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ABSORPTION COOLING WITH RENDERING PLANT WASTE HEAT

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Tämän opinnäytetyön tarkoitus on tutkia absorptiojäähdytystä renderöintilaitoksen hukkalämpöä hyödyntämällä. Opinnäytetyö on tehty Recomill Oy:lle. Eläinten renderöinti on hyvin energiaintensiivinen prosessi, jossa teurastamoiden ja lihaleikkaamojen sivutuotteista jalostetaan erilaisia tuotteita erottamalla rasvat, proteiinit sekä vesi toisistaan. Erottelu tapahtuu pääosin lämmön ja puristimien avulla. Opinnäytetyössä tutkitaan, kuinka paljon jäähdytystä saadaan aikaan hukkalämpövirtoja käyttämällä sekä perehdytään absorptiojäähdyttimen toimintaan ja taloudelliseen kannattavuuteen.

Tutkimuksen laskelmien pohjana on Recomillin laitoskonsepti Kiinaan. Laitoksessa käsiteltäisiin siipikarjaa, jolla on korkeampi ominaislämpökapasiteetti verrattuna sikaan tai nautaan. Tämän seurauksena energiaa vaaditaan enemmän, mutta myös hukkalämpöä syntyy enemmän. Opinnäytetyön tavoite on parantaa Recomillin jo olemassa olevaa kiertotalousajattelua, jossa pyritään hyödyntämään kaikki muuten hukkaan menevät resurssit tai materiaalit.

Absorptiojäähdytys on testattu ja toimiva teknologia, joka vaatii tietyt olosuhteet ollakseen taloudellisesti kannattava. Absorptiojäähdytys vaatii riittävää hukkalämpöä, joko kuuman veden tai höyryn muodossa. Lisäksi absorptiojäähdytys vaatii suuren jäähdytystornin, sillä absorptiossa vapautuu suuria määriä lämpöä. Tässä tapauksessa suurimmaksi ongelmaksi muodostuu todennäköisesti kuuman veden laatu, sillä renderöinnin seuraksena veden pH on varsin korkea, sekä se saattaa sisältää kiinteitä jäämiä. Opinnäytetyössä ei ollut mitään suunniteltua käyttökohdetta jäähdytykselle, joten lopputuloksena saatava kylmäenergian riittävyys jää tapauskohtaisesti arvioitavaksi.

Avainsanat Absorptiojäähdytys, absorptiojäähdytin, hukkalämpö

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ABSTRACT

Author	Niko Juoperi
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The purpose of this theses is to study the feasibility of an absorption chiller with rendering plant waste heat. This thesis was done for Recomill Ltd. Animal rendering is a very energy intensive process. By-products from slaughterhouses and abattoirs are refined into valuable products by separating protein, fat and water with heat energy from steam. The rendering process yields high amounts of wastewater and this thesis studies how much cooling can be achieved with the use of an absorption chiller.

The basis for calculations is from Recomill's rendering plant, planned to be founded in China. The rendering plant would process poultry, which has a higher specific heat capacity compared to cattle. The higher specific heat capacity results in a higher energy requirement, which in turn results in a higher amount of waste heat. The aim of this thesis is to improve Recomill's already existing circular economy model, where no material or resource is wasted. The sources used in this thesis are mainly articles and information from the internet.

Absorption cooling is tested and proven technology. However, it requires very specific conditions to be the most optimal cooling solution. There needs to be a sufficient source of waste heat, either steam, hot water or exhaust gases. Absorption cooling also requires a large cooling tower, due to its high amount of heat rejection during absorption. In this case, the biggest problem is most likely the quality of the hot water, as it may contain impurities and too high a pH. As there was no planned use for the cooling energy, it has to be evaluated on a case by case basis, whether the resulting cooling is sufficient.

Keywords Absorption cooling, absorption chiller, waste heat

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LIST OF ABBREVIATIONS

ABP	Animal by-product
BTU	British thermal unit
COP	Coefficient of Performance
EFPRA	European Fat Processors and Renderers Association
LiBr	Lithium Bromide
LNG	Liquefied natural gas
O&M	Operation and maintenance
PID	Proportional-Integral-Derivative

1 INTRODUCTION

Animal rendering is a very energy-intensive process. During the rendering process, the raw animal material is heated using steam. Based on the rendering technology, waste steam or waste hot water will be produced. This thesis focuses on utilizing the waste heat generated in the rendering process.

Absorption chillers have proven to be effective when there is waste heat available. The aim of this thesis is to study the profitableness and viability of absorption chillers in rendering plants. This is done by comparing absorption technology with traditional vapor compression technologies and calculating chiller cooling capacity based the raw material flow in a rendering concept plant in China.

An absorption chiller is an environmentally friendly cooling solution. When waste heat is used, no added emissions are generated. The absorption chiller uses only a fraction of electricity consumption of vapor compression chillers. Absorption chillers will not most likely replace all conventional cooling systems, but there are applications where it offers the economically and environmentally best solution.

This thesis was done for Recomill. Recomill is a joint venture between two Finnish companies, Honkajoki Oy and WOIMA Finland Oy. Recomill provides a solution for animal by-product recycling with their circular economy plants and ecoparks. By combining recycling technologies together, Recomill offers sustainable and environmentally friendly solutions for animal by-product handling.

2 HONKAJOKI OY

Honkajoki Oy recycles animal by-products using a circular-economy model. Inedible parts of animals come in from farms, abattoirs and meat cutting plants. These inedible parts are called animal by-products (ABPs) and they are classified as waste by the EU's Animal By-Products Regulation. Through Honkajoki Oy's processes, animal by-products are turned into valuable raw materials for the energy, cosmetics, feed and fertilizer industries. Honkajoki Oy is owned by two Finnish food industry companies, Atria Oyj and HKScan Oyj, each with 50% share. /1/

2.1 Circular Economy Model

The basic principle behind circular economy is to utilize materials as efficiently as possible. The efficient use of materials results in high sustainability and a reduced amount of waste. Figure 1 shows a simplified version of Honkajoki Oy's operation. The animal by-product treatment or rendering is the key process in this circular economy model. In addition to the end products from raw materials, the rendering process yields bio waste, waste water and gases that can be utilized in the ecosystem. Honkajoki Oy has a wind farm, which is not shown in Figure 1. /1/

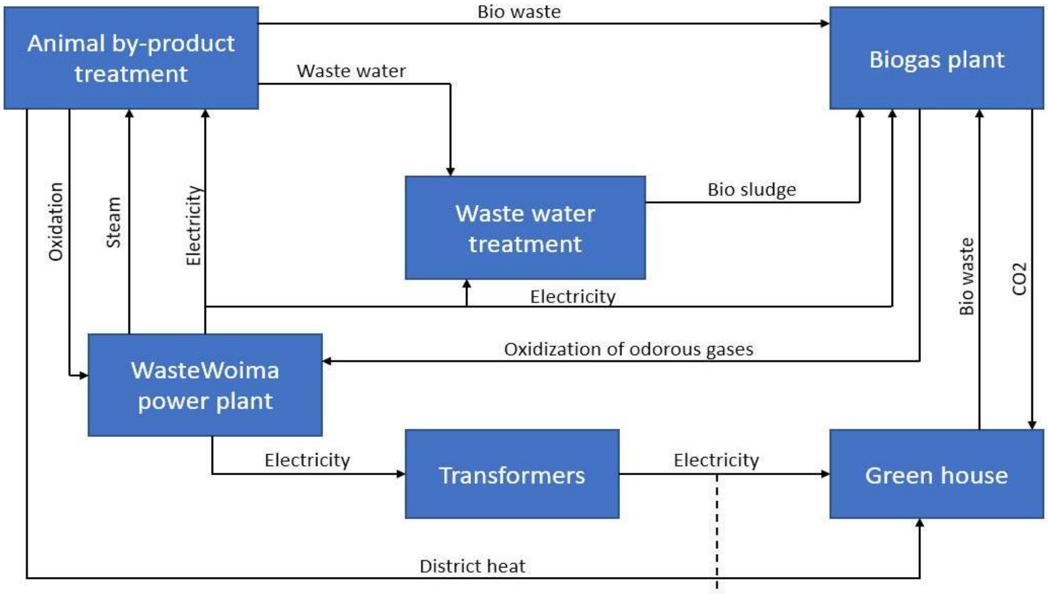

Figure 1. Honkajoki Oy's circular-economy model. /1/

2.2 Rendering Process

Rendering is a process that turns animal by-products into a wide range of usable products, by separating fats, proteins and water through heat and pressure. Approximately 50% of the slaughtered animal is used for meat production, and the rest 50% turns into by-products. Figure 2 shows the estimated division of the by-products. Rendering also stabilizes the raw material and prevents it from decomposing and therefore, polluting the environment. /2/

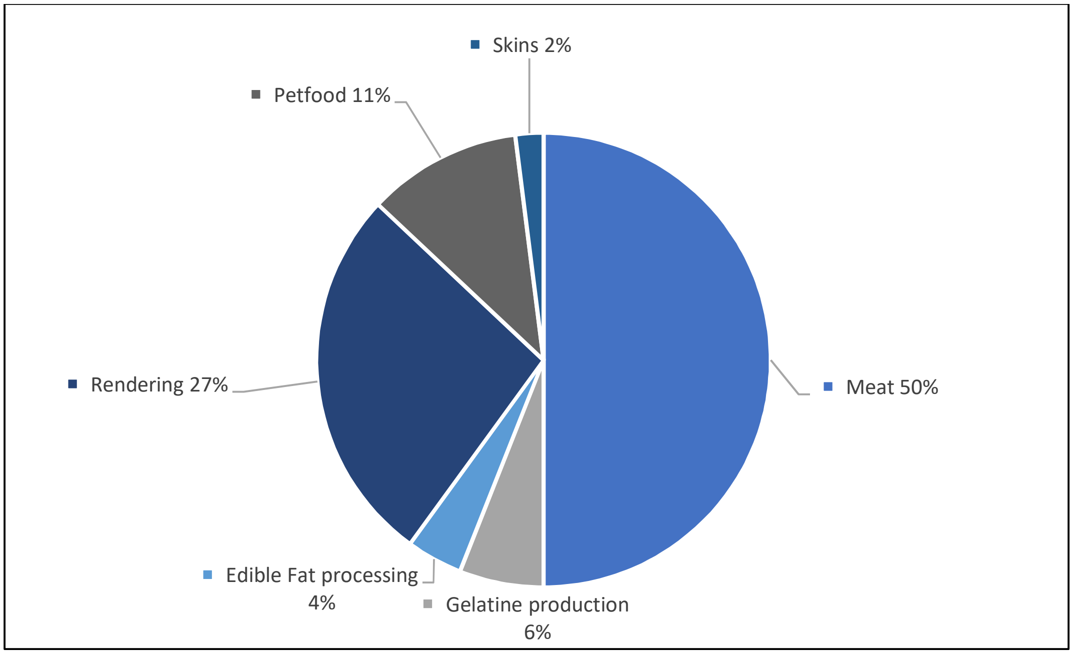

Figure 2. Estimated utilization of slaughtered animal by weight. /2/

Traditionally rendering describes a process where heat is used to separate fat, protein and water. This would cover all different aspects of animal by-products processing. Nowadays the word rendering is typically used for describing the processing of inedible animal by-products. “Edible rendering” is generally referred as fat processing. Figure 3 shows a simplified version of a high fat raw material rendering process. In practice, there are many different types of rendering processes for different system types. Different system types include batch or continuous process. There are also designated process pressures and fat levels based on the raw material. /2/

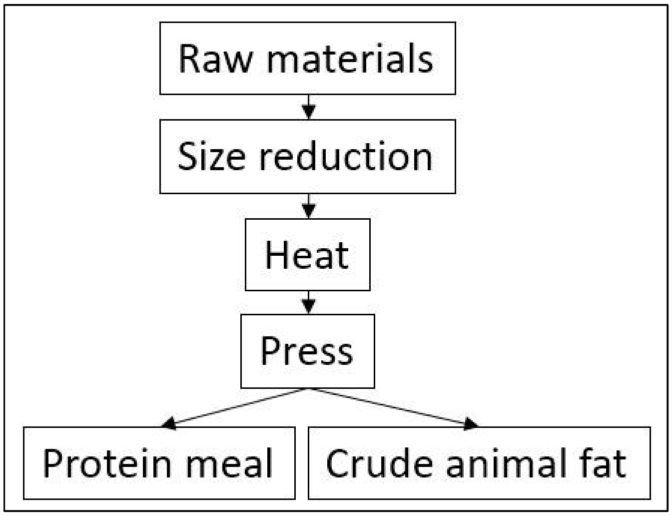

Figure 3. Generic rendering process description. /2/

2.2.1 Dry Rendering Process

Dry rendering is a process where the separation of the fat is done by dehydrating the animal by-products using steam. Heating the material breaks down the cellular structure to release the fat and dries the product. The free fat is then drained out and remaining solids are conveyed to press where the remaining fat is pressed out. Fat is then purified with a separator that removes any remaining moisture and fine solids. The purified fat can be stored, and it is ready for the use of energy or cosmetics industries. Dry rendering is typically used for category 2 material, which is not suitable for human or animal consumption. /3, 4/

2.2.2 Wet Rendering Process

Older wet rendering systems use boiling water to separate fat from the raw material. Water is added to the raw material and steam is then used to boil the water and therefore cooking the raw material to separate the fat. The material is then centrifuged to separate the remaining water and proteins from the fat. /3/

Newer systems use low temperature rendering, where no additional water is added into raw material, but instead steam is injected into the vessel to heat up the material. When the material reaches about 90 °C, it is separated using press. Pressing the heated material results in press water and press cake. As in older systems, the press water is centrifuged to separate proteins and fats from the water. The end products from wet rendering process are protein meal and purified fat (and waste water). /5/

Figure 7 in Chapter 4 shows the wet rendering process in-depth.

2.2.3 Processing Low Fat Material

Low fat materials, such as feathers and blood can also be treated. Feathers are treated with hydrolysis, which is a chemical reaction that uses water to break down bonds of the material. The final product is hydrolysed feather protein that can be used, for example, in animal feed. Blood can be processed by coagulation and drying to produce plasma and hemoglobin powders. /2/

2.3 Rendering Regulations

In Europe, the European Fat Processors and Renderers Association (EFPRA), which Honkajoki Oy is member of, strives to improve the safety, security and sustainability of European food products. EFPRA regulates the use of animal by-products, by dividing animal by-products into three different categories. /2, 6/

Category 1 includes the products with the highest risk and these are potentially hazardous. Animals in this category could potentially transmit prion diseases. The end products of category 1 animals are used as fuel in combustion and in biodiesel. Category 2 products are not fit for human consumption. They still pose a risk to humans and animals, but do not have the risk to transmit prion diseases. Category 2 products are used in combustion as fuel, biodiesel, fertilizers, fur feed and biogas fuel. Category 3 products are the safest and suitable for human consumption at the time of slaughter. Category 3 can be used for chemical industry, fish feed, pet food, animal feed in addition to the category 1 and 2 uses. /6/

2.4 Rendering Energy Usage

Rendering requires a lot of energy to separate water from the raw material. Essentially, the temperature must be elevated enough to break the molecular structure of the material. The required energy is based on the physical properties of the raw material. Different materials have different specific heat capacities. Naturally, material with a higher specific heat capacity requires more energy to increase the temperature. The energy usage is also dependent on the type of rendering system used. Low temperature wet rendering requires the least amount of energy, and it is often used in modern wet rendering plants. Dry rendering requires more energy, but there is also a better opportunity for an absorption chiller to be feasible. /5/

3 ABSORPTION COOLING

Sorption cooling uses a source of heat to produce cold. This can be very useful when there is a lot of waste heat available. Sorption is a term for both, absorption and adsorption technologies. This thesis focuses only on absorption cooling due to its better scalability, higher values of coefficient of performance (COP) and it being generally more common. /7/

Absorption cooling can be utilized in commercial buildings and industrial plants. Potential uses include air conditioning, refrigeration and process fluid cooling. Absorption cooling has up- and downsides compared to other cooling technologies, for example, vapor compression chillers. On the plus side, absorption chillers have a very low electrical power demand, quiet operation and fewer moving parts than compression chillers. Downsides include large physical size, high rate of heat rejection and higher initial investment cost. Proper maintaining is required for an absorption chiller to work as intended. The absorption cycle relies on low working pressures inside the machine and any leak in the absorption chiller may compromise the chilling process. /7, 8/

3.1 Absorption, Adsorption and Desorption

Absorption is a physical or chemical phenomenon where atoms or molecules are crossing the surface of a material and therefore entering the bulk phase of a material. Adsorption is a surface process. Instead of entering the material, gas or liquid is accumulated on the surface of a liquid or a solid material. A thin layer of the adsorbate is created on the surface of the adsorbent. In conclusion, absorption involves the whole volume of a material, adsorption involves only the surface. /9/

Desorption is an opposite process of sorption. In desorption, one substance is released from another. This can happen through the surface or from the surface, depending on whether the substance was absorbed or adsorbed. /9/

3.2 Absorption Chiller

The key difference between traditional vapor compression chillers and absorption chillers is that the compressor is replaced by a chemical cycle. This chemical cycle is called absorption cycle. There are two commonly used refrigerant and absorbent combinations, water and lithium bromide (LiBr) solution and ammonia (NH_3) and water solution. In the water and LiBr solution, water acts as a refrigerant and LiBr is the absorbent. In the second one, ammonia is the refrigerant and water is the absorbent. With lithium bromide and water, the lowest cooling temperature is around 5 °C. If the desired cooling temperature is lower than that, the ammonia and water solution is typically used. /7, 8/

The refrigerant, or often called working fluid, is the substance that goes through phase transitions, usually changing from liquid to gas and back to liquid. The absorbent stays in the same phase during the absorption process.

Absorption chillers can be divided into three different categories based on their form of heat input: direct-fired units, indirect-fired units and custom machines. Direct-fired units combust fuel an internal burner. Natural gas and LNG are the most common fuel for this type. Indirect-fired units use heat from an external source. This heat can be in the form of steam, hot water or exhaustion gases. Custom machines are tailored to support several heat sources combined. /7/

3.3 Single-stage Absorption Chiller Cycle

The absorption chiller has a similar cycle compared to the traditional vapor compression cycle, but the compressor and prime mover are replaced with a thermal compressor (Figure 4). The thermal compressor consists of absorber, solution pump and generator. The thermal compressor takes low pressure and low temperature refrigerant vapor from the evaporator and delivers high pressure and high temperature refrigerant vapor to the condenser. Instead of using mechanical energy to compress the refrigerant vapor, the thermal compressor uses an absorbent fluid to chemically bond with the refrigerant vapor. /8/

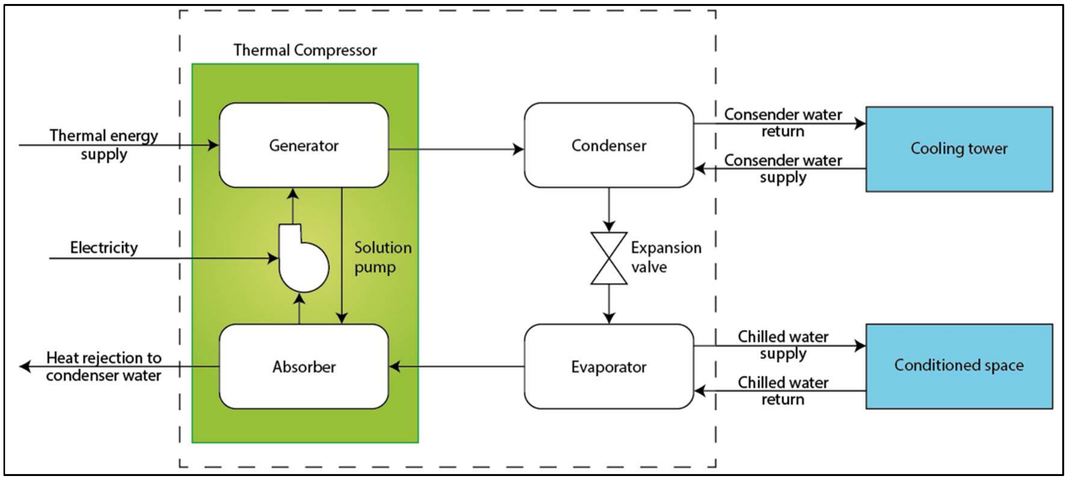

Figure 4. Single-stage absorption cycle. /7/

3.3.1 Generator

The generator uses external heat energy to boil the dilute solution of refrigerant and absorbent. This boiling causes a separation process, where refrigerant transitions into vapor form and the absorbent concentrates. The refrigerant vapor released in the generator is drawn to the condenser and absorbent flows back to the absorber. /10/

3.3.2 Condenser

In a condenser cooling tower water cools and condenses the refrigerant. Pressure inside the condenser is about 10 kPa. The refrigerant is now in the form of liquid and it flows into the evaporator. As it can be seen in Figure 5, the boiling point for water is slightly below 50 °C. The cooling water cannot be too hot, or the condensation will not happen. On the other hand, if the cooling water is too cold, crystallization may occur. Crystallization is described in chapter 4.3. Usually the cooling water goes in around 30 °C and comes out at 36-38 °C. /10/

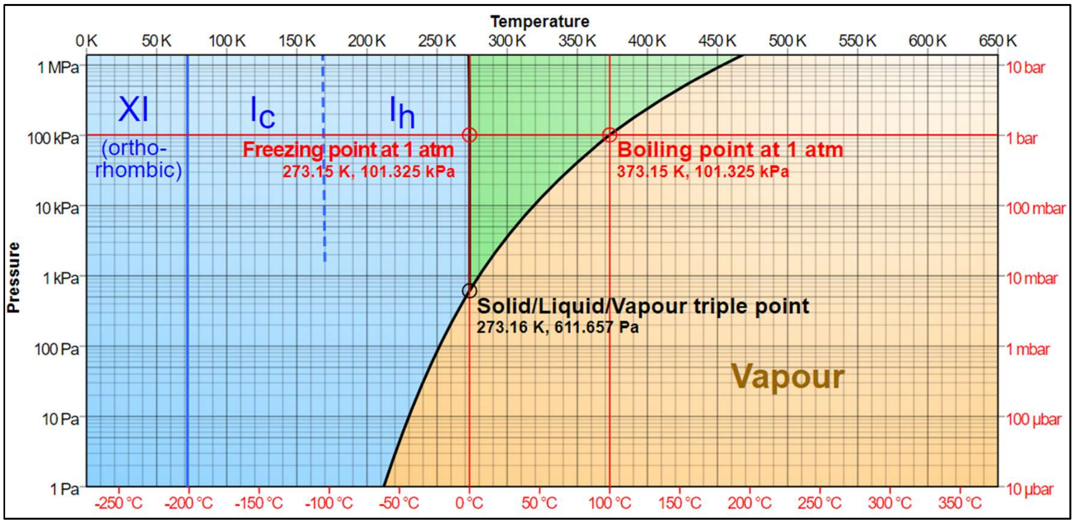

Figure 5. Water phase diagram. /11/

3.3.3 Evaporator

The evaporator has a pressure of about 1 kPa. As the condensed water enters the evaporator, the sudden pressure difference causes the refrigerant to flash, cooling it down to its saturation temperature (boiling point temperature). In the case of a water and lithium bromide chiller, where the water acts as a refrigerant, the saturation temperature is around 7 °C at the 1 kPa pressure (Figure 5). The cold water is then sprayed onto the evaporator tube bundle, chilling the system water within. This chilled system water can then be used for air-conditioning, refrigeration or any other cooling application. The transfer of heat causes the refrigerant to vaporize. The refrigerant vapor is drawn to the absorber. /10/

3.3.4 Absorber

The absorption of the refrigerant vapor into the absorbent causes the absorber section to have a lower pressure. This absorption process generates heat, which is taken away by using cooling tower water. As the refrigerant vapor is absorbed into the absorbent, the solution becomes increasingly dilute. This dilute solution is then taken again to the generator to keep the cycle continuous. /10/

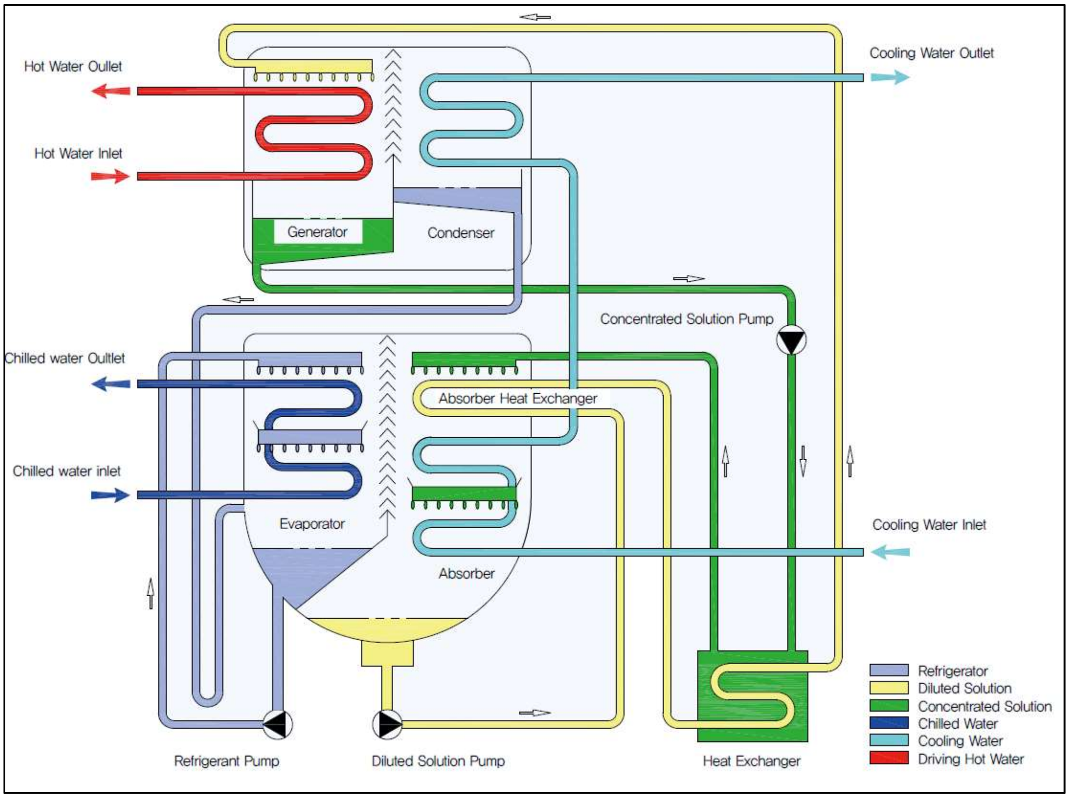

Figure 6. Single effect absorption chiller. /12/

3.3.5 Solution Heat Exchanger

A solution heat exchanger is not essential for an absorption chiller to work, but it greatly increases the efficiency of the absorption chiller. The heat exchanger exchanges heat between cool, dilute solution pumped from the absorber to the generator and hot concentrated solution returning from the generator to the absorber. The dilute solution is now closer to its boiling point and requires less thermal energy to reach it. Simultaneously, the heat rejection load in the absorber section decreases, reducing the cooling tower water usage /10/.

3.4 Performance Characteristics of Absorption Chillers

Table 4 (Appendix 1) shows the performance characteristics and capital costs for single- and two stage water-LiBr absorption chillers. Systems 1-3 are single stage chillers and 4-7 double stage. Heat sources for single-stage chillers are hot water and low-pressure steam. Two stage chillers use high-pressure steam and CHP (combined heat and power) prime mover exhaust gas. In this comparison, chiller sizes range from 180 kW to 4640 kW. All chillers have the same inlet temperature (12,2 °C) and outlet temperature (6,7 °C). /8/

The cooling COP (coefficient of performance) indicates how efficient the chiller is. COP is calculated by dividing the cooling output by the consumed thermal energy. For single-stage chillers, COP is 0,70-0,79 and for two stage chillers 1,35-1,42. The capital and O&M costs vary greatly between different sized systems. The heat source also affects these costs. The total installed costs range from 415 €/kW to 1350 €/kW for single stage systems and 460 €/kW to 760 €/kW for the two stage chillers. The capital costs decrease as the size of the chiller increases. The O&M costs range from 0,23 €/MWh to 1,38 €/MWh and they include all maintenance requirements with an absorption chiller. The maintenance costs include the periodic purging of non-condensable gases and monitoring of cooling tower and chilled water quality. /8/

As it can be seen from Table 4, a large single-stage chiller (system 3) offers the lowest capital costs and similar O&M costs to a large high-pressure or an exhaust gas fired chiller. Two stage systems have higher capital costs, but they are more efficient. The system should be selected based on the amount of available waste heat and on the amount of required cooling. If there is enough waste heat to power a large single stage chiller, it will be the most cost-effective. With high-grade waste heat, two stage chillers are usually the best option. The high-grade heat source could be steam at 3-10 bar(g), hot exhaust gases or superheated water. /8/

Bar(a) refers to absolute pressure in bars and bar(g) represents sealed gauge pressure. The absolute pressure is zero-referenced against perfect vacuum and gauge pressure is zero-referenced against ambient pressure. A gauge pressure higher than the ambient pressure is referred as positive and below the ambient pressure, it is called negative or vacuum gauge pressure. When absorption chiller manufacturers state the minimum steam pressure, it is typically stated as a gauge pressure. /13/

$$Absolute\ pressure = Ambient\ pressure + Gauge\ pressure$$

3.5 Emissions of Absorption Chillers

Absorption chiller emissions are based on the heat source. If the system is integrated with a CHP system or driven with waste heat from any other process, there are no added emissions and very low electricity consumption compared to vapor compression chillers. However, if the unit is directly fired, the emissions will depend on the fuel that is used, and specific combustion technology used for firing. Natural gas is often the only viable fuel for directly fired chillers. Natural gas emissions include CO_2, CO, SO_2, NO_x and particulates. Emissions need to comply with local laws and regulations and control measures may be required by the government. /8/

4. APPLICATION OF ABSORPTION CHILLER

Figure 7 shows the main process of the wet rendering plant. The raw material in this case is poultry. The raw material is estimated to consist of 72% water (10080 kg/h), 16% solids (2240 kg/h) and 12% fat (1680 kg/h), resulting in a total flow of 14000 kg/h. The raw material is minced to ease heating and pressing.

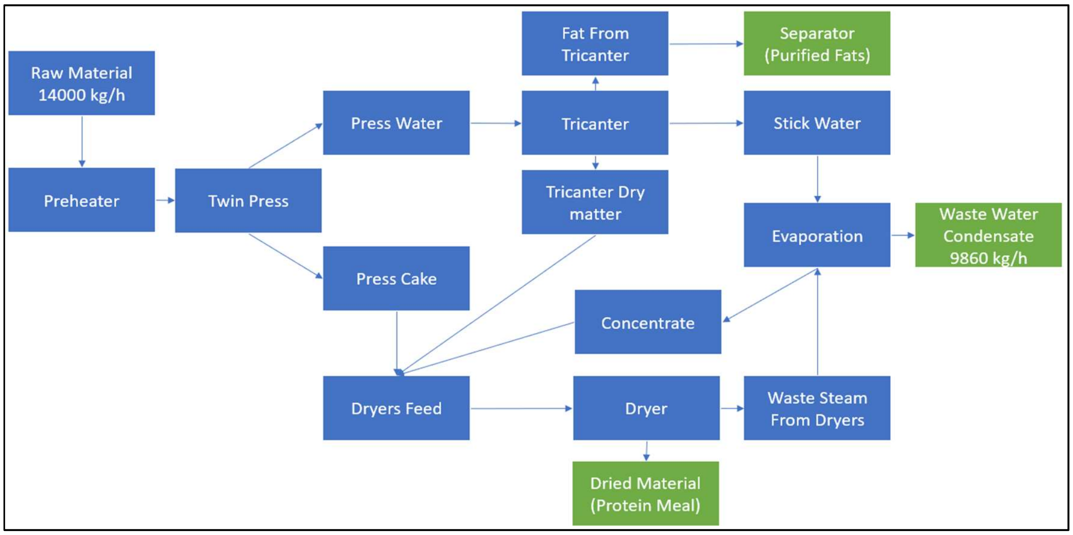

Figure 7. Wet rendering plant main process.

The minced raw material goes to the preheater, where it is heated to around 90 °C, using steam indirectly. The required amount of steam is based on the raw material and its specific heat capacity. For poultry, the specific heat capacity is estimated to be 4,34 kJ/(kg·K) and it requires 1350 kW to increase the raw material temperature from 10 °C to 90 °C.

The heated material is taken to press, and liquids are pressed out. The pressing results in press cake and press water. The press water is then taken to the tricanter, which separates fats, solids and water. Stick water still has some solids and fat left in it, so it goes through an evaporation process and forms a concentrate.

Together press cake, tricanter dry matter and concentrate form a dryer's feed. The remaining water is evaporated using indirect steam and dried material is left over. As the water from the dryer's feed is now in the form of steam, it is utilized in the evaporation plant to increase energy efficiency. Two separate waste water flows come out of the evaporation plant, evaporation water condensate from stick water and condensate from waste steam. The evaporation water condensate flow is 6200 kg/h at 80 °C and the condensate from the dryer waste steam is 3660 kg/h at 98 °C. Together these flows are 9860 kg/h.

4.1 Hot Water Absorption Chiller

The two separate flows, evaporated water condensate and condensate from waste water could be mixed together. This would result in a flow with a temperature of 86,7 °C and the mass flow rate of 9860 kg/h. The amount of cooling can be estimated with the following formulas:

$$Cooling\ energy = COP * Q$$

$$COP = \frac{Thermal\ energy\ output}{Thermal\ energy\ input}$$

COP is generally stated by the manufacturer, so it does not have to be calculated separately.

$Q = mc\Delta T$, where

m = mass flow rate (or mass), c = specific heat capacity of water, ΔT = temperature difference between hot water going in and coming out. The mass flow rate is converted from kg/h to kg/s by dividing 9860kg/h with 3600s/h. The specific heat capacity varies slightly based on the temperature of the water. The value used in the following calculation is the average between 75 °C and 87 °C. The difference between temperature values is same in Kelvins and in Celsius, so the temperatures are not converted to Kelvins.

$$Q = 2{,}74\frac{kg}{s} \cdot 4{,}197\frac{kJ}{kg \cdot K} \cdot (86{,}7\ °C - 75{,}0\ °C) = 134{,}3\frac{kJ}{s} = 134{,}3\ kW$$

The cooling energy for an absorption chiller with a COP of 0,75 would be:

$$Q_{cooling} = 0{,}75 \cdot 134{,}3\ kW = 100{,}7\ kW$$

The absorption chiller COP differs from the COP of compression chillers. With compression chillers, COP states how many units of cooling is produced per one unit of electricity. The absorption chiller COP indicates how much heat energy goes in and how much comes out. Therefore, when comparing absorption and compression chillers, the COP itself should not be a factor. The absorption chiller COP is useful for estimating potential cooling energy and comparing different manufacturers.

4.2 Single-effect Double Lift Absorption Chiller

A single-effect double lift absorption chiller features auxiliary generator, auxiliary absorber, auxiliary heat exchanger and second generator in addition to the "normal" absorption chiller components. This allows the hot water circuit to be longer, releasing heat in multiple generators. The outcoming temperature of hot water will be significantly lower.

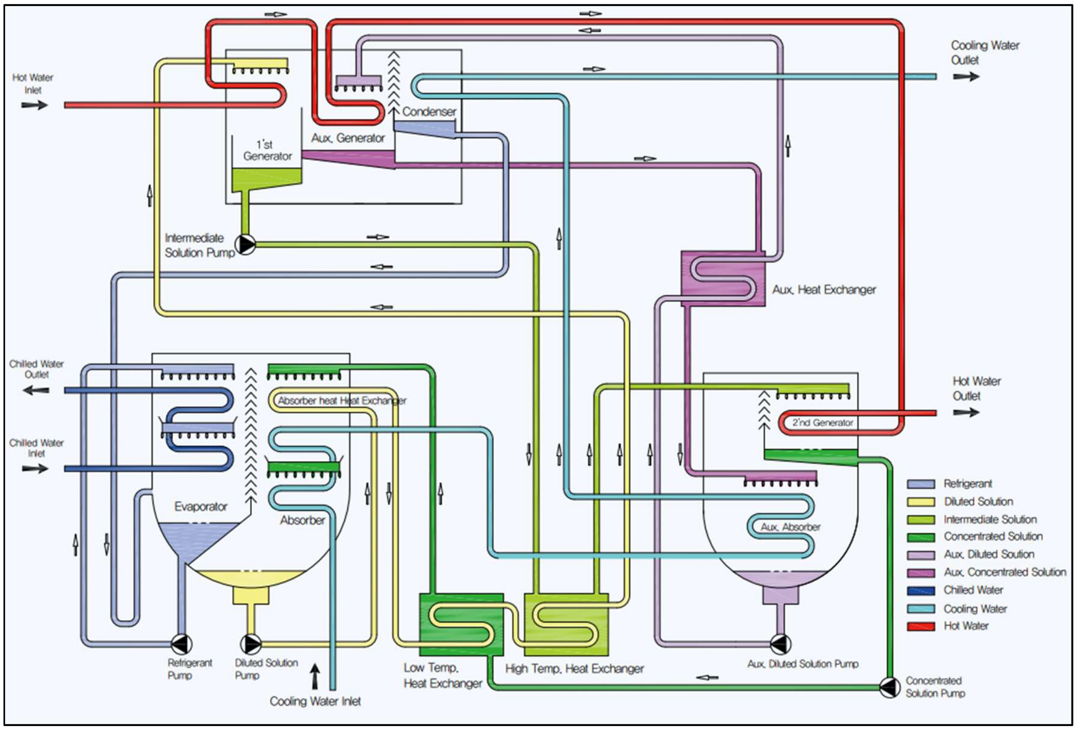

Figure 8. Single-effect double lift absorption cycle. /12/

For "normal" single-effect absorption chiller, the typical temperature of hot water going in is around 95 °C and it comes out at 75-80 °C. With double lift technology, the hot water coming out could be as low as 55 °C. The COP is usually slightly lower, around 0,65-0,70. Without double lift, single stage hot water absorption chillers usually have a COP of 0,75-0,80.

Despite having a lower COP, double lift technology results in a higher amount of cooling, due to the utilization of the wider temperature range. The following calculation has the same mass flow rate. The specific heat capacity is average of 55 °C and 86,7 °C and COP is adjusted to the double lift value (0,65 in this example).

$$Q = 2{,}74 \frac{kg}{s} \cdot 4{,}192 \frac{kJ}{kg \cdot K} \cdot (86{,}7\,°C - 55{,}0\,°C) = 363{,}7 \frac{kJ}{s} = 363{,}7\ kW$$

$$Q_{cooling} = 0{,}65 \cdot 363{,}7\ kW = 236{,}4\ kW$$

Using the double lift technology with same amount of hot water more than doubles the cooling. The drawbacks are higher investment cost, maintenance cost and electricity consumption. The most feasible option depends on the required amount of cooling and waste heat availability. Table 1 compares LG's single effect chillers (WCMW 008, WCMH 008) and single effect double lift chiller (WC2H 008) of similar cooling capacity.

Table 1. Comparison between standard and double lift absorption chillers. /14/

Manufacturer		LG		
Model		WCMW 008	WCMH 008	WC2H 008
Cooling capacity (kW)		**264**		
Chilled Water	Temperature (°C)	12 → 7	13 → 8	13 → 8
	Flow rate (m^3/h)	45,6	45,4	45,4
Cooling Water	Temperature (°C)	31 → 36,5		
	Flow rate (m^3/h)	99,7	92,1	97
Hot Water	Temperature (°C)	**95 → 80**	**95 → 72**	**95 → 55**
	Flow rate (ton/h)	**21,4**	**12,2**	**7,7**
Electricity consumption (kW)		2,6	2,6	4,0

As it can be seen from Table 1, the temperature range of the hot water has a significant effect on the consumption of hot water. Table 2 shows chillers from different series, again two single-effect chillers (WMCW 007, WCMH 011) and one single-effect double lift (WC2H 008). This time the chillers were selected based on the hot water flow rate. There were no exactly the same flow rates between different series, but these values are close enough for sensible comparison.

Table 2. Absorption chiller comparison based on hot water flow rate. /14/

Manufacturer		LG		
Model		WCMW 007	WCMH 011	WC2H 018
Cooling capacity (kW)		**229**	**387**	**618**
Chilled Water	Temperature (°C)	13 → 8	13 → 8	12 → 7
	Flow rate (m³/h)	39,3	66,5	106,4
Cooling Water	Temperature (°C)	31 → 36,5		
	Flow rate (m³/h)	85,4	135,1	227,0
Hot Water	Temperature (°C)	**95 → 80**	**95 → 72**	**95 → 55**
	Flow rate (ton/h)	**18,2**	**17,9**	**18,0**
Electricity consumption (kW)		2,6	2,6	5,1

In a real-world application, there is usually a constant stream of waste heat. Table 2 shows that there are different designs to suit different cooling requirements. It is worth noting that the cooling water requirements increase almost linearly to the cooling capacity. Electricity consumption is dependent on the pumps. Double-lift technology has more pumps, so the electricity consumption is higher.

Absorption chillers can also be tailored according to specific needs. Manufacturers may offer additional features such as auto purging, different types of tubing and chilled water from 5 °C. PID controllers and microprocessors enable safe operation of the absorption chiller, by making sure there is no crystallization taking place.

4.3 Crystallization

The crystallization of lithium bromide solution is a serious problem that must be acknowledged. Crystallization prevents the absorption chiller from working properly by blocking piping and therefore stopping the operation. If the maximum solubility limit of LiBr is exceeded, the salt component precipitates and starts forming crystals. There are three different factors that affect the solubility limit: solution concentration, solution temperature and pressure. The easiest way to prevent crystallization from happening is to monitor the solution concentration and to ensure it is always within safe limits. /15/

For optimal use of the absorption chiller, the concentration of the solution must be close to the critical concentration, but it should never exceed it. Figure 9 shows the optimal concentration for LG's absorption chiller. If the LiBr solution concentration is maintained between 54-64%, crystallization will not happen, and the operation remains efficient.

The crystallization is most likely to occur in the absorber, but it is possible to occur in the generator and the heat exchanger as well. Crystallization will start when the maximum solubility limit drops due to temperature, concentration or pressure change. If the solution temperature in Celsius (T) is known, the critical concentration (X_c) can be calculated with following formula: /15/

$$X_c = (0{,}0809 \cdot T + 61{,}341) \cdot \frac{1}{100\%}$$

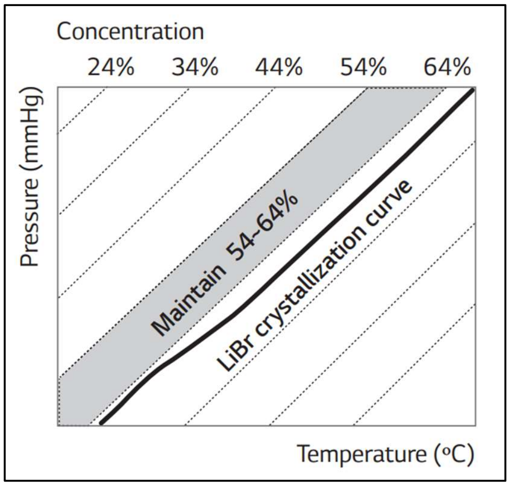

Figure 9. LG's LiBr Crystallization curve. /14/

Crystallization sets limitations for the absorption chiller. If the temperature of the cooling water is too low, the solution is cooled too much, and it will cause crystallization. A high temperature in the generator increases the efficiency, but too high a temperature will cause the solution to become too concentrated and causing crystallization. During a normal shutdown, an automatic dilution process happens. This process decreases the concentration of the solution. If this dilution fails for some reason, crystallization will occur. Preventing crystallization from happening is the key for economical and continuous operation. /16/

4.4 Steam Driven Absorption Chiller

A steam driven absorption chiller has a great cooling capacity if there happens to be suitable waste steam available. This is due to the specific enthalpy of vaporization of the steam. As steam condenses, it releases latent heat. Absorption chillers usually work with 0,5-9,0 bar(g) steam pressures. Steam at these pressures has around 2000-2200 kJ/kg energy in it (2226 kJ/kg at 1,5 bar(a) and 2014 kJ/kg at 10,0 bar(a)). /17/

A flow of 3660 kg/h at 0,5 bar(g), would have a specific enthalpy of vaporization of 2226 kJ/kg. A COP of 0,70 was used here to estimate the cooling capacity.

$$Q = \frac{3660 \frac{kg}{h} \cdot 2226 \frac{kJ}{kg}}{3600 \frac{kJ}{kWh}} = 2263{,}1\ kW$$

$$Q_{cooling} = 0{,}70 \cdot 2263{,}1 kW = 1584{,}2\ kW$$

Steam entering the generator must be dry steam. This can be achieved using a steam separator. A steam trap prevents steam from blowing through the separator into the condensate return system. Wet steam would cause erosion and lessen the chiller efficiency, so it is important to ensure that only dry steam enters the generator. /18/

If there is waste steam available and sufficient cooling or refrigeration needs, a steam driven absorption chiller has a very good potential to be the best chiller solution.

4.5 Absorption vs Vapor Compression Chiller

The following comparison is based on an absorption chiller and a screw compression chiller, both rated at 264 kW nominal power. Free waste heat is assumed to be available for the use of an absorption chiller. Figure 10 shows the estimated initial and annual costs for both chiller types. /14, 19/

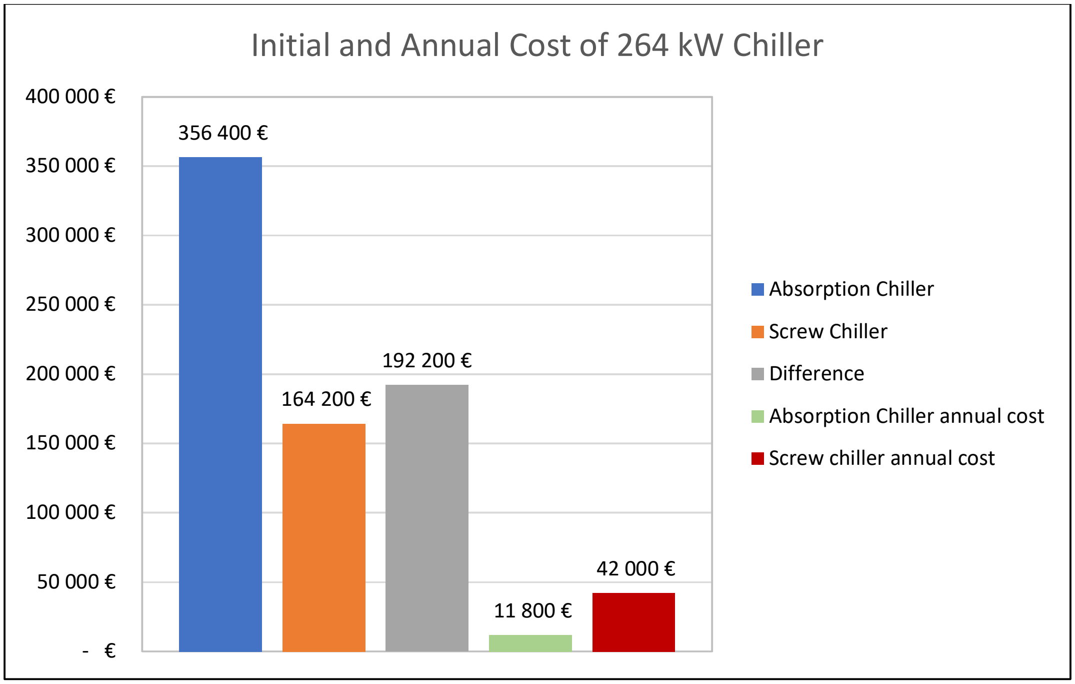

Figure 10. Absorption and screw chiller comparison.

Figure 10 shows that the absorption chiller has a higher initial cost, but the annual costs are significantly lower. The annual cost is highly dependent on the electricity price, which is assumed to be 0,12 €/kWh. The annual operation time is assumed to be 5000 hours. The annual cost consists of electricity cost and maintenance cost. Based on LG’s product catalogue /15/, this absorption chiller would require 16,7 kW of electric power. With the 5000 hours annual usage it would cost:

$$5000h \cdot 16{,}7kW \cdot \frac{0{,}12€}{kWh} = 10\ 020€$$

The absorption chiller maintenance cost is estimated to be 1,38 €/MWh.

$$\frac{(5000h \cdot 16{,}7\ kW)}{1000} \cdot 1{,}38 \frac{€}{MWh} = 1\ 822€$$

The total annual costs result in 11 842€.

For the compression chiller, the electric power requirement is 65,6 kW /18/. The maintenance cost is estimated to be slightly higher: 1,98 €/MWh.

$$5000h \cdot 65{,}6\ kW \cdot 0{,}12 \frac{€}{kWh} = 39\ 360€$$

$$\frac{5000h \cdot 65{,}6kW}{1000} \cdot 1{,}98 \frac{€}{MWh} = 2\ 611€$$

The total annual cost would be 41 971€. Figure 11 below shows the electricity price impact on the payback time. This is calculated based on the 5000 hours of annual usage. At the current assumed price (0,12 €/kWh) the payback would be 6,6 years. Inflation or discounted values are not included in the calculation.

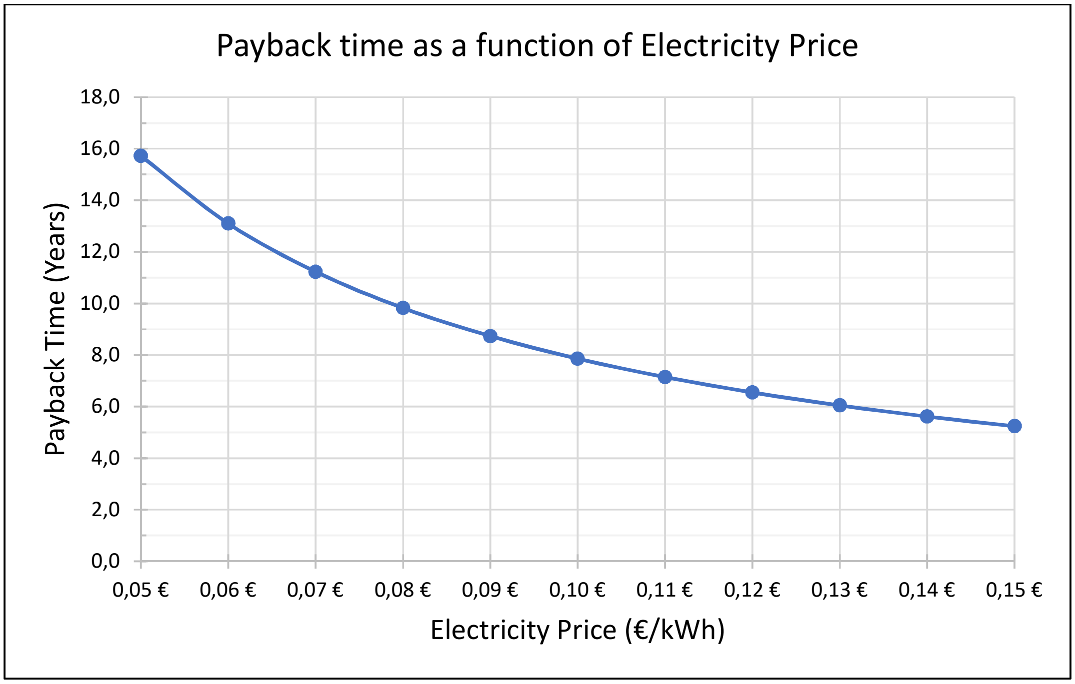

Figure 11. Payback time as a function of electricity price.

As this comparison is between small scale chillers, the absorption chiller still requires optimal circumstances to be viable. If the annual operation time and electricity cost are high enough, even a relatively small hot water absorption chiller could be feasible.

Based on Table 4, steam chillers would have a greatly reduced installation and maintenance cost per MWh, making those more economically viable. The electricity consumption of a similar sized vapor compression chiller would be much higher, making steam driven absorption chillers a desirable option.

4.6 Absorption Chiller Water Quality

Manufacturers generally state water quality requirement for their absorption chillers. LG has included a chapter for water quality in their product catalogue /14/.

Table 3. LG standard of water quality. /14/

Model	**Cooling Water**		**Chilled Water**		**Tendency**	
	Circulating	Make-up water	Circulating	Make-up water	Corrosion	Scale
pH (25 °C)	6,5-8,0	6,5-8,0	6,5-8,0	6,5-8,0	X	X
Electrical Conductivity (25 °C µS/cm)	< 800	< 200	< 500	< 200	X	X
Alkalinity (mg/L)	< 100	< 50	< 100	< 50		X
Total Hardness (mg/L)	< 200	< 50	< 100	< 50	X	
Chlorine Ion (mg/L)	< 200	< 50	< 100	< 50	X	
Sulfuric Acid Ion (mg/L)	< 200	< 50	< 100	< 50	X	
Total Ion (mg/L)	< 1,0	< 0,3	< 1,0	< 0,3	X	
Sulfur Ion (mg/L)	No Trace	No Trace	No Trace	No Trace	X	
Ammonium Ion (mg/L)	< 1,0	< 1,0	< 0,5	< 0,2	X	
Silica (mg/L)	< 50	< 30	< 50	< 30		X
Free Carbonic acid (mg/L)	-	-	< 1,0	< 1,0	X	

Different impurities in the cooling or chilled water cause corrosion and scales. Forming of slimes is another typical problem that may occur with low quality water. Water quality will degrade over time. Water evaporates during the process and salts are dissolved, therefore increasing the relative amount of impurities in the water. Make-up water has stricter quality requirements to keep the system water within safe limits. /14/

Corrosion can weaken the pipe walls and decrease the lifetime of the piping. Scaling, on the other hand, increases pressure losses in the pipe and reduces the flow capacity. There are different fouling mechanisms that cause scaling. Particulate fouling is a result from a sediment of dust, rust and fine solids. Crystallization fouling is mainly caused by calcium carbonate and it easily becomes a problem if the process involves heat transfer. As the water evaporates, the calcium carbonate concentrates. The level of concentration increases if the water evaporates multiple times. /20/

Biological fouling occurs when biological organisms grow on heat exchanger surfaces. Algae and barnacles may cause problems if the heat exchanger uses sea water to reject heat. These organisms can cause thick layers and affect the thermal performance. Chemical reaction fouling occurs when deposits are formed as a result of chemical reaction. Corrosion fouling is result from a chemical reaction that involves the pipe wall or heat exchanger surface area. /20/

The pH of the water is an important factor as well. The lower the pH, the higher the acid content of the water. Therefore, water with a low pH causes corrosion. Water with a high pH forces the calcium carbonate out of the water and causes scaling instead of corrosion. /20/

The hot water mass flows from a rendering process, which were used in Chapter 4, (3660 kg/h and 6200 kg/h) both have a pH of 9,0-9,5. There might be still a small number of solids left in the hot water. A relatively high pH is caused by ammoniacal nitrogen (NH_3-N). Ammoniacal nitrogen is present as free ammonia and as ammonium ions. These factors may cause problems, if the water cannot be purified.

4.7 Cooling Capabilities

One possible idea was to situate a meat cutting plant close to the rendering plant and use the cooling in the meat cutting plant. In Finland, 12 °C is the highest allowed temperature where the cutting takes place and storage spaces have different requirements, based on the product that is stored.

In Chapter 4.2 it was calculated that with a single-effect double stage absorption chiller, 236,4 kW cooling power could be achieved. This results from a poultry mass flow of 14000 kg/h.

In the best cast, one metric ton of poultry per hour would results in a cooling of:

$\frac{236{,}4\ kW}{14\ ton/h}$ = 16,9 kW or 57 630 BTU/h

There are many factors that contribute to the cooling requirements of the meat cutting plant. The physical size of the plant is the most important factor. Then come, for example, how well the plant is insulated, where the geographical location is, how much heat is generated inside the plant, how long the distance is between the rendering and meat cutting plants. As these factors are unique in each case, it is very hard to determine on a general level, if the given amount of cooling is sufficient.

5. CONCLUSIONS

Absorption chillers require very specific conditions to be feasible. There must be either a source of waste heat available or very expensive electricity and cheap natural gas to justify the investment of the absorption chiller. If these conditions are met, the absorption chiller can be a very attractive option compared to traditional compression chillers, as the maintenance and operating costs are lower. Absorption chillers do have a higher investment cost, but it should pay itself back in a reasonable time.

The waste heat must be evaluated on a case by case basis to determine if the resulting cooling is sufficient. If there is steam available, it is highly likely that the cooling will be sufficient as steam has a high amount of energy stored in it. Hot water must be hot enough and the mass flows must at least several tons per hour to achieve notable amounts of cooling on the industrial level.

It is important to distinguish the COP (coefficient of performance) between the absorption chiller and the compression chiller. The compression chiller COP indicates how much cooling is achieved with one unit of electricity. The absorption chiller COP is the ratio of received cooling from the released heat from the heat source. This is described more in-depth in Chapter 4.1.

An absorption chiller combined with a rendering plant is a great idea as there is generally a lot of waste heat available. When offering a rendering plant solution to the customer, the absorption chiller can be seen as an option in the preliminary phase. It adds value to the customer as the generated heat is not wasted. The main problem is most likely the hot water quality, as it may have solids and too high a pH. The manufacturer should be consulted to verify the optimal operation of the chiller. The absorption chiller also requires a cooling water tower, which might not be possible in every location.

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Table 1. Absorption chiller performance characteristics. Converted from imperial units and dollars to SI units and euros. /8/

	System						
	1	2	3	4	5	6	7
Design	Single Stage			Two Stage			
Heat Source	Hot Water		Steam	Steam (high pressure)		Exhaust Fired	
Nominal cooling capacity (kW)	180	1550	4640	1160	4640	1160	3520
Thermal Energy Input							
Hot Water Inlet Temp (°C)	88	98	-	-	-	-	-
Hot Water Outlet Temp (°C)	83	88	-	-	-	-	-
Steam Pressure (bar)	-	-	1	8	8	-	-
Exhaust Gas Temperature (°C)	-	-	-	-	-	277	454
Heat Required (kW)	250	2080	5890	820	3280	850	2550
Energy Output (chilled water)							
Inlet Temperature (°C)	12,2						
Outlet Temperature (°C)	6,7						
Cooling COP (full load)	0,70	0,74	0,79	1,42	1,42	1,35	1,38
Capital and O&M Costs							
Equipment Cost (€/kW)	452	214	189	274	230	306	214
Construction & Installation (€/kW)	898	315	226	417	276	454	246
Total Installed Cost (€/kW)	1350	529	415	691	506	760	460
O&M Costs (€/MWh)	1,38	0,46	0,23	0,69	0,23	0,69	0,23