REFRIGERANTS OF THE FUTURE:

Their Impact on Next Generation Data Centers

Refrigerants of the Future: Their Impact on Next Generation Data Centers

Like other sectors, suppliers of cooling equipment are responding to ongoing concerns around climate change by developing products and services that help reducing greenhouse gas emissions. For example, some cooling manufacturers have shifted their focus towards low-Global Warming Potential (GWP) refrigerants or alternative refrigerants (some of which are already available in the market).

However, selecting refrigerants that are future-proofed is challenging both for suppliers and operators of critical infrastructures – such as data centers - that use cooling equipment where there is often a trade-off between the ideal GWP, flammability level, cost and efficiency.

This white paper thus provides an overview on the main global trends around new refrigerants and addresses specific issues for data center operators including technical and safety aspects of new and emerging refrigerants.

Understanding the Global Context

The Refrigerant's History

In the XIX century, refrigerants such as ammonia and CO_2 were frequently used in the cooling industry. One century later, safety issues started to emerge:

- Unstable Refrigerants
- Toxicity
- Flammability
- Thermodynamic Performances

As a result of the evolution of the chemical industry, synthetic refrigerants were gradually developed including Chlorofluorocarbons (CFCs) i.e. R12. In 1974, it was discovered that chlorine, a component of CFCs, affected the ozone layer. This led to the development of Hydrochlorofluorocarbons (HCFCs) i.e. R22, where chlorine was partially substituted by hydrogen and fluorine resulting in a lower, but still significant Ozone Depletion Potential (ODP).

The effort of the chemical industry to find a refrigerant which did not damage the ozone layer eventually led to the introduction of Hydrofluorocarbons (HFCs) such as R134a, with ODP=0. Chlorine was completely substituted by hydrogen.

After the Kyoto Protocol, signed in 1997, environmental concerns shifted to focus on the greenhouse effect which required a whole new approach. In October 2016, the Kigali Amendment of the Montreal Protocol agreed on the phase down of all HFCs with high GWP. As a result, the industry began to move towards natural and low GWP refrigerants.

The Kigali Amendment and the National Regulations

The Kigali Amendment which included the phase-down of the production and consumption of HFCs, required a reduction in the use of HFCs by 80-85% by the end of 2040. The phase-down of HFCs is expected to prevent the emission of up to 105 million tons of carbon dioxide helping to avoid up to 0.5 °C of global temperature rise by 2100.

The first reductions carried out by most developed countries are expected by 2019, whilst most developing countries will follow with a freeze on HFCs consumption levels by 2024, and by 2028 for some other developing countries. Figure 1 shows HFCs phase-down schedule.

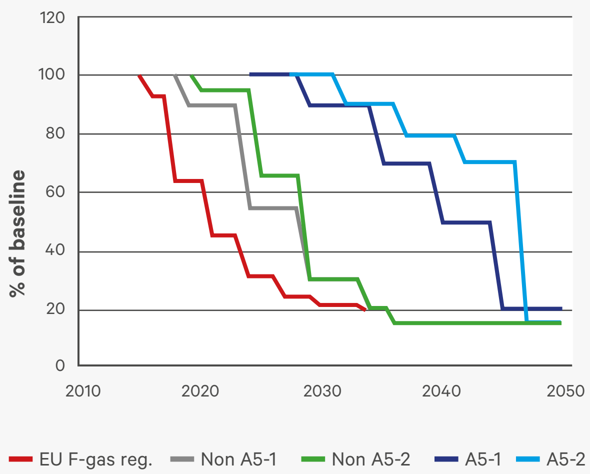


Figure 1: *HFC consumption phase-down for art.5 and non-art 5 countries.*

The Montreal Protocol prompted most countries to define national regulations to comply with the agreement. Some of the local regulations in the EU, US and China are listed below.

The F-gas Regulation in Europe

The 517-2014 Regulation defines targets and measures to reduce the use of high GWP refrigerants. The target is to reduce the equivalent tons of CO_2 incurred in 2015 to 79% less in 2030. The regulation defines quota systems and sectorial bans on high-GWP refrigerants.

BAN - Type and Number in Text	GWP limit	Year
10 - Domestic refrigerators and freezers	150	2015
11 - Commercial refrigerators and freezers - plug-in	2500	2020
	150	2022
12 - Stationary refrigeration and air-conditioning equipment	2500	2020
13 - multipack centralized refrigeration systems >40kW (exception for cascade systems)	150	2022
14 - movable room air-conditioning equipment	150	2020
Single split air-conditioning systems <3kg charges	750	2025

Figure 2: *Refrigerant phase-down by F-Gas regulation*

US' Situation

In US, the US-SNAP (Significant New Alternative Policy) defines rules that specify approved and banned refrigerants. A few examples are listed below:

- Rule 19 lists R32 and R290 as acceptable for new residential and light commercial air conditioning.
- Rule 20 lists R450A and R513A as acceptable replacements for R134a for chillers.

China's Situation

China has planned a reduction of 35% within 2020, 67,5% within 2025 and 100% by 2030. The Chinese government has also introduced a catalogue of recommended refrigerants for different applications such as:

- R744 for household and industrial/commercial heat pump water heaters.
- R32 unitary air conditioners and water chiller/heat pump units.

New Refrigerants: Challenges and Opportunities

The ideal refrigerant should be sustainable, non-polluting and safe in terms of toxicity and flammability. A good thermodynamic performance is also required such as a high cooling capacity and high critical temperature. It should be readily available and affordable, but equipment costs must also be considered.

Performance
Sustainibility
Efficiency
Refrigerant cost
Safety
Equipment cost
Knowledges
Innovation and investment
Component's availability

Figure 3: *Requirements for next generation refrigerants.*

Selecting next generation refrigerants will lead to a trade-off between the above requirements. A complexity results due to the fact that HFCs are used in many different applications and it's unlikely that one single low-GWP refrigerant will be suitable for all cases.

The Transition in Data Center Applications

There are several HFC refrigerants used in data center applications. Two of the most common are R134a, generally used in large systems, and R410A used in small and medium sized sites.

In terms of new refrigerants, there are two main groups:

- Industrial Chemicals (also called Natural Refrigerants) such as CO_2 and hydrocarbons
- Ammonia HFOs (and HFOs blends) such as R1234yf, R1234ze, R513 and many others.

Since fire prevention is a key priority in critical infrastructure environments and propane is considered highly flammable, its adoption is limited to specific niche cases. HFOs and HFOs blends do have a lower flammability, but some are still in their development phases and for the short term, at least, they are considered too expensive.

- **Low pressure refrigerants:** the most used is R134a, the long-term alternatives are the HFOs such as R1234ze and R1234yf with a GWP of 7 and 4 respectively. R513A (HFOs blend) with a GWP of 631 can be considered as a mid-term solution.
- **Medium pressure refrigerant:** the most used is R407C with a GWP of 1610. The alternatives considered are R454C and R455A.
- **High pressure refrigerants:** the most used is R410A, R32 has been adopted as an alternative and is considered as a mid-to-long term solution with a GWP of 675. Recently, a new promising refrigerant known as Solstice N41 (provisional R446A) has been introduced as substitute of R410A. Filed tests are still ongoing and the refrigerant is expected to be commercially available in Q3 2019. The first tests confirm that Solstice N41 will allow for an easy conversion from R410A and only minor changes to the equipment will be needed. Solstice N41 thus changes the perspective of the refrigerant scenario as this is a non-flammable refrigerant, its GWP is lower than 750 and it is suitable for both rooftop and indoor units.

Prioritizing efficiency

Regulations can Drive Innovation

It is important to highlight that none of these refrigerants can be used as an immediate drop-in to replace current HFCs. A re-design of existing cooling equipment is required to achieve the same efficiency standards as that achieved with HFCs. The new generation of refrigerants are often considered to be less efficient than HFCs. At the same time, the EU Ecodesign regulations require industry to develop and deploy energy-efficient technologies with ambitious standards. The average efficiency has increased during the last decades, as a result of new heat exchangers, the modulation of compressors and fans and integrated control systems, for this reason also efficiency must be considered when evaluating alternative refrigerants.

Interest is Growing in Alternative Cooling Technologies

This transition period, with the F-gas and the Ecodesign regulations acting in parallel, is an opportunity for the industry to invest in innovation and for this reason interest in technologies that use less refrigerants or even none at all is growing significantly. These include:

- Chilled Water (CW) systems installed outside the data center white space that use low GWP refrigerants.
- The adoption of indirect, and in some cases even direct, evaporative air-to-air technologies is gaining interest especially in key territories such as Northern Europe. The regulatory regime around HFCs could drive more operators to investigate on this technology.
- Other solutions include raising data center operating temperatures to increase the use of freecooling whilst reducing mechanical cooling. Microchannel condensers also enable less refrigerant charge in Direct Expansion (DX) systems

Performance

Key features of the ideal refrigerant:

- High critical temperature far from the working temperature range
- Low GWP
- Good efficiency
- Good cooling density
- Non-toxic
- Non-flammable
- Availability
- Low Cost

Low Pressure Refrigerants – R134a and Alike

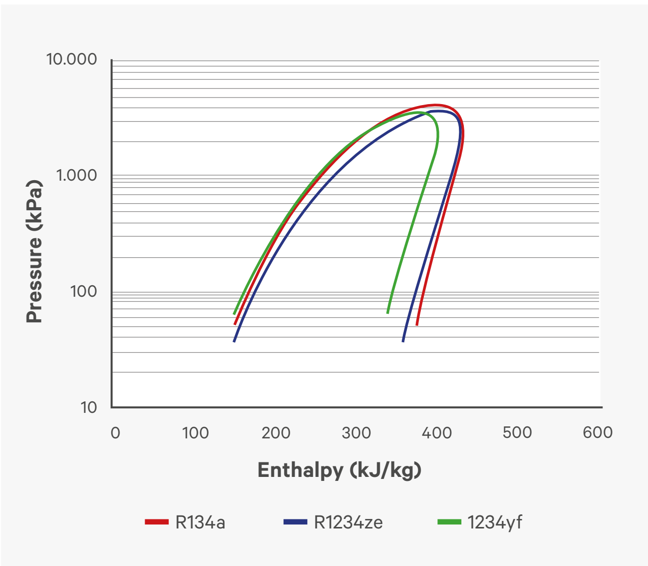
The chart shows a comparison between the leading contenders for R134a replacement.

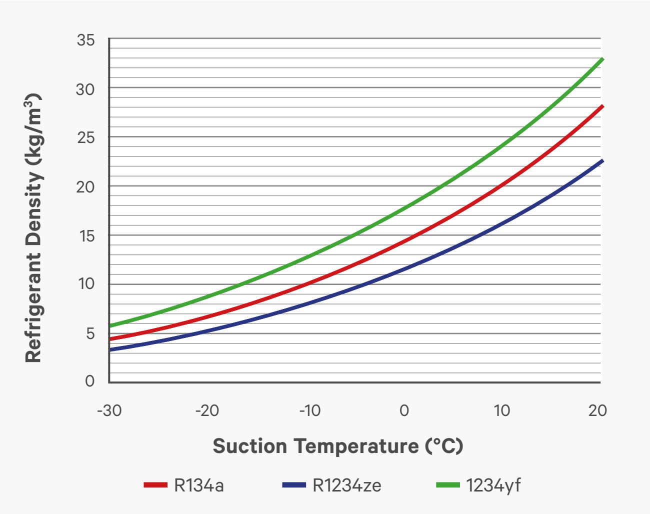
	R134a	R1234ze(E)	R1234yf	R513A
Molar mass	102,3 g/mol	114,04 g/mol	114,04	108,4 g/mol
Boiling temperature at 1,01 bar	-26 °C	-18,95 °C	-29,5 °C	-29,2 °C
Critical temperature	101,06 °C	109,37°C	94,7 °C	96,5°C
Critical pressure	40,593 bar	36,363 bar	33,82 bar	37,66 bar
Liquid density at 25°C	1207 kg/m³	1162 kg/m³	1092 kg/m³	1170,9 kg/m³
Vapour density at 25°C	32,34 kg/m³	26,76 kg/m³	37,94 kg / m³	37225 kg/m³

HFO-1234yf has working conditions close to R134a while R1234ze(E) has a slightly lower working pressure.

Looking at the P-h diagram, the R1234ze(E) curve is similar to R134a while R1234yf has a more acute curve with a consequently lower capacity.

R1234yf has a higher vapor density [kg/m³] compared to R134a while R1234ze(E) has a lower density. R1234ze(E) requires a higher refrigerant charge than R134a. The HFO refrigerants work with lower ΔT on the heat exchanger, which means that for the same cooling capacity an higher air flow is required.



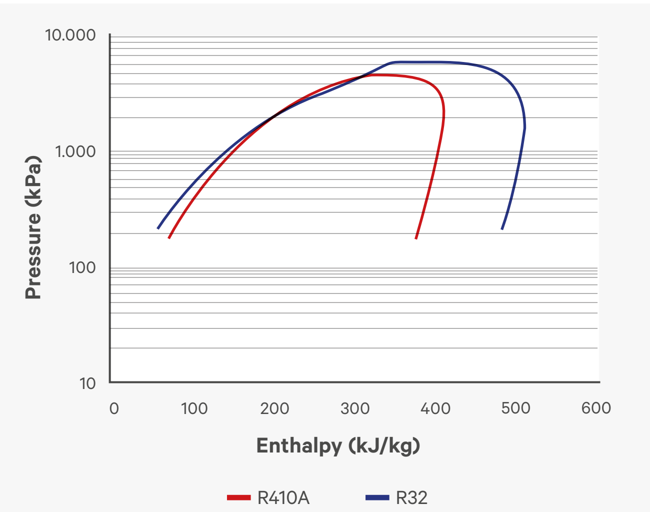


High Pressure Refrigerants – R410A and Alike

The chart below shows a comparison between R410A and R32.

	R410A	R32
Molar mass	72,585 g/mol	50,024 g/mol
Boiling temperature at 1,01 bar	-51,58 °C	-51,65 °C
Critical temperature	71,13 °C	78,1 °C
Critical pressure	49,26 bar	57,82 bar
Liquid density (saturation point)	954,1 kg/m³	876,1 kg/m³
Vapour density (saturation point)	114,3 kg/m³	80,8 kg/m³

R32 works with an operating pressure range slightly higher compared to R410A. Looking at the P-h diagram, the R32 curve is wider than the R410A curve with a consequent higher cooling capacity.



R32 density is lower than R410A, so it has a lower pressure drop with increasing efficiency and requires lower refrigerant charge. R32 works with high ΔT on the heat exchanger, this means that for the same cooling capacity, less air flow is required.

For what concerns Solstice N41, instead, tests carried out by compressor manufacturers are still ongoing.

Medium Pressure Refrigerants – R507C and Alike

R448A is a zeotropic blend designed for the replacement of R22 and R404A. It is mainly used in commercial refrigeration but it could be used also on DX systems, under specific guidelines.

R454C and R455A are also becoming interesting: studies have been carried out comparing the performances of these refrigerants with R407C (with scroll compressors) and it has been found that heating capacity is slightly lower compared to that with R407C.

Sustainability

In terms of sustainability, new refrigerants should be chlorine-free in order to avoid damage to the ozone layer, avoid excessive hydrogen content to limit flammability and have low fluorine to guarantee a low GWP. Figure 4 below shows the triangle Hydrogen – Fluorine – Chlorine, the ideal refrigerant should be a trade-off between flammability, toxicity, high ODP, high GWP and long atmospheric lifetime.

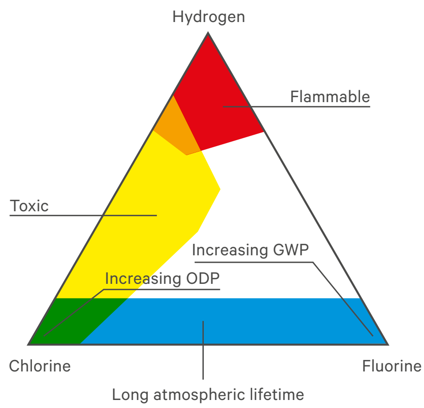


Figure 4: *Hydrogen - Fluorine - Chlorine*

HFO (hydrofluoro-olefin) refrigerants are the fourth generation of fluorine based refrigerants and are composed of hydrogen, fluorine and carbon atoms thus offering a more environmentally friendly alternative than HFCs as a result of their low-GWP.

HC (hydrocarbons) refrigerants have zero ODP and very low GWP. The drawback is their flammability.

The refrigerant scenario for replacement options is composed by more than 15 blends based on the main well-known molecules (R744, R32, R134a, R1234ze and R12324yf, R125, R152a) and by the natural refrigerants.

R1234ze and R1234yf, at the moment, are the most popular alternatives. Both contain a double bond between the carbon atoms which enables a quicker breakdown in the atmosphere. The atmospheric life of R1234yf and R1234ze(E) is respectively 11 days and 18 days compared to the 13 years of R1234a.

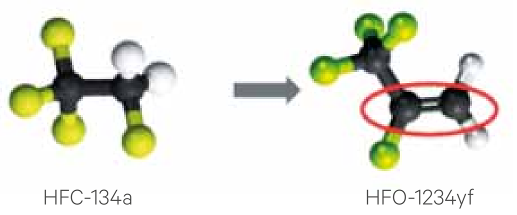


Figure 5: *Hydro Fluorocarbon (R134a) and Hydro Fluoro Olefin (R1234yf)*

Solstice N41, on the other hand, is composed by two popular molecules, R32 and R125, the presence of R32 is 49% while that of R125 is only 11%. The third component is a quite new refrigerant blend, known as trifluoroiodomethane (CF3I). Its 100-year GWP is less than 1 and it is the major contributor to the low GWP of N41.

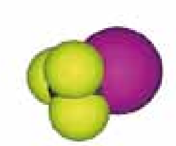


Figure 6: *Trifluoroiodomethane (CF3I)*

The table below shows a comparison between different GWPs for some of the most popular refrigerants.

Refrigerant	Type	GWP
R410A	HFC	2088
R134a	HFC	1430
R404A	HFC	3922
R407C	HFC	1774
R32	HFC	675
R452A	HFC	2140
R452B	HFC	698
R513A	HFO	631
R1234yf	HFO	4
R1234ze(E)	HFO	7
R466A (N41)	HFO	733
R448A	HFO	1387
R449A	HFO	1397
R744	N	1
R290	HC	3

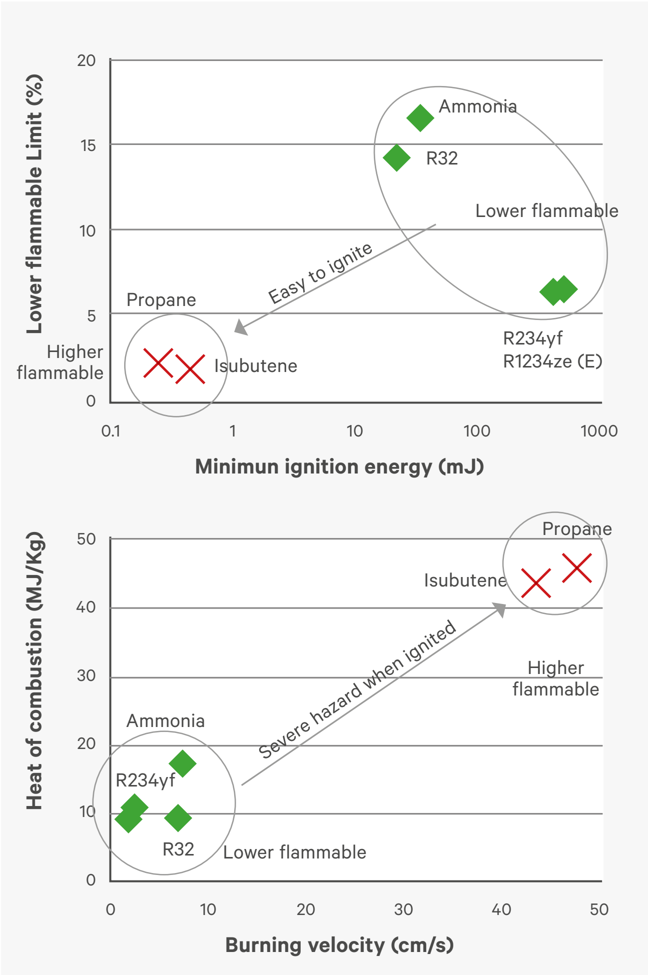
Safety

Safety must be evaluated in terms of both flammability and toxicity.

To evaluate the refrigerant's flammability several factors and their combinations must be considered.

Flammability depends on the LFL and UFL (lower and upper flammability limit) and on the Minimum Ignition Energy (MIE). Gasoline has a low LFL and low MIE, which means that a small concentration [g/m^3] needs a small amount of energy [mJ] to ignite. R1234ze and R1234yf have a medium value of LFL and they need a huge amount of energy to ignite. The consequence of a flammability event depends on the burning velocity and on the heat released. For less-flammable refrigerants the explosive power is usually small even during burning, since the laminar flow continues for a prolonged period. R32, R1234ze and R1234yf have a small burning velocity BV [cm/s] and they release a small amount of heat of combustion (HOC [MJ/kg]) while gasoline has a huge BV and a huge HOC. The range of flammability of R1234yf is from 6 to 12% of centration and to explode it requires a high energy of injection, just a spark is not sufficient. Only a flame or a hot surface at 600°C can cause an explosion.

Even temperature affects flammability, if the temperature increases, the LFL-UFL range increases as well because LFL becomes lower.



ASHRAE standard 34 “Designation Safety Classification of Refrigerants” gives a classification of the refrigerants based on safety issues such as toxicity and flammability dividing refrigerants in two toxicity classes:

A - lower toxic

B - higher toxic

Flammability is divided in different classes as shown in the chart below:

Flammability Class		Lower Flammability Limit LFL kg/m^3	Heat of Combustion HoC [MJ/kg]	Burning Velocity BV cm/s
3	Highly flammable	< 0.1 or	>19	n/a
2	Flammable	> 0.1 and	<19	n/a
L	Mildly flammable	>0.1 and	<19	<10
1	Non-flammable		cannot be ignited	

The chart below describes the main refrigerants in the market and their safety classifications.

Refrigerant	Safety Class
R410A	A1
R407C	A1
R452A	A2L
R452B	A2L
R455A	A2L
R134a	A1
R448A	A1
R449A	A1
R1234yf	A2L
R1234ze(E)	A2L
R32	A2L
R466A	A1

HFO Transportation and Storage

ADR (Carriage of Dangerous Goods by Road) states that in case of flammable gases the maximum charge is 12kg per unit/circuit. R1234ze is considered not flammable for temperatures below 28°C, for this reason there are no problems for ADR for transportation. There are no issues also for storage because it has a low reactivity and it cannot explode as long as the temperature is kept below 28°C. The R1234yf is considered more flammable than R1234ze gas so it has a limit of 12kg per unit/circuit for transportation.

HFO Product Design, Operations and Service

As previously highlighted, manufacturers cannot do an immediate drop-in replacement but instead must re-design their products with components suitable for new refrigerants. Regarding R1234ze and R1234yf no ATmosphere EXplosibles (ATEX) components are required. Precautions need to be taken in areas where a leakage can happen and areas where an injection can be generated (i.e. the electrical panel and power contacts). One suggestion is to grant continuous ventilation of fresh air from the top of the electrical panel to avoid, in case of leakage, that the gas enters inside the electrical panel.

Due to the flammability challenge, the complexity of the components is increasing and it will take time to approve products and have expert technicians on field.

Regarding maintenance, many options can be adopted. These include the use of gas leakage sensors close to the critical part of the unit during the gas charge or during testing. In case of leakage, the gas should be contained by barriers applied around the unit and extracted by fans to avoid excessive concentrations that could be dangerous for safety reasons and to avoid health risks for operators.

For servicing activities, technicians are not exposed to additional risks, but they must be careful not to weld connections that contain refrigerant and they must use only ATEX vacuum pumps and tools. The European Parliament is working on a document on HFO gases that will require technicians to have an HFO gas license and undertake leakage tests on the installed units.

Solstice N41, or R466A as per its preliminary ASHRAE number, has earned an A1 designation, being it classified as a non-toxic and non-flammable refrigerant. Solstice N41 thus does not require any special equipment for flammable refrigerants nor additional training for technicians. There are also no issues in terms of transportation and storage. With regards to costs, whereas N41 is expected to be more expensive than new A2L refrigerants, the overall costs will be pale in comparison to those required for conversion to a flammable refrigerant.

Conclusion

As explained in this paper, climatic changes and regulations behind the prevention of greenhouse gas emissions are affecting cooling manufacturers, and their customers, when it comes to selecting the optimum refrigerant for a specific use case with a low GWP but without compromising unit efficiency and performance.

Refrigerants have effectively moved from the background to the foreground for more data center operators. The key issues to consider include:

- There is no one-size fits all replacement refrigerant in development. Operators will need to work with suppliers to understand the best balance of cooling technology and refrigerant for their specific use case.
- There is increasing interest in cooling systems that require little or no refrigerant-based mechanical cooling such as indirect and direct evaporative air-to-air systems. However, even these systems have other issues to consider including water availability and usage.
- Refrigerants are facing regulatory scrutiny but so is the energy efficiency of equipment. Both need to be factored into any product development or product deployment decision.

Vertiv-Refrigerants-WP-EN-EMEA-Rev.1-09/2018