Technology Collaboration Programme
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Technology Collaboration Program on Heat Pumping Technologies (TCP-HPT)

HPT-Annex 46
Domestic Hot Water Heat Pumps

Annex 46

Refrigerants

for

Heat Pump Water Heaters

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Phetradico

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Production	Heat Pump Centre, Borås, Sweden

Report No. HPT-AN46-04

Preface

This project was carried out within the International Energy Agency Technology Collaboration Program on Heat Pumping Technologies (HPT TCP).

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Program. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a Program of energy technology and R&D collaboration, currently within the framework of over 40 Implementing Agreements.

Disclaimer

The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programs or TCPs. The TCPs are organized under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Technology Collaboration Program on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Program on Heat Pumping Technologies (HPT TCP) forms the legal basis for a Program of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP, called participating countries, are either governments or organizations designated by their respective governments to conduct. The Program is governed by an Executive Committee (ExCo), which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Annexes

The core of the TCP are the "Annexes". Annexes are collaborative tasks conducted on a cost-sharing and/or task-sharing basis by experts from the participating countries. Annexes have specific topics and work plans and operate for a specified period, usually a number of years. The objectives range from information exchange to the development and implementation of heat pumping technologies. An Annex is in general coordinated by an expert from one country, acting as the Operating Agent (manager). This report presents the results of one Annex.

Triennial Heat Pump Conference

The IEA Heat Pump Conference is one of the three major products of the Technology Collaboration Program on Heat Pumping Technologies. The Executive Committee supervises the overall organization and its quality and selects from a tender procedure the host country to organize the Conference and establishes an International Organization Committee (IOC) to support the host country and the ExCo.

The Heat Pump Centre

The Heat Pump Centre (HPC) offers information services to support all those who can play a part in the implementation of heat pumping technologies. Activities of the HPC include the publication of the quarterly Heat Pumping Technologies Magazine and an additional newsletter three times per year, the HPT TCP website, the organization of workshops, an inquiry service and a promotion Program.
The HPC also publishes results from the Annexes under the TCP-HPT.

For further information about the Technology Collaboration Program on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
Heat Pump Centre
c/o RISE - Research Institutes of Sweden Box 857, SE-501 15 BORÅS, Sweden
Phone: +46 10 16 55 12

‘no refrigerant fulfils all the ideal requirements at once’

Disclaimer

The information and analysis contained within this summary document is developed to broadly inform on world-wide developments. Whilst the information analysed was supplied by representatives of National Governments, a number of assumptions, simplifications and transformations have been made in order to present information that is easily understood. Therefore, information should only be used as guidance.

The market is developing fast and at the moment of publication some information can already be overtaken by new developments. There are some websites listed at the reference pages of the report.

In compiling, editing and writing this report I would like to thank Pavel Makhnatch (KTH – Sweden), Kashif Nawaz (Oakridge National Laboratories – USA), Yunho Hwang (University of Maryland – USA), Cordin Arpagaus (NTB-Interstaatliche Hochschule für Technik Buchs - CH), Roberto Sunyé (CanmetÉNERGIE/CanmetENERGY – Can), the Japanese National Team under Kyioshi Saito (Waseda University – Japan) and Neil Hewitt (Ulster University – UK).

Disclaimer
The views expressed in this report by the author do not necessarily reflect those of the individual project participants.

Summary

The historic amendment to the Montréal Protocol adopted in Kigali, Rwanda, is a major policy step forward in the global effort to reduce greenhouse gas emissions and the threat of climate change. The amendment sets a gradual phasedown schedule for high-GWP HFCs, which were introduced more than 20 years ago as ozone friendly alternatives to replace CFCs and HCFCs.

Hydrofluorocarbons (HFCs) are an important source of greenhouse gases globally, where climate-friendly, energy-efficient alternatives, such as natural refrigerants and HFO's, are readily available for a growing number of applications. In 2014, the EU took regulatory action to limit the use of these greenhouse gases through a combination of measures. Within not even four years, the changes in the industry are noticeable. The impact will increase as the worldwide regulatory measures switch into high gear in the next decade. It demonstrates that with clear, ambitious and timely regulatory rules, industry is able to take action more quickly than expected.

At this moment, the challenge for many of the alternative refrigerants is flammability, thus their use restricting by a number of safety codes and standards. Research spearheaded by industry is ongoing to support the new codes and safety standards available from the first half of 2017. Industry is getting together to adopt and develop best practices as well as training and certification programs to ensure proper management, servicing, and end-of-life practices for equipment using lower GWP refrigerants.

For Domestic Hot Water Heat Pumps not much focused research is available in which results show which refrigerant is the 'best solution'. GWP can be a useful metric to compare different refrigerants. However, it may to overestimate the benefits of low GWP refrigerant to environment, as it does not take into account many other affecting factors, like the use of high efficiency components and system design, such as the optimal storage size, stratification and condenser design. Ensuring proper installation, optimised control and operation, under all common operating and climate conditions are factors not directly related to the technology itself and the choice of refrigerant. In the end, the overall energy use of the installation is an important factor in the calculation of the LCCP or TEWI factor.

For a DHW HP the refrigerant used by a large part of the manufacturers is R134a, a status that will continue for a longer time to come. The tendency of the industry is to move towards natural refrigerants when it is technologically safe and economically feasible. Carbon Dioxide (R744) has a growing market in Asia, while Propane (R290) is very much in development and applied in small domestic applications in Europe. Both are well suited for DHW HP. HFO's although already applied in automotive industry is another potential alternative not yet well researched for DHW applications.

As a consequence of the regulations for legionella and the need for heat pumps suitable for retrofit, especially in collective systems, refrigerants and solutions for DHW applications with higher than traditional (> 65°C) heat supply temperature are in demand. Carbon dioxide and propane are natural refrigerants, which have higher critical temperatures and can be used to reach higher output temperatures up to 80°C. Modifications to the refrigerant cycle such as EVI or cascading refrigerant cycles can be used to increase the output temperature further up to 80°C with other refrigerants, momentary mainly R410A/R134a is used.

R152a, R1234yf, R1234ze(E) and Ammonia are interesting alternatives for DHW HP, not yet broadly in use but already tested in R&D projects , while R32 is strongly promoted by manufacturers.

However, no alternative refrigerant fulfils all the ideal requirements at once.

Contents

0. Introduction

This report is a literature study, which has been compiled and edited from a number of existing reports and gives an overview of a landscape that is developing in a fast pace.

Most publications as reference are not specifically focusing on Domestic Hot Water Heat Pumps (DHWHP's).

The report gives in the first paragraphs a survey of governmental policies worldwide, where there is common goal agreed in Kigali, but a different pace in reaching these goals. Important conditions for finding the right refrigerant for the right application is handled in the next paragraphs. The main refrigerants in play are not all suitable for DHWHP.

The thermodynamic characteristics, i.e. the condensation and evaporation processes defining the working pressures are of importance but more or less given by policy:

- Global Warming Potential (GWP)
- Safety i.e. Toxicity and Flammability in line with ASHRAE Standard 34
- Energy performance, i.e. efficiency and high COP

The report discusses the importance of the energy effects and the GWP in relation to the TEWI-factor and the LCCP factor, where in effect refrigerants with a higher GWP could be acceptable when an overall better energy performance can be achieved with a low refrigerant charge.

The market is developing in a fast pace. This report tries to give a glimpse of what is going from the perspective of DHWHPs. Further research is required to understand the characteristics of the various possible configurations of DHWHPs and the refrigerants. This is in full understanding that refrigerants are produced by large manufacturers and used by large heat pump manufacturers choosing the optimal technology that can be economically produced in a highly competitive market.

For further information, a number of websites of interest are listed here:

- http://hydrocarbons21.com/
- http://www.r744.com/
- www.naturalrefrigerants.com
- www.coolingpost.com

1 Reduction of Greenhouse gases a worldwide action

The fast increase of fluorinated gases in the atmosphere prompted the international community to discuss ways to reduce the use of HFCs. For several years in a row, attempts to amend the Montréal Protocol to phase-down the use of HFCs were unsuccessful. Meanwhile, in 2014 the European commission introduced the **F-Gas Regulation**[1] for a phase-down of HFCs as shown in Figure 1. In addition, specific bans on high GWP HFCs will be implemented as early as January 2020 for stationary refrigeration equipment.

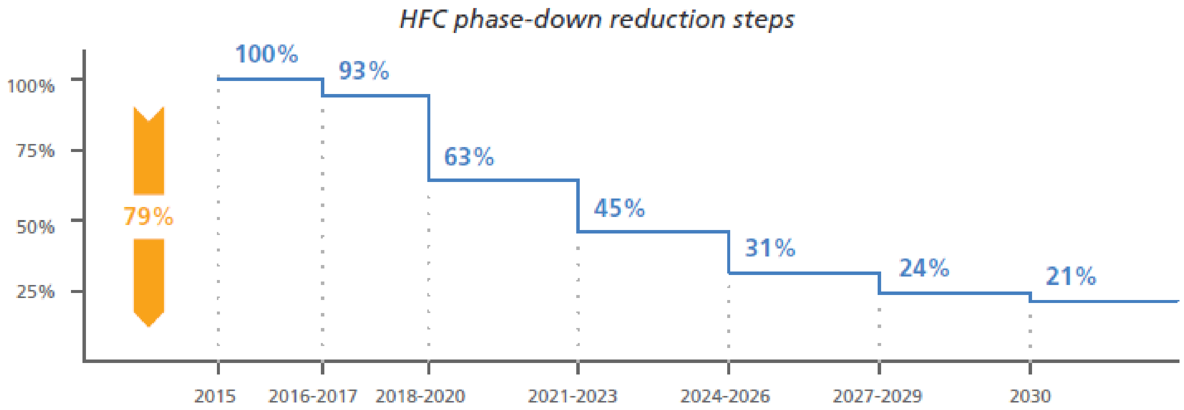

Figure 1.1: Phasedown Steps based on the European F-Gas Regulation [08]

While regulations were introduced in both Europe and the U.S., international discussions to amend the Montréal l Protocol to address HFCs were ongoing. In October 2016, an agreement was reached in Kigali, Rwanda, by nearly 200 countries to adopt a global phase-down of HFCs. According to the agreement as shown in Fig. 1.2, the amendment to the Montréal Protocol provides separate baselines and reduction schedules for developed (A2) and developing (A5) countries as well separate accommodations for certain Parties within those categories.

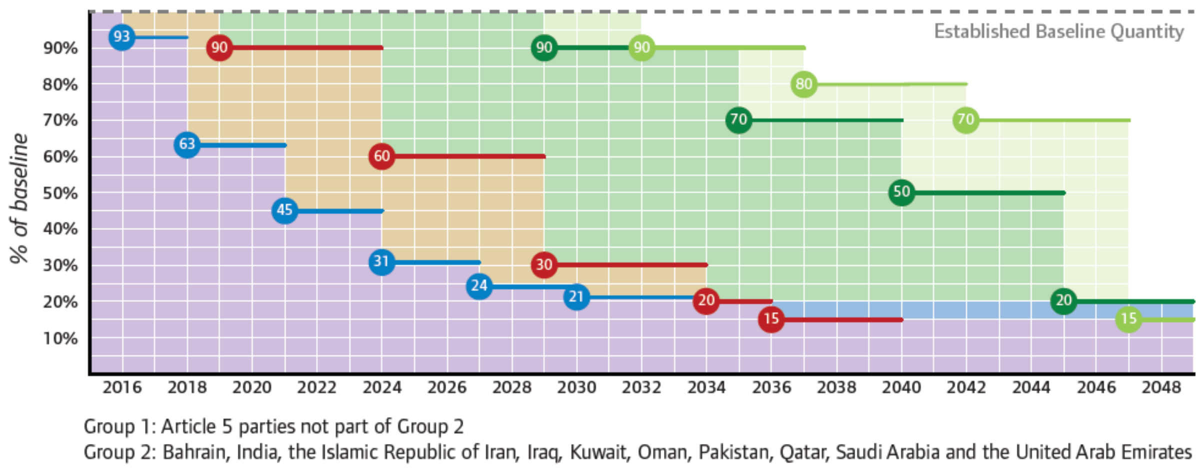

Fig 1.2 Phasedown Schedule for Developed (A2) and Developing (A5) Countries [41]

Developed countries such as in Europe, Japan, and the U.S.[2] will start phasing down HFCs as early as 2019.

[1] Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006

[2] In the U.S., the amendment has to be signed by the President and ratified by the Senate. Once ratified, the EPA will

Additional step-downs are expected in 2024, 2029 and 2034. Finally, in 2036, production and consumption of HFCs will be capped at 15% of the original baseline of 2015. As with past amendments, it will be guided by a technology and economic review process every 5 years and will provide financial assistance to developing countries. Looking at the global picture of legislation a very fragmented situation is evident. A number of experts are stating that Europe, China, Canada, New York and California are frontrunners in their approach.

Under the Montréal Protocol and the Kigali agreement 200 countries that ratified will be required to:

- phase down the consumption (imports and exports) of HFCs;
- establish a system for permitting the import and export of new, used, recycled and reclaimed HFCs;
- report on its HFC consumption;
- ban the trade of HFC with parties that have not ratified the amendment by a certain date.

Worldwide the Montréal protocol and the Kigali Agreement has prompted a large number of countries to develop legislation as the agreements allows individual countries to establish their own timelines for individual refrigerants.

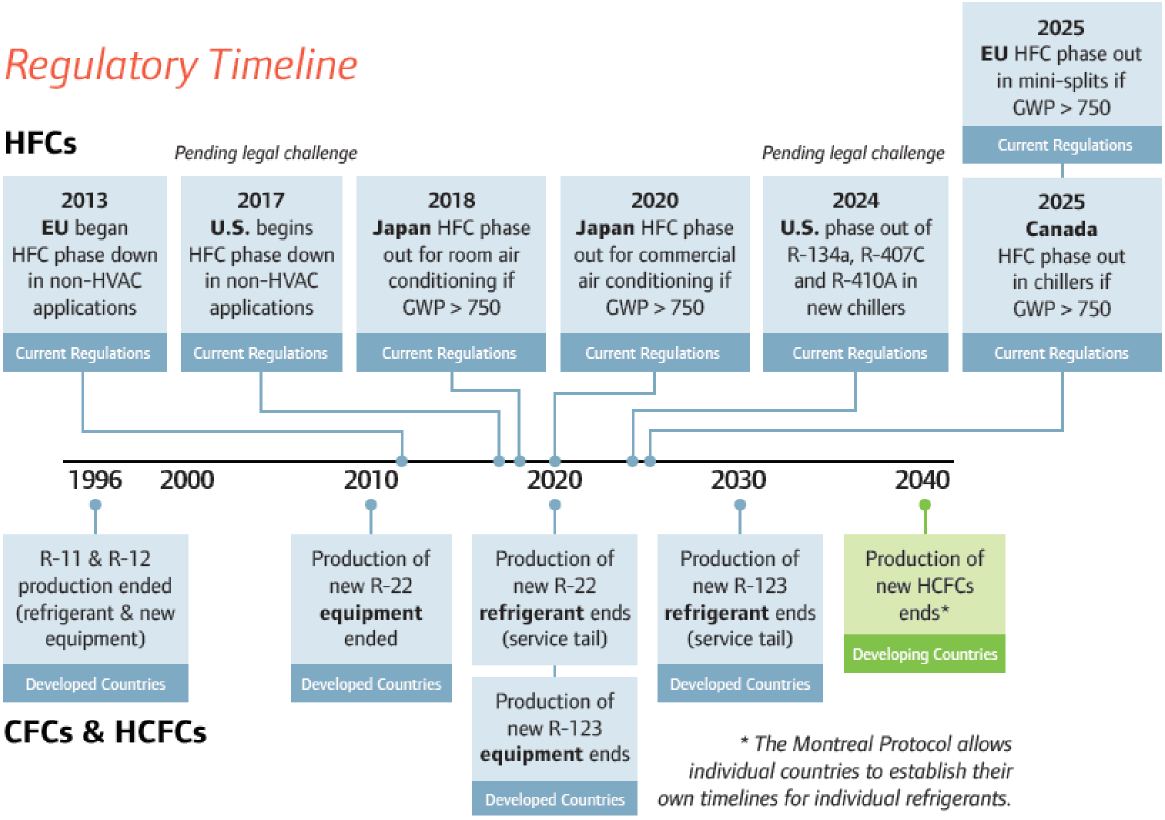

Fig 1.3 – Time schedule of a number of countries [41]

1.1 Asia

The three major economies Japan, South Korea and China all have a large number of heat pump manufacturers and a number of producers of refrigerants. All are involved and have signed the Montréal protocol up to the Kigali Agreement. Vietnam is a Party to the Montréal Protocol and has amongst others signed the Kigali

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promulgate regulations to implement it.

agreement. Others are still to follow.

1.1.1 Japan

Japan's F-Gas Law was revised almost simultaneously along with the EU F-Gas Regulation. When designing the new rules, Japan carefully examined the policies that other countries and regions, including the EU, were adopting or considering adopting in order to limit the use of HFCs. While the original fluorocarbon regulations focused on the recovery and destruction of fluorocarbons from disposed commercial air-conditioning and refrigeration units, the revised Law that entered into force in April 2015 introduced new policy measures that address the full lifecycle of HFCs. With the new legislation, Japan took a similar approach to the EU in that it introduced a combination of measures to address emissions of f-gases.

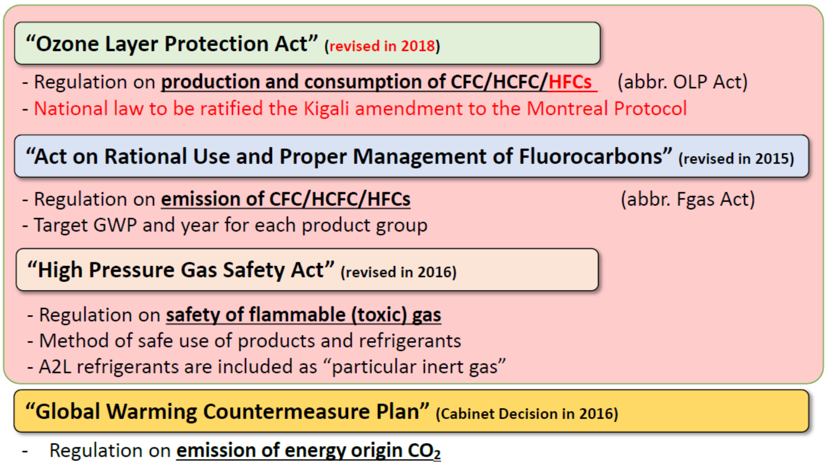


Fig 1.4 Overview from presentation by JRAIA at OEWG40 in Vienna [19]

While the measures adopted have been adapted to the technology status and legislative processes in Japan, many points of the new rules are comparable to the EU's F-Gas Regulation. These include reporting, which is now mandatory for producers and importers of F-gases, as well as leak checking for end users, the phase-down of HFCs, and the promotion of low-GWP non-fluorocarbon refrigerants in designated products.

1.1.2 South Korea

The Clean Air Conservation Act [make linked texts as footnotes or add them to the References] is the basis of the Korean policy on the reduction of greenhouse gases in line with Montréal Protocol and Kigali Agreement. For this South Korea has passed various legislations and developed a refrigerant management system based upon the:

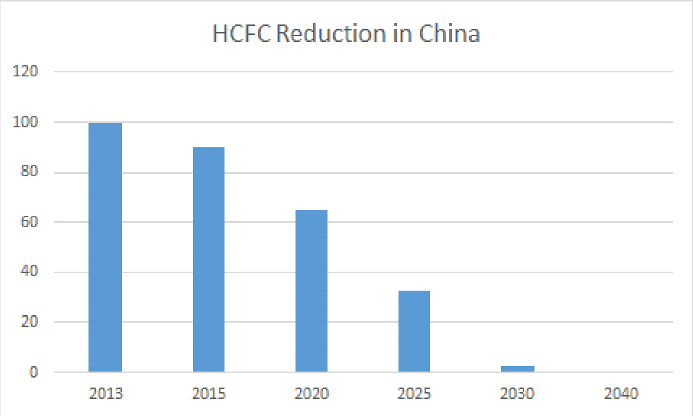
- Clean Air Conservation Act Article 9 Clause 3 (management and treatment of air conditioner refrigerant)
- Enforcement regulation of Clean Air Conservation Act Article 14 Clause 4 (size, building and facility standard of air conditioner under management) and Article 14 Clause 5 (management, recovery and treatment method for refrigerant)

The Refrigerants Information Management System (RIMS) focuses on managing the production, use, and disposal phases of refrigerants. The Korea Environment Corporation (K-eco) is responsible for this program. Public awareness is very important as the YouTube video shows.

The Ministry of Environment recently has announced a revision of the Enforcement Rule of the Clean Air Conservation Act to set the range for additional refrigerant-using machines requiring management.

1.1.3 China

As a signatory to the Montréal Protocol, China has agreed to gradually phase down the production and consumption of HCFCs by 97.5% by 2030, while allowing the remaining 2.5% for servicing of existing refrigeration and air conditioning systems during the period between 2030 and 2040 [42]. Achieving the HCFC phase down, compliance targets will be a significant task that requires the involvement of a multitude of industries and sectors, but also presents opportunities to the market to replace HCFCs with natural refrigerants.



China has agreed to completely eliminate the production of HCFCs by 2030. Between 2030 and 2040 2.5% of HCFCs (compared to 2009-2010 baseline) will be allowed to service the existing equipment. As China currently manufactures 92% of HCFCs in developing countries, the phase out will have a global impact.

Fig 1.5 HFC phase down in China [42]

Moreover, the Chinese Ministry of Environmental Protection provides technical assistance to study replacement technologies, including those using natural refrigeration, and to revise standards for new technologies. Starting in 2015, the government will take additional measures to promote heat pump technologies and CO2 technology in supermarkets. In preparation for the second stage of the HCFC phase out plan, the government is conducting a survey to gather information on the cold chain industry.

A low-GWP Label promotes natural refrigerants in room air conditioning and heat pump water heaters. In March 2015, the Foreign Economic Cooperation Office of the Ministry (FECO) of Environmental Protection launched the Low-GWP Label together with the China Household Electrical Appliances Association (CHEAA), UNEP, UNIDO and GIZ started to promote room air conditioning and residential heat pump water heaters using natural refrigerants and other low global warming potential (GWP) substances. The eligible products have to use refrigerants with no ozone depleting potential (ODP) and GWP below 150.

Fig 1.6 – Low-GWP label on water heaters [42]

1.2 North America

From North America, the United States, Canada and Mexico are effectively considered. Canada is often called as one of the front runners in terms of refrigerant legislation following the European developments very closely. Environment Canada (footnote) recognizes the importance of regulatory alignment between Canada and the U.S. and ensures a level playing field for Canadian and U.S. companies and enterprises. Environment Canada considers different approaches that minimize potential market disruption and work towards the objective of curbing HFC growth thereby avoiding future emissions, while taking Canadian environmental and economic factors into account. Ongoing non-regulatory activities in the U.S. include the Green Chill Partnership for commercial refrigeration and best practices for household refrigerator and freezer producers.

1.2.1 United States

The Climate Action Plan [43] announced by President Obama in June 2013 set out a number of measures to address HFCs. It has been estimated that eliminating certain HFCs could provide 23% of the emissions reductions needed to achieve the US's 2020 GHG emissions reduction goal of 17% below the 2005 level.

The U.S. Department of Energy's Building Technologies Office (BTO) has created a multi-pronged strategy [44] to develop, demonstrate, and deploy low- to zero- GWP HVAC, water heating, and refrigeration technologies. This strategy supports the United States' amendment to the Montréal Protocol to phase down the production and consumption of HFCs globally. BTO's vision is that non-vapor compression systems—a revolutionary new class of technologies that don't use refrigerants and can approach zero-GWP—become dominant in some end uses.

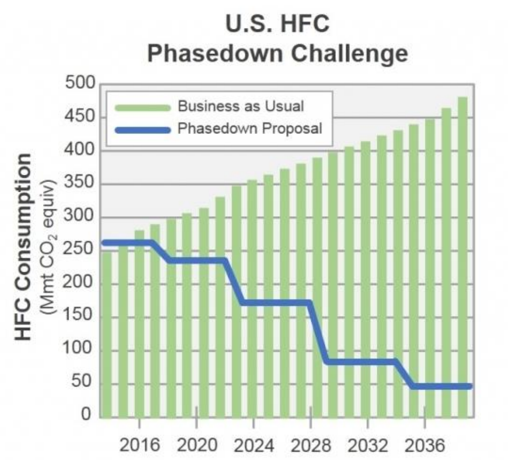


Fig 1.7 – US Phasedown challenge [44]

This action plan includes the use of the Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP)[3] programme, established to evaluate and regulate ODS replacements; the programme publishes lists of acceptable and unacceptable substances. Three new rules have recently been adopted, partly in response to petitions form environmental non-governmental organisations (ENGOs) filed prior to adoption of the Climate Action Plan [U.S. Environmental Protection Agency, 2016, *Federal Register, Vol.81]* EPA further runs the Refrigerant Management plan[4].

In August 2017, the US Court of Appeals for the District of Columbia overturned EPA directives to ban high GWP refrigerants like R404A, R134a, R407C and R410A. Chemours, Honeywell and the Natural Resources Defense Council appealed the decision but that appeal was rejected at the beginning of 2018. Now the three have taken their fight to the Supreme Court. The U.S. Supreme Court has declined to consider a request from attorneys general from 17 states and the District of Columbia to review the U.S. Court of Appeals for the District of Columbia's decision to vacate the U.S. Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) rule. In a brief filed in late July, the attorneys general said the "D.C. Circuit's ruling goes against the clear intentions of the law and has left significant uncertainty about what the EPA's regulatory authority is in regard to the replacement of ozone-depleting chemicals, and as a result, the agency has abandoned enforcement efforts." The attorneys general also had hoped to eliminate state-by-state solutions that would prove especially burdensome for manufacturers. California continues to proceed with plans to enforce the SNAP requirements. Connecticut, Maryland and New York have announced plans to do the same. In parallel, Chemours will continue to work with a growing number of industry stakeholders, including the Alliance for Responsible Atmospheric Policy and the Air-Conditioning, Heating and Refrigeration Institute, to dialogue with the Trump Administration about building on the achievements of the Montréal Protocol by advancing the Kigali Amendment toward ratification in the United States Senate in 2018.

In California, the Air Resources Board (CARB) issued a proposed strategy paper to accelerate emission reductions of short-lived climate pollutants. Among other things, the strategy proposed to reduce HFC emissions in the state

[3] SNAP was established under Section 612 of the Clean Air Act to identify and evaluate substitutes for ozone-depleting substances. The program looks at overall risks to human health and the environment of existing and new substitutes, publishes lists and promotes the use of acceptable substances, and provides the public with information

[4] On November 18, 2016, EPA issued a final rule updating its refrigerant management regulations. While the regulation took effect on January 1, 2017, some provisions had compliance dates of January 1, 2018, and January 1, 2019. Amongst other things, that rule extended the refrigerant management requirements to common substitutes like hydrofluorocarbons (HFCs). The 2016 rule and the compliance dates currently remain in effect.

of California by 40% (from 2013 levels) in 2030. The strategy mentioned the ongoing international negotiations on the phase-down of HFCs and noted that California would implement its own phase-down if the negotiations are unsuccessful. In addition, the strategy proposed a ban on refrigerants with GWP levels greater than 2'500 and a GWP limit of 750 on refrigerants used in air-conditioning (both residential and commercial) effective in 2021. For commercial refrigeration equipment, a GWP limit of 150 was proposed effective in 2020.

In late 2016, CARB issued a revised proposed strategy paper. While the revised strategy acknowledges the Montreal Protocol agreement reached in Kigali, it continues to propose a ban on refrigerants with GWP levels greater than 2500, and indicates that additional measures may be needed to achieve the emission reduction goals. Such additional measures could include setting GWP limits on refrigerants used in air-conditioning (both residential and commercial) and commercial refrigeration equipment.

1.2.3 Canada

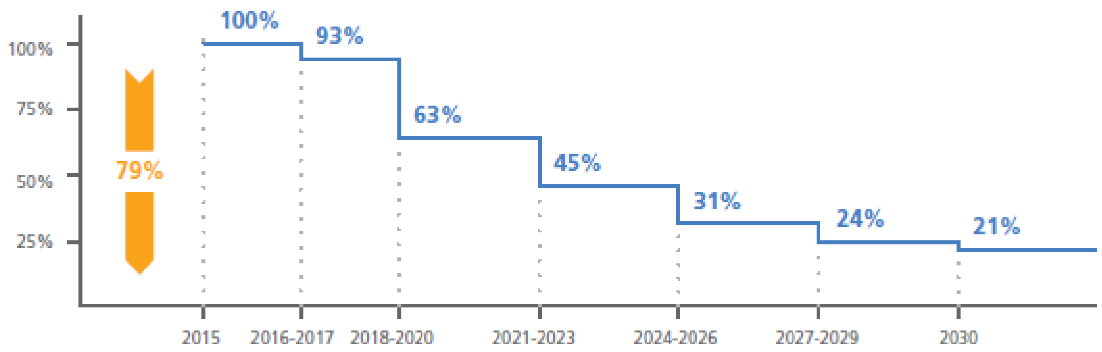
Canada's obligations under the Montréal Protocol are implemented through the Ozone-depleting Substances and Halocarbon Alternatives Regulations. The Regulations Amending the Ozone-depleting Substances and Halocarbon Alternatives Regulations (the Amendments) were published in Part II of the Canada Gazette on October 18, 2017 and enter into force on April 16, 2018. The Amendments will ensure Canada's full compliance with obligations under the Kigali Amendment before it enters into force on January 1, 2019. Canada's ratification of the Kigali Amendment will support the 2016 to 2019 Federal Sustainable Development Strategy goal of "Effective action on climate change."

1.2.4 Mexico

The UNEP Executive Committee[5] reviewed the report presented with request for the institutional strengthening (IS) project for Mexico (phase XIII) and noted with appreciation that Mexico is in compliance with the Montréal Protocol phase-out targets and the reporting obligations, and has strengthened the capacity of the National Ozone Unite (NOU) for the control of HCFCs. The Committee acknowledged that Mexico has provided support to countries in the Latin America region through information dissemination, the organization of workshops, and technical visits. The Executive Committee supports the efforts of Mexico to implement stages I and II of the HCFC phase out management plan (HPMP) and to prioritize the ratification of the Kigali Amendment.

1.3 Europe - EU legislation to control F-gases

To control emissions from fluorinated greenhouse gases (F-gases), including hydrofluorocarbons (HFCs), the European Union has adopted extensive Legislation (footnote) on a strategy of phasing down these Green House gases. For which the F-gas Regulation (footnote) is the main act covering refrigeration and heat pumping technologies.



[5] UNEP - UNIDO - 79th Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol

Fig. 1.8 HFC phase-down reduction steps [08]

The F-gas Regulation covers key applications in which F-gases are used following two tracks of action:

1. Avoiding the use of F-gases where environmentally superior. From 2015 the volume of HFCs placed on the EU market will be subject to quantitative limits which will be phased down over time. In addition, measures include restrictions on the marketing and use of certain products and equipment containing F-gases.
2. Improving the prevention of leaks from equipment containing F-gases. Measures comprise:
   - Containment of gases and proper recovery of equipment;
   - Training and certification of personnel and of companies handling these gases, and
   - Labelling of equipment containing F-gases.

The original F-gas Regulation, adopted in 2006, is being replaced by a new Regulation adopted in 2014, which applies from 1 January 2015. This strengthens the existing measures and introduces a number of far-reaching changes by[6]:

- Limiting the total amount of GWP-contribution. This is also called the "quota-regulation" and the GWP-contribution of all new sold refrigerants will be phased down in steps to nearly one-fifth of 2014 sales in 2030. This will be the main driver of the move towards more climate-friendly technologies and will result in very limited possibilities for application of high-GWP refrigerants. The use of high-GWP refrigerants has to be compensated by extra use – within the absolute amount of the available GWP-quota - of very low-GWP refrigerants. Given 0% growth in consumption since 2015 the average GWP of refrigerants used in 2030 is approximately 420, but under assumption of 5% annual growth it is 200.
- Banning the use of high GWP F-gases in many new types of equipment where less harmful alternatives, like HFO's and natural refrigerants, are widely available, such as fridges in homes or supermarkets, air conditioning and foams and aerosols;
- Preventing emissions of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life.

The phase-down of HFCs is considered to be one of the key pillars of the Regulation as it aims to reduce the amount of HFCs placed on the EU market (CO_2) by 79% by 2030, as compared to average levels in 2009- 2012. Producers and importers of F-gases are allocated annual quotas of HFCs that allow them to place a certain amount on the market. Starting in 2015 and running through 2030 these annual quotas are gradually reduced with a first reduction of 7% in 2016.

While the effects of the HFC phase-down might not be noticeable to end users at this point in time, this will change within the next three years. The first significant cut in HFC quotas in 2018 – of 37% – is expected to have a major impact on the cost of HFCs, which will become less widely available. Manufacturers are already noticing this. By 2017, all high-GWP refrigerants have suffered from sharp price increases as a result of the quota regulation laid down in the F-Gas Regulation. Figure 1.9 shows the results of the current price increase based on information from 31 service companies. As noted, the R404A, GWP 3922, had a sharp rise in prices in 2017, but prices also increased for R410A, R134a and R407C.

Apparently there is a link between price and GWP for the respective refrigerant. This is an effect of the requirements of the F gas regulation which limits the amount of fluorinated gases (measured in their CO2 equivalents) that may be placed on the European market for one year.

The European Commission monitors quarterly price developments in the sector. It recognizes that price increases are clearly related to the GWP of the refrigerant and therefore reflect expectations that successive quota reductions will increasingly benefit from the use of low GWP HFCs and natural alternatives. In addition, the

[6] There was no mention of Heat Pumps and DHWHP's in the regulation

European Commission sees the new high price as "a good incentive for stakeholders to switch to low-GWP technicians wherever and wherever possible to prevent leaks and recycle gases."

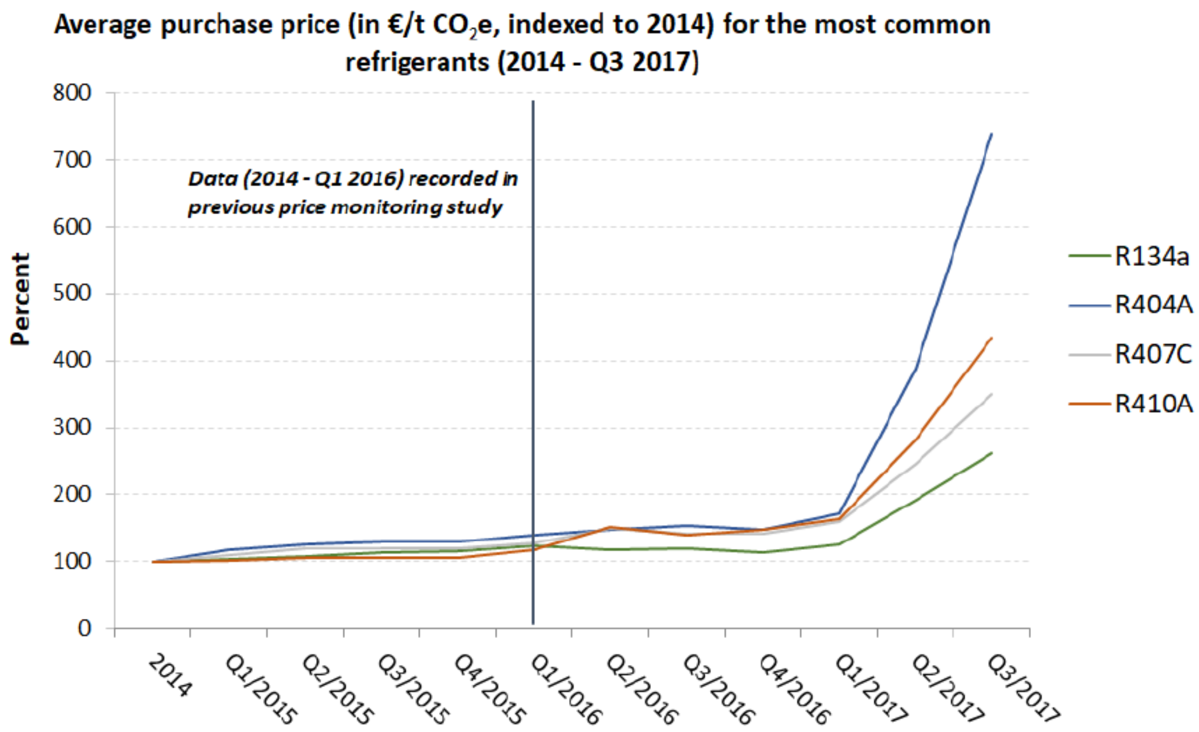


Fig 1.9 Average purchase price (in €/t CO2e, indexed to 2014) for the most common of refrigerants (2014 – Q3 2017) [30]

Considering that, as of 2017, the HFC phase-down needs to incorporate HFCs pre-charged in equipment, it is estimated that the cut in 2018 will equal 44%. Early action from manufacturers and end users is essential in anticipation of these future cuts in availability of HFCs in order to be able to reach the targets and comply with the Regulation.

What the phase-down actually means is that the average GWP of HFCs will have to fall from today's 2,000 to about 400 (approximately 420), assuming 0% growth of supply (measured in mass), by 2030 across all sectors. Natural refrigerants (and other low-GWP refrigerants like HFOs) will therefore play a major role in achieving this target.

HFC bans in new equipment in different sectors

The F-Gas Regulation also introduces bans in specific sectors on new equipment using HFCs above a specific GWP that will take effect by a certain year. This measure is crucial for ensuring that the HFC phase-down targets are achieved. The HFC ban specifies the timing for each sector to shift to refrigerants with a lower climate impact, such as natural refrigerants. Following an impact assessment by the European Commission and the compromise negotiations among the EU institutions, HFC bans have been introduced in several sectors where safe, energy-efficient and cost-effective alternatives are available across the EU.

The Regulation intends to abolish the use of very high-GWP gases (GWP above 2,500) not only in new equipment but also in existing installations. As of 2020 it will be prohibited to service existing refrigeration equipment with HFCs that have a GWP of 2,500 or above, unless these refrigerants are recycled or reclaimed. Such HFCs could still be used until January 2030 in existing equipment.

1.3.1 The Netherlands

The Dutch legislation (footnote) is in line with the European legislation and has a number decrees and guidelines specifically developed:

- Decree on fluorinated greenhouse gases and ozone layer-depleting substances
- Regulation of fluorinated greenhouse gases and ozone layer-depleting substances
- Evaluation Guideline100, version 1.2
- Evaluation Guideline 200, version 1.2

The Decree regulates inter alia the prohibitions for the directly applicable obligations from the European regulations and the principles for certification of persons and companies. The regulation provides a further interpretation of certification of persons and companies with the help of BRL 100 and BRL 200[7].

Recently, a number of changes were made to both the BRL 100 and the BRL 200 and incorporated into new versions. The changes in the BRL 100 concern, among other things. The specifications of instruments and the way these instruments are checked for the proper functioning and registration of F-gases that have been used. The changes in BRL 200 concern textual improvements, updating of references to regulations, improvements in the model of the certificate and recovery of a number of shortcomings.

1.3.2 United Kingdom

Until the UK leaves the EU in March 2019, organisation will need to comply with the regulation as at present. Post leaving the EU the intention of the Repeal Bill, published by the Government in July 2017, will be to convert existing EU law into UK law. The implications are that the F-Gas regulations will continue 'as is' until such time as they may or may not be changed. For many technical aspects such leak testing, training, records etc. this should be relatively straightforward.

The main issue is how the UK would retain and/or engage in the phasedown of the placing of F-gases in the market, which as noted above is the key facet of the current EU F-Gas regulations. The phase-down is at EU level and production and import quotas are set and monitored at EU level.

The UK is a signatory to the Montreal Protocol on ozone depleting substances. In 2016 the 'Kigali Amendment' to the Montréal Protocol was adopted by nearly 200 countries including the EU/UK. This creates new international controls on HFCs and introduces an international phase-down in HFC production and consumption. It is therefore reasonable to assume that in the UK, future phase-down regulation will probably be structured and applied in a similar manner as at present under the EU regulations.

The final position is unlikely to be clarified until well into the Brexit negotiations.

Cooling Post[8] reports that the UK Department for Environment, Food & Rural Affairs (DEFRA) and representatives from the UK groups have expressed a desire to stay within the European F-gas phase down mechanism, and the European Commission is said to be preparing for how the EU HFC quota system will operate once the UK leaves the EU.

The Commission recognises that reference values held by UK-based companies would need to be adjusted to exclude quantities placed on the UK market. Data is currently being collected to determine what the remaining

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[7] BRL – Assessment Guideline which is a process certificate for the 'Design, Installation and Management of Technical Installation' in Buildings

[8] The Cooling Post is an independent online magazine dedicated to the global air conditioning, refrigeration and heat pump industry.

EU27 market share amounts to. The adjusted reference value would allow UK-based companies to continue placing HFCs on the EU27 market post Brexit and would ensure the corresponding supply of HFCs to the EU27 market.

The Commission maintains that this approach is consistent with that for companies from other non-EU countries, which currently hold a reference value.

If the UK leaves the EU without a deal, the UK will leave the EU F gas system from 30 March 2019. Before 30 March 2019 you should continue to use your EU quota to place HFCs on the UK market. After 30 March 2019, a business will need a UK HFC quota if the business places on the UK market, HFCs equivalent to 100 tonnes or more of carbon dioxide (CO_2) per year. This total includes any imports to the UK from the EU.

The Environment Agency will manage a new UK F gas system, including UK HFC quota allocation which will be used to:

- apply for a UK quota
- report on activities

1.3.3 Switzerland

In Switzerland, the legal basis for refrigerants are regulated by Annex 2.10 of the Chemical Risk Reduction Ordinance (ChemRRV SR 814.81)[9] (ChemRRV 2016; UVEK 2014). The ChemRRV provides an extended list of substances that were prohibited or restricted for use as refrigerants due to their impact on the ozone layer and climate (**Fout! Verwijzingsbron niet gevonden.**.9).

From 1 September 2015 on, the ChemRRV implemented adaptations to the existing restrictions of refrigerants stable in the atmosphere (BAFU 2015c). Charge restriction values (e.g. R134a systems with > 100 kW cooling capacity: 0.4 kg/kW) were defined for the permitted amount of refrigerant per cooling capacity produced, and the use of waste heat was considered. The leaflet (BAFU 2015a) gives a summary about the handling of refrigerants. A detailed overview of the use of refrigerants is available online by the Swiss Federal Office for the Environment (BAFU 2015b)[10]. A special licence is required for handling refrigerants, according to the ordinance (VFB-K, SR 814.812.38)[11] (UVEK 2007).

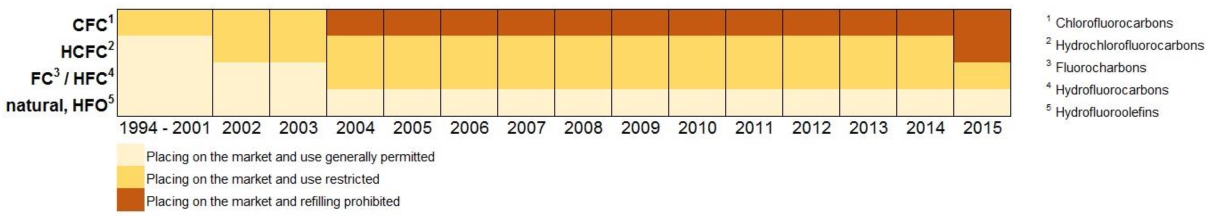


Figure 1.9: Graphical presentation of the temporal development of the refrigerants regulation in the Chemical Resik Reduction Ordinance (ChemRRV) (source online: www.bafu.admin.ch/chemicalien).

1.3.4 France

France is following the European line on Greenhouse gases has translated this into a policy approach, which is extensively described under 'Substances à impact climatique, fluides frigorigènes' at the website of the Ministère de la Transition écologique et solidaire.
The national regulations on greenhouse gases aim to define the practical modalities for the application of

9 https://www.admin.ch/opc/en/classified-compilation/20021520/index.html
10 http://www.bafu.admin.ch/chemikalien/01415/01426
11 https://www.admin.ch/opc/de/classified-compilation/20041557/index.html

Regulation 517/2014. It is essentially contained in Articles R. 543-75 to R. 543-123 of the Environment Code and in the decrees of February 29, 2016.
Because of their strong contribution to global warming, the European regulation organizes the phase-down of HFCs by a degressive quota mechanism. This regulation also provides for absolute prohibitions for certain uses in the coming years. Degressive quotas will lead to an increase in the price of fluids and thus increased operating costs for companies using HFC equipment. Companies that anticipate the substitution of HFCs will avoid this increase in operating costs and will also have the time needed to define the most technically and economically efficient solutions with their suppliers.
To best prepare for the substitution of HFCs, companies can rely on guides:

- The Ministry of the Environment has issued a very comprehensive report [44] to inform holders of refrigeration / air conditioning equipment and to provide good examples of substitution.
- The European association Environmental Protection Association (EIA) has published a teaching guide (footnote) to properly address substitution.

EREIE, Cemafroid and Armines have also drafted a study on alternatives to HFCs, financed by ADEME, AFCE and Uniclima. This report is more detailed on a technical level.
A number of alternative working fluids and their acceptance is listed in a clear table showing some restrictions of flammable refrigerants in the safety group categories A2L, A2 and A3. This is not affecting small residential heat pumps and heat pump water heaters.

2 Refrigerants

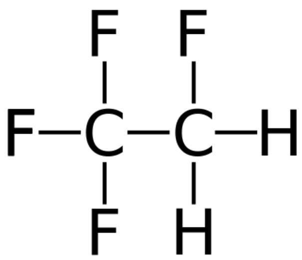
The first cooling fluids for commercial refrigeration and residential cooling processes, included chloromethane (CH_3Cl), sulphur dioxide (SO_2), ammonia (NH_3), acetylene (C_2H_2), 1,2-Dichloroethene ($C_2H_2Cl_2$), dichloromethane (CH_2Cl_2) and hydrocarbons (HCs). These offer good performance, but are flammable and toxic and therewith not approved for systems in buildings. The first-generation refrigerant compounds that were in de mid-thirties were CFCs, which contain chlorine, fluorine, and carbon atoms. R-11 and R-12 are commonly known by their brand names, Freon®-11 and -12. These refrigerant are now banned in all countries that have signed the Montreal Protocol, which makes the ban practically universal. The second-generation refrigerants introduced in the fifties, such as Freon®-22 or R-22, belong to a family of refrigerants called HCFCs. These contain hydrogen, fluorine, chlorine, and carbon. These refrigerants being also greenhouse gases still have an ODP and are currently being banned under the Montréal Protocol.

The primary HCFC refrigerant used in DHW Heat Pumps is R-22. Although chlorine free refrigerants like R134a and R404A/R507A have extensively made their way as substitutes, in many international fields. R22 is still used in new installations and for retrofitting of existing systems. Despite of the generally favourable properties R22 is already subject to various regional restrictions, which control the use of this refrigerant in new systems and for service purposes due to its ODP of 0.055.

2.1 HFC/HC blends

HFCs and blends (with R134a and HC) are the third-generation refrigerants that do not deplete the ozone (zero ODP). However, they have a relatively high GWP. The most relevant refrigerants are R134a, R32, R152a, R407C and R410A. As the GWP is still not optimal they should be regarded as medium term solutions. Only R32 and R152a have an acceptable GWP of 675 and 124 and can be seen as alternatives for the longer term.

2.1.1 High GWP and being out-phased



R 134 a ($C_2H_2F_4$) was the first chlorine free (ODP = 0) HFC refrigerant tested comprehensively. It has the formula CH_2FCF_3 and a boiling point of −26.3°C (−15.34°F) at atmospheric pressure. It is used world-wide in many refrigeration and air-conditioning units. The temperature levels of the discharge gas and oil are lower than with R12 and, therefore, substantially lower than R22 values. Good heat transfer characteristics in evaporators and condensers (unlike zeotropic blends) favour particularly an economical use. Besides used as a pure substance, R134a is also applied as a component of a variety of blends.

R134a is characterized by a comparably low GWP (1430). It will be allowed until 2022 in commercial hermetically sealed equipment (GWP < 2500 according to F-gas regulation). In 2022 the limit to GWP will be set to 150, thus making R134a less generally applicable. There is a number of exceptions in commercial refrigeration equipment[12].

In view of future use restrictions (e.g. EU F-Gas Regulation), R134a, as used by a large part of the manufacturers for DHWHPs, will continue to be applicable for a longer time to come [07]. On the other hand, the tendency of the industry in this market segment is to move towards natural refrigerants when it is technologically safe and economically feasible. In larger cascade heat pumps, it is used at the higher temperature cycle, with R410A for the low temperature cycle.

R410A is a near-azeotropic blend of difluoromethane (CH_2F_2 = R32) and pentafluoroethane (CHF_2CF_3 = R125)

[12] Refrigerators and freezers for commercial use (hermetically sealed equipment) that contain HFCs with GWP of 150 or more. Multipack centralised refrigeration systems for commercial use with a rated capacity of 40 kW or more that contain, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 150 or more. Except in the primary refrigerant circuit of cascade systems where fluorinated greenhouse gases with a GWP of less than 1 500 may be used

(high GWP of 2088) . It is the leading HFC refrigerant for replacing R22 in positive displacement residential and light commercial air-conditioning and heat pump systems. As it has nearly 50% higher volumetric cooling capacity and significantly higher pressure than R22, it should be used only in systems specifically designed for R410A.
At high condensing temperatures, energy consumption/COP initially seems to be less favourable than with R22. This is mainly due to the thermodynamic properties. On the other hand, very high isentropic efficiencies are achievable (with reciprocating and scroll compressors), whereby the differences are lower in reality. Added to this are the high heat transfer coefficients in evaporators and condensers determined in numerous test series, with resulting especially favourable operating conditions. With an optimized design, it is quite possible for the system to achieve a better overall efficiency than with other refrigerants.
However, it has a high GWP of 2088 similar to R22[13]. Since R410A allows for higher COP ratings than a R22 system, by reducing power consumption, the overall impact on global warming of R410A systems will be substantially lower than that of R22 systems.
Application is typically in new large capacity residential and commercial air conditioning and heat pumps. Cascade systems are capable of reaching temperatures of up to 80 °C for Domestic Hot Water in collective system often use R410A in the low temperature cycle and R134a in the high temperature cycle.

R407C is intended as a replacement for R22. It is a mixture of hydrofluorocarbons used as a refrigerant. It is a zeotropic blend of difluoromethane (R32), pentafluoroethane (R-125), and 1,1,1,2-tetrafluoroethane (R134a). Difluoromethane serves to provide the heat capacity, pentafluoroethane decreases flammability, tetrafluoroethane reduces pressure.

[13] HFC410A is included in the U.S. EPA SNAP de-listing of HFCs that will no longer be acceptable in new equipment in certain end use applications in the U.S. market

Table 2.1 – Overview of high GWP refrigerants available for DHW HP's

Refrigerant		GWP	Flammability	T critical [°C]	P critical [bar]	Nat. boiling point [°C]	Market	Energy Efficiency	Benefits	Limitations
R22	CHClF2	1760					The most used refrigerant in the world, for commercial refrigeration, industrial processes and mainly air-to-air conditioning systems. Its refrigerant bank is estimated to 1.6 million metric tonnes at the global level	Reference for the validation of its substitutes. COPs of their successors are in the same range as that of HCFC-22		Refrigerant is being banned and phased out, but still illegally traded in a number of countries
R134 a	CH2FCF3	1300	A1	101.08	4059.3		Most widely used in HWHP applications, as well as in small domestic HP as inlarge cascade HP for high temperatures	R134a is a reference for its replacement candidates for the different applications.		Exhibits lower pressures than R407C therefore a 50% larger compressor displacement required for a similar capacity - can make the compressor more costly.
R410A	R-32/125 (50.0/50.0)	2088	A1	72.8	48.6	-48.5	Massively used in air-air conditioning for split and centralized systems	Slightly higher than that obtained with HCFC-22 in climatic conditions with condensation temperatures up to 40°C. Beyond, especially from 55°C of condensing temperature, energy efficiencies deteriorates.	Exhibits higher pressure than R407C resulting in smaller components and less refrigerant charge.	The maximum heating temperature will be limited both by compressor discharge temperature and the relatively low critical temperature of 72.5°C. R-410A has no replacement candidate yet and its GWP is a threshold for prohibited marketing by the European regulation.
R407c	23% R32; 25% R125; 52% R134a	1770	A1	86.74	4629.8		R-407C is used in small and medium capacity commercial refrigeration and in roof-top type systems; in particular during the intermediate period where compressors designed for HCFC-22 were more available than that designed for R-410A or R-404A.	The energy efficiency is similar to that of HCFC-22, even though adaptations have to be done. However, in low temperature refrigeration, frost appears quickly because the initial evaporation temperature is lower.	R-407C has been designed to replace strictly HCFC-22 with the same volumetric capacity. By changing the expansion device and going from an alkyl-benzene oil used or HCFC-22 to POE oil adapted to HFC, the retrofit from HCFC-22 to R-407C is possible.	Refrigerant is being phased out. It will not be replaced immediately because of its GWP, but it will not be used on the long term and is replaced by R-404A on one side and R-410A on the other.

2.1.1 HFC alternatives with low GWP

R32 – CH2F2 is very different from R134a yet it suits many products using R32 in the market, such as the Daikin air-to-air heat pump and a number of other brands and products. Its flammability is classified at A2L, and GWP is 675. The refrigerant shows good theoretical performance.

R32 is not a retrofit gas. It is suitable for new equipment designed for R32 applications that commonly use R410A. R32 is designated as flammable and is therefore not suitable as a drop-in replacement for R410A. A comparison of R32 to R410A is given by Danfoss. An essential barrier for the broader application as a pure substance so far are the flammability and the high discharge temperature [07]. Also the high pressures in the compressor are a challenge.

In DHWHPs R32 is an option as alternative for CO_2 in small systems where next to hot water also space heating/cooling is generated. The elevated condensing temperatures for DHWHP could be crucial here.

Looking at these properties and taking into account the additional effort for emission reductions, R32 will increasingly be used as a refrigerant in factory-produced systems (A/C units and heat pumps) with low refrigerant charges. Previously performed tests with R32 were satisfactory and it seems possible that this substance could stay in the market [52, 53] as the due to the low refrigerant charge the TEWI Factor is very low [02]. The HVAC industry in China is next to CO2 for water heaters focusing on this refrigerant. R32's GWP level is moderate with 675, but only one third compared with R410A and R32.

Although R32 has significance in the market, it has some disadvantages, such as a high discharge temperature. As a result, a dozen new alternative blends have appeared. Many are claiming a closer capacity match to R410A, reduced energy consumption benefits and lower discharge temperatures. Thus, refrigerant mixtures are becoming more and more common. In 1965, the ASHRAE Guide and Data book Fundamentals and equipment published three azeotropic refrigerant mixtures: R500, R501 and R502. The status in the fast changing market can be found on the ASHRAE website (footnote). What is the status briefly?

One of the features of zeotropic blends is the temperature glide. At constant pressure, the mixture boiling temperature (bubble point) is lower than the condensing temperature (dew point). By matching the temperature glide of the refrigerant with the temperature glide of the fluid to cool in an air conditioning or chiller system, a 10 to 15% COP improvement can be achieved with a temperature glide of 5.5°C. If the application allows a temperature glide of 10°C, the COP of the heat pump could be improved by up to 30% theoretically [46].

R152a ($C_2H_4F_2$) is in a way the "unlucky" refrigerant that is often overlooked in favour of other refrigerants. It was considered as potential refrigerant during the transition from ozone depleting refrigerants in the nineties, and it was again considered as a replacement for R134a in mobile air conditioning systems a decade ago. Both times other refrigerants have been prioritized over the R152a [47].
This refrigerant has a critical temperature lower than 400 K, and Is usually used as a component in a mixture and can substitute, in a transitional manner, R134a - McLinden, 2014 [48]. The literature available regarding HP applications is limited, proving that the research on this refrigerant is still at an early stage. Ho-Saeng Lee et al. [31] performed a study in a water source heat pump system using a R152a/R32 mixture with varying R32 composition. It was found that the tested system required up to 13.7% lower compressor power compared to an equivalent R22 system, along with an increased COP (up to 15.8%); the refrigerant charge diminished of up to 27%. On the other hand, the compressor discharge temperature increased up to 15.4°C.

Compared to R134a, R152a is very similar with regard to volumetric cooling capacity (approx. -5%), pressure levels (approx. -10%) and energy efficiency. Mass flow, vapour density and thus the pressure drop are even more favourable (approx.-40%). R152a has been used for many years as a component in blends but not as a single substance refrigerant until now. Especially advantageous is the very low GWP of 124. R152a is flammable – due to its low fluorine content – and classified in safety group A2. As a result, increased safety requirements demand individual design solutions and safety measures along with the corresponding risk analysis [07].

RHR-1 is a mixture of R152a and R32 to improve energy efficiency and environment friendliness of space heating air source heat pumps (ASHP). It was proposed by Xiangrui Kong et al [01]. A theoretical model for refrigerants performance analysis was developed based on refrigeration cycle equations integrating REFPROP. The performance of RHR-1 including heating COP, compression ratio and discharging temperature were simulated and compared to R134a, R410A, R407C and R22. The following conclusions were obtained from this study:

1. RHR-1 has no ODP and relatively low GWP compared to commonly used refrigerants including R134a, R410A, R407C and R22.
2. The COP of RHR-1 is in the range of 2.43 to 4.93, which is higher than other candidates in most design cases. The compression ratio and the discharge temperature are in the middle levels among the compared refrigerants.
3. RHR-1 might be a reasonable refrigerant in ASHP for space heating due to its high COP, appropriate compression ratio and discharging temperature, no ODP and low GWP.
4. According to the regression analysis, the temperature difference between outdoor air and supply water of ASHP using RHR-1 is suggested to be controlled within 47.5 °C to get a reasonable COP
5. A constant water flow control strategy was suggested to improve the energy efficiency of ASHP units under partial heating load cases.

2.4 Low GWP HFO's (Hydrofluoroolefins) as alternatives

HFOs are part of the fourth-generation refrigerants and are essentially unsaturated HFCs with GWPs of around 20 or less. There is a growing focus on this new group of low GWP refrigerant family. R1234yf is in all new cars sold in EU, and 1234ze(E) or 1233zd(E) are used in many new chillers. The main members of this group are currently R1234yf, R1234ze(E) and blends with non-flammable HFCs.

For DHWHPs a number of research/test are available and published upon by research institutes such as Oakridge National Laboratory and KTH. Recently Nawaz et al. [04] conducted an extensive study evaluating the performance of a wide range of low-GWP refrigerant blends containing R1234yf and R1234ze(E) for residential split and commercial rooftop air conditioning systems. It was concluded that HFO blends are promising replacements for R134a and R410a, since there was only a marginal performance difference.

Although there have been multiple studies of the performance of HFOs as low-GWP refrigerants for HVAC&R applications, the available literature exploring the potential of these refrigerants for HPWH applications is scarce. (First HFO conference in Birmingham in 2018).

R1234yf is a low GWP alternative refrigerant for R134a with similar pressure but with slightly smaller volumetric efficiency and cooling capacity. The GWP of R1234yf is much lower than R134a (1430), and this is one of the main reasons why it has been selected by most of the car manufacturers as replacement for R134a in Europe for automotive A/C. R1234yf is an important ingredient in the most promising low-GWP HFC blends.

P.Makhnatch et al. [54]
It is estimated that 7-20% of HFC-134a emissions degrades into TFA. In contrast, HFO-1234yf that replaces HFC-134a in many applications reacts much faster and completely decomposes into TFA. It should be noted, that decomposition is not similar for all HFOs, as for instance less than 10% of HFO-1234ze(E) decompose into TFA. Considering recent actions to reduce the use of HFCs, it can be expected that the amounts of HFO refrigerant or HFO containing bends will increase in future and replace HFCs in some applications. Several studies therefore predicted TFA levels associated with the replacement of HFC-134a refrigerant with HFO-1234yf. The studies predict peak TFA levels of 1.26-1.70 μg/L that are 60-80 times lower than accepted safe level. The difference of these results compared to the previous study can be explained by much lower lifetime of HFO-1234yf (16.4 days) compared to HFC-134a (13.4 years) that leads to the spatially variable degradation products with more localized peaks and less global transport when compared HFO-1234yf to HFC-134a.
Still, these results can be considered as underestimated as they do not take into account widespread use of HFO-1234yf in other than MAC applications, which gains popularity as a component of many refrigerant blends. Also, considering the TFA concentration variations caused by seasonal precipitation patterns and the possibility that TFA will accumulate in some closed aquatic systems after deposition the ratio between the estimated concentration in surface water and safe concentration limit for aquatic ecotoxicity appears not to be sufficiently large.
Overall, preliminary analyses indicate that global replacement of HFC-134a in MAC systems with HFO-1234yf at today's level of use is not expected to produce harmful levels of TFA. But given the use of HFO-1234yf beyond MAC sector, and potential TFA formation from some other HFOs, the potential TFA toxicity to ecosystems is still an open question.

R1234ze(E) (trans-1,3,3,3-Tetrafluoroprop-1-ene, $CF_3CH=CHF$) is another low GWP HFO alternative to R134a with similar pressure but with smaller volumetric efficiency and cooling capacity. Its GWP is < 1. Originally developed for foam blowing the production cost is lower than for R1234yf. In addition, the high molecular weight this is among the reasons why R1234ze(E) is being considered for replacing R134a in centrifugal chillers for large A/C systems. R1234ze(E) is an important ingredient in future HFC blends just like R1234yf.

According to the recent announcement from Honeywell, the company has started full-scale production of R1234ze(E).

R1234ze(E) is used in newly designed systems as alternative for R134a, but current application is mostly in chillers. This is probably due to quite lower volumetric cooling/heating capacity compared to R134a. R1234ze(E) is less flammable than R1234yf but research on flammability is ongoing [KTH].

It should be noted that R1234ze has 2 isomers, R1234ze(Z) and R1234ze(E), with rather different properties. R1234ze(Z) has a high boiling point (9.8°C) associated with a higher critical temperature (153.7°C) and a volumetric capacity roughly 50% lower than R1234ze(E). Therefore R1234ze(Z) could be primarily utilized in specific applications like high temp heat pumps, whereas R1234ze(E) will show operating conditions and applied costs much more in line with R-134a according to system and compressor sizes.

Up to day there was no big incentives to use R1234ze(E). With the adoption of new F-gas regulation that aims to significantly reduce use of HFC, and with introduction of standards that will facilitate use of mildly flammable refrigerants, it is expected to see the increase of interest to this refrigerant.

2.5 Natural Refrigerants

Natural refrigerants are the green alternative with a very low environmental impact having zero ODP and ad a minimal to zero GWP. Natural refrigerants can be divided into three families:

- Carbon Dioxide
- Hydrocarbons (Propane, isobutane)
- Ammonia

Each of these families have their specific application areas and especially Carbon Dioxide and Hydrocarbons are very suitable for small hermetic heat pumps in domestic applications, performing generally well in DHWHPs.

2.5.1 Carbon Dioxide (CO_2) - R744

Carbon dioxide is the benchmark for the calculation of GWP, and is extremely respectful of the environment in terms of global warming, while having no impact on the ozone layer. In the past, it was used extensively, until the advent of CFCs and HCFCs. In addition to good heat transfer, CO_2 offers high volumetric cooling capacity, which makes it possible to use small volume compressors, as well as excellent thermodynamic efficiency at low and medium temperatures.

In Japan, the Eco Cute hot water heat pump using CO_2 as a refrigerant has been a run-away success over the past decade. By 2020, the Japanese government aims to reach 10 million R744 Eco Cute units. In Europe DHWHPs mainly run with the refrigerant R134a. Japanese experience shows that CO_2 HP technology is a well-proven and well-tested solution for DHW production. Currently only a trickle of activity is seen in Europe, with a handful of manufacturers active. Sanden, a Japanese manufacturer that has a French manufacturing base, has already launched a CO_2 DHWHP in France. Denso sells its CO_2 technology through Stiebel Eltron in Europe – though it is still very much a niche product. As the Heat Pump Water heater with CO2 as refrigerant is esteemed to be mainly convenient with a high consumption of hot water.

CO_2 heat pump water heaters have the potential for higher efficiency under certain conditions, e.g. hot water set points above 60°C or very low ambient temperatures. The CO_2 HPWH cycle is transcritical, operating at much higher temperatures and pressures than conventional subcritical cycles. The transcritical cycle operation provides a large continuous temperature glide and can offer a higher supply temperature with limited capacity loss. CO_2 HPWH systems are currently used in Asia and Europe for water heating. Development is needed to configure the technology for replacement and integration in the US water heating market [06].

Even though the system has shown promising results and has been widely accepted commercially in Japan and other areas, the performance of a CO_2 heat pump is severely affected (negative or positive, this is also the case with other refrigerants) by the air temperature as well as the inlet and outlet water temperatures (Lin et al. [49]).

2.5.2 Hydrocarbons (HCs)

Hydrocarbons were widely employed until the advent of CFCs and HCFCs, both in the homes and in industry. Today there is renewed interest in their use. Almost all domestic fridges currently sold use hydrocarbons (e.g. butane R600a) and considerable number of large European heat pump manufacturers are switching towards hydrocarbons for domestic space and hot water heating. The risks of using hydrocarbons are now very low, thanks to the reduced quantity of HC present in the devices, and to the provisions of regulation EN378. A recent report by LIFE FRONT[14] gives a good overview of the state of developments in the market and the legal challenges [29].

HC refrigerants are natural compounds that are generally available at a low cost and have excellent thermodynamic properties. HCs have been widely used in petrochemical applications, where the use of flammable substances is well understood. They are chemically stable and their application outside the petrochemical area is rapidly growing. Domestic refrigeration is an obvious application; here, safe systems are easy to achieve because the system charges are small (smaller than contained in a cigarette lighter, in many cases). Many small and medium commercial applications are also feasible for various HC refrigerants, where safety requirements are adhered to [29].

HC refrigerants include propane, propylene, butane, ethane, isobutene, and isopentane. These refrigerants (e.g., propane and propylene) have been used for over 10 years in small capacity chillers (up to 200 kW) in Article 5 countries and in some non-Article 5 countries. The recent development of domestic refrigerators and freezers using HCs as refrigerants has contributed to the use of these refrigerants in small air-conditioning units. Air-conditioning units using HC technology have a high energy-efficiency rating and can be designed to achieve good safety measures.

R290 and R600a

Heat pump models using propane (R290) as refrigerant from manufacturers like Heliotherm, Glen Dimplex, Alpha Innotec and NIBE have had their introduction on the European market in 2017 at the ISH in Frankfurt.

The main drawback of propane to be used as a refrigerant is the flammability. Propane is classified as A3 (non-toxic, highly flammable) by ASHRAE (2009). Therefore, due to strict regulations (EN 378-1:2008), propane has been used in small installations or in open vented locations. For instance, a propane heat pump can be installed in places with general occupancy like hospitals, courts, schools, supermarkets, hotels, restaurants, etc., if the system is installed in a separated vented enclosure and the refrigerant charge is lower than 5 kg.
Converting DHWHPs from R134a to R290 is possible, but takes a thorough consideration of a number of technology adaptations. Suppliers and manufacturers like Danfoss [50} are working, publishing and presenting [51] on this.

Apparently, the safety issues due to the combustibility of hydrocarbons still prevent the wider use of them in larger systems. Many publications have therefore presented results that focus on understanding and managing the combustibility of these refrigerants, especially propane. Such studies will contribute to the safer design of refrigeration equipment using combustible refrigerants.

In order to ensure safe use of combustible refrigerants, refrigerant charge and location are limiting factors for such systems. Some studies therefore focus on minimizing the charge when using combustible refrigerants. A study presented at the recent Gustav Lorentzen Conference 2018 by Klas Andersson [24] showed that with the right system it is possible to create a heat pump system that can deliver up to 10 kW heating capacity with as

[14] LIFE FRONT is a demonstration project funded under the LIFE programme of the European Union (Climate Change Mitigation 2016 priority area). It aims to remove the barriers posed by standards for flammable refrigerants in refrigeration, air conditioning and heat pump (RACHP) applications.

little as 100 g of propane in the system, indicating that it is possible to meet a large cooling needs with a small amount of propane. The results presented by Klas were received with great interest from the audience during the conference.

Klas Andersson [24]: The evaporator and condenser were asymmetrical plate heat exchangers with small channel height (< 1 mm) on the refrigerant side. They were developed and manufactured exclusively for this project with a new type of press pattern, including a special, small volume sub-cooling section at the end of the condenser. A DC-motor scroll compressor for AC in electric vehicles was used, characterized by small internal volumes, small oil charge and wide capacity range (800-9000 rpm). A PAG-type oil was used, which however seemed to cause some problems with heat transfer and pressure drop in the evaporator.

The paper presents test results for a heating capacity range of 2-10 kW. The performance was reasonable in this range with a charge of 100 g of propane (-1<T2<5°C, 30<T1<55°C). The charge that is required is determined at the lowest capacities, at low compressor speed and high evaporating pressures. A lower charge is beneficial at higher capacities.

In Europe, a review of the standard governing the amount of refrigerant charge for combustible refrigerants is underway. The possibility of changing the limit from 150 g to 500 g is explored. In the U.S., on the other hand, the charge amount is limited to 57 g according to safety standards.

2.5.3 Ammonia (NH_3)

Ammonia is a natural refrigerant known for its very high performance in refrigeration cycles. It has been used in the refrigeration industry since the 1930s. It has a very low boiling point and high energy efficiency thanks mainly to its very high latent heat of evaporation.

In contrast to its excellent refrigerant properties, ammonia is toxic and inflammable, and is not compatible with copper circuits. To get around these problems, systems with a secondary fluid are used (thus avoiding direct contact) together with glycol-water or carbon dioxide. The complexity of these systems means that ammonia is generally used in large industrial plants, supermarkets or sports facilities, rather than in DHWHPs

Table 2.2 Overview of alternative refrigerants for DHWHP's

Refrigerant		GWP	Flammability	T critical [°C]	P critical [bar]	Nat. boiling point [°C]	Market	Energy Efficiency	Benefits	Limitations
R744	Carbon Dioxide (CO2)	1	A1	31.80	7377.3				Low global warming potential. Flexibility to accommodate relatively higher temperatures for water (~80 C which can be helpful for some industrial processes) Suitable for extreme cold climate environment	A transcritical cycle is necessary. This makes it most suited to domestic hot water (DHW) when heating incoming mains water to a relatively high temperature. Requires appropriate infrastructure due to higher working pressures. Not suitable for the combination with space heating
R290	Propane (C3H6)	3	A3	96.7	42.5	- 42.2	Large scale introduction by European manufacturers has started in 2017 with a number of heat pumps for domestic applications	Generally, the energy efficiency is proven good in most of conditions. In principle, they present thermophysical properties that lead to energy efficiency as least equal to that of HFCs and low discharge temperatures.	No effect on global warming or ozone depletion. The costs for these refrigerants is low, but because of safety classification, additional costs can exist.	Highly flammable. Large scale commercialization of HCs is limited because of restrictive uses defined by safety standards (EN378 or ASHRAE 15) in occupied spaces.
R600a	Iso-Butane (C4H10)	0	A3							
R32	CH_2F_2	675	A2L	78.1	57.8	-52				Has a relatively high GWP
R1234yf	CH_2=CF-CF_3	4	A2L	94.7	33.8	−29	This is a pure refrigerant that can replace HFC-134a in the same systems because pressure-temperature characteristics are quasi identical. It is A2L, non-toxic and very slightly flammable in the Ashrae 34 classification.	This refrigerant presents efficiencies similar to that of HFC-134a, even if its theoretical COP is of few per cents lower.		Barriers are linked to the safe use of a low flammability refrigerant (A2L according to ASHRAE 34). Standards such as EN-378 and IEC-60335-2-40 are to be updated to take into account the low flammability.
R1234ze(E)	CHF=CH-CF_3	7	A2L	109.4	36.3	-19	This is a pure refrigerant that can replace HFC-134a in new equipments where its low volumetric capacity could be considered in their design. Its classification is A2L according to FDIS ISO 817 (low toxicity, low flammability). This refrigerant is already produced at industrial scale, as a blowing agent for insulation foams.	When this refrigerant is used in scroll or reciprocating compressors, it presents efficiencies similar to that of HFC-134a.		
R152a	$C_2H_4F_2$	124	A2	113.3	45.2	-25	HFC-152a has been assessed as a pure refrigerant in the 90s to replace CFC-12 in domestic refrigeration but it has not been used. It was primarily evaluated in the 2000s as a replacement for HFC-134a in mobile air conditioning; its GWP < 150 served as a reference to Directive 40/2006.	The HFC-152a energy efficiency is close to that of HFC-134a in mobile air conditioning and in domestic refrigeration but adaptations have to be made to take into account its evaporation pressure, which is lower than that of HFC-134a. Test results concern only prototype systems because of the lack of commercialized references.	A priori, its plausible future uses are in low-GWP refrigerant blends.	Main constraints are related to the safe use of a flammable refrigerant (Class 2).

2.6 Refrigerants in Domestic Hot Water Heat Pumps

Since the phase-down of R22 due to high ODP, R134a has been widely accepted as the refrigerant of choice for most DHWHPs on the market today. While seeking a replacement for R134a, it is critical to investigate refrigerants that do not require significant modification of the existing system configurations. A drop-in-replacement refrigerant resulting in a measurable improvement in performance will be an ideal candidate.

In order to short-list appropriate refrigerants an extensive list of potential candidates was considered. The following table lists the refrigerants down-selected for further analysis. It can be observed that most of the refrigerants have comparable properties to R134a such as critical temperature and pressure and volumetric capacity (density * condensation enthalpy difference).

Those that are suitable to be used in a given application (considering e.g. operation temperature range, safety requirements), and those that are seen as retrofit replacements to "conventional" refrigerants such as R134a, R410A.

As there is a number of different types of DHWHP, thus a number of different options for refrigerants, where there is an obvious split between single family house standalone heat pumps only supplying hot water and those also supplying space heating, and heat pumps supplying hot water in a collective domestic systems. The latter do have to supply higher temperatures and do have more constant demand over the day.

Though multiple studies have addressed the performance of HCs (pure and mixtures) for HVAC&R applications, no (there are some literatures available, please check) available literature explores the potential of such refrigerants for HPWH applications.

Among the natural refrigerants, Propane and CO_2 seem to be the most appropriate refrigerants for the DHW application (why? Give some reasons).

A study by Zühlsdorf et.al. [28] showed an increase in the thermodynamic performance of a booster heat pump, which was achieved by choosing the working fluid among pure and mixed fluids. The booster heat pump was integrated in an ultra-low-temperature district heating network with a forward temperature of 40°C to produce domestic hot water, by heating part of the forward stream to 60°C, while cooling the remaining part to the return temperature of 25°C (i.e. 35 K temperature glide on the heat sink). The screening of working fluids considered 18 pure working fluids and all possible binary mixtures of these fluids. The most promising solutions were analysed with respect to their performance under off-design conditions and their economic potential. The best-performing mixture showed a COP of 9.0 and thereby outperformed R134a by 47%. Although the mixed working fluids resulted in higher investment cost, the economic performance was comparable to the pure fluids. (The GWP of these working fluids were all <10, in some cases it can be slightly higher but still trivial increase) The mixtures showed similar performance as the pure fluids at off-design conditions. It was concluded that the mixtures 50% Propylene/50% Butane and 50% R1234yf/50% R1233zd(E) could considerably improve the thermodynamic performance of the overall heat supply system while being economically competitive to pure fluids.

Table 2.3 – Overview of refrigerants observed by Zühlsdorf et.al. [28] for Booster Heat Pumps

No.	Name of Fluid	Ref. No.:	Type	ODP, -	GWP,-	Normal Boiling Point, °C	Crit. Temp., °C	Crit. Pressure, bar	Safety Class
1	Methane	R50	HC	0	25	−161.5	−82.6	46.0	A3
2	Ethylene	R1250	HO	0	6.8	−103.8	9.2	50.4	A3
3	Ethane	R170	HC	0	2.9	−88.6	32.2	48.7	A3
4	CO_2	R744		0	1.0	–	31.0	73.8	A1
5	Propylene	R1270	HO	0	3.1	−47.6	91.1	46.7	A3
6	Propane	R290	HC	0	3.0	−42.0	96.7	42.5	A3
7	Dimethyl ether (DME)	RE170	HC	0	1.0	−24.0	127.3	53.4	A3
8	Iso-Butane	R600a	HC	0	3.0	−11.7	134.7	36.3	A3
9	Butane	R600	HC	0	3.0	−0.5	152.0	38.0	A3
10	Iso-Pentane	R601a	HC	0	4.0	27.8	187.3	33.8	A3
11	Ethyl ether (DEE)	R610	HC	0	4.0	34.6	193.7	36.4	A3
12	Pentane	R601	HC	0	4.0	36.1	196.6	33.7	A3
13	Hexane		HC			68.7	234.5	30.3	
14	Heptane		HC			98.4	267.0	27.4	
15		R1234yf	HFO	0	4.0	−26.0	94.7	33.8	A2L
16		R1234ze(E)	HFO	0	7.0	−19.0	109.4	36.4	A2L
17		R1234ze(Z)[a]	HFO	0	<10.0	9.8	150.1	35.3	A2L
18		R1233zd(E)	HFO	0	4.5	17.9	166.5	36.2	A1

3 Energy efficiency

By using an integrated approach to DHWHP equipment design and selection, the opportunities to improve energy efficiency or reduce energy use can be maximised. This approach includes:

- Ensuring minimisation of cooling/heating loads;
- Selection of appropriate refrigerant;
- Use of high efficiency components and system design;
- Ensuring proper installation, optimised control and operation, under all common operating conditions;
- Designing features that will support servicing and maintenance

The largest potential for DHW improvement comes from improvements in total system design and components, which can yield efficiency improvements (compared to a baseline design) that can range from 10% to 70% (for "best in class" unit). One of the first can always be minimisation of demand. On the other hand, the impact of the refrigerant on the Energy Efficiency is usually relatively small, yet not to be ignored – typically ranging from +/- 5 to 10%.

3.1 Energy and refrigerants

The GWP is a useful metric to compare different refrigerants. However, over 80% (if not more) of the global warming impact of HP systems comes from indirect emissions generated operating the HP (i.e. electrical power consumption), with a lower proportion coming from the use/release (direct emissions) of GHG refrigerants through leakage (2%/year) and recovery [02]. To translate this into numbers the factor describing the Total Equivalent Warming (TEWI) is used (see Appendix 4).

It is obvious that a system with a high COP and dependent on the application and climate zone the SCOP (Seasonal COP) has a good TEWI score, when low GWP refrigerants are used. However, power consumption of the heat pump in relation to efficiency and emissions of power generation become very important factors where in general the benefits of low GWP refrigerant to environment may be overestimated, as it does not take into account many other affecting factors. The thesis by Longhini et. al. [02] confirms this for a number of alternative refrigerants for R134a in domestic applications.

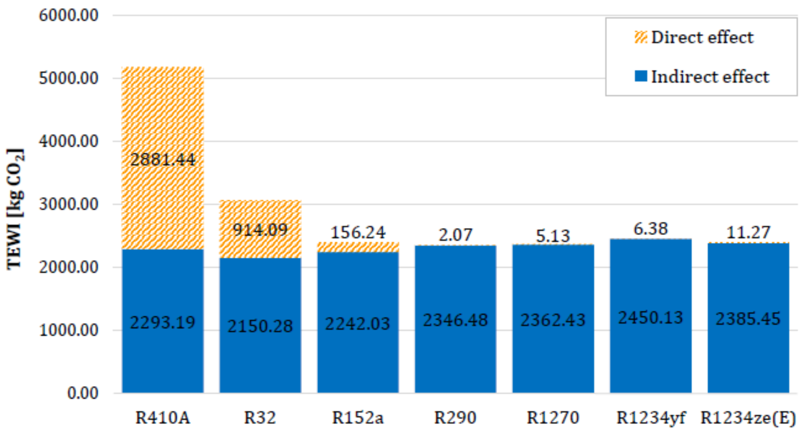


Fig 3.2 TEWI - Direct and indirect effect (radiator heating in Sweden) [02]

In order to evaluate the influence of the characteristics of the system on the TEWI, Longhini et. al. [02, 03]

performed a sensitivity analysis on three of the parameters:

- Leakage rate, this is assumed being 2%, but can in the best situation be lower than 1%. The higher the GWP, the more pronounced are the consequences of a leakage increase[15].
- Lifetime, is assumed to be 15 years, having a major impact in the indirect emissions
- Recovery factor, only influences the direct effect of refrigerant choice

Moreover, the electricity mix is of great importance as with an increased share of renewables the indirect emissions will decrease. The results in Figure 3.1 are valid for Sweden with a CO2 emission factor for the Sweden energy mix of 0.023 kg CO2/kWhe. This is justified by the fact that Sweden has a very clean energy mix for energy production, and thus does not have a large indirect effect. The lowest reduction is obtained by R32, with a reduction of 40.8%.

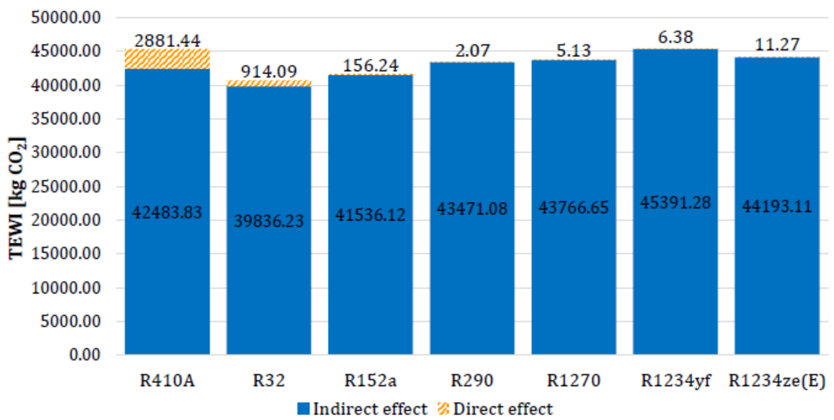


Fig 3.2 TEWI - Direct and indirect effect based upon the European energy mix (radiator heating) [02]

When evaluating TEWI with the emission factor for the European average, i.e. β=0.4261 kg CO2/kWhe, the outcome is completely different as seen in Figure 3.2. While not affecting the direct effect of the refrigerants, the increase of the emission factor shows a large increase in their indirect effect and thus in the overall TEWI. The major increases are experienced by refrigerants with lower SCOP.

It is important from this study by Longhini et al. [02, 03] to understand that the results obtained are highly dependent on the area for which they have been calculated and that these are only valid for a number of space heating conditions. Furthermore, the results may be comparable to results to be expected for DHWHP applications, but are not directly valid.

The Japanese Refrigeration and Air Conditioning Industry Association has made a study on the Life Cycle Climate Performance (LCCP) (footnote) of a number of refrigerants assuming:

- CO2 emission coefficient: 0.425[CO2-kg/kWh]
- Lifetime: 12 years
- Operation hours: 9 h/day;
- Refrigerant leakage ratio: 2%/year
- Refrigerant recovery ratio at disposal: 30%

[15] In the case of R410A, in fact, the TEWI can increase up to 41.8% for a leakage increase of 3 percentage points. When considering the HCs and the HFOs, instead, an imperceptible variation is observed, being maximum 0.066%, 0.16%, 0.19% and 0.35% respectively for R290, R1270, R1234yf and R1234ze(E). This could represent a further advantage in the usage of such refrigerants, as the number of leakage checks could be reduced and thus the maintenance cost.

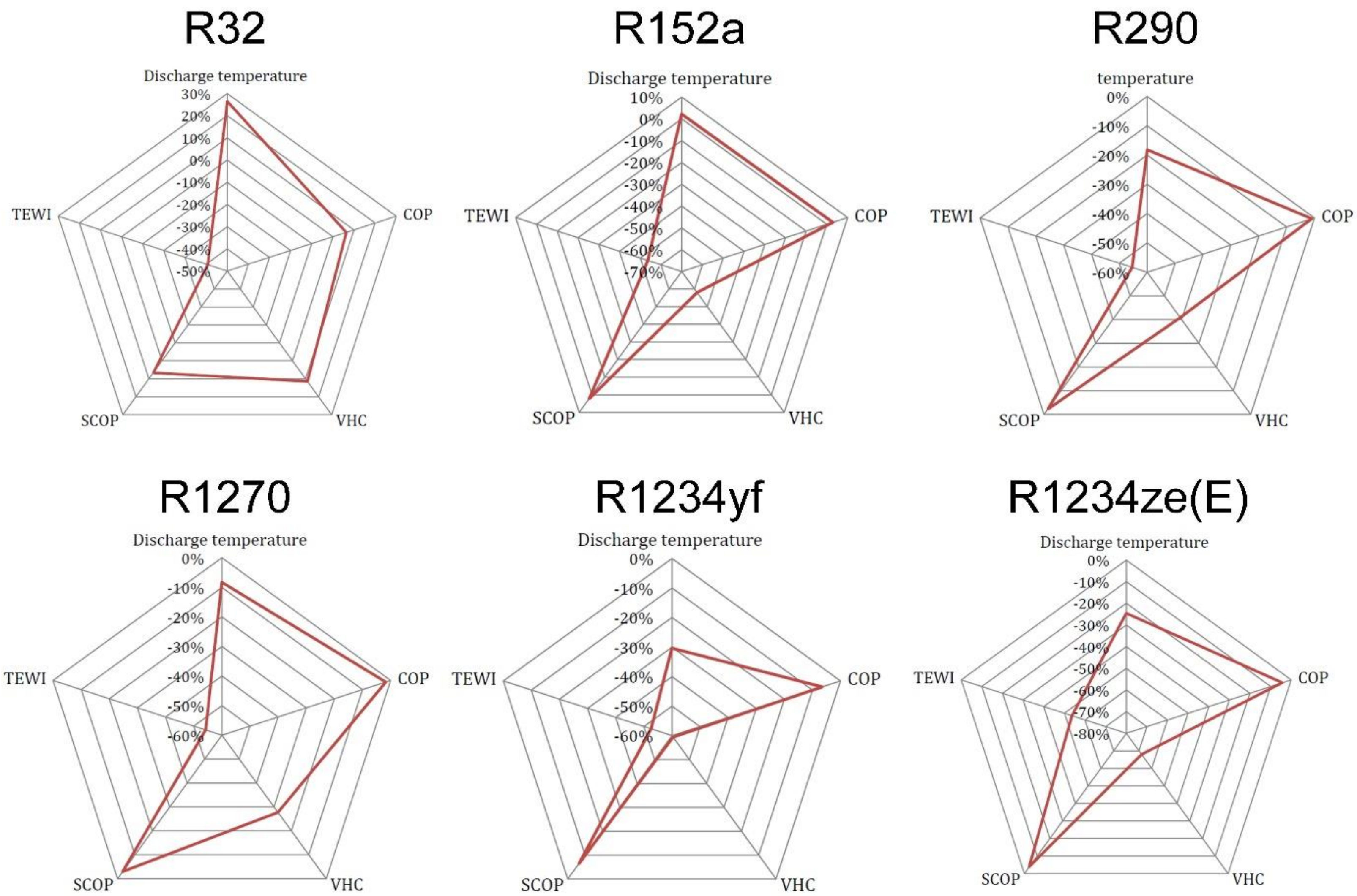


Fig 3.1 Relative difference of refrigerants performance (Discharge temperature, COP, VHC, SCOP, TEWI) compared to R410A at operating conditions corresponding to -22°C to 16°C outdoor temperature (adapted from Longhini et al. [02].

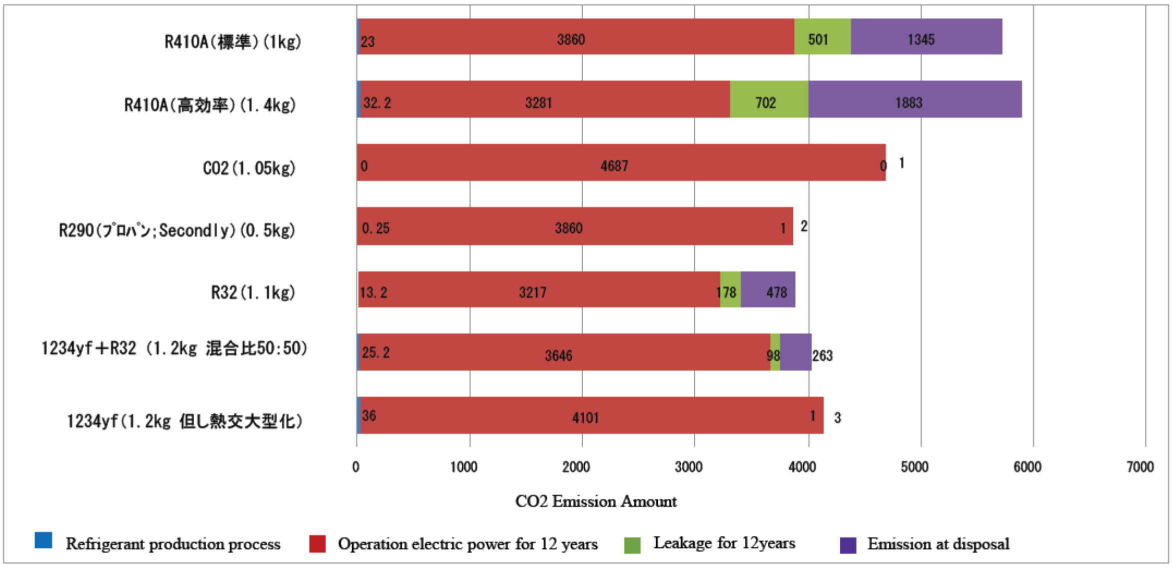


Fig 3.3 Presentation (footnote) by Japan Refrigeration and Air Conditioning Industry Association at the 5th Three Associations Meeting in Seoul November 2011

However, in practice, the LCCP is more complex than TEWI and the contribution of additionally accounted emissions is debatable. While the results given by each of the environmental metrics were different from one metric to another, TEWI as an environmental metric is simpler to use than LCCP.

SKVP requests exemptions for heat pumps

Some months ago, the Swedish Kyl & Värmepumpföreningen (SKVP) requested that the Swedish state apply for exemptions from the European Union pursuant to Article 15.4 of the F-Gas Regulation for products listed in the Ecodesign Directive Lot 1 (boilers and heat pumps), as well as Lot2 (water heaters and accumulator tanks). This is to give the heat pump industry access to refrigerants outside the F-Gas Regulation quota system in order to ensure a qualitative and energy efficient transition to new low-GWP refrigerants [4].

SKVP in their letter (footnote) mentions the following challenges and obstacles for the heat pump council [10] (check lit. ref):

- Most low GWP refrigerants are flammable to a higher or lower degree. Something that in most EU countries creates problems, as neither building rules nor industry standards have yet to be updated and adapted.
- Market prices for F-gases have risen sharply during the year, in some cases up to 1000%. Nevertheless, it has been found that most players in our industry, from manufacturer, through wholesalers to installers, are increasingly unable to obtain the required amount of refrigerant to ensure the delivery of equipment and the operation of facilities.
- The use of low GWP refrigerants requires a completely new design solution. A solution that not only needs to take into account technical, and security challenges, but also the requirements for high energy efficiency and reliability.
- The necessary components such as compressors and heat exchangers have so far been developed by the manufacturers mainly towards the industrial industry and air conditioning. The relatively small segment of heat pumps has until recently been largely unprecedented. The consequence of this is a lack of access to key components, both in number and capacity.
- The expected shortage of refrigerants can reduce the sale of heat pumps and instead lead consumers to alternative technologies, such as fossil fuel based boilers. This is contrary to the European and global targets for reducing greenhouse gas emissions.

Discussions on the effects of the F-Gas Regulation on the heat pump industry are also conducted by the European Heat Pump Association (EHPA). EHPA, the association representing the majority of the European heat pump industry, is currently in dialogue with the European Commission on the consequences of the F-gas regulation for European heat pump manufacturers.

3.2 Energy components and system design

On the basis of the small number of investigations found, it can be established that the configuration of the heat exchanger (HX) is important for the efficiency of the heat pump. This requires further research into the optimal design that can be used flexibly in a large part of the market. Theoretically, if a single component refrigerant is used (e.g. propane) and a HX with infinitely large heat transfer area, an infinitely low-temperature difference can be created between DHW and refrigerant, and thus the effect of HX on energy efficiency can be eliminated. Traditionally two main types of HX are applied, being the wrap around and the in tank spiral. Due to the size of the storage tank, the heat transfer area can be limited. The choice of an HX is thus a trade-off between the fixed cost of the HX and energy efficiency gain, where manufacturers end up making trade-off analysis and select the HX that best fits the application and the refrigerant.

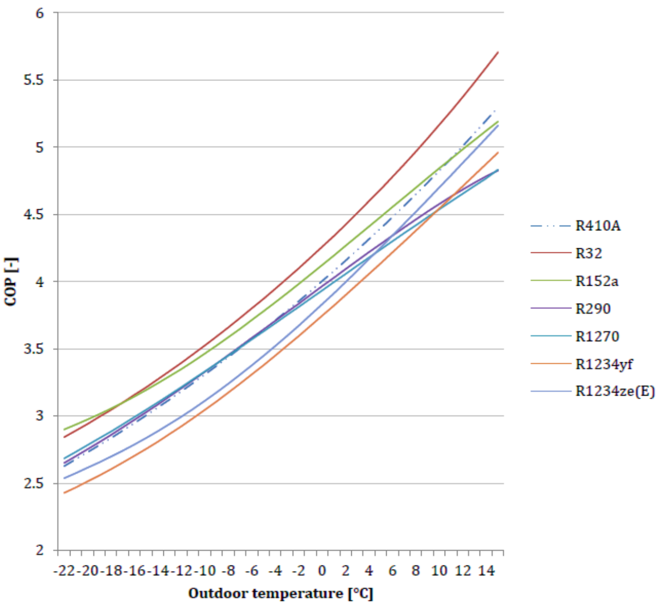


Fig 3.4 – Comparison of COP for different refrigerants [30]

Theoretical energy efficiency of pure refrigerants varies (+/- 5%), but the difference in their thermophysical properties influence the heat transfer and thus have an effect on the temperatures that have to be established in the condenser and evaporator to facilitate the heat transfer through a specific heat exchanger (Domanski et al [21]) to see the theoretical COP excluding HX, and including HX. The study shows that the low-GWP refrigerant options are very limited, particularly for fluids with volumetric capacities similar to those of R410A or R404A.

The identified fluids with good COP and low toxicity are at least mildly flammable. Refrigerant blends can be used to increase flexibility in choosing trade-offs between COP, volumetric capacity, flammability, and GWP. Independently of which refrigerants will be used in the future there are strong incentives to reduce the charge of refrigerant in each system. Especially with hydrocarbons the trend is to go to reducing the charge as much as possible by using brazed plate heat exchangers outside of the storage tank. The first published papers by Anderson et al. [23] recorded a reduction of the charge of refrigerant in a 5 kW liquid to liquid heat pump (heating only) to 200 g of propane using mini-channel tubes. It was expected that a further decrease of the charge was possible by redesigning the condenser and by reducing the amount of propane in the compressor, either by using oils in which propane is not soluble or by using compressors with low charge of oil. The same researchers showed at the recent Gustav Lorentzen Conference 2018 [24] that with the right system design it is possible to create a heat pump system that can deliver up to 10 kW heating capacity with as little as 100 g of propane in the system, indicating that it is possible to meet a large cooling needs with a small amount of propane. The designs suggested may open up for the safe use of flammable refrigerants with high energy efficiency such as R152a, R32, R290 and R600a.

Not much of the research is focusing directly on DHWHPs. One report on this is from Kashif Nawaz et. al [06] who concluded the performance of CO_2 HPWH can be comparable to that of HPWHs using R-134a, more so with a separated gas cooler configuration. This configuration showed better performance than the wrapped tank configuration for both CO2 and R134a systems.

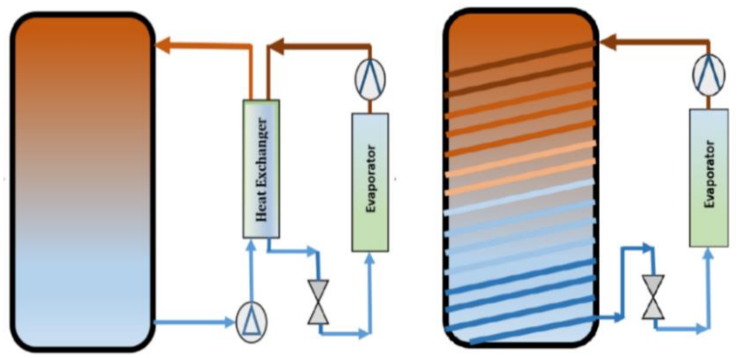


Fig 3.5 – HX configurations tested at Oakridge. Left: separated heat exchanger, Right: HX wrapped around the tank [06] (check ref).

The Unified Energy Factor for both configurations with CO2 and R134a as working fluids where the water temperature set-point is 125°F (about 52 °C) and both systems have variable speed pumps to control water flow rate for optimized performance.

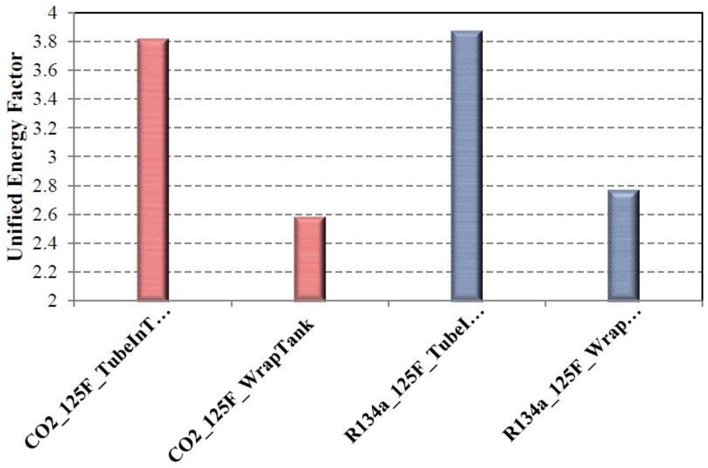


Fig 3.6 – Unified Energy Factor for two HX configurations [06]

It is clear that a tube-in-tube gas-cooler (for CO2 system) or condenser (for R-134a) results in a significantly higher UEF for the same operating conditions.

One important reason for the performance improvement is that variable water flow control can better match the tank stratification under changing conditions than does a fixed tank wrap configuration.

Based on the findings described above, it can be concluded that CO2 can be an effective substitute for refrigerant (R-134a) for HPWH applications. However, substantial modifications of the system configurations are required to achieve comparable performance such as the additional infrastructure of an appropriate compressor, pump, water-flow control, and gas-cooler. The system is highly sensitive to water circulation rate which directly impacts the stratification and system efficiency and this is an additional requirement along with relatively higher maintenance cost due to potential fouling of the gas cooler. Regardless of these apparent complexities, the system can perform well in lower ambient temperatures and is most suited for split (i.e. modular) DHW HP systems using some or all outdoor air.

Chen et.al. [37] have studied gas coolers for CO_2 as refrigerant in DHGW applications. Due to strong nonlinear variation of supercritical CO_2 specific heat capacity with temperature, pinch point would occur in water-cooled CO_2 gas cooler, which has great impacts on the heat transfer characteristics of gas cooler and overall system performance. Pinch point analysis was conducted for CO_2 gas cooler in the present study. The effects of refrigerant pressure, mass flow ratio (mw/mc), inlet water temperature and heat transfer area on pinch point location, approach temperature difference and heat transfer rate were analysed in detail. Based on the analysis of pinch point location in CO_2 gas cooler, the critical flow ratios were proposed to effectively control the approach temperature difference. Furthermore, the actual conductance of gas cooler was calculated and compared with that estimated by LMTD method. The results showed that CO_2 gas cooler may be undersized by as much as a factor of 30 to 60% for different pressures if LMTD method is used. However, the UA value evaluated by LMTD method also may be overestimated under high refrigerant pressures when the approach temperature difference tends to be zero. Results of the present study can be helpful to practical designs of CO_2 gas cooler and heat pump water heaters.

The thesis of Pitarch i Mocholí [17] focuses on sanitary hot water production with heat pumps and concludes that Propane (R290) and CO2 (R744) seem to be the more appropriate refrigerants for the DHW application. The high water temperature lift in DHW applications (usually from 10°C to 60°C) involved has conditioned the type of used solutions. On the one hand, transcritical cycles have been considered as one of the most suitable solutions to overcome the high water temperature lift. Nevertheless, the performance of the transcritical CO2 heat pump is quite dependent on the water inlet temperature, which in many cases is above 10°C. Furthermore, performance highly depends on the rejection pressure, which needs to be controlled to work at the optimum point in any condition. On the other hand, for the subcritical systems, subcooling is critical for the heat pump performance when working at high temperature lifts, but there is not any published work that optimizes subcooling in the DHW application for these systems. Therefore, the subcritical cycle should require a systematic study on the subcooling that optimizes COP depending on the external conditions, in the same way as it has been done for the rejection pressure in the transcritical cycle.

In the study of Mocholí two different approaches to overcome the high degree of subcooling were designed and built to test them in the laboratory:

- Subcooling is made at the condenser: The active refrigerant charge of the system is controlled by a throttling valve. Subcooling is controlled independently at any external condition.
- Subcooling is made in a separate heat exchanger, the subcooler. Subcooling is not controlled, it depends on the external condition and the heat transfer at the subcooler.

The heat pumps were tested at different water temperatures at the evaporator inlet (10°C to 35°C) and condenser inlet (10°C to 55°C), while the water production temperature was usually fixed to 60°C. The obtained results have shown that COP depends strongly on subcooling. In the nominal condition (20°C/15°C for the inlet/outlet water temperature at the evaporator and 10°C/60°C for the inlet/outlet water temperature in the heat sink), the optimum subcooling was about 43 K with a heating COP of 5.61, which is about 31% higher than the same cycle working without subcooling. Furthermore, the system with subcooling has been proved experimentally as being capable of producing water up to 90°C and has shown a higher COP than some CO2 commercial products (catalogue data reference).

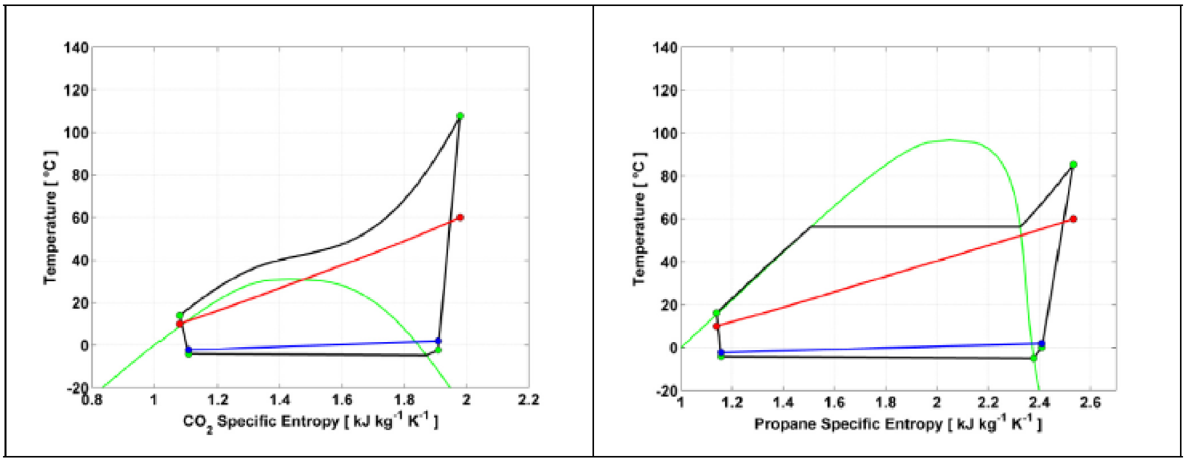


Fig 3.7 CO2 (left) and propane (right) heat pump thermodynamic cycle on the T-s diagram at nominal design conditions (Tamb = 2°C, Tw,in,gc or Tw,in,co = 10 °C). [36]

In the study by M. Tammaro et.al. [36] two heat pump systems for the production of sanitary hot water were modelled and simulated. The two systems were based one on the refrigerant CO2 and the other one on propane.

It resulted that, in order for the heat pumps to have the same heating capacity, the compressor size of the propane unit was 2.5 times larger than the CO2 one while the brazed plate heat exchanger needed to heat water was 3 times larger than the CO2 one.

Ambient temperature has the most influence on the increase of the heating capacity with a higher slope for the propane unit, which had higher heating capacity than the CO2 at ambient temperatures above 8 °C and lower for colder temperatures. Water inlet temperature increase, instead, had a detrimental effect on the heating capacity, more pronounced on the CO2 unit. In both cases, a stratified storage was found to be functional to obtaining better energy performance while retaining a correct water delivery temperature in order to preserve user comfort.

More follow up on these studies by the Universitat Politècnica de València is give in Addendum 6.

4. Discussion

The EU has regulations and high taxes that go beyond the Montréal Protocol, while the US and Asia closely follow the Montréal Protocol obligations. Several countries are giving incentives for use of green technology either by direct financial support or by reduced demands on efficiency[16]. Most regions and countries will try to enable industry to live up to legislation by investing in research programs with industry participants. Investing in research programs with focus on reducing the environmental impact - whether it is energy efficiency or low GWP refrigerants - has led to good industry spin offs. Universities provide a very good pre-competitive environment where new technologies are evaluated before potentially being later adopted by industry.

All companies face the challenge of optimizing their usage of resources and the obvious choice would always point at the safest and fastest return on investment. There are thousands of manufacturers of refrigeration and air conditioning systems. In such a competitive arena, it is risky for one firm to develop new products utilizing new refrigerants for a market with fragmented S&L (what is this?) and an uncertain outlook. Even many large firms are hesitant to proceed until they know that regulation will require their competitors to take similar actions.

The trend that is set by the current legislations (F-gas regulation, Kigali amendment to Montreal protocol) is, de facto, to use refrigerants with low GWP. How low "low GWP" is not defined and will depend on the demand for fluorinated gases over the upcoming years. Given 0% growth in consumption since 2015 the average GWP of refrigerants used in 2030 is approximately 420, but under assumption of 5% annual growth it is about 200. Given this industry should accommodate refrigerants with lowest GWP possible for a given application. The preference can be extended towards the use of so called "natural refrigerants" in order to avoid any future environmental risks associated with their use

Given a number of possible refrigerants and refrigerant mixtures that are under consideration these days, it is conveniently to separate the alternatives into 2 categories:

- those that are suitable to be used in a given application (considering e.g. operation temperature range, safety requirements),
- those that are seen as retrofit replacements to "conventional" refrigerants such as R134a, R410A.

When talking about (2) the choice of a refrigerant is very much limited by the original equipment design, and such alternatives as R450A, R513A are proposed as can replace R134a in systems that are designed to be used with non-flammable refrigerants. Or such as R1234yf as flammable alternative to R134a, in system where flammable refrigerants can be used instead of non-flammable R134a (e.g. systems with small refrigerant charge). Even though these refrigerants are often marketed as "drop in replacements" their use implies change in operation parameters (mass flow, heat transfer characteristics, etc.), not to considered as drop-in replacements.

If choosing a refrigerant for a new system one has more selection options. For example, R1234ze(E) is often more preferable than R1234yf. R1234ze(E) is often more energy efficient than R1234yf, but does not provides as close match to R134a in terms of vapour pressures. If flammable refrigerants are an option – the use of hydrocarbons is advantageous. Here the options are R600a, R290 (propane), R1270 (propylene). Propylene shows better energy performance than propane theoretically, but due to its chemical structure it is less stable than propene, and therefore the latter is normally chosen. There is a known limit to flammable refrigerant charge amount under which there is no limitation on usage and placement of refrigeration equipment that contain propane. For propane the limit is 150 g (there is process in Europe to increase it to 500 g, it will be decided in the end of 2018). The work that has been presented recently showed that it is possible to design a prototype heat pump capable of delivering 10 kW heating capacity using less than 150 g of propane. For comparison, traditional DHW HP using

[16] In September 2018, the Japanese Ministry of Environment asked for subsidies to promote natural refrigerants in commercial and industrial refrigeration for the 2019 financial year. The budget request has been submitted to the Ministry of Finance for review (IIR).

R134a delivers approx. 1 kW heating capacity per 1 L of R134a.

While CO2 components and controllers are challenging from a technical perspective due to high pressures and material compatibility concerns, hydrocarbons show a more complicated scenario. Thermodynamically, hydrocarbons are naturally very close to HFCs or HCFCs. As an example R290 has often been claimed to be a R22 drop-in, which is dangerously misleading in a broad sense. Technically R290 properties are close to R22 but seen from a safety perspective special precautions must be taken. This especially means that service technicians, who for decades may have been servicing non-flammable systems, suddenly have to change habits on systems that look and perform the same. As a component supplier, it is very important to be sure that the markets are ready to handle hydrocarbons before approving sales, and that system manufactures can show their compliance to existing safety standards.

Carbon dioxide and hydrocarbons are low GWP refrigerants that can be used in DHW HPs and replace synthetic refrigerants to help achieve global environmental goals. These refrigerants are known for a long time, their properties have been studied a lot and their environmental impact is known. Thus, it is safe to say that natural refrigerants are the most studied of all the low GWP refrigerants that are now lifted as alternatives.

The limited number of natural refrigerants has allowed the conference to focus on the details of their applications. This contrasts with the situation with new synthetic refrigerants and their mixtures, where the large amount of new media does not allow the components to be optimized sufficiently or that the environmental impacts are properly evaluated. The great importance of component optimization to achieve maximum energy efficiency, which applies to all refrigerants, has also been noted during the conference.

Both CO2 and ammonia have thermophysical properties that distinguish them from other conventional refrigerants. This should be considered when comparing these refrigerants with other refrigerants, as the choice of "comparable" conditions can cause these media to be disadvantaged in a comparison.

Minimizing filling amounts is relevant for building safe systems with combustible refrigerants. It is also important to limit the amount of conventional synthetic refrigerants for environmental reasons or for reasons such as high prices or uncertain availability in the future. Thus, the minimization of fillings will be a measure of both natural and synthetic refrigerants and we are therefore likely to see more research in this direction.

5. Conclusions

Due to physically realisable environmental concerns, there has been a continuous effort to phase out harmful refrigerants and to find suitable substitute which are not only environment friendly but also don't require considerable system design modification to acquire acceptable performance. The legislations (F-gas regulation, Kigali amendment to the Montréal protocol) suggest a general phase-down of HFC refrigerants and the use of the 4^{th} generation of refrigerants with low GWP by 2040. As a result of this extensive effort multiple countries across the world have agreed a workable plan and serious research efforts are underway. Replacement fluids with low GWP for DHWHPs are natural refrigerants like CO2, propane, or synthetic low GWP HFOs like R1234yf and R1234ze(E). Each potential substitute working fluid has its own specific operational characteristics which are comparable to existing refrigerants (R134a and/or R410A) or are remarkably different. In few cases a direct drop-in-replacement is possible due to matching thermo-physical behaviour. However, in often situation that's not the case as such system redesign is required. A classical example is deployment of CO2 which require an infrastructure compatible to significantly higher operating pressure. Similarly, the introduction of A3 (hydrocarbons) and A2L (HFOs and blends) refrigerants requires to mitigate obvious safety concerns due to flammable nature of working fluids.

Specifically to heat pump water heating application, research and development activities have been mainly focused on aspects such as reduction/minimization of the refrigerant charge amounts in heat pumps (e.g. HFOs and propane) due to flammability and higher cost issues. Development of compatible components (compressors and heat exchangers) and system optimizing to acquire improved performance has been another area of active research and development. For storage system, tank modelling to achieve desired thermal stratification for improved COP or UEF has been of great interest where deployment of appropriate wrapped/submerged condenser and selection of refrigerant can have considerable implications. Development of hybrid water heating technologies and system integration for grid interactiveness as well as energy storage for resiliency are few other area of great interest among researchers.

While there has been a continuous effort to identify, develop, deploy and characterize alternative working fluids, its equally important to establish new system performance rules and regulations by reviewing and revising existing practices or by developing new procedures for residential and commercial sector to expediate the adoption of environment friendly and energy efficient refrigerants in heat pump waters as well as in general for all HVACA&R applications.

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8. Evaluation and Development of Air-conditioners using Low GWP Refrigerant Shigeharu Taira; Tomoyuki Haikawa; Tomoatsu Minamida – 12th IEA Heat Pump Conference Rotterdam 2017
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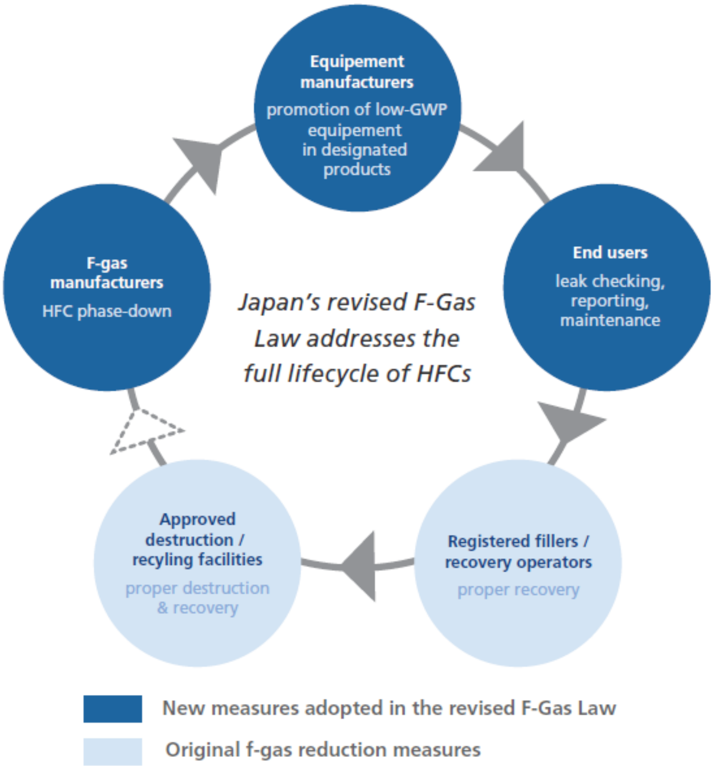
ADDENDUM 1 Japan

While the measures adopted have been adapted to the technology status and legislative processes in Japan, many points of the new rules are comparable to the EU's F-Gas Regulation. These include reporting, which is now mandatory for producers and importers of f-gases, as well as leak checking for end users, the phase-down of HFCs, and the promotion of low-GWP / non-fluorocarbon refrigerants in designated products.

Specifically, the regulatory measures encourage entities involved in each process of the lifecycle to carry out the following:



1. Entities that manufacture and import fluorocarbons: To reduce environmental impact through technology development and manufacturing of fluorocarbons with lower global warming impact, and the recycling of set amounts of used fluorocarbons.
2. Entities that manufacture and import products using fluorocarbons: To change from products using fluorocarbons in certain product categories, such as freezer showcases, to either fluorocarbon-free products or products using fluorocarbons with low global warming impact, by certain target years depending on the product category. This measure is comparable to the EU's sector-specific bans, but instead of imposing a strict prohibition, Japan has opted for setting target GWP values that need to be reached by each manufacturer by a certain year.
3. Users that manage commercial air-conditioning and refrigeration units: To properly manage such units in order to prevent the leakage of fluorocarbons through pro- per installation and inspection, as well as to repair damaged units. Moreover, certain users are required to submit an annual report on the amount of fluorocarbons leaked, and the data is compiled and disclosed by the Government of Japan. If the top-up of refrigerant due to leakages exceeds certain quantities, it will be prohibited.
4. Proper filling of air-conditioning and refrigeration units with fluorocarbons and proper recycling of used fluorocarbons: The revised Law introduced a registration system for entities that fill commercial air-conditioning and refrigeration units with fluorocarbons, as well as a permission system for entities that recycle fluorocarbons.

Preliminary calculation of the effects of HFC emission reduction measures made by the Ministry of Environment (MOE) and the Ministry of Industry (METI) indicate that the promotion of f-gas alternatives can help achieve substantial emissions reductions

Instead of imposing restrictions on the use of high-GWP refrigerants in certain applications, as is the case in the EU F-Gas Regulation, the Japanese law sets GWP targets per product group, which each manufacturer needs to reach by a certain target year.

Designated products	Present refrigerant (GWP)	Target value (GWP)	Target year
Room air-conditioning	R410A (2,088), R32 (675)	750	2018
Commercial air-conditioning (offices & stores)	R410A (2,088)	750	2020
Condensing units and refrigeration units (> 1.5kW)	R404A (3,922), R410A (2,088), R407c (1,774), CO_2 (1)	1,500	2025
Cold storage warehouse (> 50,000m³)	R404A (3,922), NH_3 (0)	100	2019
Mobile air-conditioning	R134a (1,430)	150	2023

Fig GWP Targets for designated products

The GWP targets are set for the sectors with the highest environmental impact where it has been proven that non-fluorinated refrigerants or other low-GWP substances are commercially available and energy-efficient. Weighted average GWP values of entire production and imports are taken into account to measure compliance by manufacturers.

Financial support

Besides the regulatory requirements concerning the production, use and end of life of f-gases, the Japanese Ministry of Environment (MOE) initiated a subsidy scheme, which has provided significant benefits for companies and organisations opting for and working with natural refrigerants. The scheme, designed to accelerate the introduction of natural refrigerants, was first put in place in 2005, and has been in full gear since 2014.

The budget of five billion JPY in FY2014 was increased by 24% for FY2015 (6.2 billion JPY) and again by 18% for FY2016 (7.3 billion).

Initially (in 2014), the subsidy scheme covered support of display refrigerators in food retail and refrigeration technology for cold storage warehouses. In 2015, the food manufacturing sector was added. Most recently, the scheme will also cover chemical manufacturing processes and ice skate rinks in FY2016

ADDENDUM 2 United States

The Climate Action Plan announced by President Obama in June 2013 [2] set out a number of measures to address HFCs; it has been estimated that eliminating certain HFCs could provide 23 per cent of the emissions reductions needed to achieve the US's 2020 GHG emissions reduction goal of 17 per cent below the 2005 level.

This action plan included the use of the Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) programme, established to evaluate and regulate ODS replacements; the programme publishes lists of acceptable and unacceptable substances. Three new rules have recently been adopted, partly in response to petitions form environmental non-governmental organisations (ENGOs) filed prior to adoption of the Climate Action Plan [U.S. Environmental Protection Agency, 2016, *Federal Register, Vol.81*,]

- October 2014 – expanded the list of acceptable substitutes for refrigerants, foam-blowing agents and fire suppressants.
- February 2015 – changed the listing status of some HFCs in various end uses in the aerosols, refrigeration and air-conditioning and foam-blowing sectors from acceptable to unacceptable, and restricting the use of HFCs as aerosol propellants where there are no environmentally acceptable substitutes available.
- July 2015 – removed a long list of high-GWP HFCs from the SNAP list of acceptable substances on schedules comparable or slightly later than the EU's F-Gas Regulation (recognising the later enactment and the time necessary for industry to respond).
- As shown in Table 1, effective July 20, 2016, R-404A and R-507A are no longer allowed to retrofit supermarkets, remote condensing units and low and medium temperatures stand-alone commercial refrigeration equipment. More restrictions on the use of R-404A, R-410A, R-407A/C/F and R-134a will take effect from 2017 to 2020.

Table 1: Phase-Out Refrigerants and Dates for Commercial Refrigeration Equipment

Phase-Out Refrigerant	Super-market (New)	Super-market (Retrofit)	Remote Cond. Unit (New)	Remote Cond. Unit (Retrofit)	Stand-Alone			
					Medium Temp<2,200 Btu/h without flooded evap. (New)	Medium Temp≥2,200 Btu/h with or without flooded evap. (New)	Low Temp. (New)	Low & Medium Temp. (Retrofit)
R-404A/507A	Jan 1, 2017	Jul 20, 2016	Jan 1, 2018	Jul 20, 2016	Jan 1, 2019	Jan 1, 2020	Jan 1, 2020	Jul 20, 2016
R-410A	OK	-	OK	-	Jan 1, 2019	Jan 1, 2020	Jan 1, 2020	-
R-407A/C/F	OK	OK	OK	OK	Jan 1, 2019	Jan 1, 2020	Jan 1, 2020	OK
R-134a	OK	OK	OK	OK	Jan 1, 2019	Jan 1, 2020	OK	OK

Table 2 shows that all HFCs currently used in new chillers will be phased out in 2024. For retail food refrigeration (food processing and dispensing) and cold storage warehouses, most HFCs (at the exception of R-134a) will be phased out for new equipment in 2021 and 2023 respectively.

In California, the Air Resources Board (CARB) issued a proposed strategy paper to accelerate emission reductions of short-lived climate pollutants [5]. Among other things, the strategy proposed to reduce HFC emissions in the state of California by 40% (from 2013 levels) in 2030. The strategy mentioned the ongoing international negotiations on the phasedown of HFCs and noted that California would implement its own phasedown if the negotiations are unsuccessful. In addition, the strategy proposed a ban on refrigerants with GWP levels greater than 2500 and a GWP limit of 750 on refrigerants used in air-conditioning (both residential and commercial) effective in 2021. For commercial refrigeration equipment, a GWP limit of 150 was proposed effective in 2020.

Table 2: Phase-Out Refrigerants and Dates for Chillers, Cold Storage Warehouses and Retail Food Refrigeration Equipment

Phase out Refrigerant	Chillers (New)	Cold Storage Warehouse (New)	Retail Food Refrigeration – Food Processing & Dispensing (New)
R-134a	Jan 1, 2024	OK	OK
R-404A	Jan 1, 2024	Jan 1, 2023	Jan 1, 2021
R-407 A&B	-	Jan 1, 2023	Jan 1, 2021
R-407C	Jan 1, 2024	-	Jan 1, 2021
R-410A	Jan 1, 2024	Jan 1, 2023	Jan 1, 2021
R-507A	Jan 1, 2024	Jan 1, 2023	Jan 1, 2021

In late 2016, CARB issued a revised proposed strategy paper [6]. While the revised strategy acknowledges the Montreal Protocol agreement reached in Kigali, it continues to propose a ban on refrigerants with GWP levels greater than 2500, and indicates that additional measures may be needed to achieve the emission reduction goals. Such additional measures could include setting GWP limits on refrigerants used in air-conditioning (both residential and commercial) and commercial refrigeration equipment. A final decision will be made in the Spring 2017.

ADDENDUM 3 Europe

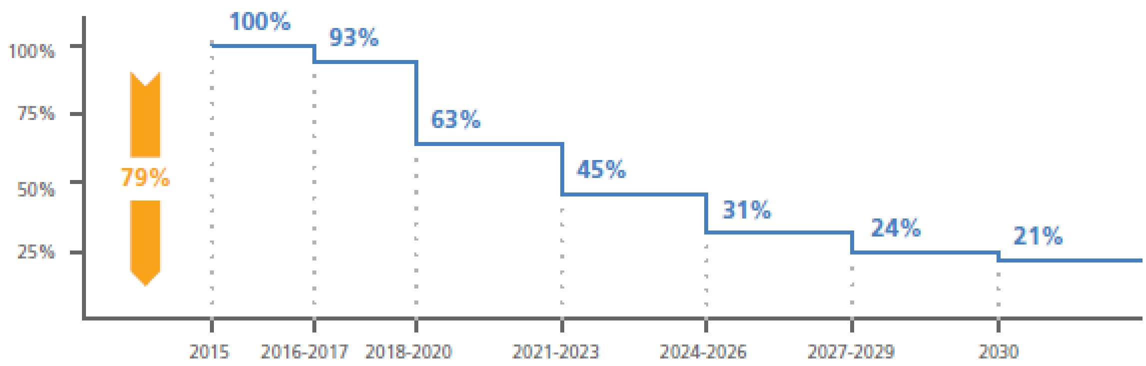
To control emissions from fluorinated greenhouse gases (F-gases), including hydrofluorocarbons (HFCs), the European Union has adopted two legislative acts:

- MAC Directive on air conditioning systems used in small motor vehicles. This prohibits the use of F-gases with a global warming potential of more than 150 times greater than carbon dioxide (CO2) in new types of cars and vans introduced from 2011, and in all new cars and vans produced from 2017.
- F-gas Regulation which covers all other key applications in which F-gases are used. The F-gas Regulation follows two tracks of action:
    6. Avoiding the use of F-gases where environmentally superior alternatives are cost-effective. From 2015 the volume of HFCs which can be placed on the EU market will be subject to quantitative limits which will be phased down over time. In addition, measures include restrictions on the marketing and use of certain products and equipment containing F-gases.
    7. Improving the prevention of leaks from equipment containing F-gases. Measures comprise:
        - containment of gases and proper recovery of equipment;
        - training and certification of personnel and of companies handling these gases, and
        - labeling of equipment containing F-gases.

Legislation

The original F-gas Regulation, adopted in 2006, is being replaced by a new Regulation adopted in 2014 which applies from 1 January 2015. This strengthens the existing measures and introduces a number of far-reaching changes by:

- Limiting the total amount of GWP-contribution. This is also called the “quota-regulation”. and the GWP-contribution of all new sold refrigerants will be phased down in steps to one-fifth of 2014 sales in 2030. This will be the main driver of the move towards more climate-friendly technologies and will result in very limited possibilities for application of high-GWP refrigerants the use of high-GWP refrigerants has to be compensated by extra use – within the absolute amount of the available GWP-quota - of very low-GWP refrigerants. This regulation results in an average GWP allowance of 400 for new refrigerants in 2030.
- Banning the use of F-gases in many new types of equipment where less harmful alternatives are widely available, such as fridges in homes or supermarkets, air conditioning and foams and aerosols;
- Preventing emissions of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life.



HFC phase-down reduction steps

The phase-down of hydrofluorocarbons (HFCs) is considered to be one of the key pillars of the Regulation as it aims to reduce the amount of HFCs placed on the EU market (CO2e) by 79% by 2030, as compared to average levels in 2009- 2012. Producers and importers of f-gases are allocated annual quotas of HFCs that allow them to place a certain amount on the market. Starting in 2015 and running through 2030 these annual quotas are gradually reduced with a first reduction of 7% in 2016.

While the effects of the HFC phase-down might not be noticeable to end users and manufacturers at this point in time, this will change within the next three years. The first significant cut in HFC quotas in 2018 – of 37% – is expected to have a major impact on the cost of HFCs, which will become less widely available. Considering that, as of 2017, the HFC phase- down needs to incorporate HFCs pre-charged in equipment, it is estimated that the cut in 2018 will equal 44%. Early action from manufacturers and end users is essential in anticipation of these future cuts in availability of HFCs in order to be able to reach the targets and comply with the Regulation.

What the phase-down actually means is that the average GWP of HFCs will have to fall from today's 2,000 to about 400 by 2030 across all sectors. Natural refrigerants will therefore play a major role in achieving this target.

HFC bans in new equipment

The F-Gas Regulation also introduces bans in specific sectors on new equipment using HFCs above a specific global warming potential (GWP) that will take effect by a certain year. This measure is crucial for ensuring that the HFC phase- down targets are achieved. The HFC ban specifies the timing for each sector to shift to refrigerants with a lower climate impact, such as natural refrigerants. Following an impact assessment by the European Commission and the compromise negotiations among the EU institutions, HFC bans have been introduced in several sectors where safe, energy-efficient and cost-effective alternatives are available across the EU.

In the refrigeration sector, the restrictions especially target the commercial sector, where the EU foresees that as of 2022 new equipment will use refrigerants with a GWP below 150 in both small plug-in applications (e.g. bottle coolers, vending machines) and in larger centralised systems in supermarkets (with some exceptions).

In the air-conditioning sector, the HFC ban addresses only small equipment, including portable air-conditioners and single split AC units4 with less than 3kg of refrigerant.

The Regulation intends to abolish the use of very high-GWP gases (GWP above 2,500) not only in new equipment but also in existing installations. As of 2020 it will be prohibited to service existing refrigeration equipment with HFCs that have a GWP of 2,500 or above, unless these refrigerants are recycled or reclaimed. Such HFCs could still be used until January 2030 in existing equipment.

Consultation Forum

A Consultation Forum is mandated by the F-gas Regulation. Its mission is to provide advice and expertise to the Commission in relation to the implementation of the F-gas Regulation, in particular with regard to the availability of alternatives to fluorinated greenhouse gases, including the environmental, technical, economic and safety aspects of their use.

This Forum consists of experts from national authorities, transnational industry associations, NGOs and international organisations. Representatives of single companies or associations of a single country are not invited to the group. Additional experts may be invited on an ad hoc basis according to the topics to be discussed at the relevant meeting. The Forum is established as a permanent expert group of the European Commission. More information can be found in the official register of Commission Expert Groups. The Commission will call a meeting when technical input from stakeholders is required for the implementation of the F-gas Regulation.

Addendum 4: TEWI = Total Equivalent Warming Impact

All halocarbon refrigerants, including the non-chlorinated HFCs belong to the category of the greenhouse gases. An emission of these substances contributes to the global warming effect. The influence is how- ever much greater in comparison to CO2 which is the main greenhouse gas in the atmosphere (in addition to water vapour).

Based on a time horizon of 100 years, the emission from 1 kg R134a is for example roughly equivalent to 1430 kg of CO2 (GWP100 = 1430).

It is already apparent from these facts that the reduction of refrigerant losses must be one of the main tasks for the future.

On the other hand, the major contributor to a refrigeration plant's global warming effect is the (indirect) CO2 emission caused by energy generation. Based on the high percentage of fossil fuels used in power stations the average European CO2 release is around 0.45 kg per kWh of electrical energy. A significant greenhouse effect occurs over the lifetime of the plant as a result of this.

As this is a high proportion of the total balance it is also necessary to place an in- creased emphasis upon the use of high efficiency compressors and associated equipment as well as optimized system components, in addition to the demand for alternative refrigerants with favourable (thermodynamic) energy consumption.

When various compressor designs are compared, the difference of indirect CO2 emission (due to the energy requirement) can have a larger influence upon the total effect than the refrigerant losses.

A usual formula is shown in Fig. 5, the TEWI factor can be calculated and the various areas of influence are correspondingly separated.

In addition to this an example in Fig. 6 (medium temperature with R134a) shows the influence upon the TEWI value with various refrigerant charges, leakage losses and energy consumptions.

This example is simplified based on an overall leak rate as a percentage of the refrigerant charge. As is known the practical values vary very strongly whereby the potential risk with individually constructed systems and extensively branched plants is especially high.

Great effort is taken worldwide to reduce greenhouse gas emissions and legal regulations have partly been developed already. Since 2007, the "Regulation on certain fluorinated greenhouse gases"– which also defines stringent requirements for refrigeration and air-conditioning systems – has become valid for the EU. Meanwhile, the revised Regulation No. 517/2014 entered into force and has to be applied since January 2015.

The method of calculating TEWI is provided below:

TEWI = GWP (**direct**; refrigerant leaks incl. EOL) + GWP (**indirect**; operation)

$= (GWP \times m \times L_{annual} \times n) + GWP \times m \times (1 - \alpha_{recovery})) + (E_{annual} \times \beta \times n)$

Where:

GWP	=	Global Warming Potential of refrigerant, relative to CO_2 (GWP CO_2 = 1)
L_{annual}	=	Leakage rate p.a. (Units: kg)
n	=	System operating life (Units: years)
m	=	Refrigerant charge (Units: kg)
$\alpha_{recovery}$	=	Recovery/recycling factor from 0 to 1
E_{annual}	=	Energy consumption per year (Units: kWh p.a.)
β	=	Indirect emission factor (Units: kg CO_2 per kWh)

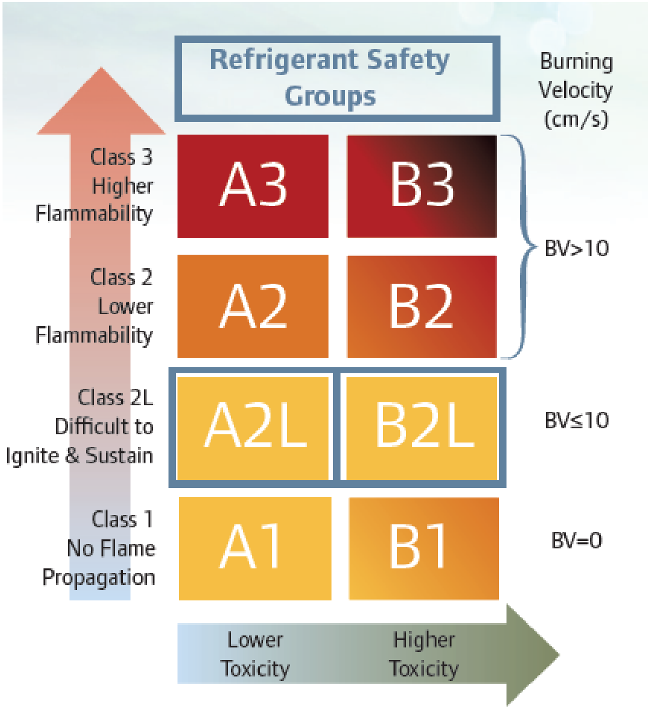
Source: http://nasrc.org/articles1/2017/1/23/what-exactly-is-tewi-anyway

https://www.airah.org.au/Content_Files/BestPracticeGuides/Best_Practice_Tewi_June2012.pdf

Addendum 5 - Refrigerant flammability

Refrigerants are divided into three main groups and a sub-group, according to flammability based on ISO 817 and ISO 5149:

1. Higher flammability: Class 3 indicates refrigerants that are highly flammable as defined by a lower flammability limit of less than or equal to 0.10 kilograms per cubic meter (kg/m3) at 21°C and 101 kiloPascals (kPa), or a heat of combustion greater than or equal to 19 kilojoules per kilogram (kJ/kg) (18).
2. Flammable: Class 2 indicates refrigerants with a lower flammability limit of more than 0.10 kg/m3 at 21°C and 101 kPa and a heat of combustion of less than 19 kJ/kg.
3. Lower flammability: Class 2L indicates lower flammability than Class 2 refrigerants.
4. Not flammable: Class 1 indicates refrigerants that do not show flame propagation when tested in air at 21°C and 101 kPa.



In other words, Class 1 refrigerants are not flammable, and Class 3 refrigerants are the most flammable. The commonly used refrigerant R-22 is assigned a safety rating of A1, while the safety rating of R-32 is B2. Many of the new refrigerants are blends or mixtures. The commonly used, blended refrigerant R-410A has a safety rating of A1, while R-411A is rated A2.

The ASHRAE Standard Committee is the only place in the world where physical characteristics, toxicity and flammability of refrigerants are reported. The examination is carried out in parallel in the sub-committees “nomenclature”, “toxicity”, and “flammability”. These subcommittees report to the Committee which validates the work, thereby introducing new fluids or new mixtures with R-prefix for refrigerant.
Preliminary studies are costly and time consuming especially for toxicity. Strategically, ISO 817 Committee should have replaced the ASHRAE 34 Committee but it is undeniable that the ISO organization has not yet demonstrated an ability to move faster than the ASHRAE 34 Committee. So much so that the introduction of the burning velocity (BV), which was made in ISO 817 in 2003, was actually introduced in 2010 ASHRAE 34 (see Figure 3.4) whereas ISO 817-5 is still awaiting approval.
The classification of fluids of EN 378 depends of the ASHRAE committee works, for the safety classification as well as for the nomenclature; hence the update of EN-378 is still several years behind that of ASHARE 34 which proceeds by addenda.
ASHRAE 15 is the equivalent of EN 378, which is organized in the same way: category of occupancy, types of systems (direct or indirect) and refrigerant class. However, the calculation rules differ, but restrictions on the use of refrigerants 2 and 3 are lower than in previous versions (ASHRAE 15-2010).

Addendum 6 – Studies by Universitat Politècnica de València

[36] - Tammaro, M & Montagud, Carla & Corberan, Jose & Mauro, Alfonso & Mastrullo, R. (2016). Seasonal performance assessment of sanitary hot water production systems using propane and CO2 heat pumps. International Journal of Refrigeration. 74. 10.1016/j.ijrefrig.2016.09.026.

Heat pump water heaters can increase the energy efficiency in sanitary hot water production, which is a relevant share of the final energy consumption inmultiresidential and tertiary buildings. Refrigerants for these heat pumps are changing due to the F-Gas Regulation which bans high-GWP fluids. While CO2 is an established solution, propane is a promising low- GWP alternative for heat pump water heaters serving large users in the tertiary sector, where refrigerant charge limits (due to propane's flammability) can be bypassed by installing the heat pump outdoors. Here, the components of a CO2 and a propane air-water heat pump systems of 40 kW are sized and their COPs are compared in different climates; then, the two heat pumps are coupled to a storage tank and a user demand profile (hospital and school). For three different locations, tank size necessary to maintain users' comfort and seasonal performance factor are evaluated through simulation.

[38] - Hervas, Estefania & Pitarch, Miquel & Navarro, Emilio & Corberan, Jose. (2017). Optimal sizing of a heat pump booster for sanitary hot water production to maximize benefit for the substitution of gas boilers. Energy. 127. 558-570. 10.1016/j.energy.2017.03.131.

Heat recovery from water sources such as sewage water or condensation loops at low temperatures (usually between 10 and 30 °C) is becoming very valuable. Heat pumps are a potential technology able to overcome the high water temperature lift of the Sanitary Hot Water (SHW) application (usually from 10 °C to 60 °C with COPs up to 6). This paper presents a model to find the optimal size of a system (heat pump and recovery heat exchanger) based on water sources to produce SHW compared to the conventional production with a gas boiler in order to maximize the benefit. The model includes a thermal and economic analysis for a base case and analyzes the influence of a wide set of parameters which could have a significant influence. Even the uncertainties involved, results point out considerable benefits from this substitution based on the capacity of the system. Thus, demonstrating the importance of the optimal size analysis before an investment is done.

[39] - Navarro, Emilio & Corberan, Jose & Pitarch, Miquel & Gonzálvez-Maciá, José. (2017). Experimental study of a heat pump with high subcooling in the condenser for sanitary hot water production. Science and Technology for the Built Environment. 10.1080/23744731.2017.1333366.

The use of heat pumps in order to produce sanitary hot water (SHW) have been demonstrated as a very efficient alternative to traditional boilers. Nevertheless, the high water temperature lift involved in this application has conditioned the type of used solutions. In order to overcome it, transcritical cycles have been considered as the most suitable solution. In this article, a new heat pump prototype able to enhance the heat pump efficiency using a subcritical cycle is analysed. The proposed prototype is able to control the system subcooling and make it capable to work at different subcoolings in the condenser. That kind of mechanism has demonstrated its capability to increase the efficiency of the heat pump. The obtained results have shown that COP depends strongly on subcooling. In nominal condition inlet /outlet water temperature at evaporator is 20ºC/15ºC and the water inlet/outlet temperature in the heat sink is 10ºC and 60ºC, the optimal subcooling is 42 K with a heating COP of 5.35, which is about 25% higher than the same cycle working without subcooling

[40] - Pitarch, Miquel & Navarro, Emilio & Gonzálvez-Maciá, José & Corberan, Jose. (2017). Evaluation of different heat pump systems for sanitary hot water production using natural refrigerants. Applied Energy. 190. 911-919. 10.1016/j.apenergy.2016.12.166.

Heat pumps that work with a high degree of subcooling in subcritical systems have shown a significant margin of improvement when working with sanitary hot water applications. Recently, two different approaches to overcome the high degree of subcooling have been presented in the literature: with a subcooler (separate from the condenser) and by making all the subcooling in the condenser. In this paper, a comparative evaluation between both alternatives is presented, and the obtained results are compared with a representative solution already available on the market using natural refrigerants for this application. The results of this analysis have shown that in a system with subcooling in the condenser, it is possible to obtain a COP comparable to that of transcritical CO2 heat pump water heaters. Furthermore, the system with subcooling has been demonstrated experimentally as being capable of producing water up to 90 °C and has shown a COP up to 20% higher than some CO2 commercial products (catalogue data reference).

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