational revenues, shorter payback periods, and better ROI for SGHP systems. Emissions trade system that sets a price for CO_2 would have a similar impact with increasing boiler steam price. On the other hand, lower waste heat load, more expensive electricity, or higher interest rate can easily lengthen the payback period to over 10 years and decrease ROI.

When comparing the results of S1-S3, it is important to note that the flash steam (300 kW) that S1 can utilise is considered free, and on the other hand, the economic value of flash steam utilisation in case of S2-S3 for some other purpose is not estimated in the calculation. This gives advantage to the results of solution S1, but also describes the reality that using the flash steam energy in the steam generation is more valuable than for other heating purposes that in many cases are inconsistent and dependent on outside temperature. If a price would have been set to the flash steam, the relative feasibility of S2-S3 would have improved to some extent.

Choosing the system is a financial issue of course and there is a large difference between solutions S1 and S2-S3 in the investment costs. Solutions S2-S3 are available with lower investment cost than S1. Depending on choices for investment calculations, it can also be that during payment period the yearly net profit is lower for S1 than S2-S3. For example, five-year payment period would lead to larger yearly losses with S1 than with S2-S3 during the payment period. After payment period, however, the net profit would grow faster with S1 as the long-term feasibility is better. Shorter payment period would in general reduce the net profit during payment period but also decrease the total investment cost since the amount of the rate would be lower.

According to the results of this TEEA and sensitivity analysis, the solution S1 is the suggested system to the case plant. Long term feasibility is significantly better than of other solutions. Solutions S2 and S3 are also beneficial options that offer steam production with close-to-zero emissions, result to lower total cost of steam than fuel boiler, and involve lower capital costs than S1. Differences in feasibility between solutions S2 and S3 are small and can change one way or another in the implementation phase. One significant advantage of S2-S3 compared to S1 is broader part load range that allows flexible operation at low waste heat load and designing the system to higher maximum capacity. By wise dimensioning, the part load range should be flexible enough for smooth operation in different operational situations.

It is good to note that results of TEEA comparing solutions S1-S3 only indicate the feasibility of the solutions at the studied case, with assumptions and values used in this study. With different design criteria such as temperature levels, heating capacity, and waste heat properties, the results may look different. Results of this kind of case study can be used as reference for comparison, but since each case have their unique properties, case by case feasibility studies are necessary.

The MVR technology of solution S1 is well-known and proven for a longer time than technology of the HTHPs using piston compressors (S2-S3). MVR HP consists of similar equipment that are already used in rendering industry in evaporation process. Having MVR-based evaporation systems at the site, the case plant owners are more familiar with the equipment of MVR HP. In addition, CCHP solutions S2-S3 use synthetic refrigerants, that do have some risks, though the new refrigerants are much safer than conventional refrigerants. MVR HP only uses water/steam as working media, so refrigerant-related risks are avoided with S1. In general, it seems that technological risks of S1 at this kind of integration are the lowest of available SGHP solutions.

As mentioned in chapter two, some process equipment may require larger dimensioning for a certain capacity, if the steam pressure is decreased from the pressure level that the equipment is originally designed to. In the case study, it was estimated that due to the lower operating steam pressure, the area of the dryers must be larger. The cost effect of this change is estimated to be around 0.5 M€. This investment cost is not included in the investment calculation to keep the focus on the SGHP systems, but this subject should be considered in the investment decision.

The uncertainties in the results should be considered in decision-making. For example, it is to be noted that the budgetary offers from SGHP suppliers that are used in this work are not final, binding offers. Hence, in the later phases of procurement process changes may arise that affect the technical details and/or the investment and operational costs way or another. Waste heat load is probably the largest technical uncertainty, also affecting the economic feasibility. It would be important to be able to assess the recoverable waste heat by the heat exchanger as accurately as possible. This should be done in cooperation with heat exchanger designers, using measured data of waste heat properties at case plant or similar process. There is also possibility that process vapour temperature may be a bit lower, which would decrease the COP and affect the feasibility of the solutions.

With stock exchange electricity contract, the steam production with a SGHP could at times be basically free of operational costs, and on the other hand, sometimes the operational cost could peak to very high levels. Whether to operate a SGHP with fixed price or stock exchange electricity contract is a risk management subject. However, a SGHP is an operation that is preferred to be run at maximum possible capacity, so slowing or shutting the operation down based on the electricity price is probably not justified. An electric boiler (S4) is probably the best option for taking advantage of low prices of stock exchange electricity for steam generation. Electric boiler can also act as flexible spare capacity for steam generation to cover the peaks and back-up other steam generation systems.

6.6 Contribution and future suggestions

Main outcome of this study is that SGHPs can be feasibly integrated to a rendering plant, improving the energy efficiency of the processes, lowering the energy-related costs, and cutting the CO_2 emissions of respective steam production close to zero. There are already proven SGHP solutions in industrial use and commercial SGHPs are available in the market by several suppliers. The research on SGHPs is active, and new inventions are being developed to help optimise and adopt SGHPs in the industry.

This case study can be used as a reference in similar cases on integration of SGHP technology into industrial plants. Methods used in TEEA can be used as tools in identification of suitable SGHP solutions and assessment of technical, economic, end environmental performance. The results are encouraging and show that SGHP solutions have potential for feasible heat recovery systems. Of course, the feasibility is case specific and must be evaluated thoroughly for every case. A same kind of assessment process is suggested for other similar case studies.

If the accuracy of this kind of case study was to be improved, it would probably require dynamic analysis of SGHP functionality based on measured data of case plant time-power profiles. Obtaining this data would require having online energy flow measurement of steam supply and waste heat load. The dynamic analysis would of course be more complex. Conducting a dynamic analysis of a SGHP integration into drying process is suggested for future research on this topic.

7. CONCLUSIONS

Improving energy efficiency and saving the energy related costs and emissions are the main drivers for integration of SGHP system into rendering process. Integration of SGHP into a rendering case plant was investigated through a techno-economic-environmental analysis. In the studied system, 2 MW of impure process vapour at 98 °C from drying process is utilised as heat source for the SGHP system generating steam at 2 bar_g (134 °C). Generated steam is used by the process equipment of the case plant indirectly, and the condensate from steam users is returned to the steam generation at 105 °C. Around 2.5 MW steam is generated by the SGHP with 0.34-0.51 MW of electric power. An important insight was that recovering heat from waste heat vapour is more efficient than having a water circuit between the waste heat source and the SGHP. Thus, process vapour from dryers is a great heat source for SGHP integration.

Three commercial SGHP solutions of type MVR (S1) and CCHP (S2-S3) were identified as the most potential solutions for SGHP integration in the case plant. COP value of S1 was highest, 6.9, followed by solutions S2-S3 with COP of 4.9. A part of the difference can be explained by the utilisation of flash steam in solution S1, which also increases the production of steam a bit. The MVR technology (S1) is well-known among rendering industry and the case plant owners, as similar equipment is used in evaporation processes in rendering. Risks related to refrigerants are avoided in case of S1, as it only uses water/steam as working media.

Due to higher COP and steam production, S1 had the highest operational revenues, which also provided an advantage in the investment calculation. The total price of steam including investment cost was approximately 19 €/MWh with S1 and 24 €/MWh with S2-S3. Payback period for all SGHP solutions were around 8 years. Only if there would be an increase in boiler steam price or carbon price, solutions S2-S3 would offer shorter payback periods than S1. ROI was highest for S1, S2, and S3, respectively. Solutions S2 and S3 were good alternatives for the case plant with smaller investment cost than S1, but long-term feasibility of S1 was estimated to be considerably better.

In terms of environmental performance, all the studied SGHP solutions are revolutionary compared fuel boilers, saving around 98 % of CO_2 emissions compared to peat-driven fuel boiler when using electricity from Finnish grid mix. The emission factor of electricity defines the carbon footprint of SGHP, but due to significant energy saving, the CO_2 emissions decrease even when using electricity of higher emission factor.

Overall, this case study shows that SGHPs are potential solution to decarbonise process heating at rendering plants and decrease the costs of steam production. The decrease in specific energy consumption of 118-135 kWh per ton raw material would result in specific energy consumption of only 250-270 kWh/t, which would probably be difficult to achieve with other kind of process modifications. The results of this study suggest that SGHP technology will soon become more widespread among industrial steam heating systems, as they can provide steam at lower cost compared to other current steam generation methods such as fuel boilers and electric boilers.

REFERENCES

A2EP Australian Alliance for Energy Productivity, 2023. High-temperature Heat Pumps Update with Dr Cordin Arpagaus [WWW Document]. URL https://www.youtube.com/watch?v=i8SoDmIrb1o (accessed 11.15.23).

Aneo Industry, 2024. About High Temperature Heat Pumps [WWW Document]. URL https://www.aneo.com/tjenester/industry/english/technology/ (accessed 1.5.24).

Annex 58, 2023. Annex 58 about HTHP Task 1 - Technologies [WWW Document]. Annex 58. URL https://heatpumpingtechnologies.org/annex58/task1/ (accessed 5.24.23).

Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., Bertsch, S.S., 2018. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 152, 985–1010. https://doi.org/10.1016/j.energy.2018.03.166

Bergamini, R., Jensen, J.K., Elmegaard, B., 2019. Thermodynamic competitiveness of high temperature vapor compression heat pumps for boiler substitution. Energy 182, 110–121. https://doi.org/10.1016/j.energy.2019.05.187

Bless, F., Arpagaus, C., Bertsch, S., 2021. Theoretical investigation of high-temperature heat pump cycles for steam generation. Presented at the 13th IEA Heat Pump Conference, Jeju, Korea.

Bless, F., Arpagaus, C., Bertsch, S.S., Schiffmann, J., 2017. Theoretical analysis of steam generation methods - Energy, CO2 emission, and cost analysis. Energy 129, 114–121. https://doi.org/10.1016/j.energy.2017.04.088

de Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wilk, V., Elmegaard, B., Corberán, J., Benson, J., 2020. Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat (Report), Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat.

Dusek, S., Lauermann, M., Helminger, F., Wilk, V., 2021. Analysis of a steam generating high temperature heat pump for industrial waste heat recovery. Presented at the 13th IEA Heat Pump Conference, Jeju, Korea.

EIPPCB, 2023. Final Draft of Best Available Techniques (BAT) Reference Document for the Slaughterhouses, Animal By-products and/or Edible Co-products Industries.

EIPPCB, 2005. Integrated Pollution Prevention and Control - Reference Document on Best Available Techniques in the Slaughterhouses and Animal By-products Industries.

Ember, 2023. Yearly electricity data [WWW Document]. Ember. URL https://ember-climate.org/data-catalogue/yearly-electricity-data/ (accessed 10.24.23).

ENTSO-E, 2023. ENTSO-E Transparency Platform [WWW Document]. URL https://transparency.entsoe.eu/dashboard/show (accessed 1.2.24).

Fingrid, 2023. Real-time CO2 emissions estimate [WWW Document]. Fingrid. URL https://www.fingrid.fi/en/electricity-market-information/real-time-co2-emissions-estimate/ (accessed 10.19.23).

Forman, C., Muritala, I.K., Pardemann, R., Meyer, B., 2016. Estimating the global waste heat potential. Renew. Sustain. Energy Rev. 57, 1568–1579. https://doi.org/10.1016/j.rser.2015.12.192

Grönman, K., Pajula, T., Sillman, J., Leino, M., Vatanen, S., Kasurinen, H., Soininen, A., Soukka, R., 2019. Carbon handprint – An approach to assess the positive climate impacts of products demonstrated via renewable diesel case. J. Clean. Prod. 206, 1059–1072. https://doi.org/10.1016/j.jclepro.2018.09.233

Holmgren, K., Kirkinen, J., Savolainen, I., 2006. The climate impact of energy peat utilisation – comparison and sensitivity analysis of Finnish and Swedish results.

Honkajoki Oy, 2022. Honkajoki Sustainability report 2022.

HPTTCP, 2023. Annex 58 High-Temperature Heat Pumps Task 1 - Technologies, Task Report. (Task Report).

IPCC, 2023. Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. Geneva, Switzerland, (in press).

Jiang, J., Hu, B., Wang, R.Z., Deng, N., Cao, F., Wang, C.-C., 2022. A review and perspective on industry high-temperature heat pumps. Renew. Sustain. Energy Rev. 161, 112106. https://doi.org/10.1016/j.rser.2022.112106

Kaida, T., Sakuraba, I., Hashimoto, K., Hasegawa, H., 2015. Experimental performance evaluation of heat pump-based steam supply system. IOP Conf. Ser. Mater. Sci. Eng. 90, 012076. https://doi.org/10.1088/1757-899X/90/1/012076

Kang, D.H., Na, S.-I., Yoo, J.W., Lee, J.H., Kim, M.S., 2019. Experimental study on the performance of a steam generation heat pump with the internal heat exchanging effect. Int. J. Refrig. 108, 154–162. https://doi.org/10.1016/j.ijrefrig.2019.09.003

Kosmadakis, G., 2019. Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. Appl. Therm. Eng. 156, 287–298. https://doi.org/10.1016/j.applthermaleng.2019.04.082

Kosmadakis, G., Arpagaus, C., Neofytou, P., Bertsch, S., 2020. Techno-economic analysis of high-temperature heat pumps with low-global warming potential refrigerants for upgrading waste heat up to 150 °C. Energy Convers. Manag. 226, 113488. https://doi.org/10.1016/j.enconman.2020.113488

Liu, C., Han, W., Xue, X., 2022. Experimental investigation of a high-temperature heat pump for industrial steam production. Appl. Energy 312, 118719-. https://doi.org/10.1016/j.apenergy.2022.118719

Lu, Z., Yao, Y., Liu, G., Ma, W., Gong, Y., 2022. Thermodynamic and Economic Analysis of a High Temperature Cascade Heat Pump System for Steam Generation. Processes 10, 1862. https://doi.org/10.3390/pr10091862

Mateu-Royo, C., Arpagaus, C., Mota-Babiloni, A., Navarro-Esbrí, J., Bertsch, S.S., 2021. Advanced high temperature heat pump configurations using low GWP refrigerants for industrial waste heat recovery: A comprehensive study. Energy Convers. Manag. 229, 113752. https://doi.org/10.1016/j.enconman.2020.113752

Meeker, D.L. (Ed.), 2006. Essential rendering: all about the animal by-products industry. National Renderers Association : Fats and Proteins Research Foundation : Animal Protein Producers Industry, Alexandria, Va.

Mengden, A., 2023. Carbon Taxes in Europe [WWW Document]. Tax Found. URL https://taxfoundation.org/data/all/eu/carbon-taxes-in-europe-2023/ (accessed 10.9.23).

Merritt, C., 2015. Process Steam Systems: A Practical Guide for Operators, Maintainers, and Designers. John Wiley & Sons, Incorporated, Hoboken, UNITED STATES.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Zhang, H., Aamaas, B., Boucher, O., Dalsøren, S.B., Daniel, J.S., Forster, P., Granier, C., Haigh, J., Hodnebrog, Ø., Kaplan, J.O., Marston, G., Nielsen, C.J., O'Neill, B.C., Peters, G.P., Pongratz, J., Ramaswamy, V., Roth, R., Rotstayn, L., Smith, S.J., Stevenson, D., Vernier, J.-P., Wild, O., Young, P., Jacob, D., Ravishankara, A.R., Shine, K., 2013. 8 Anthropogenic and Natural Radiative Forcing, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ockerman, H.W., Hansen, C.L. (Conly L.), 1988. Animal By-Product Processing. Weinheim: VCH; Chichester: Horwood.

Roberts, I., Stoor, P., Carr, M., Höcker, R., Seifert, O., 2017. Steam Handbook - An introduction to steam generation and distribution, 1st Edition. ed. Endress+Hauser Flowtec AG, Reinach/BL.

Saini, P., Ghasemi, M., Arpagaus, C., Bless, F., Bertsch, S., Zhang, X., 2023. Techno-economic comparative analysis of solar thermal collectors and high-temperature heat pumps for industrial steam generation. Energy Convers. Manag. 277, 116623. https://doi.org/10.1016/j.enconman.2022.116623

Salonen, N., 2020. Teollisuuden hukkalämpöjen hyödyntäminen : Case: moottorivoimalaitos. Tampere University.

SFS, 2023. ISO 14000 Ympäristöjohtamisen standardisarja [WWW Document]. SFS. URL https://sfs.fi/standardeista/tutustu-standardeihin/suositut-standardit/iso-14000-ymparistojohtamisen-standardisarja/ (accessed 12.20.23).

Spirax Sarco, 2023. Learn about steam | Spirax Sarco [WWW Document]. URL https://www.spiraxsarco.com/learn-about-steam (accessed 6.9.23).

Spirax-Sarco Limited, 2008. The steam and Condensate Loop, First Edition. ed. Spirax-Sarco Limited, Cheltenham.

Suomala, P., Manninen, O., Lyly-Yrjänäinen, J., 2011. Laskentatoimi johtamisen tukena, 1. painos. ed, Business. Edita, Helsinki.

Tilastokeskus, 2023. Tilastokeskus [WWW Document]. URL https://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html (accessed 10.24.23).

Wilk, V., Windholz, B., Helminger, F., Lauermann, M., Riedl, J., Sporr, A., Schneeberger, A., Fleckl, T., 2022. DryFiciency closed loop heat pumps: Operation experience and outlook. Presented at the High Temperature Heat Pump Symposium, 29.-30.3.2022, Copenhagen.

X-eng, n.d. Steam tables by Magnus Holmgren according to IAPWS IF-97. [WWW Document]. URL https://xsteam.sourceforge.net/ (accessed 1.15.24).

Zeilerbauer, L., Hubmann, F., Puschnigg, S., Lindorfer, J., 2023. Life cycle assessment and shadow cost of steam produced by an industrial-sized high-temperature heat pump. Sustain. Prod. Consum. 40, 48–62. https://doi.org/10.1016/j.spc.2023.06.016

Zhang, S., Wang, F., Mei, Z., Lv, L., Chi, Y., 2021. Status and Development of Sludge Incineration in China. Waste Biomass Valorization 12, 3541–3574. https://doi.org/10.1007/s12649-020-01217-9

Zhao, Z., Gao, S., Tian, Y., Zhang, H., 2021. Study on performance of high temperature heat pump system integrated with flash tank for waste heat recovery employed in steam production. Int. J. Energy Res. 45, 20318–20330. https://doi.org/10.1002/er.7116

Zühlsdorf, B., 2019. High-performance heat pump systems: Enhancing performance and range of heat pump systems for industry and district heating. Technical University of Denmark, Kgs. Lyngby.