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Refrigerants Used in Industrial Heat Pumps in the Future

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ABSTRACT

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The objective of this thesis was to study potential opportunities in the industrial heat pump market. More specifically, to find out what refrigerants will be used in industrial scale heat pumps in the future. Heat pump market is growing, and sustainable solutions are of increasing interest. It is important for Vahterus also to know where the market is heading to match the customer requirements. The study resulted with two different scenarios of the future.

The thesis introduces industrial scale heat pumps and provides an overview on design aspects and available technology on the market. Different types of refrigerants are introduced to the reader. Review of current legislation and regulation aspects affecting refrigerants are presented as a part of this study. Reader gets a basic understanding of the technology, market, and state of the industry.

Future studies section concentrated on scenario building. From futurology techniques, PESTE, futures table and scenario work were used. In addition to the general overview of the industry and factors affecting selection of the refrigerant, industry professionals were interviewed to get their outlook on the current state and possible future.

The outcome of the future studies was two scenarios for possible future, naturals only and natural and new synthetic refrigerants. Naturals only would lean towards complete phase out of synthetic refrigerants. Natural and new synthetic refrigerants would assume new development for synthetic refrigerants to be accepted in the market. Futurology is not an exact science and will not result to one absolute. Notable is also, that scenarios are not forecasts, they are alternative states of the future, which are all possible.

Keywords: heat pump, industrial, refrigerant, future, natural refrigerant, synthetic refrigerant, F-gas, PFAS, market, development, PESTE, futures table, scenario work

FOREWORD

I want to express my gratitude to Vahterus Oy for supporting my studies and enabling me to research the future of refrigerants. Special thanks deserve my immediate superior, Mr Heikki Oksanen and my thesis supervisor Mr Valtteri Haavisto, for the support throughout the process. I want to also recognise my thesis supervisor at SAMK, Mr Kimmo Kauko, for guiding and giving me useful advice along the way. I also want to thank all my interviewees, my family and loved ones and all my friends for their patience.

Rauma, March 2024

Johanna Reinvall

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LIST OF SYMBOLS AND TERMS

CFC	Chlorofluorocarbon
COP	Coefficient of Performance
ECHA	European Chemical Agency
EU	European Union
F-Gas	Fluorinated gases
GWP	Global Warming Potential
HC	Hydrocarbons
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IEA	International Energy Agency
ODP	Ozone Depleting Potential
PESTE	Analysis of Political, Economic, Social, Technological and Environmental factors in external environment
PFAS	Per- and polyfluoroalkyl substances
PSHE	Plate and Shell Heat Exchanger
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
TFA	Trifluoroacetic acid
UN	United Nations

1 INTRODUCTION

This thesis is done for Vahterus Oy, which is my employer. The company is a manufacturer of fully welded Plate and Shell Heat Exchangers (PSHE) and a major part of their business on refrigeration sector comes from heat pump applications. This study is a part of a larger research and development project. My role in the company is a Key Account Manager on Industrial Refrigeration team.

Vahterus Oy is a manufacturer of fully welded heat exchangers, which are especially suitable for heat pumps and the use of natural refrigerants. About 50% of the total business is in the refrigeration sector and heat pump applications are the fastest growing section on the market. Manufacturers in the refrigeration industry are developing components suitable for this growing demand. Heat exchangers are a major component of a heat pump and Vahterus manufactures fully welded heat exchangers on industrial scale. It is important for Vahterus to know where the industry is going and what are the preferred refrigerants in the future for their own development purposes.

The idea is to study rules and regulations affecting the selection of the refrigerant for heat pump systems, effect of use of chosen refrigerants on climate, what is happening in the industry at the moment, and what is likely to happen in the future. The main purpose is to find out potential opportunities in industrial heat pump market, whether it is going to be towards natural refrigerants or something else.

This thesis is concentrating on the industrial scale of equipment. It is not going to study use of refrigerants on commercial, small scale heat pumps; therefore, these will be narrowed out.

Basic functions of a heat pump and main components will be introduced on this thesis as well as an overview of the current legislation for refrigerants. However, the purpose of this study is not to go to in-depth analysis of these topics, but to concentrate on different scenarios what would be the likely future for the use of refrigerants.

This thesis will give the reader an overview of the current state of the industry, as well as introduction to possible future scenarios. The expected outcome of this project will be a prediction of future needs for heat pump applications, whether the market is going towards natural refrigerants or something else. This will help the company to adapt and develop their products to the right direction. Answer to this main question will either verify or possibly adjust the future planning.

1.1 Research problem, goals, and theoretical framework

Main goal of the study is to answer the question: What refrigerants will be used in the future to operate industrial size heat pumps. This will be achieved by first mapping history and current state of the industry, collecting information by interviews, applying different futurology tools, and finally coming up with scenarios for the future. The thesis has 4 major points of interest: concept of a heat pump, refrigerants, legal and regulatory aspects, and future studies.

Research approach is qualitative. Methods used in the thesis are literature review, semi-structured theme interviews, and selected futurology techniques. Expected outcome will be a prediction of future needs for heat pump applications in a form of scenario creation.

The thesis starts with an introduction in general and more detailed on industrial heat pumps, and why they are becoming increasingly important. This is mainly done by literature review. Following chapter will go more detailed into industrial heat pumps: what they are, why they are used and what are the deciding factors on design aspects. Next chapter is concentrating on different refrigerants used on industrial refrigeration and heat pump equipment, and the legislation related to the refrigerants. This is followed by a technology review. This background information is part of the input applied on the futurology tools. Overview of the current state of industry is studied by semi-structured interviews of industry professionals. The interviewees give their opinion on what is going on in the market, and what they see is likely to happen. Future research section chapter will give an introduction on the topic, and the techniques used. The tools used for the future studies are Peste, futures table, and scenario work. Applying the acquired information for the use these tools, the outcome is two possible future scenarios. Final part of the thesis combines the research with conclusions and gives an estimation of the possible and probable future scenarios.

1.2 The importance of heat pumps

There are two major reasons for the increasing interest in heat pumps: energy costs and growing concern of our environment. Treaties and regulations, like the EU F-gas Regulation, are steering the transition to more environmentally friendly refrigerants. Ongoing progress with the PFAS regulation is predicted to have even larger effect on the refrigeration sector. With the proposed regulation, most of the lower GWP refrigerant blends would be banned (Cooling Post, 2023).

Primary purpose of a heat pump is to generate heat. The heat can be utilised e.g., in air conditioning, central heating, district heating or steam generation. The heat source for a heat pump can be e.g., ground heat or process waste heat. (Aittomäki et al., 2012, pp. 336, 354-355) As fuel prices are constantly rising and the availability is going to be limited in the coming years, it is important for industrial sector to think about alternative solutions to generate heat and save energy. This can be achieved with the utilisation of heat pumps. As a basic example, by introducing a heat pump to a refrigeration system, water outlet temperature can be greater than the condensing temperature of the refrigerant.

1.3 Energy saving, heat recovery, green tech

A recent brief by UN states that the world is suffering in an unprecedented energy crisis. The whole world is affected by high and unstable prices, especially on fossil energy sources. (United Nations, 2022, p. 6) We all need to think on more sustainable way of working and living. Industries worldwide have taken this challenge and are developing new and improving existing technologies to green tech options.

In this situation, the international community must evaluate how to deal with the crisis to ensure targets set in the Paris Agreement to not exceed a rise above 1,5 °C compared to pre-industrial temperatures. The ways on how to achieve these targets can be divided into short-term, medium-term, and long-term operational principles and on all of which, immediate action is needed. (United Nations, 2022, p. 6)

On short-term actions, the most important measure would be to find ways to manage and steer energy demand. This is extremely important especially on developed countries where energy consumption is high. UN Brief suggests measures like deployment of new technologies and changing behaviour on how we use heating, cooling or how we take care of transporting goods and people. Energy efficient solutions and controlling or reducing demand, would have the fastest and most efficient interventions that can mitigate the short-term impact of energy prices. (United Nations, 2022, p. 6) In Finland, we have seen a large national campaign to save energy, Astetta alemmas, which translates to “one degree lower”. The main objective of this campaign was to ensure enough energy for everyone on the cold winter season 2022-2023. Finns were successful to save circa 4 terawatts of energy. The campaign is planned to be continued on autumn 2023. (Astetta alemmas, n.d.)

It is imperative that the medium- and long-term decisions comply with the Sustainable Development Goals and the Paris Agreement. This can be achieved by pushing the consumption further towards renewable energy sources and with investments to expand clean energy access through on-grid connections and decentralized, off-grid solutions. (United Nations, 2022, p. 7) Heat recovery and process optimization with heat pumps are one of the solutions that can be used to reduce waste heat and lost energy.

Further on the UN Brief, 6 policies were introduced to ease the crisis. For shorth term actions they are: “Countries, especially developed countries, must manage energy demand” and “Governments must identify and target vulnerable populations, to provide solutions for accessing and affording energy” (United Nations, 2022, pp. 9, 12).

For medium term actions there is one: “Governments must identify and address bottlenecks in renewable energy supply to foster clean energy and economic growth and leverage opportunities for a just transition” (United Nations, 2022, p. 15).

Long-term policies would be: “Governments must combat energy waste”, “Governments must strategize and regulate now, for the policy environment of tomorrow” and finally “Public, private and multilateral finance for the green energy transition must be scaled up” (United Nations, 2022, pp. 19, 21-22).

2 INDUSTRIAL HEAT PUMPS

The demand for heat pumps, both for small domestic and large industrial installations, has been growing steadily. They play a key factor on achieving the decarbonisation targets. For different plants, a heat pump is a great addition for energy saving, and it can also be used to improve processes.

2.1 What is a heat pump

Industrial heat pumps are usually based on the basic vapor compression refrigeration cycle, illustration shown below. On the basic refrigeration process, stage 1-2 stands for gas compression to the condensing pressure, stage 2-3 includes desuperheating and condensation on constant pressure, stage 3-4 includes expansion through an expansion valve to the low-pressure side and 4-1, evaporating to saturated vapor. (Stoecker, 1998, p. 55)

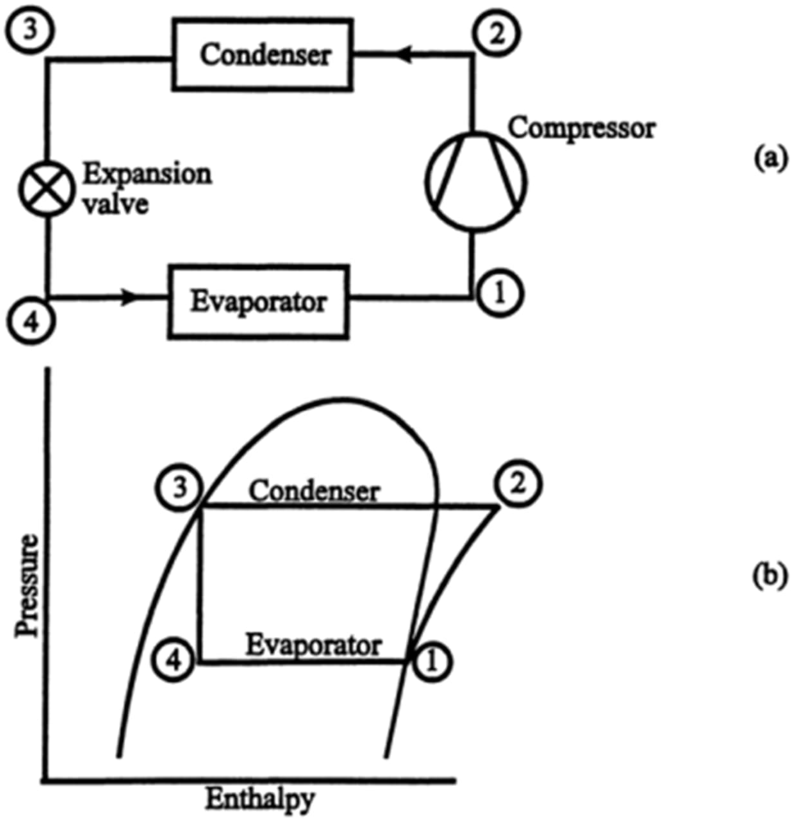

Figure 1: Standard vapor compression cycle with (a) the flow diagram, and (b) the pressure-enthalpy diagram (Stoecker, 1998, p. 55)

Heat pumps work in the same cycle, and by adding a desuperheater and a subcooler to the system, we can increase the COP of the system and get higher water temperatures than just on a single condenser as also shown on the below figure.

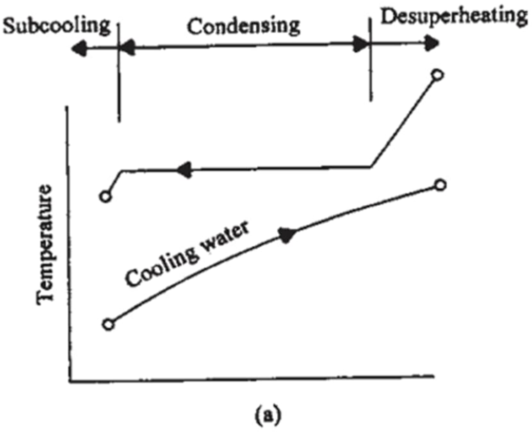

Figure 2: (a) Actual, and (b) idealized temperature profiles in a water-cooled condenser (Stoecker, 1998, p. 259)

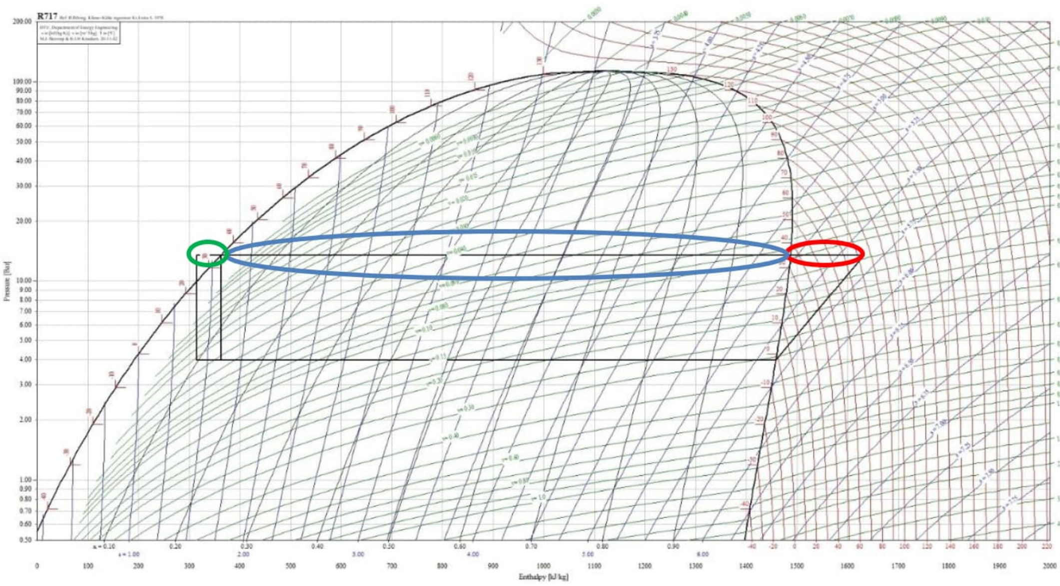

Figure 3: ph-chart for ammonia. System with and without subcooling.

The above figure 3, presents the refrigeration cycle and heat pump functions are marked with red, blue, and green. Red is desuperheating, blue condensation, and green subcooling. The effect of subcooling is also presented with two lines; first without subcooling and second with 10 K subcooling. Adding subcooling, evaporation capacity increases, and flash gas part is smaller. (Vahterus, 2021)

The efficiency of a heat pump can be determined by calculating coefficient of performance, COP, $\varphi = Q / W$. Theoretical limit would be $\varphi = T / T - T_0$. (Aittomäki et al., 2012, p. 5-6).

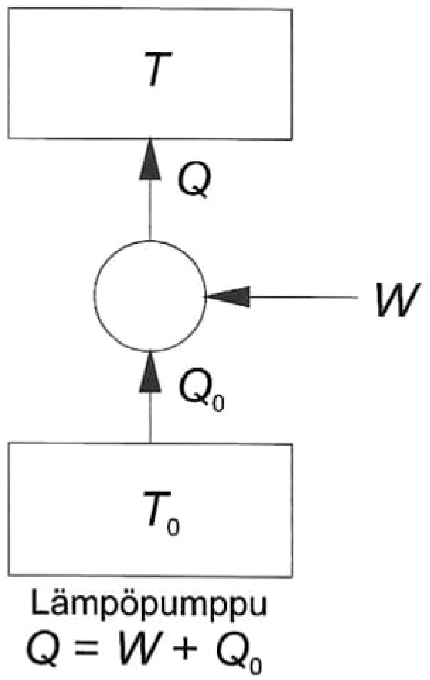

Figure 4: The principle of a heat pump (Aittomäki et al., 2012, p. 5)

Configuration of a heat pump system varies depending on the principal of operation and used refrigerant. As an example, ammonia heat pump would have a compressor, heat exchanger(s), oil separation and return, and various measuring and controlling devices, as well as leakage detecting equipment. Pressure class on ammonia operated heat pumps would be up to 63 bar. (Eckert et al., 2022, pp. 44-54, 81). On ammonia operated heat pumps, heat exchangers usually include evaporator, desuperheater, condenser and a subcooler or a combination of these, like the Multicondenser from Vahterus, which has the desuperheating, condensing and subcooling function on a single heat exchanger.

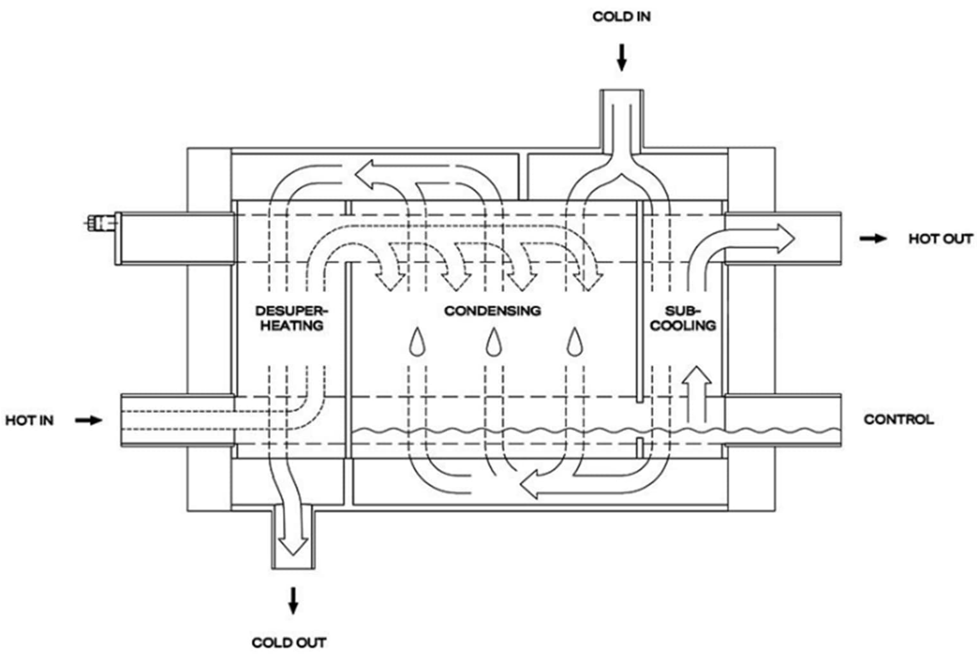

Figure 5: The Vahterus Multicondenser (Vahterus Oy, n.d.)

2.2 Why heat pumps are used

Heating homes and businesses worldwide still relies heavily on fossil fuels, like oil and natural gas. Our environment is at the point where increasing amount of greenhouse gas emissions forces us moving towards cleaner energy sources. As stated on a recent report of the International Energy Agency, heat pumps can provide sustainable and reliable heating and are the key technology for future heating. Potentially 500 million tonnes of carbon dioxide emissions could be reduced by 2030 by simply introducing heat pumps to processes. (IEA, 2022, p. 3) There is an anticipation for this development throughout the industry. From discussions and external communications, like press releases or LinkedIn posts, it can be seen, that a great deal of the companies working in cooling and heating, are developing their activities on heat pumps.

Especially in Europe, the current crisis in Ukraine is a large factor on diminishing the dependence of Russian gas. Heat pumps are proven to be cost efficient option and the interest worldwide is growing amongst consumers, businesses, and governments. They play a pivotal role on decarbonising heating of both space and water in buildings. (IEA, 2022, pp. 3, 17)

2.3 Thermal design and aspects

Industrial heat pumps, compared to domestic ones, run on higher demands on input and output temperature. Industrial processes are often complicated, and the equipment needs to be tailored to a specific use or need. Currently, heat pumps are mainly used in low temperature processes, meaning temperatures under 100 °C. However, recent developments allow output temperatures of even 150 °C and development is continuing to reach even higher temperatures. (IEA, 2022, p. 36) Sensing from discussion within the industry, generating process heat with heat pumps is likely to be a huge market in the future.

Heat pumps can be classified to two different types: open system and closed system. Closed system type is currently more extensively available and used in the industry. (Arpagaus et al., 2018)

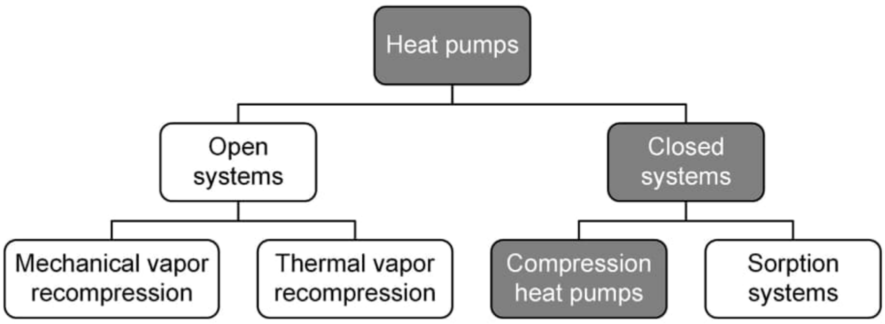

Figure 6: Classification of heat pumps (Arpagaus et al., 2018)

In their study of high temperature heat pumps, Arpagaus et al. also classify heat pumps to 3 classes: heat pumps, high temperature heat pumps and very high temperature heat pumps. (Arpagaus et al., 2018)

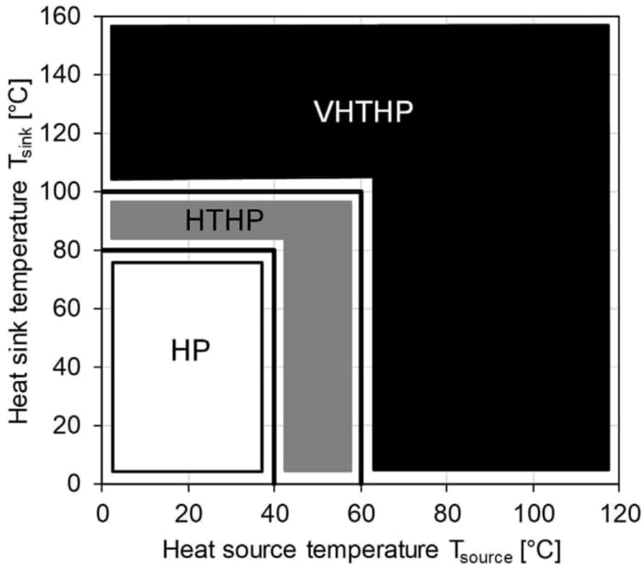

Figure 7: Development of temperature levels for compression heat pumps (Arpagaus et al., 2018)

Whether a heat pump or a (very) high temperature heat pump, selection of a refrigerant plays a pivotal role on the whole system design, from the system design pressure to compressor type. There are manufacturers with different factory-built solutions available for industrial scale equipment. Below figures, from review of Arpagaus et al., are illustrating the capacity and temperature range as well as refrigerants and compressor types available at the moment for (HT)HPs. New development projects amongst the manufacturers are on-going all the time, so this listing may well not be all-inclusive.

Manufacturer	Product	Refrigerant	Max. heat sink temperature	Heating capacity	Compressor type
Kobe Steel (Kobelco steam grow heat pump)	SGH 165 SGH 120 HEM-HR90,-90A	R134a/R245fa R245fa R134a/R245fa	165 °C 120 °C 90 °C	70 to 660 kW 70 to 370 kW 70 to 230 kW	Twin screw
Vicking Heating Engines AS	HeatBooster S4	R1336mzz(Z) R245fa	150 °C	28 to 188 kW	Piston
Ochsner	IWWDSS R2R3b IWWDS ER3b IWWHS ER3b	R134a/ÖKO1 ÖKO (R245fa) ÖKO (R245fa)	130 °C 130 °C 95 °C	170 to 750 kW 170 to 750 kW 60 to 850 kW	Screw
Hybrid Energy	Hybrid Heat Pump	R717/R718 (NH_3/H_2O)	120 °C	0.25 to 2.5 MW	Piston
Mayekawa	Eco Sirocco Eco Cute Unimo	R744 (CO_2) R744 (CO_2)	120 °C 90 °C	65 to 90 kW 45 to 110 kW	Screw
Combitherm	HWW 245fa HWW R1234ze	R245fa R1234ze(E)	120 °C 95 °C	62 to 252 kW 85 to 1301 kW	Piston
Dürr thermea	thermeco$_2$	R744 (CO_2)	110 °C	51 to 2'200 kW	Piston (up to 6 in paralle
Friotherm	Unitop 22 Unitop 50	R1234ze(E) R134a	95 °C 90 °C	0.6 to 3.6 MW 9 to 20 MW	Turbo (two-stage)
Star Refrigeration	Neatpump	R717 (NH_3)	90 °C	0.35 to 15 MW	Screw (Vilter VSSH 76 ba
GEA Refrigeration	GEA Grasso FX P 63 bar	R717 (NH_3)	90 °C	2 to 4.5 MW	Twin screw (63 bar)
Johnson Controls	HeatPAC HPX HeatPAC Screw Titan OM	R717 (NH_3) R717 (NH_3) R134a	90 °C 90 °C 90 °C	326 to 1'324 kW 230 to 1'315 kW 5 to 20 MW	Piston (60 bar) Screw Turbo
Mitsubishi	ETW-L	R134a	90 °C	340 to 600 kW	Turbo (two-stage)
Viessmann	Vitocal 350-HT Pro	R1234ze(E)	90 °C	148 to 390 kW	Piston (2–3 in parallel)

Figure 8: Selection of industrial HTHPs with heat sink temperatures above 90 °C (Arpagaus et al., 2018)

From this table, we can see the duality of development on the market. Part of the manufacturers offer solutions with synthetic refrigerants, and some are concentrating solely on natural refrigerants. Only one manufacturer has product for both types of refrigerants. From the manufacturers, 6 are using screw compressors, 6 are using piston compressors and 3 manufacturers have turbo compressors on their selection, one manufacturer using all the above.

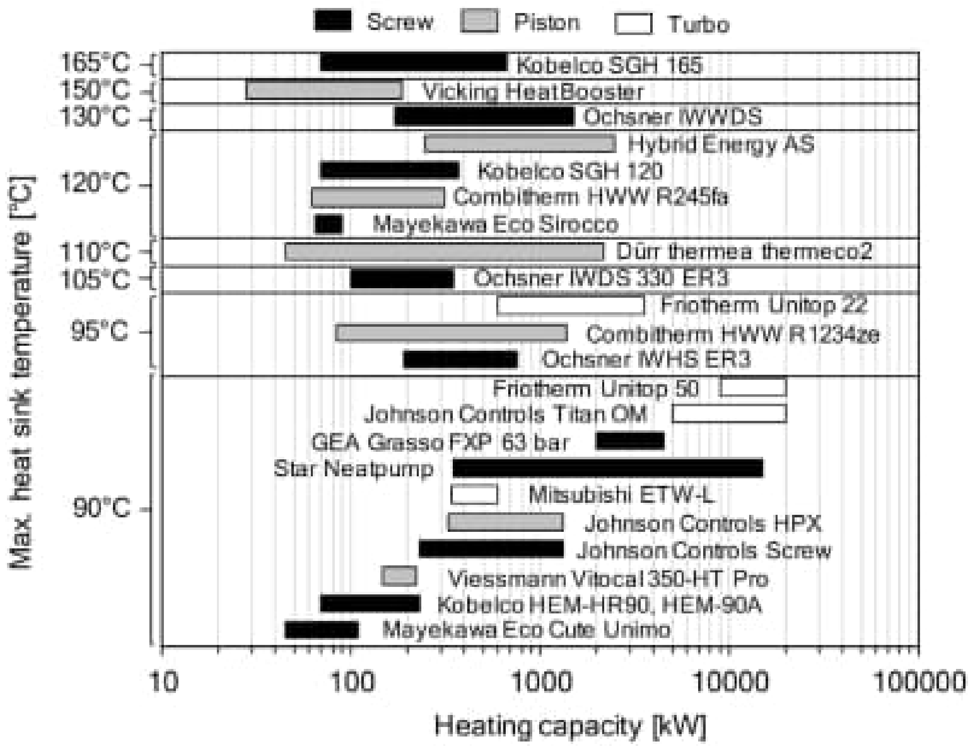

Figure 9: Commercially available industrial HTHPs sorted by maximum heat sink temperature and heating capacity. The implemented compressor types are color-coded (black: screw, grey: piston, white: turbo compressor). (Arpagaus et al., 2018)

3 REFRIGERANTS

A definition of refrigerant can be found e.g. on Kianta's book on refrigeration, Kylmätekniikan käsikirja. Refrigerants are liquified gases used on heat transfer in refrigeration cycle. The use of refrigerants allows heat transfer by their ability for phase change. Refrigerants change from gas to liquid when they release heat and from liquid to gas when they receive heat. (Kianta, 2013, p. 40)

Refrigerants can be classified in many ways. One common classification would be to divide the refrigerants into pure hydrocarbons (HC), hydrocarbon derived compounds where hydrogen molecules have been replaced with halogens, so called halocarbons or synthetic refrigerants (HFC, CFC, HCFC) and inorganic compounds. ASHRAE classification is based on letter R marking a refrigerant and series of numbers indicating the chemical composition of the refrigerant. (Aittomäki et al., 2012, p. 106)

3.1 Natural refrigerants

Due to harmful effects of synthetic refrigerants on the environment, natural refrigerants are increasingly more attractive to use. Natural refrigerants include media like air, water, ammonia, hydrocarbons, and carbon dioxide. Some of the most used hydrocarbons in this refrigerant group are propane, butane, isobutane, and propylene. Ammonia or NH3 (R717) is one of the first media used for refrigeration purposes in history. First cooling units with ammonia were introduced in the 19^{th} century. (Aittomäki et al., 2012, pp. 116-121)

3.1.1 Ammonia (NH3, R717)

The thermodynamic properties of ammonia are exceptional compared to alternative refrigerants. High specific heat capacity allows high heat transfer coefficient on condensation and evaporation. It is widely used in food industry and also NASA is using it in applications on space. (Eckert et al., 2022, p. 3) On heat pumps, ammonia is a good solution up to about 90 °C output. On higher temperatures, design pressures rise above 60 bar.

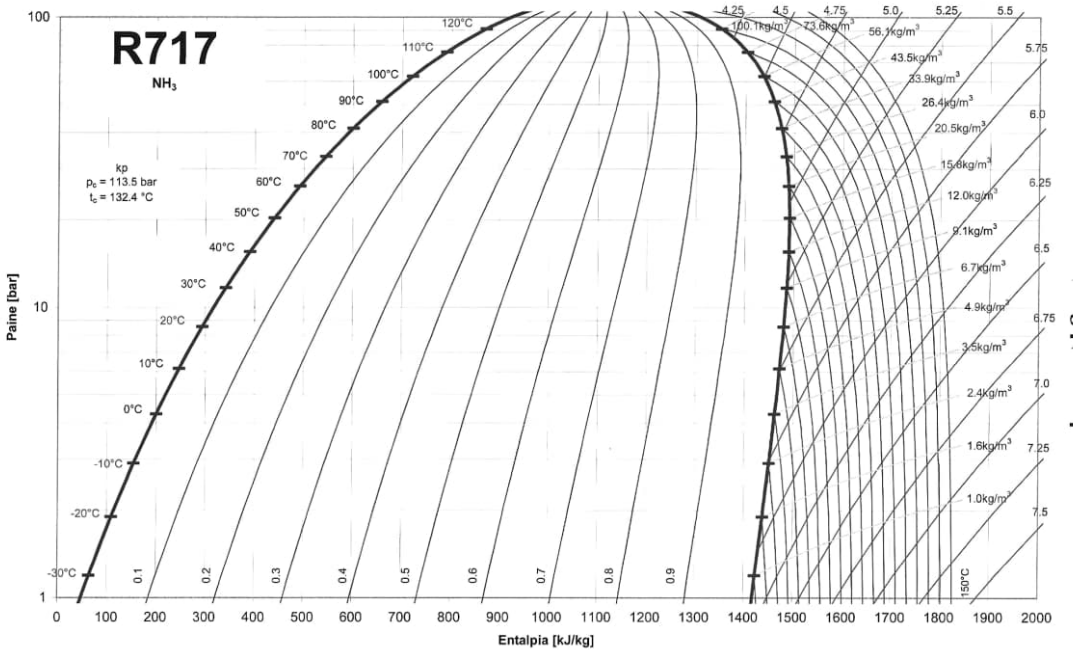

Figure 10: R717 (ammonia), log pH diagram (Aittomäki et al., 2012, p. 398)

3.1.2 Carbon dioxide (CO2, R744)

Another old natural refrigerant is carbon dioxide (R744). It has been historically used especially on ship refrigeration systems. It has rather high pressure requirement for the system and low critical temperature. Transcritical systems are widely used on commercial refrigeration, like in supermarkets. (Eckert et al., 2022, pp. 4-5) The benefits for CO2 include it being non-toxic and not flammable. It is also very cheap and completely harmless to nature. (Aittomäki et al., 2012, pp. 121-122)

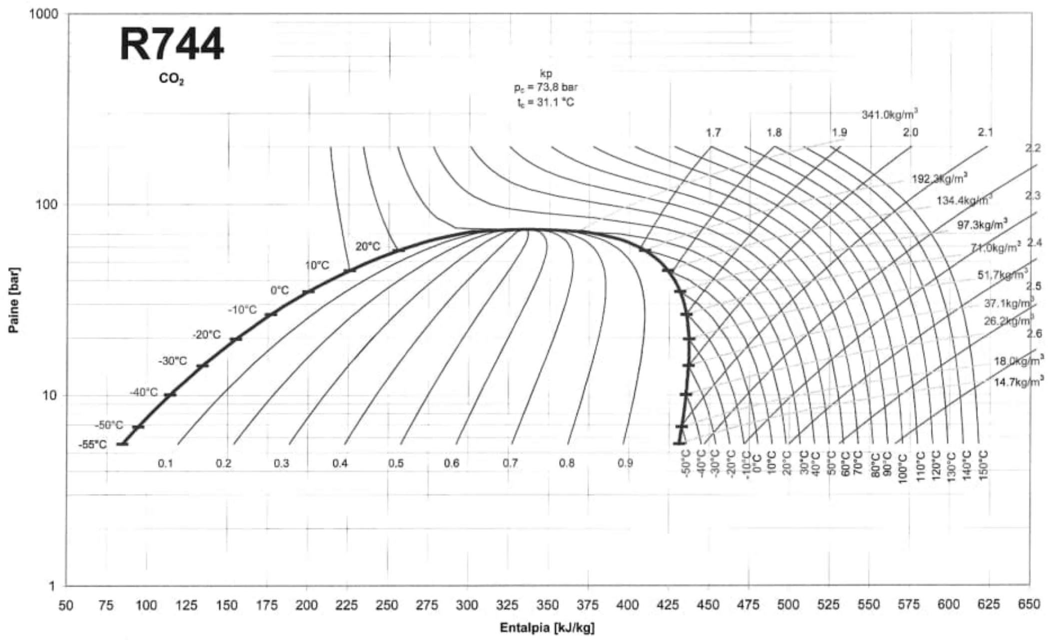

Figure 11: R744 (carbon dioxide, CO2), log pH diagram (Aittomäki et al., 2012, p. 399)

3.1.3 Water (H2O, R718)

Water as refrigerant would be the ideal solution for environment. It is efficient, it is not toxic, and it does not burn. Water has one of the highest specific heat capacities (4.2 kJ/kgK) and its thermal conductivity is 0.6 W/(m*K) at 20 °C. However, refrigeration systems are more volume than mass specific and, in that respect, water has a disadvantage with volumetric cooling capacity being only 12 kJ/m^3 at 0°C. Water also freezes at 0°C and refrigeration systems with water can only be operate above this temperature. For high temperature heat pumps, water is a promising refrigerant. In higher temperatures and pressures, the disadvantages have less impact. (Eckert et al., 2022, pp. 7-8)

3.1.4 Hydrocarbons (HCs)

Hydrocarbons are very attractive options as refrigerants. They have no ozone-depleting potential and minimal global warming potential. Propane and butane have been used since the beginning of the 1900s. As a refrigerant, most interesting hydrocarbons are ethane, propane, n-butane, isobutane, and propene (propylene). (Eckert et al., 2022, pp. 179-180) Hydrocarbons are soluble to widely used mineral oils, therefore being an attractive alternative amongst refrigerants. A downside on the hydrocarbons comes from their high flammability. Different laws and regulations limit the size of the installation and filling. (Aittomäki et al., 2012, p. 120)

Ethane (R170) and Ethylene/Ethene (R1150) are both good choices as a refrigerant and especially suitable for very low temperatures, below -50 °C. (Baha et al., 2022) These refrigerants are more suitable for cryogenic cooling applications and not so much on heat pump use.

Propane (R290) is non-toxic, affordable, and stabile refrigerant. (Aittomäki et al., 2012, p. 120) Propane systems operate on similar pressures and cooling capacities as e.g., earlier widely used R22, but with significantly smaller refrigerant fill. (Hakala & Kaappola, 2007, p. 25)

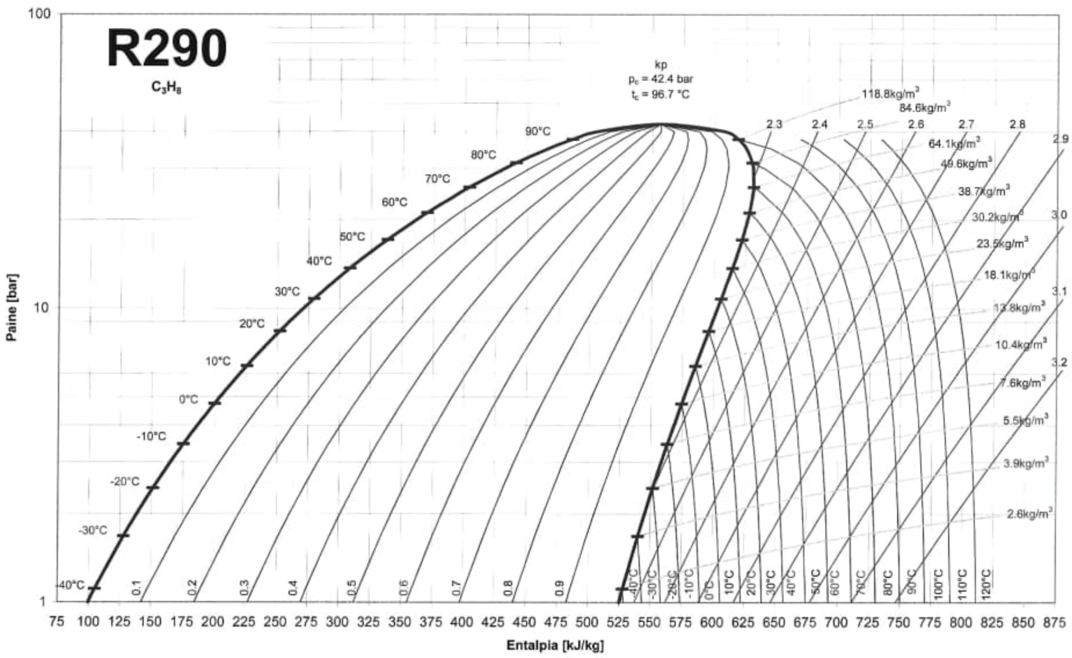

Figure 12: R290 (propane), log pH diagram (Aittomäki et al., 2012, p. 400)

Butane/n-butane (R600) and Isobutane (R600a) are both attractive options to R134a. Operating pressures are low or on vacuum. (Aittomäki et al., 2012, p. 120)

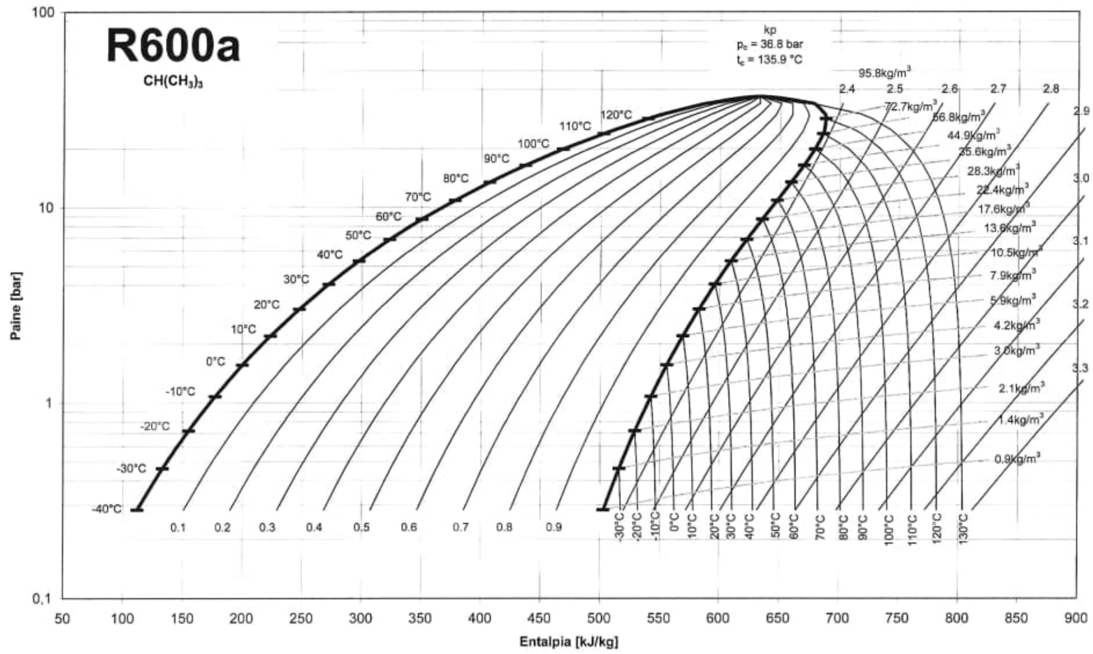

Figure 13: R600a (isobutane), log pH diagram (Aittomäki et al., 2012, p. 401)

Propylene/Propene (R1270) can be used to replace synthetic refrigerants as R22 or R502. Propylene systems are operated on slightly higher pressures as propane systems. (Aittomäki et al., 2012, p. 121) Similar to propane systems, propene systems operate on similar pressures and capacities as R22, but with less amount of refrigerant in the system. (Hakala & Kaappola, 2007, p. 25)

Pentane (R601) is a natural refrigerant with very low GWP and no ODP. The critical temperature of pentane is 196.6 °C at 33.7 bar. (Arpagaus et al., 2018, p. 18) Due to its properties, pentane could be an interesting option for high temperature heat pumps generating steam.

3.2 Synthetic refrigerants

Synthetic refrigerants include CFCs, HCFCs, HFCs, HFOs and HCFOs. CFCs (chlorofluorocarbons), commonly also called freons, have already been banned due to them being extremely harmful to the environment and ozone layer. This classification of refrigerants include media such as R11, R12 and R502. (Hakala & Kaappola, 2007, p. 23)

HCFCs (hydrochlorofluorocarbons) are also harmful to the ozone layer and have been banned. This group of refrigerants include e.g., R22 and R401A. (Hakala & Kaappola, 2007, p. 23)

HFCs (hydrofluorocarbons) are harmless to ozone layer and include refrigerants e.g., R134a and R404A. (Hakala & Kaappola, 2007, p. 23) Whereas HFCs are not a threat to the ozone layer, they were proven to be accelerating the global warming and thus were later heavily regulated on installations. (Eckert et al., 2022, pp. 1-2)

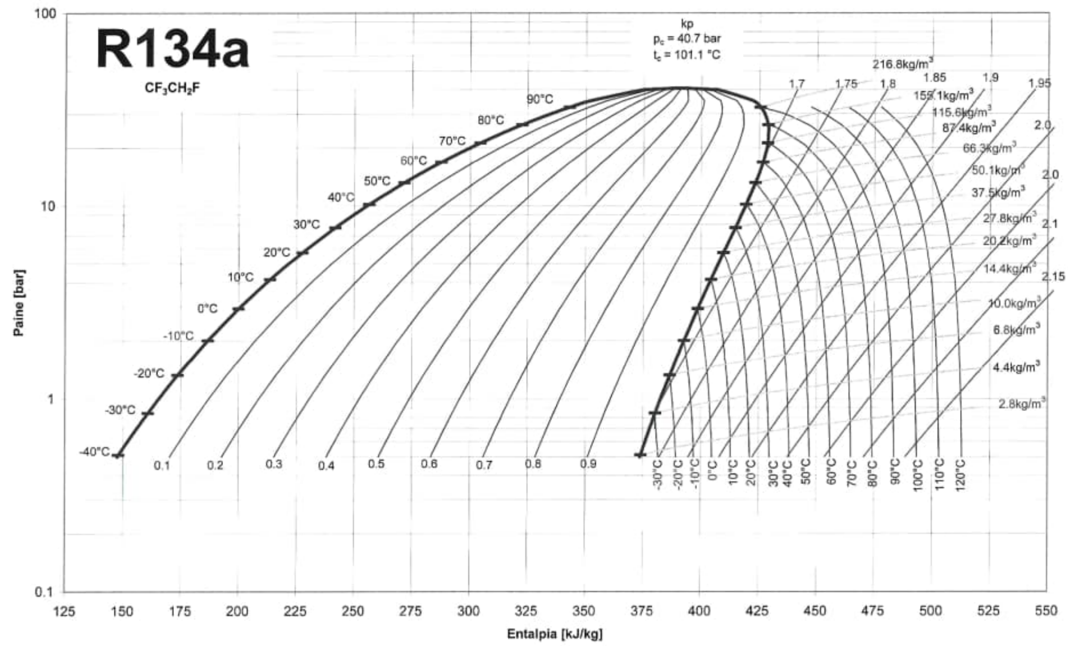

Figure 14: R134a, log pH diagram (Aittomäki et al., 2012, p. 402)

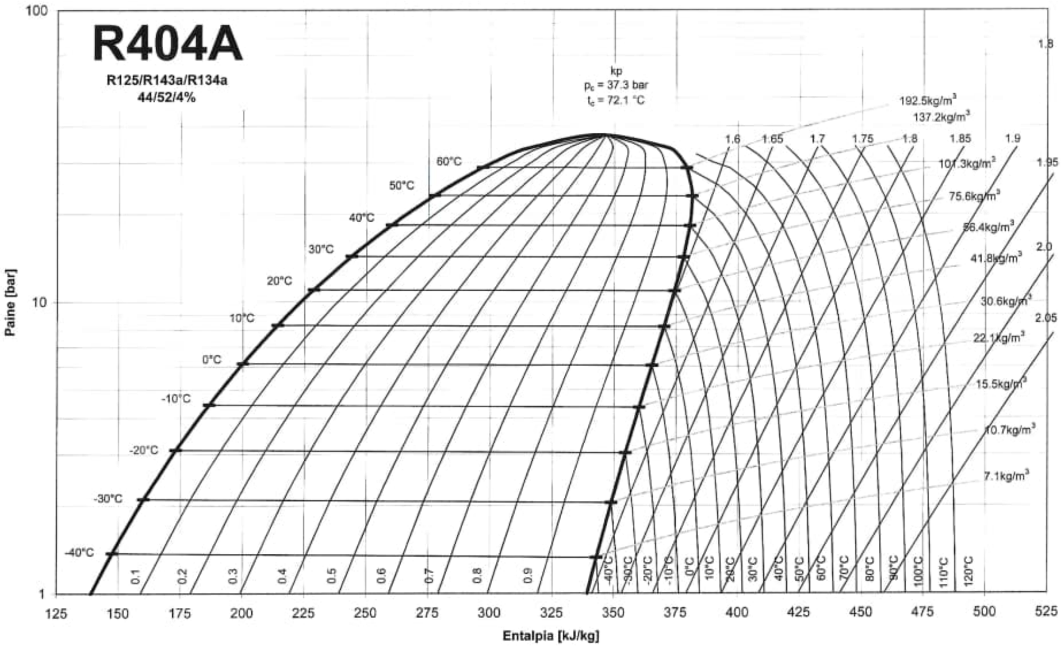

Figure 15: R404A, log pH diagram (Aittomäki et al., 2012, p. 403)

Next development on the synthetic refrigerant industry were the HFOs (hydrofluoroolefins), like R1234yf. Issue with the HFOs is with their quick disintegration to the atmosphere, creating TFA (trifluoroacetic acid) on certain weather conditions. TFA is so called forever chemical, it does not disintegrate naturally and cumulates to water. (Eckert et al., 2022, pp. 1-2) Also R1234ze(E) and R1336mzz(Z) are used on heat pump applications. (Arpagaus et al., 2018) HCFOs (hydrochlorofluoroolefins) include refrigerants such as R1233zd(E) and R1224yd(Z). (Arpagaus, 2019, p. 81)

Synthetic refrigerants have been subject to restrictions and bans but are still widely used also on new installations. Recent development with the F-gas regulation and PFAS restriction will make new installations and service of systems with synthetic refrigerants very challenging. Overview on the current status and development on the legislation will be introduced on the next paragraph.

3.3 Legislation related to refrigerants

Montreal Protocol is the most important environmental agreement affecting refrigerants. It was signed in 1987 and universally ratified. It is regulating and controlling the production and usage of ozone depleting substances (ODS). First affecting the production and usage of and finally phasing out CFCs and HCFCs. With the Kigali Amendment in 2016, the Montreal Agreement included also HFCs. (United Nations Environment Programme, n.d) Even though HFCs are not ozone-depleting substances, they were added in the Kigali Amendment due to their impact on the climate. (European Commission, 2023)

Another major factor on the field of refrigeration, is the EU F-Gas regulation and its new revision. Originally ratified 2015, F-gas regulation is in the process of a significant update. Aim of the new legislation is to further reduce greenhouse gas emissions from fluorinated gases (F-gases) and ozone depleting substances (ODS). The new regulation will help on the targets set for 2030 and finally enable climate-neutrality by 2050. The new regulation on F-gases will tighten the quota system for the HFCs, restrict the usage of said substances, restrict trade on used equipment operated with HFC refrigerants, ensure compliance with the Montreal Protocol and its amendments, and create new opportunities for environmentally friendly equipment on the market. New measures are also taken to prevent the usage of any ODS on still available and permitted products. The agreement still needs to be formally ratified by the European Parliament and Council. Once this process is completed, the regulation will be in force. (European Commission, 2023) Recent news in February 2024 inform that the revised F-Gas regulation is now law. As from 20th of February 2024, it is published in the Official Journal of the EU and the law will be effective from 11th March 2024. (Trevisan, 2024)

Overview of historical milestones on regulation affecting refrigerants can be seen on the following illustration.

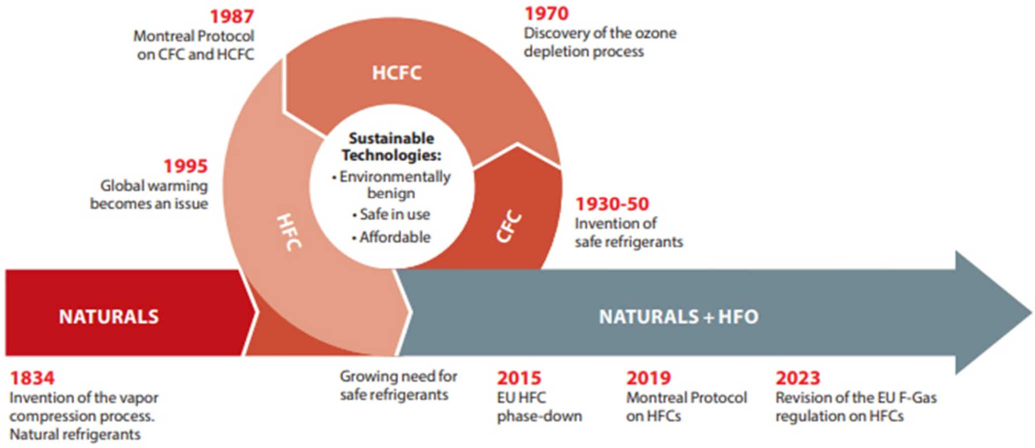

Figure 16: The historical cycle of refrigerants (Danfoss, 2023)

On January 2023, authorities in Denmark, Germany, the Netherlands, Norway, and Sweden submitted a proposal to European Chemical Agency, ECHA, to decrease PFAS emissions to the environment. ECHAs committees did a compliance check against REACH, and the proposal was later released for an open consultation for a six month period. (ECHA, 2023)

Figure 17: Timeline for the steps on the proposal (ECHA, 2023)

PFAS are per-and polyfluoroalkyl substances. PFAS are very durable substances and propose a significant threat for health and environment unless they are limited. It is estimated that ca. 4.4 million tons of PFAs will end up in the environment over the next 30 years if nothing is done to prevent this. (ECHA, 2023) PFAS include synthetic refrigerants, such as R134a, R125 and low GWP HFOs R1234yf, R1234ze(E) and R1233zd(E). (Cooling Post, 2023)

HFOs disintegrate into the atmosphere, creating TFA (trifluoroacetic acid) on certain weather conditions. TFA does not naturally disintegrate and cumulates to water, it is a so-called forever chemical. (Eckert et al., 2022, pp. 1-2) In addition to refrigerant selection, a full-scale ban for would also have a significant effect on equipment manufacturing as some of the sealant material e.g. on valves and compressors include PFAS.

Heat pump market is one of the highest growing markets and due to the shift on the legislation, there is a certain anticipation on what the decision in the EU will be regarding the refrigerants. In case the wide ban of refrigerants is adopted on full scale, that would mean replacing or transforming huge amount of refrigeration and heat pump system installations with new or retrofitted equipment.

4 INDUSTRIAL HEAT PUMPS, TECHNOLOGY

Requirements for heat pumps are different to the refrigeration plants. The main components are similar, but e.g. the design pressures are higher, depending on the selected refrigerant. There are both customized and ready-made packages available on the market and new developments especially for higher temperature range are ongoing.

4.1 Available technology

In addition to the refrigerant, main components of a heat pump are condenser, evaporator, compressor, and expansion device. (Arpagaus, 2019, p. 18) There are multiple manufacturers offering plug-and-play solutions, for easy integration of a heat pump. From large compressor manufacturers, Johnson Controls/Sabroe, GEA and Mayekawa, all have their own solutions. (Arpagaus et al., 2018)

Independent contractors provide solutions made with variety of components. Suitable heat exchangers for heat pumps you can get e.g. from manufacturers like Vahterus or Alfa Laval. Danfoss and Hansen Technologies, among others, provide valves and control devices for different refrigerants. Industrial scale compressors you can get from e.g. GEA, Sabroe or Vilter. Above mentioned companies are not an extensive list to all manufacturers worldwide, but more of an introduction on what is available on the market. This information can be found by a simple internet search.

Currently there are new developments and ideas on design or prototype stage with multiple companies, even more on the high temperature heat pump side. Hydrocarbons are of big interest, but some parties are still concentrating on the newly developed synthetic refrigerants like R1336mzz(Z) or R1234 ze(Z). (Arpagaus, 2019, pp. 50-52)

4.2 What is required from the equipment using natural refrigerants

With NH3 being dangerous substance, its use as a refrigerant and filling of the installation is restricted. Special design and additional safety measures are needed in the machine room, such as leak detection sensors and emergency ventilation. (Eckert et al., 2022, pp. 3-4) Due to its properties, the equipment on heat pump installations with NH3 needs design pressure from 40 bar up to 65 bar. Fully welded construction, like the PSHE from Vahterus, provides additional safety.

The operation pressure of CO2 installations is very high, this needs to be properly taking into consideration on planning. Standstill situations may increase the pressure dangerously high. CO2 is also heavier than air, it cumulates to the bottom of the machine room, or bottom level of a multistore building, and proper detection system and ventilation is needed. (Eckert et al., 2022, p. 100) For high temperature heat pumps, transcritical CO2 is very attractive option. (Arpagaus, 2019, p. 82)

Water is natural, safe, and harmless to the environment. It is especially attractive for temperatures above 150 °C. Typically vapor recompression systems are operated with turbo compressors. (Arpagaus, 2019, pp. 81-82)

System components for hydrocarbons are currently well available and are somewhat the same as used for fluorocarbons. (Eckert et al., 2022, p. 194) N-butane (R600) and pentane (R601) are quite a good match to heat pumps. They are environmentally friendly and have high critical temperatures (152 °C and 196.6 °C) with moderate operating pressure (38 bar and 33.7 bar). Standard range of compressors can be used with these refrigerants. Flammability of the refrigerants adds some safety precautions to the system design. (Arpagaus, 2019, pp. 82-83) Propane (R290) has a critical temperature of 96.7 °C and pressure of 42.4 bar. (Aittomäki et al., 2012, p. 402) This makes it suitable for standard temperature range heat pumps.

4.3 What is required from the equipment using synthetic refrigerants

Solutions by manufacturers like e.g. Kobe Steel, Combitherm or Viessmann, rely on factory made packages with synthetic refrigerants like R134a, R245fa or R1234ze(E). R134a and R245fa will be phased down on the near future. R1234yf, R1336mzz(Z), R1234ze(E) and R1234ze(Z) are considered low GWP options to replace R134a and 245fa. R1336mmz(Z) has high critical temperature (171.3 °C) with moderate pressure of 29 bar. R1234ze(Z) has critical temperature of 150.1 °C in 35.3 bar. (Arpagaus et al., 2018) As earlier stated, even though HFOs do not have high GWP, they are facing restrictions due to being PFAS.

5 OVERVIEW OF THE INDUSTRY

There is a large change going on in the field of industrial refrigeration. Numerous of widely used refrigerants are in a risk or even probably facing phase out in the near future. The situation is followed closely by the companies and the players are all thinking on their next move, where to go next.

5.1 Interviews: state of the industry and ideas on the future

For this study, I interviewed 7 proficient persons on the refrigeration and heat pump industry. Method for the interview was semi-structured theme interview, and altogether 3 topics were discussed with every interviewee. The geographical distribution of the interviewees was 4 in Europe, 1 in Africa, 1 in Americas and 1 in Asia-Pacific region.

The topics discussed were:

1. How do you see the situation with refrigerants on heat pumps currently? Which refrigerants are you and / or your customers working with? What is happening in industry at the moment?
2. How do you see the near future developing? Based on your knowledge on the market, which refrigerants would you expect to be used in the future?
3. Any open comments?

All the responses indicated that the industry is facing a drastic change, even if the regions are on different stages on adopting the heat pumps as a technology. Demand is increasing and laws and regulations are steering towards energy saving, and sustainable options on refrigerants. There are still some synthetic refrigerants widely used, but the industry is changing. Many multinational corporations are specifying their procurement instructions on the favor of natural refrigerants.

Based on their comments, the respondents think that natural refrigerants will be the future. However, Europe is the leader on this development and Americas, Asia-Pacific, and Africa are gradually getting to the stage where the mindset will be towards more sustainable options.

The respondents see that the demand in the industry is going towards higher and higher temperatures on heat pumps and there is growing interest on generating steam with refrigerants. Common opinion was also that the market has a growing need for easy installation, in the form of factory-made packages.

The respondents see that the heat pump market is one of the highest growing markets in the industry. Now, the market is waiting for concrete decisions on to what extent and with what timescale the ban is going to be realized.

When we take in detail a market like Switzerland, it is already very saturated with heat pumps and the national legislation has pushed companies and people to get rid of e.g., burning oil. Also in that market, on top of the national legislation, they are waiting for the decision on the F-gas and PFAS what direction to go to.

Whilst ammonia is widely used in industrial scale heat pumps, is not the best option for temperatures above 90 degrees Celsius. On that temperature range, the respondents see that the industry will have to go towards flammable options, like propane or butane. This on the other hand, will bring some challenges on the filling of the system as well as servicing.

Ammonia has been used on heat pumps for several decades already. The respondents see ammonia still as a strong option on the market. The downside on ammonia is rather high pressures on higher temperatures.

Other hydrocarbons, like propane (R-290) and isobutane (R600a) would be more suitable for high temperature heat pumps. With propane and butane, water outlet temperature of 100 degrees Celsius can be reached with reasonable pressure, whereas with ammonia, to reach 90 degrees Celsius, you need 60 bar design pressure for the equipment. Pentane could be used to reach temperatures on the scale of 150 degrees Celsius water outlet.

CO2 is also suitable for heat pumps, and companies like MAN, are investing on developing packages for large scale heat pumps with CO2.

The experts feel that even though heat pumps are in rapid growth, the demand of steam generation will be multiple compared to the demand of heat pumps in the future. When countries are phasing out on burning oil and gas, you need alternative solutions to generate steam for process use and district heating.

Still there are lot of installations and new projects with HFCs like R507a or HFOs like R1234yf, especially on other parts of the world than Europe. As an example, in the Americas, there is interest on heat pumps, but the market is not there yet. The industry will lead the development there and not the laws. Also, energy saving does not play such a big role yet on worldwide scale. Where fuel prices are low, the need for energy saving is not as big factor as in the regions where oil and gas are expensive.

6 FUTURE

Futurology is not an exact science and does not result to the only truth. However, certain patterns apply: One cannot predict the future. It is also not predestined in any way. Future can also be affected by choice and action. In this sense, the emphasis is on imagination, analysis, and participation. What is possible, probable, desirable, and executable. (Meristö, 1991, p. 22)

6.1 Introduction on the futurology techniques

Methods for futurology, or future research, can be classified in several ways. Qualitative and quantitative, analytical, expert, and communicative methods are all examples of different ways to gather information and study the future. They are all tools of the process on foresight, how to predict the future. Stages of the foresight process being information gathering, analyzing, and editing the information, building alternative futures, and evaluation and selection of the alternative futures. (Kettunen & Meristö, 2010, p. 18) These four stages, and examples of different methods used in them can be found on the below illustration, which I have translated from Finnish to English for the reader.

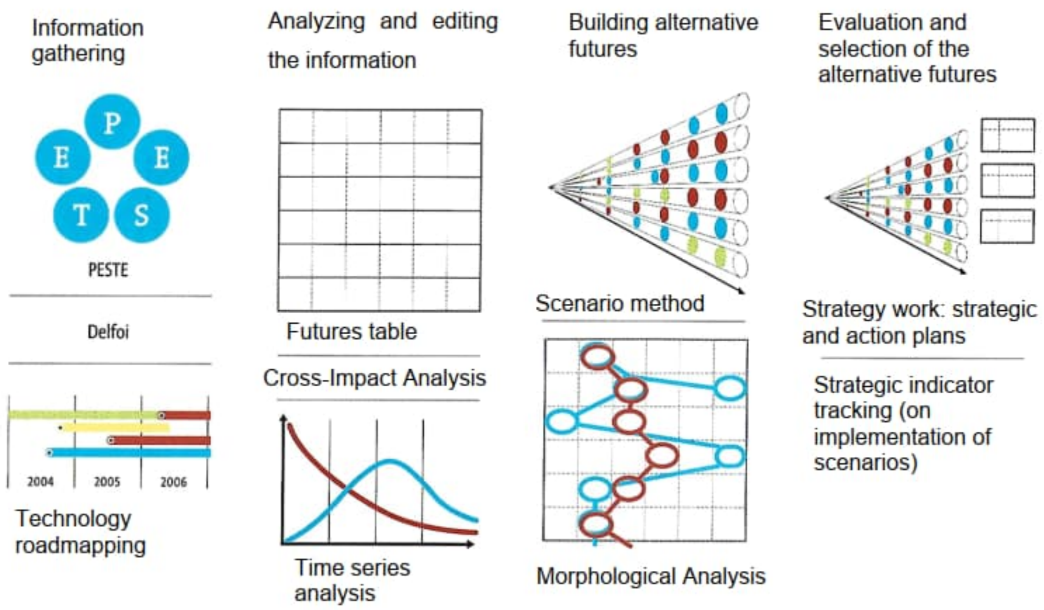

Figure 18: The stages of foresight process. (adapted from Kettunen & Meristö, 2010, p. 18)

In my study, I am concentrating on the stages of information gathering, and sorting and analyzing data. I will also create a possible future scenario, but the strategic decisions will be done by the management of the company. From the introduced methods, I have chosen PESTE and Futures table for tools to gather, sort and analyze data. For alternative future modeling, I will use Scenario method. Semi-structured theme interviews with industry professionals were also an important part of the data gathering.

PESTE analysis is a tool intended for mapping the external impact of defined factors to an organization's operations. PESTE is an abbreviation for Political, Economic, Social, Technological and Ecological. The idea for this method is to end up with a structural definition of dynamics for all the abovementioned factors and their effects. It is used as a tool on strategic decision making, as it makes the information more structured and easier to perceive. (Vuorinen, 2013, p. 220) In my study, PESTE analysis is suitable tool for structuring the data for further analysis.

Futures table is a method widely used on future studies. It is quite effective way of sorting and analyzing data. It gives an overview of possible situation(s) in the future. It consists of different variables and their possible and probable outcomes in the future. (Mannermaa, 1999, pp. 92-93) Futures table gives the basics for scenario building. Basic idea is to list factors, which are essential for creating an overview of the possibilities of the future. Each factor will further be divided into variety of possible outcomes on the other axis of the table. Completed table is a visualization of the different possibilities of the future. (Kamppinen et al., 2002, pp. 123-124)

Scenario is a hypothetical series of event, that has been formed into processes and phases important to decision making. Scenarios will define how a hypothesis can play out step by step, and what possibilities the involved parties have on either preventing, directing, or advancing the process. (Kamppinen et al., 2002, p. 120) Scenario describes chain of possible events in the future. It is not about predicting, but more mapping how things could progress. Scenarios will help the leadership on strategic decision making. There are two possible approaches, explorative and targeted. Explorative method studies the trends of the past and present and continues the development to possible future trends. Targeted (normative) method is based on vision of the desired outcome and it is built from the future vision to the present time. Targeted method aims on enabling transition from the present to the desired future. (Vuorinen, 2013, pp. 109-111) My approach in this thesis is explorative, based on facts and trends in the past and present.

Scenario work is a process, and the strategic decisions that follow, will be done by the management of the company. For successful execution, Meristö is suggesting that the following facilities are realized: The management needs to be part of the scenario work process. The project needs enough time and resources for managing data. Imagination and creativity need to be applied, so that both qualitative and quantitative material can be acquired and utilized. Scenario work should precede the strategic work. One should also remember that scenarios are not forecasts, they are alternative states of the future, which are all possible. (Meristö, 1991, p. 164)

6.2 Foresight on the future

The main theme of this thesis is to get an overview of possible future scenarios on refrigerants used in industrial heat pumps. Further to use for prediction of future needs for heat pump applications, depending on if the market is going towards natural refrigerants or something else.

For the background I have been mapping the history and current situation in the overview on earlier sections of my thesis. Background information and introduction is a vital part of better understanding the factors affecting the foresight process.

6.2.1 PESTE

First, I will use PESTE analysis to map the factors affecting the selection and the use of selected refrigerant on industrial heat pumps. The following analysis is based on the historical and background information introduced in this thesis, as well as the interviews, and my personal knowledge and experience on this field of industry.

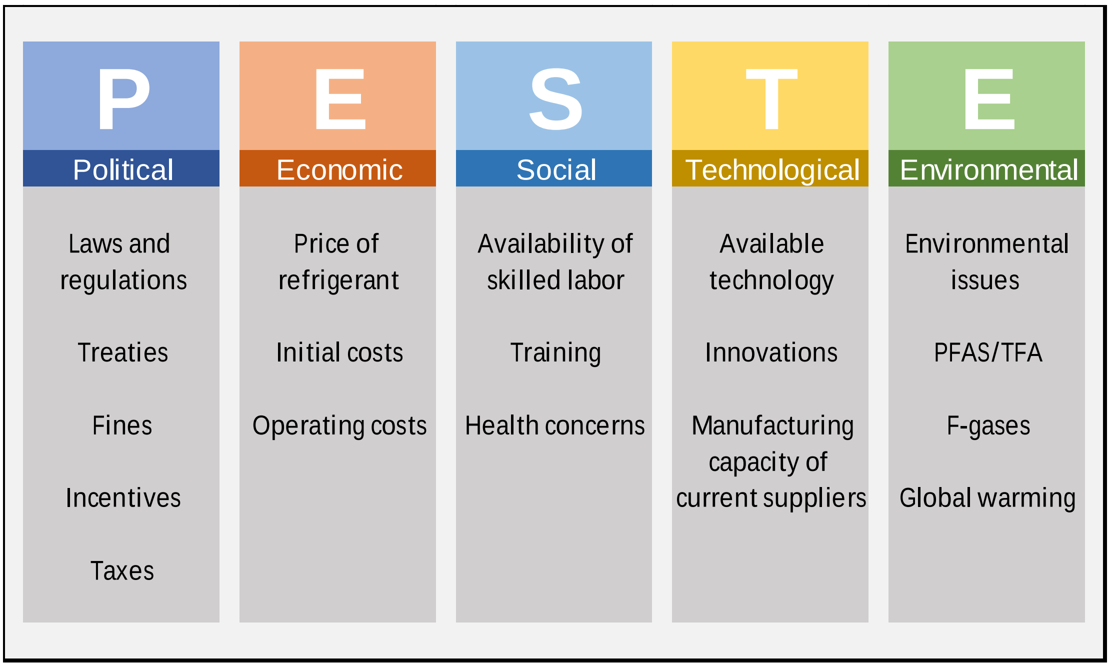

Figure 19: PESTE analysis (Reinvall, 2024)

When first looking at the political field, selection of a refrigerant is very much dependent and regulated by the national and international regulations as well as environmental agreements. Whether a natural refrigerant or synthetic, some form of regulation always applies.

On the economical side, selection of the refrigerant influences the initial installation price as well as the operating costs. Building the machine room and safety features differ from one refrigerant to another, affecting the costs. Also, the price of the refrigerant plays a role on the decision, whilst one might be able to use a system built with phased out refrigerant, servicing and filling the system during maintenance may prove to be very costly in the future.

On the social factors, we have health concerns due to PFAS. Completely different social factor, and a major one, is the availability of skilled labor. When the world is moving forward from burning oil to more sustainable options, like heat pumps, there will be a huge demand for skilled people in manufacturing, installation, and maintenance, just to name a few.

The transition from oil burning to heat pumps and other sustainable options, is also giving challenges to the manufacturing capacity. There is a steady amount of existing technology and also new innovations are done, both on equipment and refrigerant side. The growth in demand is estimated to be huge, so manufacturing capacity of the suppliers may become a bottleneck issue.

Another major factor is naturally the environmental issues. Refrigerants have historically played a huge role in impacting our atmosphere and environment. Late developments, that were considered to be safe and harmless options, are proven to be problematic. The effect of the forever chemicals cumulating in bodies of water are not yet completely clear.

6.2.2 Futures table

Based on the background information, interviews, and general discussion in the industry, I have selected the ten variables of interest, 2 from each section from the PESTE analysis. I mirrored these variables against 3 different states of possible future: strict, static, and permissive. These outcomes are mirrored against the selected factors on my PESTE analysis. The selections I have made in my futures table are introducing and mapping some of the possible situations. There are endless possibilities for the future to come, thus I have used educated guessing to limit the scope to be suitable for a thesis.

FUTURES TABLE	A	B	C
	Strict	Static	Permissive
Laws and regulations	Short phase out	Long phase out	No phase out
Treaties	Only natural	Favor natural	Allowing both
Initial costs	Favor natural	Favor synthetic	No favoring
Operating costs	Only natural	Favor natural	No favoring
Availability of skilled labor	Market explodes with transition, large amount of skilled workers needed	Market is steady, skilled workers available	Market is growing, more skilled workers needed
Health concerns	Some natural refrigerants are hazardous to health	PFAS. Some natural refrigerants are hazardous to health	Not all effects of synthetic are known yet. Some natural refrigerants are hazardous to health
Available technology	Well available, new developments	Well available	Available, new developments
Manufacturing capacity of current suppliers	Huge pressure on growth, more capacity needed for market needs	Moderate growth, slight capacity increase needed	Pressure on growth, more capacity needed for market needs
Environmental issues	None	Not all effects of synthetic are known yet	Effects on the new developed synthetics unknown
F-gases	Favor transition	Against synthetic	Effects on the new developed synthetics unknown

Table 1: Futures table (Reinvall, 2024)

6.2.3 Scenario work

FUTURES TABLE WITH SELECTED SCENARIOS			
	Naturals only		Natural and new synthetics
	A Strict	B Static	C Permissive
Laws and regulations	Short phase out	Long phase out	No phase out
Treaties	Only natural	Favor natural	Allowing both
Initial costs	Favor natural	Favor synthetic	No favoring
Operating costs	Only natural	Favor natural	No favoring
Availability of skilled labor	Market explodes with transition, large amount of skilled workers needed	Market is steady or moderate growth, skilled workers available	Market is growing, more skilled workers needed
Health concerns	Some natural refrigerants are hazardous to health	PFAS. Some natural refrigerants are hazardous to health	Not all effects of synthetic are known yet. Some natural refrigerants are hazardous to health
Available technology	Well available, new developments	Well available	Available, new developments
Manufacturing capacity of current suppliers	Huge pressure on growth, more capacity needed for market needs	Moderate growth, slight capacity increase needed	Pressure on growth, more capacity needed for market needs
Environmental issues	None	Not all effects of synthetic are known yet	Effects on the new developed synthetics unknown
F-gases	Favor transition	Against synthetic	Effects on the new developed synthetics unknown

Table 2: Futures table with selected scenarios (Reinvall, 2024)

I prepared 2 different scenarios by selecting development paths from the futures table, Naturals only, and Natural and new synthetics. With the current development on the market and regulation of the refrigerants, it is not likely that the future would remain as is.

6.2.4 Scenario 1: Naturals only

Naturals only would mean short and quick phase out of synthetic refrigerants. There is indication of this development on the renewal of the F-Gas regulation on EU. Ongoing PFAS discussion also supports the transition, so that the natural refrigerants could be the only option in the form of full scale PFAS ban.

Cost factor would be in favor of the natural refrigerants, if that is the only option. Compared to the current state of industry, equipment using natural refrigerant is higher on the initial cost, but lower on the operating cost. In some sense, this factor would become irrelevant in this scenario.

In this scenario, the health risks are known, and can be avoided with good design and proper education. Training would be needed to get adequate number of skilled workers. Designing, installing, or operating equipment with natural refrigerant is different from that with synthetic refrigerant.

Market would be expected to grow rapidly, as part of the options today would not be available anymore. Technology is there and development is ongoing for new applications and products, however, manufacturers would struggle to either fulfil the growing demand or with switching their product portfolio to different types of products. Some products would be interchangeable, but not all.

Natural refrigerants pose no threat to the atmosphere or our environment. This promotes the change towards naturals only.

6.2.5 Scenario 2: Natural and new synthetics

On the second scenario, the phase out would affect the old generation synthetic refrigerants. Current treaties favor natural refrigerants, and it is unlikely that for instance universally ratified Montreal protocol would be discarded. However, the timeline in this scenario is rather long. Effects and regulation of any new synthetics is at this stage unknown.

On the cost side, it is challenging to estimate. I would say that the initial cost would be on the same level with both types of refrigerants. Equipment used with older generation synthetic refrigerants may be suitable for the new generation in principle, but some upgrading would be likely. Operating costs I would say to favor slightly naturals, as new products usually have premium prices. Costs for operating system with natural refrigerants is rather steady.

As the market would be growing, more skilled workers would be needed for manufacturing, designing, installing, and operating units with both optional refrigerant types. Health concerns in this scenario would be significant. Concerns with natural refrigerants are manageable, as the properties of the media are well known. For the new developments, not all effects on health and environment are known. Throughout history, the developed refrigerants have been thought to be safe, until the discovery of the ozone hole or TFA.

Market would have pressure on growth and more manufacturing capacity would be needed for new equipment and increasing demand. There are new developments going on, especially with the refrigerant side with the new synthetic. New applications are likely to be found for both types of refrigerants.

Natural refrigerants pose no threat to the atmosphere or our environment. This promotes the change towards naturals only. Environmental effects of the new developments are not known yet.

7 CONCLUSIONS

The idea in this thesis was to find potential opportunities in the industrial heat pump market. Main problem was to find out what refrigerants will be used in industrial scale heat pumps in the future. As a heat pump component manufacturer, it is important to Vahterus to know this and to be able to adapt to the customer needs, where needed.

This required a thorough review of the historical aspects and current state of the industry. The reader is given an overview of heat pumps, different types of refrigerants, legislation affecting the selection of the refrigerant, and available technology. Suitable futurology techniques are introduced, selected for further utilization and finally with the help these techniques, the thesis results in introducing two different scenarios for the future.

The market for industrial scale heat pumps is heavily growing, with two major factors affecting the demand. The energy crisis due to war in Ukraine, has a big effect on availability of gas for heating. The other factor is the growing concern of our climate and environment. The whole world needs to start thinking in more sustainable way of working, living, and consuming.

Heat pump is an ideal solution to help on the transition away from burning fossil fuels. Well designed heat pump can help on improving the efficiency of a plant. Heat pumps are also an important factor on decarbonising space and water heating in buildings.

Several manufacturers offer ready-made packages, which are easier to install at site. They usually have proven and tested operating conditions and are a good fit to many processes and plants. Heat pump systems can also be tailor made from components by skilled contractors. In any case, installing and operating of a heat pump differs somewhat from a traditional refrigeration plant and needs a bit of training.

Refrigerants are the working fluid within the system and allow heat transfer by phase change. On the basic refrigeration cycle, gas is compressed to the condensing temperature, including desuperheating and condensing at constant pressure. After condensing, the liquid refrigerant goes further through expansion valve the and enters the low-pressure side where it is evaporating to saturated vapor. There are many different categorisations for refrigerants, and in this thesis, they are divided into natural and synthetic refrigerants.

Natural refrigerants have been used as long as people have been refrigerating goods. Ammonia is one of the first media used for refrigeration and its history dates to the 19th century. Natural refrigerants include media such as water, carbon dioxide, ammonia, and hydrocarbons, like propane, butane, pentane, just to name a few. They are climate friendly, so they do not contribute to ozone depletion or global warming, but some are toxic and / or flammable.

Synthetic refrigerants include CFCs, HCFCs, HFCs, HFOs and HCFOs. CFCs and HCFCs were proven to cause ozone depletion and have been already banned. HFCs are harmless to the ozone layer but contribute on the global warming and are heavily regulated and facing phase-outs based on international agreements. The next generation synthetic refrigerants, HFOs are climate friendly, but have a downside creating TFA on disintegration. TFA (trifluoroacetic acid) is a so called forever chemical, cumulating to our environment. The effects of HCFOs are yet to be seen. Synthetic refrigerants are subject to restrictions and bans but are still widely used in old and new installations.

The most important decision effecting refrigerants was the Montreal Protocol and its amendments. It was initially affecting production and usage and finally the phase out of CFCs and HCFCs. Kigali amendment included also HFCs to this list. In Europe, the F-gas regulation is aiming to further reduce greenhouse gas emissions from fluorinated gases. The regulation has just now on February 2024 gone through a major revision, and it will help on reaching the targets set for 2030 and further lead to climate-neutrality by 2050. In addition, ECHA is aiming on PFAS regulation on REACH. Full scale ban on PFAS would heavily impact both the selection of a refrigerant as well as equipment manufacturing. The decisions made in the near future could result to replacing or retrofitting huge amount of refrigeration and heat pump installations.

The interviews made for this thesis were in the form of semi-structured theme interviews. Three topics were discussed, what is the current state, how do the interviewees see the development, and open comments. The respondents were in the consensus that the industry is facing a drastic change. Even when the regions they represent, are on different stages of adopting the technology, they all recognised the importance of energy saving and sustainability on the market. In some regions, the change will be both market and legislation led, and others mainly market or industry led. Based on the interviews, the respondents believe natural refrigerants clearly to be the future. The also see huge potential coming from steam generation with high temperature heat pumps.

On my future research, I concentrated on the information gathering, data sorting and analysis, and building alternative futures. The techniques used in this thesis were PESTE, Futures table, and scenario work. Strategic decision making will be done by the management of the company and is not part of the thesis.

The research resulted into two different scenarios. From the futures table, two development paths were selected: Naturals only, and Natural and new synthetics. Both scenarios are possible states for the future, alternative to each other. They are not forecasts in any sense.

Naturals only would mean quick and strict phase out of synthetic refrigerants. Environmental and health factors promote this scenario more than the other. Current developments with both F-gas and PFAS give indication that the progress is towards natural refrigerants. By this scale of phase outs, the need for manufacturing capacity and skilled workers will be substantial.

Natural and new synthetic would mean phase out of the old synthetics but at the same time, development of new substances. Effects and possible regulation of any new refrigerants is yet to be known. Unfortunately, history has proven that what once has been considered to be harmless, can have unforeseen impact on climate, environment and health. The risk factor in this scenario is higher than on its alternative. Some installations may be converted to be using the new developments with minimal changes, so the anticipated increased need for additional capacity and workforce would not be as large.

As stated, both scenarios are possible. What is clear in my mind is that the interest in natural refrigerants will be steadily growing, in both scenarios. Regulations and initiatives point to this direction, as well as the expert opinions. There is heavy lobbying for synthetic refrigerants, and even for the ones facing phase outs. Manufacturers may rely on the long phase out period, with decades of time to develop new media or equipment. There is increasing amount of promotion for natural refrigerants as well. Individuals are often also very passionate supporters of the natural refrigerants. Different interest groups are promoting the use of natural refrigerants and increasingly popular hashtag used e.g., in LinkedIn posts is #NatRefs.

For the main question, what refrigerants will be used in industrial scale heat pumps in the future, I would say both natural and synthetic. We will be seeing synthetic refrigerants through the phase out period on both scenarios, but also in the form of new developments. Whether the new developments on the refrigerants will succeed or not, is yet to be seen. People are more and more conscious on their selection of choices, both in personal and professional life. I believe this is one of the factors that will be on favour of the natural refrigerants.

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