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PFAS ban – Challenges and Consequences for District Heating in Norway

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Norsk Fjernvarme represents 50 Norwegian District Heating and Cooling companies and 80 industry related companies. Our members supply over 90 % of all District Heating in Norway.

Content

1 Temperatures in district heating – important requirement for heat pump design

District heating (DH) systems have a wide range of customers with heating systems designed for different temperature levels. Typically, older buildings with heating systems using local fuel-oil boilers, have heating systems designed for forward water temperatures in the range 80-90 °C and return temperature in the range 60-70 °C. When these local boilers are replaced by a connection to a district heating system, the temperature in the district heating system must be higher than the design temperature of the heating system in the buildings. Thus, the forward temperature in the district heating system must be at least 85-90 °C.

The largest DH system in Norway is established in the capital of Norway, Oslo. In Oslo, about 70 % of all district heating customers have heating systems designed for temperatures between 80 °C and 90 °C, and thus the heat production plants must be designed accordingly. These customers represent a heat demand of 1300-1400 GWh/year (approximately 15 mill m2 floor area). Capex for the reconstruction of the heating systems I these building, adapted for lower temperatures, is estimated to 0,75-1 billion Euros, just in Oslo.

For the decades to come, the refurbishment and construction of new buildings will reduce the temperature demands, but this will take time. District heating needs to meet the demand from the market, the existing buildings, in cities all around in Norway.

2 Natural refrigerants suitable for high temperature district heating

For high-temperature heat pumps in district heating plants, there are three types of natural refrigerants that are relevant:

- Ammonia
- Carbon dioxide
- Hydrocarbons, such as propane and isobutane

Table 1 Natural refrigerants suitable for high temperature heat pumps

Refrigerant	R-number	Safety class, ISO 817	Comment
Ammonia (NH3)	R717	B2L	Toxic, flammable
Carbon dioxide (CO2)	R744	A1	Nontoxic, non-flammable
Propane	R290	A3	Nontoxic, extremely flammable
Isobutane	R600a	A3	Nontoxic, extremely flammable

Ammonia has good thermal properties but is toxic also in small quantities. The gas has a very pronounced odour, and there may be a risk of panic if a leakage occurs. Ammonia is not particularly suitable in centrifugal compressors due to its low molecular weight. Therefore, screw or piston compressors are used in heat pumps that use ammonia as the refrigerant. The typical amount of refrigerant in larger heat pumps is 50-200 kg/MW.

Carbon dioxide is nontoxic as well as non-flammable, and appropriate as a refrigerant. The most important challenge in terms of being suitable for district heating plants is that a low return temperature (below 40 °C) of district heating water is required due to its thermodynamic properties. The requirement for a high forward temperature of district heating water requires very high pressures on the condenser side.

Hydrocarbons such as propane and isobutane have good thermal properties. However, they are extremely flammable and explosive, requiring special safety measures. Hydrocarbons can be used in centrifugal compressors, as well as screw and piston compressors. The typical amount of refrigerant in larger heat pumps is 500-700 kg/MW.

3 Risks associated with natural refrigerants

Of the three most relevant natural refrigerants carbon dioxide, ammonia, and hydrocarbons, it is particularly important to consider the safety aspects of the use of ammonia and hydrocarbons. Ammonia is flammable, but its safety is primarily about toxicity. Hydrocarbons are not considered to be toxic but are extremely flammable and explosive.

In Norway, all heat pump systems with hydrocarbon refrigerants are regulated by:

- Act relating to the prevention of fire, explosion and accidents involving hazardous substances and the fire service /Act related to fire and explosions[1]
- Regulations of 8 June 2009 relating to the handling of flammable, reactive and pressurized substances including requisite equipment and installations /Regulations regarding handling of hazardous substances[2]
- Directive 2014/68/EU – Pressure Equipment Directive (PED) / [3]
- Directive 2006/42/EC – Machinery Directive /[4]
- Directive 99/92/EC – Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres /[5]
- Directive 2014/34/EU – Equipment and protective systems intended for use in potentially explosive atmospheres /[6]
- EN 378:2016 Part 1-4 Refrigerating systems and heat pumps - Safety and environmental requirements

EN 378 describes how technical rooms for cooling and heat pump systems should be designed to ensure safety. Engine rooms with access for authorized personnel only (Category III) and built in accordance with EN 378, with the necessary safety measures for ammonia or hydrocarbons, do not set any upper limit for refrigerant filling. Besides, according to EN 378 there are no requirements for the location of the technical room.

[1] Brann og eksplosjonsvernloven
[2] Forskrift om håndtering av farlig stoff
[3] Forskrift om trykkpåkjent utstyr
[4] Forskrift om maskiner
[5] Forskrift om helse og sikkerhet i eksplosjonsfarlige atmosfærer
[6] Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område

All systems handling flammable substance must according to Act related to fire and explosions (Section 3.2.1) § 26 be safe and suitable for the intended use. According to Regulations regarding handling of hazardous substances (Section 3.2.3) it is mandatory to perform a risk assessment (§ 14) and equipment used to handle hazardous substances must be in compliance with recognized norms (§ 8). The purpose of both the act and regulation is to protect life, health, environment, and material values.

The Seveso III Directive[7] lays down rules for the prevention of major accidents which involve dangerous substances, and the limitation of their consequences. For hydrocarbon heat pumps, with a heating capacity of 5-30 MW it is estimated large refrigerant charges rates in the range of 2 000 - 20 000 kg. For large hydrocarbon refrigerant charge more than 10 000 kg the Seveso III Directive will be effective. For ammonia the Seveso III directive will be effective at 50 000 kg. There are no national or international regulations or standards that directly forbids the use of large amounts of hydrocarbons or ammonia as a refrigerant for heat pumps in Norway.

However, international directives and national acts and regulations set requirements of, and limits, where such systems can be located depending on the risk assessment. National regulations require pressure relief surfaces for building/room classified as EX-zones and requires equipment in general to be safe and in compliance with recognized norm (e.g. EN 378).

For systems below ground, the risk of a building collapse may be increased and pressure relief surfaces difficult to place due to the lack of windows and walls to open areas. National regulations require pressure relief surfaces if a room is classified as containing an explosion hazard. However, EN 378 has no specific requirements for pressure relief surfaces to protect the building construction in the event of an explosion. The national requirement for pressure relief surfaces of machinery rooms is therefore not fulfilled by meeting the requirements of EN 378 alone.

With increased amount of refrigerant, the responsibility of the district heating company increases, both in terms of requirements from local and national authorities, quality of the risk assessment and a general responsibility to make sure that the plant is safe and does not pose an unacceptable risk to either life, health, environment, or material values. For systems with over 10 000 kg of flammable refrigerant, a quantitative risk assessment (QRA) is required, but a QRA is recommended also for smaller systems, especially in densely populated areas. The QRA is likely to result in large zones which might limit the land use also for nearby properties. In densely populated areas this limits the suitable locations for such systems.

For further information see Annex Norway 3.

4 Large scale high temperature ammonia heat pumps - still immature technology.

Summary: Despite claims in referred literature that there are many large high-temperature ammonia heat pumps in district heating plants in Europe, there are few if any real examples that prove that this is technology that is on the market and has been well tested. Major suppliers are

[7] It is implemented in the Norwegian legal system by the regulation "Storulykkeforskriften".

working to develop and offer such solutions, but it will take some years before these are sufficiently tested and eligible to be installed in district heating plants with strict requirements on reliability and uptime.

4.1 Misleading information about ammonia heat pumps in literature

The conclusions and recommendations in the draft law proposal against PFAS substances are based on reports and articles from reputable scholars, e.g. Hafner and Ciconkov (1) and Heat Roadmap Europe (2).

To the best of our knowledge, some statements in the referenced articles are not correct, especially regarding long time experience with high-temperature ammonia heat pumps. The authors of the articles have been contacted and asked to substantiate their claims.

> ***Hafner and Ciconkov*** *(1): "Ammonia is also widely used as working fluid in heat pumps up to a supply temperature of about 90 °C. These units are installed in numerous district heating systems in Europe.».*

When asked to supply information about which plants the article is referring to, the authors were very forthcoming. We received information about ammonia heat pumps primarily in Denmark, all operating at significantly lower temperatures than 90 °C. When stressed to come up with large plants operating above 90 °C, we received no further information about relevant plants. We claim, based on our dialogue with the major suppliers of large ammonia heat pumps (see chapter 4.2), that currently there is no examples of large ammonia heat pumps operating efficiently and reliable around or above 90 °C.

> ***Heat Roadmap Europe*** *(2): "Ammonia is a refrigerant generally used in medium and large-scale applications. It can work to temperatures up to 90 °C, such as at the Drammen heat pump plant (Norway), with a COP over 3. "*

Figure 4-1 shows an overview of supply temperature and capacity for large heat pumps using the refrigerant R134a in European district heating plants, mapped as part of the Heat Roadmap Europe project (2). Most of the larger R134a heat pumps operate at temperatures between 80 °C and 90 °C.

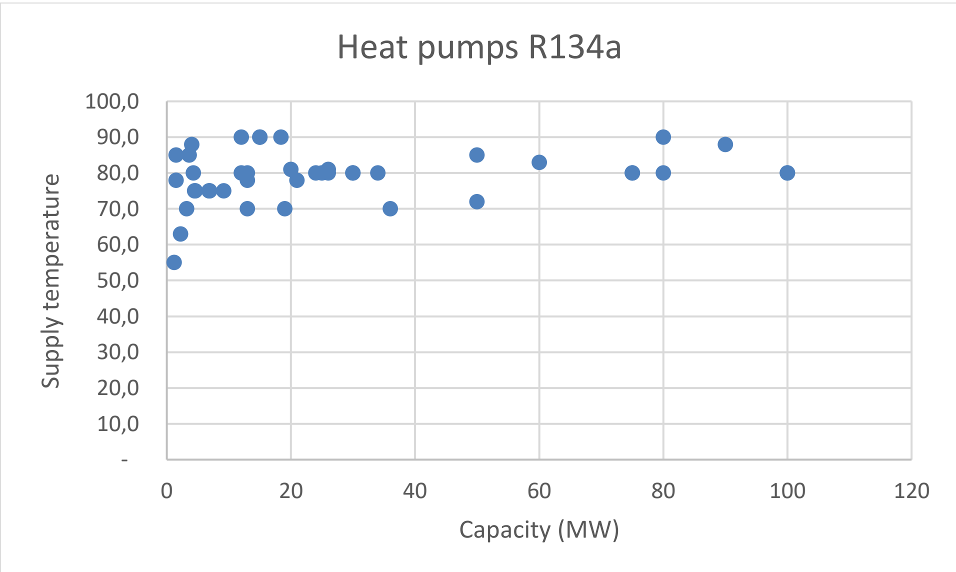

Figure 4-1 Heat pumps in District heating, refrigerant R134a. Source: Heat Roadmap Europe (2017) (2)

As shown in Figure 4-2, ammonia heat pumps operate at a lower temperature than equivalent heat pumps with R134a. Most ammonia heat pumps have less than 5 MW capacity.
The number of heat pumps is low, but based on the information available, it appears that the supply temperature from the heat pumps is falling with increasing size. According to Figure 4-2, the only heat pump that operates at 90 °C are the three units installed in Drammen District Heating. As discussed in Chapter 6.1, the heat pump is not capable of operating at this temperature. The Drammen ammonia heat pump is frequently referred to in the literature, without mentioning the challenges in terms of operational reliability.

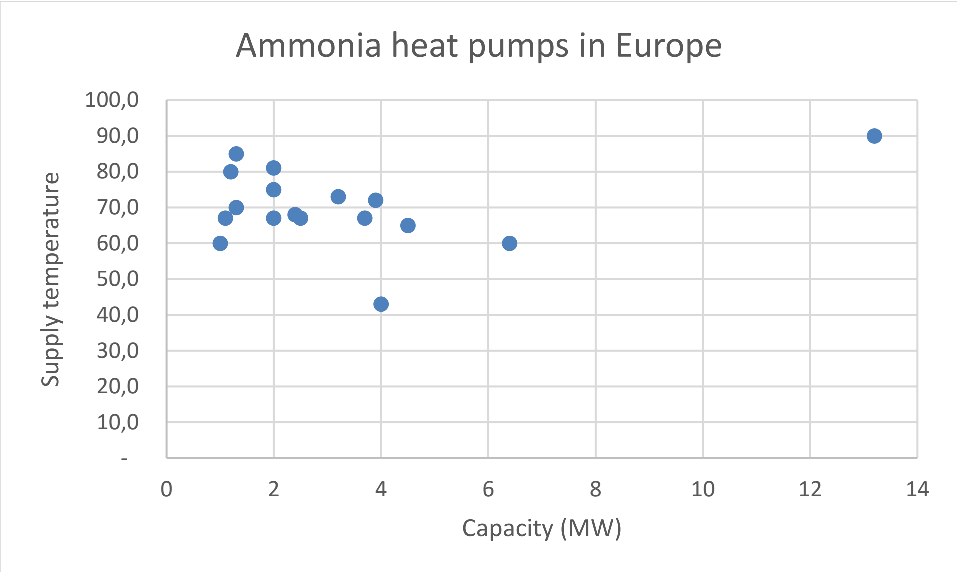

Figure 4-2 Heat pumps in District heating, ammonia as refrigerant. Source: Heat Roadmap Europe (2017) (2)

4.2 Dialogue with major supplier of ammonia heat pumps

Summary: The major suppliers of ammonia heat pumps are fully aware of the challenges of high-pressure lifts and are working on developing new compressors that will be able to operate stably even at temperatures above 90 °C. However, it will take several years before these compressors are tested in actual operation and for several heating seasons, which is required for a district heating company to be able to invest in such a solution.

A district heating supplier is subject to a very high degree of security of supply. It is therefore crucial that the equipment installed has a guaranteed availability and uptime, and that the supplier can demonstrate similar projects with operational experience of 3-5 years.

The Oslo based district heating company Celsio is in the process of acquiring a large heat pump and we have used their project as a reference in meetings with different suppliers. Celsio contacted four key suppliers of large ammonia heat pumps to get access to references on plants that have been delivered and that are comparable to the energy plant planned in Oslo. All suppliers provided expertise in heat pumps and the use of natural refrigerants, while Celsio provided similar expertise.

Star Refrigeration (Star): Meeting held on May 26th, 2023.
Supplier of the heat pump plant (14 MW) in Drammen (Norway). Often mentioned in articles and literature as an example of large heat pumps with ammonia operating at 90 °C. Star acknowledges that the plant in Drammen has had a lot of problems and that it has never had stable operation at design temperature 90°C. The plant has suffered many compressor

breakdowns, high maintenance costs and can only run stably at temperatures significantly lower than 90°C.

In the last 2-3 years, Star has also supplied ammonia heat pumps to two plants in the UK of 3 and 5.2 MW respectively with temperatures of 80 °C. According to Star, these have worked well.

Johnsons Controls (JCI): Meeting held on June 9th,, 2023.
The NH3 machines that are on the market today and that are supposed to deliver high pressure are intended for lower pressure lifts. The screw compressors are "long and thin" and take on a "banana shape" when the pressure lift gets too high, thus causes leaks. JCI has developed a new screw compressor originally intended for natural gas, to cope with high pressure lifts. The compressor has been in 2000 hours of operation in a rig in the factory and will be further tested by a customer where two compressors are now installed. JCI has provided a capacity guarantee on these. JCI is working to reduce NH3 filling. Today it is about 500 kg NH3 per MW, but it is possible to reduce this significantly by changing the design, especially of the evaporator. Measures are also being taken on the condenser side.

JCI could not provide references to customers who have large ammonia heat pumps that have operated stably with as high a pressure lift as is required in Oslo.

GEA: Meeting held on June 12th, 2023.
GEA can supply high-temperature NH3 heat pumps but has few relevant references. The supplier focuses on developing new compressors (both screw and piston) for high pressure lifts where robustness is a key prerequisite. A new type of reciprocating compressor (70 bar) has been test-driven for several thousand hours in GEA's test rig but has not yet been tested at the customer's premises. The compressor will be put into trial operation from the autumn. GEA stated that NH3 heat pumps require somewhat longer time from installation to acceptable stability, as they are sensitive to vibrations, among other things. In terms of ammonia filling, GEA stated 50-100 kg per MW for the smaller machines, for the larger machines 200 kg/MW must be calculated.

GEA could not provide references to customers who have large ammonia heat pumps that have operated stably with as high a pressure lift as is required in Oslo.

MAN: Meeting held on August 11th, 2023.
MAN has long experience from the oil and gas industry. Previously, the heat pump market was too small, but this is now changing as it is interesting for MAN to supply large heat pumps for district heating and industry. MAN can offer solutions with hydrocarbons, ammonia and CO_2 depending on the customer's requirements. For Celsio, MAN expressed that it would probably be NH3 that is most relevant based on our temperature requirements. In the meeting, MAN claimed that they *can* supply high-temperature NH3 heat pumps, even with a temperature higher than 90 °C, but they have no operational experience. MAN emphasized that it is the blending of oil in the refrigerant that poses the greatest challenge during high pressure lifts, and that its compressor solution avoids interference and thereby the operational challenges faced by other compressor types.

MAN could not yet provide references to customers who have large ammonia heat pumps that have operated stably with as high a pressure lift as is required in Oslo.

5 Ammonia heat pumps in Norway

The consulting company Norconsult has mapped ammonia heat pumps in Norway outside district heating plants. A summary is shown in Table 2. As shown, the ammonia heat pumps operate at temperatures significantly below 90 °C, and they range from 1,1 MW to 5 MW in capacity.

Table 2 Ammonia heat pumps in Norway. Source: (Norconsult, 2023)

	Supplier	Effect	Average supply temperature	Year of delivery
Sarpsborg heating plant	GEA	2 MW and 5 MW	80 °C	2010 2013
Horten heating plant	GEA	2*1.2 MW 2.6 MW	68 °C	2012 2019
NTNU	GEA	1.1 MW	80 °C	2014
Kalnes Energy Plant	GEA	1.35 MW	80 °C	2014
Førdefjorden heating plant	Mayekawa	5 MW	72 °C	2017
Kongsberg Technology Park (KTP)	Mayakawa/Therma	2.2 MW 1.7 MW 1.25 MW	72 °C 75 °C 75 °C	2006 2008 2013
Marienlyst Local Heating	GEA	1.4 MW	70 °C	2000

In 2023 a simple survey was conducted to map current installations of heat pumps, owned and operated by district heating companies in Norway. The results shows that heat pumps are widely used for different purposes among district heating companies in Norway, and a total of 200 MW heat production is installed. The district heating companies have experience from all aspects of demands in pre-feasibility studies of an energy plant to detailed reports from operation of different heat pump installations.

There are several installations of heat pumps using ammonia as refrigerant operated by district heating companies. The common experience is that industrial heat pumps connected to standard district heating systems struggles to meet the demands for design temperature promised by the supplier.

6 Operational experiences with ammonia heat pumps

Summary: Experience with ammonia heat pumps that have been in operation for a few years indicates that there are major challenges in operating at high pressures and thereby high condensation temperatures. It is recommended to operate at significantly lower temperatures than the plants are designed for, to avoid compressor breakdowns and leakage of refrigerants.

6.1 Drammen District Heating plant

In 2011, Drammen District Heating installed three ammonia heat pumps with a total capacity of 13.5 MW of heat, designed for an outgoing district heating temperature of 90 °C.

During the 12 years the plant has been in operation, there have been major challenges. Experience has shown that it is very difficult to achieve steady operation at temperatures above 85 °C, so the plant currently operates at an outgoing temperature of 72-75 °C. Furthermore, there have been leaks of refrigerant, both during operation and during standstill. Since start-up, it has been necessary to replace several compressors, and it is feared that at least one compressor every year will have to be replaced. In addition, oil filters need to be changed frequently.

Due to leakages giving significant odour outside the heat central building, over the years the fire brigade has had at least 3 full calls with chemical protective equipment. There has also been leaks to the district heating water, which was discovered by a customer experiencing the smell of ammonia in the shower.

Maintenance costs are very high compared to similar plants with heat pumps that use synthetic refrigerants. The supplier of the heat pumps (Star Refrigeration) has many weeks of maintenance work each year. In addition, 1-2 man-years of internal time are used. According to Drammen District heating, the yearly cost for external service and maintenance is 200 000 NOK/MW, while for the heat pumps operated by Oslofjord Varme using a synthetic refrigerant at Fornebu the comparable cost is 10 000 NOK/MW. Total capacity at Fornebu is around 30 MW, with one heat pump using R134a and another use R1234 ze.

The challenges with ammonia as a refrigerant have led Drammen District Heating to choose the synthetic refrigerant R1234ze for their new large-scale heat pumps that will deliver heat to the local hospital.

6.2 Norconsult's mapping of experiences with ammonia heat pumps.

The consulting company Norconsult has conducted a survey of experiences with high-temperature ammonia heat pumps. The purpose has been to get feedback on operations, maintenance, costs and possible breakdowns. In total, information and feedback has been collected from 10 different heating plants.

Norconsult's summary highlights that operation, supervision and service are important to avoid breakdowns. In addition, it is important to avoid excessively high condensation temperatures. In general, one should be at least 5 °C below the dimensioning condensation temperature in normal operation. Some compressor models have been shown to have a poor design that leads to breakdowns. Long delivery times for parts from some manufacturers have also been a recurring problem, leading to long plant downtimes.

6.2.1 Recommends reduced condensing pressure.

All the examined plants have ammonia as a refrigerant and heat output ranging from 0.5 MW to 2.2 MW. The focus has been on plants with condensation temperatures from 72 °C to 90 °C. Lower operating pressure, and thus lower pressure pipe temperature, are important. The investigation concluded that there are fewer breakdowns for plants where the condensation temperature is lower than 75-80 °C.

Two of the plants that have been running the longest, Kongsberg Technology Park (KTP), since 2006, and Marienlyst Local Heating, since 2000, have operated at 72°C, a relatively low condensation temperature. Based on experience from their own ammonia plant, the Norwegian

University of Science and Technology (NTNU), recommends not to operate at too high condensation temperatures to avoid breakdowns

6.2.2 Regular maintenance is expensive but reduces operational problems.

Based on the feedback, Norconsult observed that plants with regular maintenance with people who physically walk around the plant every day have had the least problems with breakdowns. Therefore, these plants also have higher operating costs.

At the Norwegian University of Science and Technology (NTNU), there is annual service with service costs around 100 000 NOK per year. NTNU has people who go around the plant on a regular basis to inspect the plant and correct errors quickly.

6.2.3 Major downtimes because of compressor breakdowns

Førdefjord and Kongsberg Technology Park (KTP) have experience with the Mayakawa GHS rotary screw compressor. The supplier has confirmed that the bearings cannot withstand the load from vibrations, thus KTP is now replacing this compressor after only 4 500 operational hours. It has been a long delivery time and difficult to obtain parts for the GHS compressor. This led to several months of breakdown in 2022/2023 for KTP and Førdefjorden had 6 months of downtime.

There have generally been reports of major downtimes because of breakdowns. The main reason for this is that there is a long delivery time on parts. At Drammen and Ahus extra compressors are stored at site to minimize down time.

6.2.4 High pressure causes leaks.

Some of the plants have had problems with leaks. In these cases, it is mostly gaskets that have broken in connection with high pressure (high condensation temperature). The Førdefjorden heating plant had problems with the high-pressure condenser not being able to withstand the condensation pressure.

7 For refrigerants used in high-temperature heat pumps, drop-in alternatives don't exist.

According to Hafner and Ciconkow (1) *"… all temperature levels and most applications can be cooled by applying natural refrigerants. There is no technical barrier to replace currently used synthetic fluorinated gas refrigerants with natural working fluids."*

The assertion that there is no technical barrier to replace synthetic refrigerants with natural refrigerants is inaccurate at best. None of the natural refrigerants can be a drop-in alternative to R134a or R1234ze. Partly because of the large differences in molecular weight, and not least in thermodynamic properties, refrigerants such as ammonia, carbon dioxide or propane cannot simply be used in heat pumps designed for the synthetic alternatives. Besides, ammonia corrodes cupper, a commonly used material in heat pumps.

Therefore, there is no possibility of drop-in today, and it is difficult to envisage that this will be available as the natural refrigerants have different properties than the synthetic ones. See table 3.

Table 3 Molecular weight and thermodynamic properties for different refrigerants

	Molecular weight (g/mol)	Critical temperature (°C)	Critical pressure (bar)	Comment
R134a	102,0	101,1	40,7	
R1234ze	114,0	109,4	36,4	Flammable
R290 (Propane)	44,1	96,7	42,5	Highly flammable and explosive
R717 (Ammonia)	17,0	132,0	114,8	
R744 (CO_2)	44,0	31,0	72,8	

8 Bibliography

1. Current state and market trends in technologies with natural refrigerants.
Hafner, Armin og Ciconkov, Risto. 2021.

2. Heat Roadmap Europe: Large-scale Electric Heat Pumps in District Heating.
David, Andrei, et al. 2017.

3. IREES - Institute for Resource Efficiency and Energy Strategies GmbH. District Heating and Cooling in the European Union. s.l. : European Commission, Directorate-General for Energy, 2022.

4. Erfaringer med høytemperatur-varmepumper med ammoniakk.
Norconsult. 2023.