environmental investigation agency

Pathway to NET-ZERO
COOLING PRODUCT LIST

"The development and expansion of net-zero cooling is a critical part of our Race to Zero emissions ... I welcome the EIA cooling product list as an important contribution to accelerating the race."

UK High Level Climate Champion, COP 26, Nigel Topping

Above: A cool roof painted white to reflect sunlight and absorb less heat.

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ABOUT EIA

We investigate and campaign against environmental crime and abuse. Our undercover investigations expose transnational wildlife crime, with a focus on elephants, pangolins and tigers, and forest crimes such as illegal logging and deforestation for cash crops such as palm oil. We work to safeguard global marine ecosystems by addressing the threats posed by plastic pollution, bycatch and commercial exploitation of whales, dolphins and porpoises. Finally, we reduce the impact of climate change by campaigning to eliminate powerful refrigerant greenhouse gases, exposing related illicit trade and improving energy efficiency in the cooling sector.

OUR CLIMATE WORK

EIA has almost three decades of experience working with international bodies, governments and enforcement agencies and industry to reduce the environmental impacts of harmful refrigerant gases. Our pioneering investigations have shone a light on illegal trade in ozone-depleting substances (ODS) and hydrofluorocarbons (HFCs) across the globe. Our exposés and advocacy help increase awareness of illegal trade in ODS and HFCs and spur action to curtail it.

Our work also focuses on promoting rapid greenhouse gas mitigation opportunities through the uptake of climate-friendly HFC-free cooling solutions.

ABOUT SHECCO

Over the past 18 years, shecco has developed a unique expertise on natural refrigerant technologies, built an extensive knowledge (sheccoBase) and a large network of experts active in this field. shecco has worked with 150-plus industry partners in the heating, air-conditioning and refrigeration sector with the aim of accelerating the introduction of HFC-free technologies and removing market, technology, policy and knowledge barriers. Having completed a number of research and consultancy projects for leading European, North American and Asian manufacturers of climate-friendly technologies, end users, associations and non-profit organisations, shecco's experts have particular skills in providing in-depth market and policy analysis, conducting feasibility studies and consultancy support with the aim of advancing the use of natural refrigerants in different applications.

EIA UK
62-63 Upper Street,
London N1 0NY UK
T: +44 (0) 20 7354 7960
E: ukinfo@eia-international.org
eia-international.org

EIA US
PO Box 53343
Washington DC 20009 USA
T: +1 202 483 6621
E: info@eia-global.org
eia-global.org

Environmental Investigation Agency UK
UK Charity Number: 1182208
Company Number: 07752350
Registered in England and Wales

Design: www.designsolutions.me.uk

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Pathway to net-zero cooling product list Executive summary

The climate impact of cooling equipment, including fridges and air-conditioners, is two-fold: they use huge amounts of electricity and often rely on super-polluting refrigerant gases such as hydrofluorocarbons (HFCs). In 2020, as part of the work of the COP26 High Level Champions, a Climate Action Pathway for Net-Zero Cooling was launched.

This product list has been designed to support the net-zero cooling transition and demonstrate the feasibility of urgent action. The product list provides a selection of products across all major cooling sectors, with a unique focus on ultra-low Global Warming Potential (GWP) natural refrigerants alongside appliance energy efficiency to help businesses, governments and consumers around the globe make sustainable cooling choices.

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to strengthen the global response to climate change by keeping global temperature rise this century to well below 2°C above pre-industrial levels and to pursue efforts to limit warming to 1.5°C. To meet these goals, it is recognised that global greenhouse gas emissions must decline to net-zero[1] by about 2050.

Since 2015, when the Paris Agreement was signed, nations and businesses alike have begun to plan their transition to net-zero emissions, including action to mitigate cooling emissions.

The product list provides evidence that natural refrigerant solutions are viable alternatives available to the cooling sector as it transitions along the pathway to net-zero emissions. While the focus of this report is on vapour compression cooling appliances, we recognise that adoption of not-in-kind cooling solutions, such as passive cooling and holistic city and building planning, will play a key role toward net-zero cooling.

Net-zero cooling products are defined here as accessible, energy efficient and using ultra-low GWP (<5 GWP) natural refrigerants. Synthetic ultra-low GWP refrigerants such as unsaturated HFCs, more commonly known as HFOs, are not included. This is due to concerns over environmental impacts relating to by-product emissions from certain HFOs[2] and accessibility and illegal trade issues arising from the higher costs of HFOs.

Sectors covered in this report are domestic, commercial, industrial and mobile air-conditioning; domestic, industrial, commercial and transport refrigeration; and domestic, commercial and industrial heat pumps. Information on how to avoid the use of cooling and reduce energy consumption of existing equipment is also provided.

While this product list showcases numerous commercially available products, we find that access to net-zero cooling products varies regionally and across the sectors. It is hampered by various factors including inadequate government policies, poor energy performance standards, higher product costs, outdated building and product regulations and a lack of support for training service and installation personnel.

The products featured in this report offer a first step on the pathway to net-zero cooling. We have strived to provide examples of net-zero cooling products from around the world; however, we recognise that it has a strong European focus. We hope many more guides will follow to show the full geographic breadth of available products.

Further research and development will continue to improve the energy efficiency and cost competitiveness of products compatible with the pathway to net-zero. Some of the subsectors discussed in this report are much further along in this process than others which may require policy and industry intervention to accelerate the transition. Detailed information about the products on this list is available at [EIA's net-zero cooling product list website](#).

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Key findings

Domestic air-conditioning

Small split systems are the most popular domestic air-conditioning product, with more than 100 million units produced annually.[3] **Despite the availability of highly efficient and ultra-low GWP equipment, access to these products is severely hampered by restrictive product safety standards and perceived safety fears relating to the use of flammable refrigerants**. One manufacturer, Godrej, stands out in this sector due to its roll-out of energy efficient propane domestic air-conditioning units across India, using a network of skilled service engineers. Portable air-conditioning units are not featured in the product list, due to the inherent lower energy efficiency of this type of system and poor availability of net-zero compatible products.

Given the scale of growth expected in the domestic air-conditioning sector, urgent attention is needed to increase development and uptake of net-zero compatible products. With energy usage related to domestic cooling increasingly at odds with a pathway to net-zero emissions, measures to avoid, shift and improve the way we meet domestic cooling demand are imperative.

Commercial and industrial air-conditioning

Chillers are the key products featured in this subsector. The product list highlights a variety of net-zero products with cooling capacities ranging up to 1,730kW. **Most are available around the globe, with training often provided by the manufacturer or supplier. However, market penetration of net-zero products remains low with major manufacturers failing to provide natural refrigerant-based products**. Innovative products using indirect evaporative cooling technologies show good efficiency in warmer climates, where sufficient water is available. Other equipment types such as multi-spilt systems and variable rate flow systems are not covered in this report due to lack of net-zero ready products. There is an urgent need for manufacturers to develop natural refrigerant solutions.

Mobile air-conditioning

Direct emissions from mobile air-conditioning in cars, van, buses, truck cab and trains account for almost a quarter of global GWP-weighted HFC emissions, making this a priority subsector.[4] **Natural refrigerant systems are being used in buses and some cars, but uptake is slow. The efficient combined heating and cooling options provided by CO_2 systems may increase their attractiveness as the shift towards electric vehicles places increased attention on energy use for both passenger heating and cooling**. Systems using HFOs are gaining popularity however HFOs are not considered to be net-zero compatible for reasons outlined on page 11.

Domestic and commercial heat pumps

Heat pumps provide an energy efficient way of converting heat from a low temperature to a higher one. Some can be used for cooling as well as heating and hot water production. **Access to the most energy-efficient net-zero products appears strongest in Europe and Japan**; however, obtaining detailed product information beyond Europe was challenging. Higher product costs and lack of technician training continue to be barriers to the uptake of heat pumps in domestic settings.

Domestic refrigeration

Global access to net-zero compatible products in this subsector is high, with 75 per cent of all new domestic fridge manufacturing using natural refrigerants; however, widespread adoption of the most energy-efficient models is currently restricted by higher product costs.

Commercial refrigeration

Centralised supermarket systems are significant sources of energy and refrigerant related emissions in this sector. The development of new components such as ejectors, boosters, electronic expansion valves, parallel compression and transcritical modes have facilitated the widespread roll out of efficient CO_2 systems. Holistic approaches which integrate refrigeration, air-conditioning, lighting and heat recovery have proven effective in further reducing energy consumption.

Proactive regulation in Europe has demonstrated how policy can help drive net-zero product development and reduce product costs. There is now an abundance of net-zero compatible centralised systems. Therefore, instead of creating a product list for this subsector, we have offered a guide highlighting key aspects to look for when choosing net-zero centralised systems.

Condensing units are popular in smaller stores and emerging economies. Access to net-zero products is mainly limited to Europe and Japan, although some manufacturers are willing to export internationally. Increased costs of net-zero condensing units appear to be a barrier to their uptake; this could be addressed by product bans which increase production numbers thereby reducing end-user costs.

Access to net-zero stand-alone commercial refrigeration equipment is good and is expected to increase further due to recent updates to relevant product standards. Water-cooled stand-alone systems using natural refrigerants are gaining popularity in Asia and Europe. They can offer increased energy efficiency and provide flexible, low maintenance alternatives to centralised systems.

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Vaccine coolers which combine natural refrigerants and solar power have increased access to net-zero vaccine coolers across the globe.

Industrial refrigeration

Access to industrial refrigeration net-zero cooling systems is well established, with many manufacturers offering products and training support across the globe but market share remains relatively low. Products featured include chillers and direct ammonia or CO_2 systems. Recent developments reducing the charge size of ammonia systems are allaying safety concerns.

Transport refrigeration

Transport refrigeration is an overlooked subsector urgently in need of innovation and policy support. Emissions from transport cooling systems can account for around 40 per cent of the vehicle's total emissions, half of which is due to the direct emissions from the refrigerant. **Despite the urgent need for net-zero products, availability is low. CO_2 shows a lot of potential for widespread uptake in shipping**. Truck and trailer net-zero systems using cryogenics are also showing promise however, the energy intensity of producing the liquid CO_2 or nitrogen raises questions about their suitability as net-zero compatible products.

Recommendations

Recommendations for policy-makers

Ambitious cooling plans which promote uptake of ultra-low GWP and energy efficient technologies, as well as not-in-kind solutions, are urgently needed and should be included in Nationally Determined Contributions (NDCs) under the Paris Agreement.

HFCs are subject to a phase-down under the Kigali Amendment to the Montreal Protocol. However, the scheduled phase-down for developing countries allows for business-as-usual growth until 2026. While the Kigali Amendment was a huge step forward, it does not reflect the urgent pace of transition towards ultra-low GWP refrigerants needed and outlined in the Climate Action Pathway for Net-Zero Cooling. This could be addressed through an accelerated global HFC phase-down.

The EU's 2014 F-gas Regulation has demonstrated the transformative power of progressive policy. Seven years on Europe is reviewing this landmark piece of legislation. Increasing the ambition of the phase-down schedule alongside further product bans would support and spur technological innovations needed to meet the climate emergency.

Recommendations for cooling equipment manufacturers

We are facing a climate emergency and cooling equipment manufacturers have a pivotal role to play in delivering accessible, ultra-low GWP, energy-efficient, sustainable cooling technologies. In 2014, cooling equipment was responsible for more than seven per cent of global greenhouse gas emissions. This figure is expected to rise to 13 per cent of projected greenhouse gas emissions in 2030.[5] Despite the significance of cooling emissions, a 2020 report by the Carbon Disclosure Project found that the cooling sector was behind the curve on business readiness for a low-carbon transition and highlighted a lack of innovation, below-average investment in research and development compared to other capital goods sectors and a significant gap between Minimum Energy Performance Standards (MEPs) and the most efficient technologies available.[6]

The slow pace of change in the sector must be addressed to put cooling on the pathway to net-zero. Manufacturers should join the UNFCCC's Race to Zero campaign and step up to the climate challenge through a rapid roll out of accessible net-zero compatible cooling equipment.[7]

Additionally, immediate action should be taken to halt the practice of technology-dumping of inefficient HFC cooling equipment in developing countries.

Finally, manufacturers should support capacity development within the servicing sector to enable the safe uptake of natural refrigerants around the globe.

Recommendations for companies using cooling equipment

Adoption of net-zero cooling equipment can provide cost-effective and rapid opportunities for emission reductions. Companies using significant amounts of cooling should commit to net-zero emissions targets and prioritise investment in net-zero cooling.

It is essential for consumers of cooling equipment to act with urgency since purchasing choices made now can have significant impacts on a company's carbon footprint for decades to come.

Recommendations for all consumers of cooling equipment

As consumers of cooling, we all have a role to play in achieving net-zero cooling, both through the purchasing choices we make and the way we use the cooling available to us. This report also features tips and guidance on behavioural ways to reduce emissions from cooling.

Table 1: *Actions needed at a sectoral level to speed up the transition to net-zero cooling*

SECTORAL ACTION TABLE	
Cooling sector	**Recommendations**
Domestic air-conditioning	• Update international and national product standards and building regulations to allow increased and safe use of flammable refrigerants. • Introduce product bans which prohibit the use of HFCs. • Introduce Minimum Energy Performance Standards (MEPS) linked to GWP limits. • Introduce incentives to help consumers afford the most climate-friendly products. • Update government procurement policies to prioritise net-zero compatible appliances. • Support service technician training through mandatory requirements which add training on hydrocarbons to any existing training requirements.
Commercial and industrial air-conditioning	• Introduce product bans which prohibit the use of HFCs. • Introduce MEPS linked to GWP limits. • Update government procurement policies to prioritise net-zero compatible cooling.
Mobile air-conditioning	• Car manufacturers should reassess the use of CO_2, given its promising outlook with electric vehicles. • Further research into the environmental impacts of HFO-1234yf is needed.
Domestic and commercial heat pumps	• Significant incentives to support uptake of domestic heat pumps are needed and these should be linked to GWP limits to avoid additional uptake of HFCs. • Increase awareness of heat pump technology and availability in the domestic heating sector. • Support service technician training through mandatory requirements which add training on natural refrigerant to any existing training requirements.
Domestic refrigeration	• Introduce or strengthen MEPS. • Introduce product bans which prohibit the use of HFCs in countries where such prohibitions do not yet exist. • Introduce incentives to help consumers afford the most efficient natural refrigerant products.
Commercial refrigeration	• Introduce product bans which prohibit the use of HFCs. • Equipment manufacturers should continue to keep on driving energy efficiency of natural refrigerant-based cooling equipment.
Industrial refrigeration	• Introduce product bans which prohibit the use of HFCs. • Introduce MEPS linked to GWP limits to drive uptake of net-zero cooling products.
Transport refrigeration	• Equipment manufacturers must invest in research and development of net-zero compatible products. • Policy signals which drive net-zero product innovation are urgently needed. • Gases used for cryogenic systems must only be compressed using renewable energy. • Regulation to limit pollution from diesel engines powering transport refrigeration units should be introduced.

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Introduction:
Why we need to act now on cooling

Keeping cool as the world gets hotter will become increasingly urgent for human health and development. Mechanical cooling, from refrigerators to air-conditioning, is necessary to store and transport vaccines and medicines, to keep food fresh, for human productivity and comfort and for many industrial processes. But as climate change advances and global temperatures rise, the cooling products we use risk exacerbating the problem.

Cooling products not only use huge amounts of electricity (refrigeration, air-conditioning and heat pump equipment is estimated to consume 25-30 per cent of global electricity)[8]**, they also rely on super climate pollutant refrigerant gases**. Fluorinated gases – including hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) – are the most commonly used refrigerants. **HFCs are potent short-lived greenhouse gases (GHGs) with high GWPs, meaning they quickly exacerbate atmospheric warming when they leak from equipment or are released to the atmosphere when the equipment is disposed of**.

Scientists warn that we are currently on a catastrophic warming trajectory of above 3°C by 2100.[9] The impacts of this level of warming are huge and could be beyond the threshold of many climate system tipping points. Climate tipping points are positive feedback loops which, once passed, have the potential to greatly exacerbate global warming. For example, as permafrost thaws it releases significant amounts of stored methane which further contributes to warming.

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to strengthen the global response to climate change by keeping global temperature rise this century to well below 2°C above pre-industrial levels and to pursue efforts to limit warming to 1.5°C. To meet these goals, it is recognised that global greenhouse gas emissions should decline to net-zero by about 2050.[10]

International agreements to phase down HFCs

In recognition of the threat HFCs pose to our climate system, the world is acting to globally phase down these gases under the 2016 Kigali Amendment to the Montreal Protocol. Under this agreement, developed countries began to reduce HFC production and consumption in 2019, while most developing countries will begin in 2024. **The Kigali Amendment was a huge achievement, but the pace of the HFC phase-down could be accelerated**.

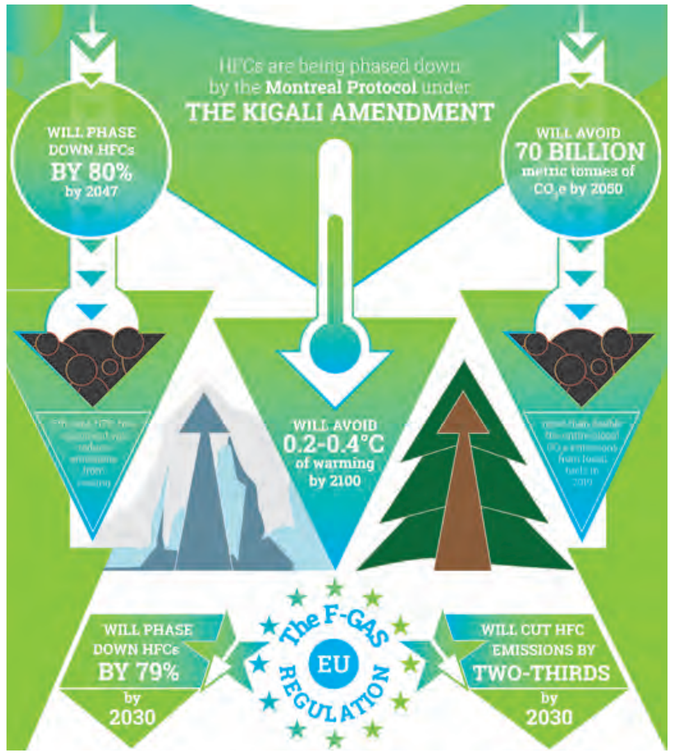
For example, a recent analysis by the Montreal Protocol's Technical and Economic Assessment Panel (TEAP) reveals that an over-generous baseline allows the majority of developing countries to adopt a business-as-usual approach until sometime after 2026.[11] This risks locking in high-GWP HFC cooling equipment and encourages technology dumping of highly polluting cooling equipment in developing counties. **A 2020 study by the Climate and Clean Air Coalition reveals it is technically feasible to achieve near-complete HFC mitigation by 2030, 20 years ahead of the Kigali phase-down**.[12]

A pathway to net-zero cooling

A Climate Action Pathway for Net-Zero Cooling was launched in late 2020.[13] The pathway is a collaboration between the Kigali Cooling Efficiency Programme (K-CEP), Cool Coalition, Carbon Trust and CoP26 High-Level Champions and provides actions outlining ways the cooling sector can reach net-zero emissions by 2050.

It is part of a larger initiative of climate action pathways which outline sectoral visions of how we can reach a 1.5°C climate-resilient world by 2050 and the actions required to achieve that goal.

The Climate Action Pathway for Net-Zero Cooling outlines a 2050 vision for the cooling sector. This vision focuses on three areas:[14]



- widespread adoption of passive cooling;
- a transformation to super-efficient cooling equipment and appliances;
- market domination of ultra-low (< 5) GWP refrigerants across all cooling sectors and appliances.

The pathway to net-zero cooling uses the Avoid/Shift/Improve framework, highlighting options that avoid the use of mechanical cooling, such as passive cooling, as well as ways to shift and improve the way we cool.

The Cool Coalition defines the Avoid/Shift/Improve hierarchy for cooling as:[15]

- **Avoiding (reducing)** the need for mechanical cooling through better urban planning and nature-based solutions;
- **Shifting** cooling to renewables, thermal storage and district cooling;
- **Improving** conventional cooling by increasing the efficiency and reducing the GWP of air conditioning and refrigeration equipment and demand response measures.

This product list aims to provide a selection of net-zero cooling products which primarily fall within the 'Improve' and, to a smaller extent, 'Shift' hierarchies across most cooling sectors.

Why do we need a net-zero product list for the cooling sector?

This product list has been developed to support the Climate Action Pathway to Net-Zero Cooling and as such highlights efficient, ultra-low GWP cooling products.

A number of cooling related product lists already exist, for example the UK Government's Energy Technology List,[16] the Green Technology Selector[17] and WWF's Topten database.[18] However, they primarily focus on energy efficiency and, with the exception of WWF's Topten list, most do not apply any refrigerant-related criteria to the products they feature.

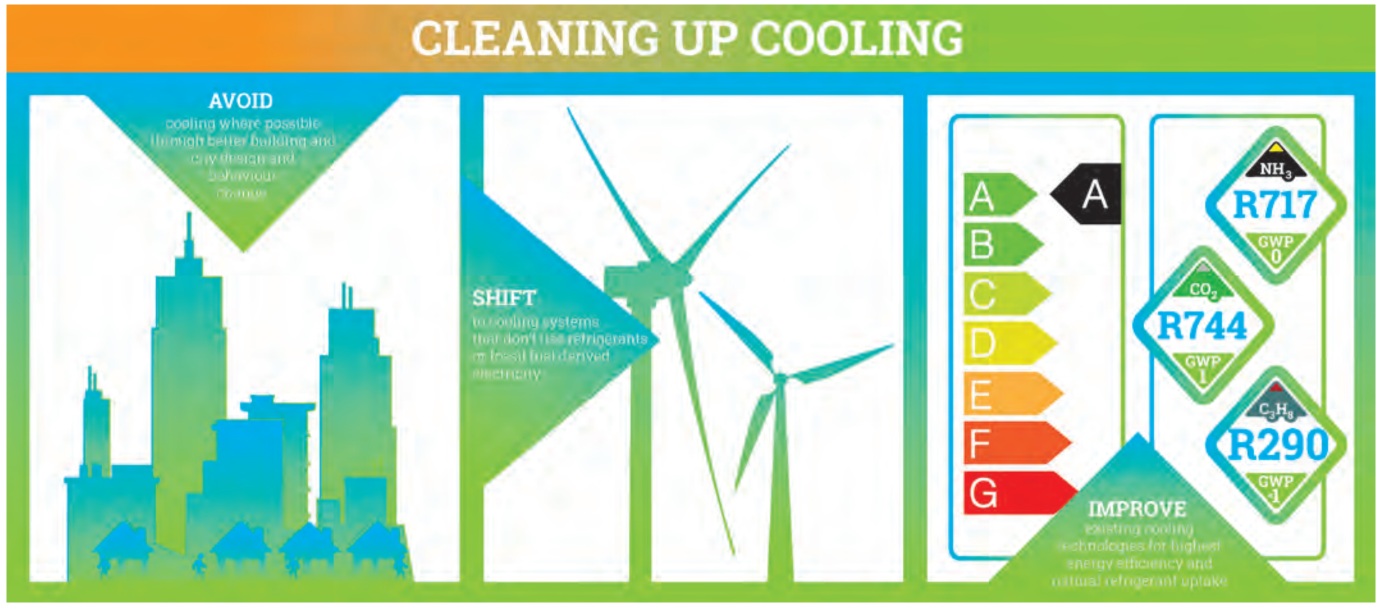
Furthermore, no list – including this one – is exhaustive and most tend to consider only products offered by large multinational manufacturers, thereby overlooking the smaller green cooling product innovators which are less widely visible to end users.

What is a 'net-zero' cooling product?

Net-zero cooling is defined in the Climate Action Pathway as "reducing greenhouse gas (GHG) emissions from cooling during operational life of products (excluding resource extraction and manufacturing) to as close to zero as possible and any remaining GHG emissions would be balanced with an equivalent amount of carbon removal – for example, by restoring forests and through direct air capture and storage technology."[19]

Greenhouse gas emissions from cooling products considered within this definition include indirect emissions associated with energy use and direct emissions associated with the refrigerant.

Most cooling equipment in use employs electrically driven vapour compression technology. Energy-related emissions from this equipment are affected by various factors, including the energy source, energy efficiency of the product and usage behaviour. Unless the power comes from renewable sources, indirect emissions will be associated with the product's use. As energy efficiency levels increase and electrical grids transition to renewable energy sources the indirect emissions of these products will decline.



Emissions from the production of equipment and refrigerants tend to represent a small percentage of the lifetime emissions, although concerns about the manufacturing emissions associated with HFO production remain.

Direct emissions result from the use of refrigerant with significant GWPs. **On average, direct emissions account for approximately 30 per cent of cooling equipment's climate impact, across all sectors**.[20] Direct emissions occur through leakage from equipment, during use and servicing as well as when the equipment is discarded at the end of life. Almost entirely eliminating direct emissions is possible when using ultra-low GWP refrigerants, such as natural refrigerants, and has therefore been prioritised in this product list.

Above: Flooding in Dhaka, Bangladesh.

Access to cooling is increasingly regarded as a human right and increasingly important as the world warms. **Access to cooling is defined by the Montreal Protocol's Technical and Economic Assessment Panel as the ability for consumers across regions/countries to purchase and install cooling appliances**.[21] Accessibility to net-zero cooling remains an issue. Barriers to access include geographical location, cost, local regulations, international and national standards, lack of compatible components and lack of an adequately trained technician workforce in-country.[22]
The report makes a concerted effort to include a range of products that are widely accessible.

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Criteria

1. Direct emissions: Refrigerant

The Pathway to Net-Zero Cooling is dependent on the uptake of ultra-low Global Warming Potential (GWP) refrigerants.[23] GWP is a measure of how much heat a greenhouse gas traps in the atmosphere relative to CO_2. **As defined by the Climate Action Pathway for Net-zero Cooling, for a refrigerant to be net-zero compatible it should have a GWP of less than five**.

The net-zero products featured in this list use natural refrigerants. Natural refrigerants include carbon dioxide (CO_2) (GWP of one), hydrocarbons (propane with GWP of <1, isobutane with GWP of <1, propylene with GWP of two), ammonia (GWP of zero), water (GWP of zero) and air (GWP of zero).[24]

This list does not include unsaturated HFCs (marketed as HFOs), despite their low GWPs. This is due to concerns about their potentially significant environmental impacts and is in line with selection criteria of national procurement policies and standards such as the German ECO label, Blue Angel[25] and the Nordic region Green Public Procurement guidelines.[26]

2. Indirect emissions: Energy

Where possible, an energy efficiency baseline has been set for each cooling subsector.

There are various ways of measuring the energy efficiency of a product. The Coefficient of Performance (COP) is the ratio of the refrigerating capacity of the system to the energy consumed. The Seasonal Energy Efficiency Ratio (SEER) is related to the COP and reflects the efficiency of a product over an entire year/season, thus accounting for the variations in ambient temperatures. SEER values are specific to equipment, nominal capacity, operating temperature range and determination factors vary regionally. **It should be noted that various factors other than product design play a role in maintaining optimum**

Why a precautionary approach to HFOs is needed

EIA has not considered cooling equipment or systems which utilise HFO refrigerants for inclusion in the product list for several reasons:

1. Increased levels of TFA

HFO-1234yf is currently the most commonly produced HFO, with 2017 production levels estimated in the 10,000 tonnes range.[27] It is used alone as a refrigerant and is a core ingredient of many HFO blends. HFO-1234yf releases high levels of trifluoroacetic acid (TFA) when it breaks down in the atmosphere. Recent studies have found significant increase of TFA levels in rainfall on glaciers and in groundwater, with several studies finding higher-than-permitted TFA levels in some ground water samples.[28] **The Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC) of the Montreal Protocol stated that the high rate of TFA "may be of considerable environmental relevance in view of the expected future HFO production expansion"**.[29]

2. High manufacture-related emissions

HFOs are complex chemical compounds requiring significant amounts of energy to manufacture. Depending on the production route, HFO-1234yf produces at least 13.5kg CO_2e emissions per single kilo of refrigerant produced.[30] This means a system using 35kg of refrigerant would have associated manufacturing emissions of at least half a tonne of CO_2. In contrast, ammonia produces 1kg CO_2e of emissions for every 1kg manufactured[31] and refrigerant grade CO_2 produces 0.5 kg CO_2e for each kilo manufactured.[32]

Furthermore, EIA is concerned that HFO production may be associated with the unprecedented levels of HFC-23 emissions reported earlier this year in Nature.[33] HFC-23 (GWP 12,400) is created as a fugitive emission during the production of HCFC-22, a feedstock chemical used to make some HFCs, including HFOs.[34]

3. High refrigerant costs, associated accessibility problems and risks of driving illegal trade in HFCs

As of 2017, the market price for bulk quantity HFO-1234fy was approximately 10 times higher than HFC-134a.[35] While it is anticipated that this differential will drop over time, the higher price of HFO refrigerants may reduce their accessibility and could inadvertently drive illegal trade in HFCs. For example, HFO-1234yf has been selected to replace HFC-134a for use in mobile air-conditioning. However, it is possible to top up new HFO-based systems with HFC-134a. **There is a risk that HFCs could be used instead of HFOs during servicing, stimulating further demand for HFCs and thus potentially driving illegal trade in HFCs as they are phased down.**

energy efficiency. These include regular product maintenance, cleaning and servicing, correct use of settings and controls and behavioural factors such as temperature setting and usage patterns.

Energy efficiency information for domestic products is widely available globally; however, similar easily accessible and globally comparable information for transport, commercial and industrial cooling products is often lacking. Our correspondence with manufacturers reveals that globally standardised energy efficiency measurements are difficult to obtain, with testing conditions varying regionally and on a product-by-product basis.

The bespoke nature and system requirements of many commercial and industrial systems makes direct comparisons of energy efficiency within the scope of this project challenging. Where possible, we have sourced products from other energy efficient focused cooling product lists such as the UK's Energy Technology List, Topten and Energy Star to ensure the equipment meets their energy efficiency criteria. While there has been a concerted push for increasing energy efficiency in cooling, it has in some cases been prioritised without consideration for the refrigerant choice. **Montreal Protocol experts have warned of growth in the uptake of high-GWP HFC cooling equipment in developing countries due to the 'introduction of Minimum Energy Performance Standards (MEPS) solely focused on improving energy efficiency without wider consideration of the climate impact from the high GWP of the refrigerants and blowing agents.'**[36]

On average, direct emissions account for approximately 30 per cent of cooling equipment's climate impact, across all sectors.[37] Therefore, significant emission reductions can be achieved by adopting ultra-low GWP alternatives.

3. Accessibility

Accessibility centres around a consumer's ability to purchase a product. It is different to availability, which is defined as "the ability of the industry to manufacture products with new technologies of lower-GWP refrigerants and higher efficiency."[38] In recognition of limited accessibility to the most energy efficient products in certain regions of the globe, we have occasionally chosen to include some products which have less optimal energy efficiency but offer a more accessible option.

Costs and cost ranges are included where available, but for various subsectors this information was not possible to obtain as products are bespoke and built to order or the information is commercially sensitive.

The process

Product information was collected by shecco, which conducted a public call for information in July 2020 followed by extensive market research and direct contact with manufacturers.

The product list is designed to offer a 'Gold Standard' rather than a tiered 'best/okay/avoid' approach of comparing products. It is not intended to be an exhaustive catalogue of the most energy efficient products or all products using natural or no refrigerants on the market. It serves as a snapshot of what is available on the market and to highlight the subsectors where more research, development and policy support is required to align with a pathway to net-zero cooling.

The product list shows that natural refrigerant options can be energy efficient and cost-competitive already, but more effort is required for them to dominate the market and shift the entire cooling sector onto the pathway to net-zero emissions. Further research and development can continue to improve efficiency and bring down costs, while government intervention can remove barriers including outdated safety restrictions and lack of technician training.

The equipment featured on the product list has been chosen to show various natural refrigerant choices, equipment capacities and temperature ranges and the breadth of suppliers offering these products. As such, we have chosen only one product from individual manufacturers in each subsector (except for domestic air-conditioning). We recognise that there are manufacturers which make products on demand; unfortunately, these are beyond the scope of this list.

We welcome manufacturers and suppliers to get in touch should they wish to share updated information on their listed products or would like their product to be considered for addition to our database of pathway-to-zero compatible products. Detailed information about the products is available at **EIA's net-zero cooling product list website**.

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Domestic air-conditioning

Definition and scope of sector

With warmer global temperatures, more frequent heat waves and rising incomes, domestic air-conditioning ownership is growing at a staggering pace and is projected to continue growing. **By 2100, 75 per cent of the global population could be at risk of potentially deadly heat exposure for more than 20 days per year, up from 30 per cent today**.[39]

However, cooling for all does not mean an air-conditioner for everyone; if everyone who needed it had access to air-conditioning there could be 14 billion pieces of cooling equipment by 2050.[40] This would have huge negative impacts on refrigerant and energy-related emissions.

Sustainable cooling for all requires a holistic rethink of how we meet our cooling needs.

Below: Air conditioning units on a building in Singapore.

The Green Cooling Initiative states that unitary air-conditioning emissions are currently 1.28 gigatonnes of CO_2 equivalent ($GtCO_2e$), with about one quarter of those emissions coming from the refrigerant.[41] Domestic air-conditioning units are used to maintain the temperature of rooms in people's homes. There are a variety of equipment options, but this subsection focuses on single-split systems up to 7kw. Portable air-conditioning units are not featured in this product list. Despite availability of appliances using natural refrigerants, the energy efficiency of these products does not support their inclusion. Portable air-conditioners are inherently inefficient due to waste heat from the unit requiring an opening in the room, which may compromise the efficiency of the unit. Current EU energy labelling scales for portable units are less ambitious than those associated with single-split units and can be misleading. For example, the efficiency of a Class A portable unit corresponds to a Class F split air-conditioner.[42] Finally, domestic heat pumps are covered in the heat pump section of the report.

Single-split systems dominate the domestic air-conditioning market with about 100 million units produced annually, the majority of which run on high- and mid-GWP HFCs.[43] HFC-410A (GWP 2,088) is the most commonly used, but the use of HFC-32 (GWP 675) in these systems is increasing; however, the GWP of HFC-32 means that it cannot be considered a net-zero compatible alternative and products using it are therefore not included in this product list.

Propane (R-290) is a natural refrigerant alternative used in small split systems. Its flammable nature means that design considerations and adequate training and certification of technicians is needed to address health and safety concerns.

Currently, some national building regulations and outdated product safety standards are restricting the allowable amount of propane charged into systems and are thus hindering the use of propane in domestic air-conditioning.

SINGLE SPLIT AIR-CONDITIONER PRODUCT LIST

CRITERIA

- **F-gas free**
- **Local Seasonal Energy Efficiency Ratio (SEER) of at least six or compatible with U4E Model Regulations**
- **Commercially available and/or in demonstration projects**
- **Cooling capacity below 7kw**

An update to the international standard based on thorough product safety design and better understanding of risks involved is being discussed by the International Electrotechnical Commission (IEC), with a final outcome expected in late 2021.[44]
The product list features five products, all of which use propane. Although other propane units are available, we have selected the most energy-efficient models from reputable manufacturers on the market. We have selected more than one model per manufacturer to enable larger consumer choice as the range of net-zero compatible products is low. United 4 Efficiency has developed Model Regulation Guidelines for energy efficient and climate-friendly single-split air-conditioners.[45]

The Model Regulation is based on the based on the ISO 16358 Cooling Seasonal Performance Factor which is correlated with Indian SEER levels. However, comparison with EU SEER levels is less reliable. Where reliable comparisons are possible, the appliances featured in the product list meet the minimum energy efficiency requirements set out by the guidelines and exceed the ambition of the GWP limit of 750, currently set by the Model Regulation.

ElectrIQ introduced its 2.6kw and 3.5kw split air-conditioning units to the UK and European markets in summer 2020 and has since sold thousands of units. The safety of the units has been certified by Bureau Veritas. ElectrIQ has developed an innovative design with pre-connected copper pipes, so all connections are outside of the building. Despite the extra in-built safety measures, it is recommended installation of these product be carried out by certified technicians.

Godrej began production of propane split air-conditioning units in 2012. The air-conditioner is available in two sizes, 3.5kw and 5.2kw. Since the product's launch, Godrej has reduced the power consumption of its units to surpass India's ever improving five-star efficiency label. Godrej is increasing the range of units available on Indian markets with new 12kw and 18kw units expected to be launched in April 2021.[46] It ensures the safe use of its products via its trained service technicians.

In 2012, Midea's All Easy Series became the only domestic split air-conditioner <12kW to be awarded the Blue Angel certification. To date, introduction of this product to the EU market has not yet occurred. Midea also has several models available on the Chinese market, although we were unable to obtain energy efficiency data on them.

Although not featured on the product list, two manufacturers – ElectrIQ and Life Zero GWP[47] – have recently launched through-the-wall propane-based monoblock units with no condensing unit outside of the building, which offer a simpler alternative to a spilt system.

Is this sector on the pathway to net-zero emissions?

Conversion of single-split air-conditioner production lines to propane are under way in China, South-East Asia and South America.[48]

Chinese manufacturers Gree, Midea, Haier, Hisense, Changhong, TCL, Aux and Yair are all reportedly producing propane room air-conditioners.[49] Midea alone has installed more than 200,000 units in China.[50] We were unable to obtain detailed product information relating to appliances in use across China and South America. Globally, market penetration is still small although increasing in India, with more than 600,000 units on the market as of 2018.[51]

An EIA-commissioned report by Öko Recherche found that 5.6 $GtCO_2e$ of emissions could be avoided by 2050 by switching the refrigerant in domestic split system air-conditioning units globally to propane from 2025[52] but, to date, major equipment manufacturers are reluctant to promote this technology and are favouring HFC-32 units as an interim solution.

We recognise there is scope for further energy efficiency improvements of products featured. The efficiency of propane split systems is currently limited by safety standards which prevent the use of larger refrigerant quantities and thus larger capacity systems. The standard in question, IEC (and EN) 60335-2-40, is now under revision to consider allowing the safe use of larger amounts of flammable refrigerants. **A positive vote would enable the safe use of larger charge sizes which would significantly boost the energy efficiency and range of domestic air-conditioners using propane**.

There is also a perceived fear associated with new technologies using flammable refrigerants, although the single spilt air-conditioners featured are designed, constructed and tested to eliminate any flammability risk, as evidenced by an absence of any incidents reported by the three manufacturers featured.

Finally, a lack of legislative drivers allows for ongoing use of dominant technologies. For example, the EU F-gas Regulation banned the use of HFCs with GWP>750 in single split systems from 2025. This GWP limit allows for the use of HFC-32, which has subsequently been heavily promoted by the manufacturing industry and is now commonly use in European systems.

In 2020, the European Commission published a report stating: 'It appears technically possible to avoid F-gases today in new single-split air-conditioning with a cooling capacity below 7kW by using the refrigerant

Table 2: *Single split air-conditioner product list*

Manufacturer	Product name	Refrigerant	Refrigerant GWP	Cooling capacity (kW)	SEER	Energy label	Geographic availability	Price	Equipment manufacturer servicing scheme
ElectrIQ	12WNIMV	R-290	<1	3.5	6.14	A++ (EU)	UK and Germany	GBP apx £480	No
ElectrIQ	9WNIMV	R-290	<1	2.6	6.16	A++ (EU)	UK and Germany	GBP apx £450	No
Godrej Appliances	GIC 18 LAH 5 GWQG	R-290	<1	5.2	5.25	5- star (India)	India	67,000 Rs	Yes
Godrej Appliances	1 Ton (12000 BTU) Inverter AC	R-290	<1	3.5	6.15	5- star (India)	India	Unknown	Yes
Midea	MSAEBU-09HRFN7 -QRD6GW	R-290	<1	2.64	7.10	A++ (EU)	will be available in EU	N/A	No

Öko-Recherche, (2020). 'Explanatory Note on modelling of climate benefits of charge size changes for air conditioning equipment in relation to the revision of the product standard IEC 60335-2-40', Environmental Investigation Agency.

R-290 (propane), unless national legislation or codes prohibit its use.'[53]

A ban on the use of HFCs with GWP>5 in single-spilt air-conditioners in the upcoming legislative review of the F-gas Regulation would support uptake of net-zero technologies in this sector.

Access to the most energy efficient domestic air-conditioners is poor across the sector. **A recent report by the Carbon Disclosure Project found that major cooling manufacturers were failing to make the most efficient technologies widely available, partly due to significant gaps between national Minimum Energy Performance Standards (MEPS) and the best available technology**.[54] For example, in the United States, the most efficient model on the market is three times more efficient than the least.[55] This trend is reflected globally, with the majority of units bought today being two to three times less efficient than the most efficient units.[56]

Ambitious MEPS can help drive the market, but these must not counterproductively drive the uptake of high-GWP HFCs. The Montreal Protocol has raised concerns about technology dumping of high-GWP HFC domestic air-conditioners in developing countries fuelled by the introduction of MEPS which do not take refrigerant GWP into account.[57]

In addition to energy efficiency of the product, the way we use products has a significant impact on their energy consumption. In recognition of this, India's 2019 Cooling Action Plan introduced guidelines for air-conditioning thermostats to be set to warmer temperatures (24-27°C). Similar action was taken by the Chinese Government in 2007. These measures are expected to reduce energy consumption by about 20 per cent.[58,59]

The products featured in this subsection offer a first step on the pathway to net-zero emissions. We must act now to explore alternative ways of cooling while avoiding the associated planetary warming to ensure that access to cooling is addressed in an equitable and sustainable manner.

This requires a vast overhaul of how we meet our cooling demands sustainably for the planet and equitably for the people.

The use of domestic cooling is closely tied with weather conditions. Demand for air-conditioning on hot days in cities such as New York and Beijing can be responsible for up to 50 per cent of domestic peak electricity demand.[60] This is particularly damaging to the climate as peak demand is often met with extremely polluting coal-fired power plants built specifically to meet only these short periods of very high demand.[61]

With energy usage related to domestic cooling becoming increasingly at odds with the pathway to net-zero emissions, measures to avoid, shift and improve the way we meet residential cooling demand are urgently needed.

Avoid

- Optimise building and city design to harness passive cooling by inter alia creating cross breezes, maximising shade and installing wind catchers on buildings.
- Cool Roofs are suitable for almost any building and can cool a building by 1-2°C and reduce annual cooling use from air-conditioning by 10-20 per cent on the floor directly below the roof.[62]
- Reduce demand for cooling by making the most of natural ventilation by opening windows at night if safe (and possible) to do so.

Shift

- Use a fan instead of an air-conditioner if possible. Solar-powered fans are a more sustainable option.
- Research and development is accelerating on providing wearable cooling technology in the form of clothing or patches to provide personalised cooling and heating. These can use evaporative cooling or phase-change materials and be powered by battery packs, fans or by being soaked or filled with water or another fluid.[63] Patches made of thermoelectric alloys cool or heat the skin to a chosen temperature. These technologies could be particularly important for workers who spend long hours outdoors in high temperatures, including construction workers and farmers, but can also be worn in homes and offices.
- District cooling systems deliver chilled water to multiple users via a network of insulated pipes. District cooling can be run with natural refrigerants and renewable energy and/or waste heat and is up to 40 per cent more energy efficient than delivering cooling through individual domestic and commercial air-conditioning systems in cities.[64] District cooling systems in Dubai are reducing the amount of energy used for cooling by 50 per cent and are expected to meet 40 per cent of the city's needs by 2030.[65]

Improve

The best way to improve this subsector is by choosing HFC-free energy-efficient air-conditioners. While more efficient air-conditioners can cost more, awareness of the longer-term savings due to reduced energy costs should be factored into purchasing decisions. This could be supported via government subsidies.

Additionally, behavioural change can play a key role in reducing the emissions of air-conditioning equipment. For example:

- set the default temperature to between 24-27°C to maintain thermal comfort, reducing your electricity bill and reducing emissions;
- use only your air-conditioner to cool rooms in use and set a timer to turn it off while sleeping, rather than cooling an entire house throughout the day and night;
- regular maintenance can also improve the energy efficiency of products over their lifetime.

Global Cooling Prize: supporting net-zero cooling innovation

The Global Cooling Prize was launched to find residential cooling solutions with emissions five times lower than current technology at no more than double the price.

The shortlisted solutions include solid state cooling technology, hybrid solutions utilising evaporative cooling and ventilation alongside vapour compression, membrane dehumidification and desiccant dehumidification, with some integrating on-site renewable energy.[66]

These products could not be included in the product list as they are not yet commercially available, but they could potentially revolutionise the domestic air-conditioning sector, aligning it with the net-zero pathway.

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Commercial and industrial air-conditioning

Definition and scope of sector

This subsector covers large chillers for commercial and industrial applications such as in the automotive, electronics, data storage, energy and utilities, food and beverage, pharmaceutical, chemical, cement and oil and gas sectors, among others.

There may be overlap between the chillers presented here and some of those in the industrial refrigeration subsection.

Multi-spilt air-conditioners, including variable rate flow (VRF) systems, are popular alternatives to chillers. One rooftop ducted system using propane is featured in the innovation product list, but we were unable to find net-zero compatible multi-spilt air-conditioning equipment. There is an urgent need for manufacturers to develop natural refrigerant solutions for these applications.

Chillers are used to dehumidify and cool buildings and facilities and are split into two broad categories – air-cooled and water-cooled.

Air-cooled chillers are typically installed outdoors and used predominantly in smaller applications and where water resources may be scarce. Air-cooled chillers are cheaper to install and maintain than water-cooled chillers.

Water-cooled chillers tend to be used for larger spaces and are connected to an external cooling tower but are typically installed indoors. While more expensive, water-cooled chillers can offer a more consistent performance as they are affected less by changing ambient temperatures.[67]

Above: Ammonia refrigeration tanks.

Chillers can be further broken down into four categories based on their compressor type – reciprocating, centrifugal, screw and scroll.

Vapour compression is the dominant technology for chillers. However, alternative approaches exist. Indirect evaporative cooling is a 'shift' alternative to vapour compression. Systems use water as the refrigerant and can display very high COPs; some are highlighted in the innovation section. Adsorption chillers which combine water (or other fluid) evaporation with the use of a porous surface, such as silica gel, are also featured in the innovation section of this subsector.

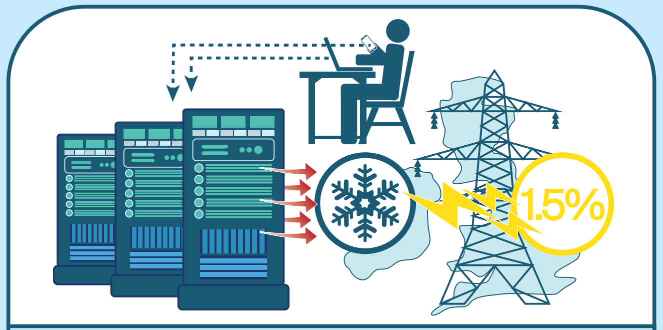
However, evaporative cooling and water sorption technologies are constrained in their application by near- and sub-zero temperatures. Sorption systems tend to have low COPs and also require thermal energy to drive them and if this energy is derived from fossil fuel sources (such as gas or oil), total CO_2 emissions can increase. If sorption systems are driven by excess heat generated through industrial processes, solar heating or other renewable energies, they can be attractive net-zero technologies.[68]

The subsector is slowly transitioning away from HCFC and high-GWP HFC refrigerants such as HFC-410A (GWP 2088), HFC-407C (GWP 1774) and HFC-134a (GWP 1300) to natural refrigerants and lower GWP HFCs and HFO blends.[69]

A range of natural refrigerants is available for use in industrial and commercial chillers, but their market share remains low due to the market being dominated by a small number of large multinational producers with rather conservative refrigerant policies.

Carbon dioxide is well-suited for chillers operating in temperate climates, especially where heat recovery can be employed to raise efficiency.[70] Water as a refrigerant (R718) has been used in limited applications, but increased research has led to water being used for more general chiller applications, including cooling for industrial processes, data centres and industrial and commercial air-conditioning. Ammonia and hydrocarbons are also used in chiller applications. Most chillers using these refrigerants are located outdoors or in machinery rooms, which eases the burden of additional safety measures for handling toxicity and/or flammability.[71]

Ensuring properly trained technicians are familiar with the safety precautions required for working with natural refrigerants is essential to mitigate the health and safety risks associated with these systems. **Many of the manufacturers of the products featured in the**



Data centre cooling requires huge amounts of energy. In the UK, data cooling accounts for 1.5% of electricity consumption.

Toby Peters and David Strahan, (2016). 'The cold economy – Why? What? How?', Birmingham Energy Institute.

Data centres are a growing end user of industrial air-conditioning and this market is expected to continue to grow.

Data centre cooling requires huge amounts of energy; in the UK, keeping data centres cool consumes about 1.5 per cent of the country's electricity.[72] Rapid growth in this sector means that by 2030, the energy required to cool data centres globally will reach about 35GW.[73]

With consistent and predictable demand, data centres offer opportunities for using renewable energy, free cooling and heat recovery, among other innovations.[74]

product list supply training in person or virtually during commissioning of products. This issue is covered in detail in the later section on training.

Is this sector on the pathway to net-zero emissions?

All chillers listed can provide air-conditioning and many also meet process cooling specifications – depending on the process.

The list includes a variety of chillers, both air-cooled and water-cooled, using a range of natural refrigerants such as ammonia, carbon dioxide, water and hydrocarbons.

Many of the products are available on European markets and meet stringent Ecodesign Minimum Energy Performance Standards. **More than half of the products are available globally, suggesting that access to these net-zero chillers is good**. The significant capital investment required, and sometimes-bespoke nature of these systems, means that manufacturers are more willing to export their products to any destination.

Chillers typically have long lifetimes (at least 15 years) so the refrigerant chosen today, and its associated direct emissions, will be locked in until 2035 or later.[75] The long lifetimes mean that few end users will look to replace their systems before the end of life, so an added emphasis should be on reducing leakage and ensuring good energy efficiency in existing systems to reduce emissions.[76]

Chillers consume a lot of energy and their indirect emissions dominate their environmental impact.[77] Therefore net-zero chillers and innovative products must show good energy efficiency.

Energy efficiency improvements can be gained through better equipment design, the use of more efficient parts, including heat exchangers and inverter compressors, and regular maintenance and cleaning.

Since chillers are often associated with large buildings, there are opportunities to use solar panels or other on-site renewables to further mitigate the indirect emissions.

COMMERCIAL AND INDUSTRIAL AIR-CONDITIONING PRODUCT LIST

The chillers featured are used for comfort cooling in commercial buildings and process cooling, including in data centres.

There is significant overlap between industrial and commercial uses for chillers. Choice of chiller, capacity and temperature range is dictated by the specific needs of the end user and application. Therefore, we have combined these subsectors into one product list, with products applicable to both commercial and industrial end users.

CRITERIA

- **F-gas free**
- **Commercially available**
- **One product per manufacturer**

The chillers featured cover large capacity (56kW to 1730kW) and temperature (-35°C to +28°C) ranges making a direct comparison of energy efficiency performance between products difficult.

All European chillers featured in this list are subject to Ecodesign requirements which stipulate a minimum Seasonal Energy Performance Ratio (SEPR).

Table 3: *Commercial and industrial air-conditioning product list*

Manufacturer	Product name	Method of condensation and chiller compressor	Refrigerant	Refrigerant GWP	Cooling capacity (kW)	Possible temperature range of chilled heat transfer fluid	EER	Geographic availability	Training availability
Compact Kältetechnik	CombiChiller MCL 100-12E	Water-cooled	R-290	<1	70.5	-10°C - +10°C	3.47	At least Europe	Not found
CRS	Cobalt	Not found	R-744	1	300-1000	Not found	4.5	Worldwide	Not found
Efficient Energy	eChiller	Air-cooled	R-718	0	30	+10°C - +28°C	4	Europe	Virtually throughout Europe
Enerblue	Purple (unit size 30.1)	Air-cooled, semi-hermetic compressor	R-290	<1	56.4	+7°C	2.8	Europe	Training available at their Italian Factory
Enex	Yukon Ejector 2-120	Air-cooled, reciprocating compressor	R-744	1	137.5	-25°C - +10°C	2.27	Worldwide	Installation technicians are used and further training available at their Factory
Frick (JCI)	PowerPac packaged ammonia chiller PAC 316	Water-cooled, Rotary screw compressor	R-717	0	266.6	+4.4°C	Not found	North/South America, Europe, Middle East, Africa, Asia Regions.	Field support is given
GEA	BluAstrum 1800	Water-cooled/air-cooled/ evaporative condensing, Screw compressor	R-717	0	1730	-15°C - +18°C	5.4	Worldwide	Not found
Sabroe (JCI)	ChillPac 116 E-A	Water-cooled, reciprocating compressor	R-717	0	1422	-25°C - +7°C	Not found	Worldwide	Not given
SCM Frigo	CO_2 chiller MWT 2x178 CMT	Probably air-cooled	R-744	1	73	Not found	Not found	At least Europe	Not found
Secon	STRATOS VP2-2-770.S-I2-NIS_HT	Air-cooled, Semi-hermetic reciprocating compressor	R-290	<1	120.4	+7°C	3.21	Europe; would be easy to supply worldwide if there are local partners	Offers training programs in German and English
Tecnofreddo	ECO3 R290 series	Air-cooled, semi-hermetic/ reciprocating compressor	R-290	<1	102.4	Range not found, definitely 7°C and -8°C possible	3.8	Europe	Training is possible either in their factory and/or client location
Zudek	airmatik® air4	Air-cooled, screw compressor	R-717	0	640	-35°C - +12°C	4.14	Worldwide	Not found

Commercial and industrial air conditioning innovation

Jordanian manufacturer Petra has developed a commercial packaged rooftop air-conditioning system using propane, which has demonstrated higher energy efficiency than HFC alternatives across a range of outside temperatures.[78]

Seeley's Climate Wizard indirect evaporative cooling system is used in thousands of locations around the world and is well-suited to high ambient temperatures of up to 55°C, provided there is ample water available. Seeley claims that its product can result in 80 per cent energy savings and peak electrical demand reduction of 60 per cent when compared to an equivalent chiller plant.[79]

Oxycom's evaporative cooling system is also well-suited to hot climates, reporting energy savings of up to 90 per cent over conventional air-conditioning, which can lead to 80 per cent lower operating costs.[80]

Adsorption chillers are another option for industrial cooling and air-conditioning (when driven by renewable thermal energy), such as those offered by Fahrenheit GmbH, which won the German Data Centre Award in 2018.[81]

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Mobile air-conditioning

Definition and scope of sector

Mobile air-conditioning (MAC) covers air-conditioning systems installed in cars, buses, vans, trains and freight truck cabins to keep driver and passengers comfortable.[82] **MAC accounted for 30 per cent of global sales of cooling equipment in 2018.**[83]

HFC-134a (GWP 1,300) is the dominant refrigerant used in MAC systems today, although regional legislation in the EU, Japan and Canada, which set GWP limits of 150 for MAC, are prompting a switch to alternative refrigerants including HFC-152a (GWP 138), HFO-1234yf (GWP<1) and CO_2 (GWP 1).[84] HFO-1234yf is currently used in more than 18 million vehicles.[85]

CO_2 has been adopted by a number of German car manufacturers and is seen as a promising solution, especially for electric vehicles where CO_2 can be used in heat pump mode, saving energy when using integrated cooling and heating systems.[86]

Propane is not yet considered a commercially viable option due to perceived flammability concerns but it may be an attractive option, particularly for electric vehicles with hermetically sealed refrigerant systems.[87]

Evaluations are underway in China and Italy on the use of hydrocarbons using a secondary system. There have been activities in Australia and the United States that used hydrocarbons in MAC systems.[88]

As this product list features only natural refrigerants, HFO-1234yf units are not considered. Full details about why EIA is adopting a precautionary approach to HFOs, especially HFO-1234yf which is associated with significant amounts of TFA emissions, are available in the text box on page 11.

MOBILE AIR-CONDITIONING PRODUCT LIST

CRITERIA

- **F-gas free**
- **Commercially available**

Unfortunately, there is little available information of energy efficiency metrics for this subsector. As such, the product list showcases examples of MAC using natural refrigerants that are commercially available.

Table 4: *Mobile air-conditioning product list*

Personal vehicles (cars)					
Manufacturer	**Product name**	**Type of product**	**Refrigerant**	**Refrigerant GWP**	**Energy efficiency measures**
Doowon	Doowon CO_2 Compressor DC28	Compressor	R-744	1	Not supplied
Mahle	Mahle R744 air conditioning circuit	AC system	R-744	1	Not supplied
Sanden	Sanden R744 Piston Type Compressor	Compressor	R-744	1	Manufacturer estimates increased driving range of up to 50% in electric vehicles in winter conditions
Valeo	Valeo A/C loop R-744	AC system	R-744	1	Not supplied
Buses					
Manufacturer	**Product name**	**Type of product**	**Refrigerant**	**Refrigerant GWP**	**Energy efficiency measures**
Aurora - HeaVac	Roof Heat Pump BOREALIS 2.0 (HeaVac-Aurora)	Heat Pump	R-290	<1	COP: 2.5 - 4.5 It reduces the energy consumption of the bus by 40 percent by comparison with conventional buses.
Bitzer	Bitzer ECOLINE TE compressors	Compressor	R-744	1	COP: 11.38
Daimler	Daimler CO_2 AC and Heat Pump for electric buses (part of Citaro bus)	Heat Pump	R-744	1	Reportedly reduces the energy consumption of the bus by 40 percent by comparison with conventional buses.
GEA	StarCO2mpressor	Compressor for use in buses and trains	R-744	1	Manufacturer reports up to 20 % energy efficiency gains
Konvekta	Konvekta Ultralight 700 CO_2 Heatpump	Heat Pump	R-744	1	COP: 1.7-4.0 (based on temperature ranges -20°C to +15°C) Manufacturer reports increased range of electric buses by up to 60%
Panasonic	Compressor hermetic rotary Panasonic C-CV753L0V	Compressor for use in buses and trains	R-744	1	Not supplied
Valeo	VALEO - REVO®-E HP R744	Heat Pump	R-744	1	COP: 2

Current emissions

Mobile air-conditioning accounts for approximately 23 per cent of GWP-weighted HFC consumption globally.[89] In 2019, the International Energy Agency (IEA) estimated that with no further policy action, increased vehicle sales and penetration rates for MAC could result in MAC emissions more than tripling to 1.3 $GtCO_2e$ by 2050.[90]

Direct emissions are a core emissions source for this subsector, as refrigerant leakage rates can be as high at 125 per cent of the original charge over 10 years.[91] While avoiding HFCs can address a significant proportion of emissions, energy used by the system is also of concern. **MAC systems can use 3-7 per cent of a car's fuel consumption and this can peak at up to 40 per cent in hot, humid and congested areas.**[92] For electric vehicles, the additional energy demand from the air-conditioning system can have implications on the range of the vehicles.

Is this sector on the pathway to net-zero emissions?

The list features products which use natural refrigerants in passenger cars and buses. The subsector has low levels of commercially available, F-gas free technology, although numerous prototypes were found during the research for this subsector showing a promising trend in research and development into natural refrigerant MAC alternatives.

The list contains four products for personal vehicles (cars), all of which use CO_2 as the refrigerant. Three are manufactured by German companies and one by a South Korean, although all but one explicitly state that the units are available worldwide. MAC units are tailor-made to the specifications of vehicle manufacturers and technical information is therefore difficult to obtain. Daimler, Mercedes and Volkswagen use CO_2 MAC systems in some of their car lines, including in electric vehicles.

Switching to ultra-low GWP refrigerants has a significant impact on direct emissions from MAC, reducing them by about 95-99 per cent.[93] MACs using ultra-low GWP refrigerants have also been found to reduce indirect emissions associated with fuel used to power the system. A 2019 report by the International Council on Clean Transportation found that the use of HFO-1234yf in a direct expansion system and HFC-152a in a secondary loop system can achieve substantial direct and indirect emission reduction benefits compared to HFC-134a systems in all climates. The study also showed that CO_2 in a direct expansion system demonstrates even higher direct and indirect emission reduction benefits in cooler climates.[94]

Addressing leakage, using better components and system design can further improve energy efficiency of MAC systems by up to 40 per cent.[95]

The products featured in this list for buses are suitable for electric buses and all but one uses CO_2. One product uses propane. **Germany has deployed CO_2 MAC systems in some city buses, saving about 30 per cent of total MAC emissions.**[96] Available options include complete standardised heat pump systems for mobile applications or compressors – which are especially compact and can be used for mobile applications.

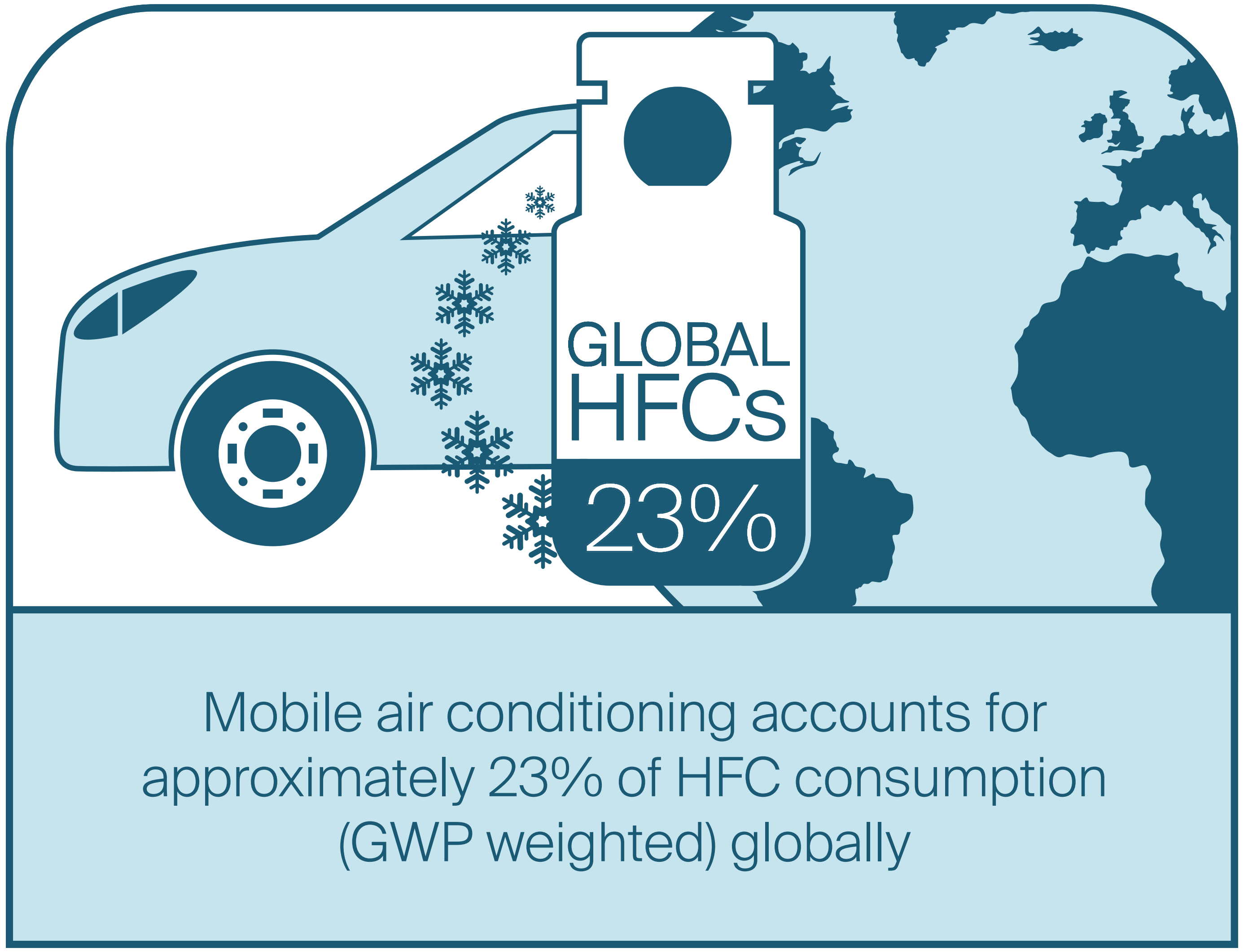
Trains have been slower to transition their air-conditioning systems due to different ownership schemes that vary between countries and higher costs of new systems. Nevertheless, alternatives for trains are being trialled, including systems using CO_2 and air-cycle technology which have shown energy efficiency and life cycle cost advantages compared to F-gas refrigerant systems.[97]

How the shift to electric vehicles may warrant reconsideration of refrigerant choice

The shift towards the electrification of vehicles will impact the choice of MAC system as the energy consumption of the MAC system can decrease the range of electric vehicles by up to 50 per cent on hot and humid days.[98] Improvements in MAC energy efficiency will be imperative to the widespread roll out of electric vehicles and reduce their real-world emissions.

Furthermore, electric vehicles don't have the benefit of excess waste heat to warm the cabin, therefore auxiliary heating is needed. Some models use electric heaters, but this can have significant impacts on vehicle range.

Another method is to run the MAC system in heat pump mode. CO_2 is a promising option for this as it is well suited to both air-conditioning and heat pump applications. Equipment manufacturer Sanden claims that using a CO_2 heat pump can increase the range of an electric vehicle by up to 50 per cent in the winter.[99] Given the importance of efficient heating as well as cooling in electric vehicles. this could tip the balance in favour of CO_2, as indicated by Volkswagen's 2020 announcement that all of its new ID.3 and ID.4 model electric cars will use CO_2 heat pumps and the company will look to equip other models with CO_2 systems in the future.[100]



Öko-Recherche, (2020). 'Explanatory Note on modelling of climate benefits of charge size changes for air conditioning equipment in relation to the revision of the product standard IEC 60335-2-40', Environmental Investigation Agency.

Avoid and Shift MAC cooling

Moving from private vehicle use to public transportation greatly reduces per capita cooling demand.[101]

Other strategies for reducing the demand for MAC include altering driver behaviour – parking in the shade, driving earlier in the morning and later in the evening when temperatures are lower and encouraging car-pooling.

Pre-cooling when an EV is plugged in and parked in the shade can reduce MAC energy consumption by 20-30 per cent.[102] Reflective windows and the body colour of the vehicle could reduce initial energy consumption for cooling by up to 50 per cent.[103]

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Heat pumps

Definition and scope of sector

Heat pumps provide an energy efficient way of converting heat from a low temperature to a higher one or vice versa. They can be used to heat radiators and water. **In Europe, more than 13 million domestic heat pumps have been installed since 1996**.[104]

For domestic applications, air source heat pumps are the most widespread and are split between air-to-air and air-to-water (including exhaust air heat pumps). Ground source heat pumps are also used in domestic settings in colder climates, although are more popular in commercial and industrial applications.

Domestic heat pumps often use HFC-410A (GWP 2,088) and typically have a refrigerant charge of between 3kg and 5kg.[105] The average lifetime of a domestic heat pump is 20 years, meaning that HFC reliant technology is currently being locked in until 2040 at the earliest. Natural refrigerant alternatives exist, including propane and carbon dioxide for domestic and commercial heat pumps and ammonia for large scale heat pumps, including those used in district heating.

Commercial heat pumps can be used for hot and cold distribution simultaneously. Those used in hotels can reach 100kW but smaller heat pumps are used in other commercial spaces such as offices.[106]

Industrial heat pumps are used to recover process waste heat and used in dehumidification, distillation and evaporation processes as well as for water heating and comfort heating.

Industrial heat pumps are normally designed to specification, varying in size, operating conditions and heat sources.[107] Many commercial heat pumps can be used for industrial applications and vice versa; as such, these two subsectors have been combined into one product list.

Heat pump technology is also used in tumble dryers for improved efficiency and increasingly in dishwashers, but these are outside the scope of this product list.[108]

Current emissions

Heat pumps are essential tools in the race to decarbonise the way we heat space and water in the built environment, potentially reducing emissions by up to 66-80 per cent compared to heating options reliant on fossil fuels.[109]

Further benefits of heat pumps include air pollution reduction, as they do not emit particle matter.[110] **They can also be used to act as thermal batteries. reducing peak demand on grids.**[111]

As heat pump installation numbers grow, we risk unintended consequences associated with unrestrained use of HFCs in these products. The use of HFCs in heat pumps can add up to 20 per cent to their carbon footprint.[112] Common HFCs used are HFC-410A (GWP 2,088), HFC-407C (GWP 1,774) R-134a (GWP 1,430) and HFC-32 (GWP 675).

Domestic heat pumps

Is this sector on the pathway to net-zero emissions?

The product list covers domestic heat pumps with heating capacities from 2.5-12 kW. Products are largely air-to-water heat pumps. with one air-to-air and one ground source heat pump included to show diversity. Propane is predominantly used, although two CO_2 options are provided.

Availability of net-zero products in Europe is good; we found a broad variety of manufacturers offering products with high energy efficiency. Heat pumps available in Australia, North America and the Caribbean are also featured. Information on net-zero compatible products from other regions was not possible to obtain.

The domestic heat pump market share remains low in most countries. To accelerate the roll out of this technology, a number of barriers will have to be addressed. The central barrier is price; the upfront cost of purchasing and installing a domestic heat pump system is still considerably higher than for a conventional boiler. **Some countries offer incentives and subsidy schemes to offset these higher costs for end-users, but very few have specifications relating to the refrigerant used and should integrate GWP limits into their criteria**.

DOMESTIC HEAT PUMP PRODUCT LIST

CRITERIA

- F-gas free
- COP of 4.2 or above and/or an EU A++ rating or above, where this information is available.
- Products have been chosen to showcase a range of heat pump types and refrigerants
- Commercially available
- One entry per manufacturer

Table 5: *Domestic heat pump product list*

Manufacturer	Product name	Type of heat pump	Application	Refrigerant	Refrigerant GWP	Heating capacity (kW)	COP	Energy label	Geographical availability
Vaillant GmbH	aroTHERM plus range	Air-to-water	Heating, cooling, water production	R-290	<1	4.1-11.6	4.6-4.7	A+++	Europe
Eco2 Systems	R744 water heater	Air-to-water	Hot water production	R-744	1	4.5	4.2	unknown	North America, Carribean
Wolf	Monoblock Air-water heat pump CHA-07	Air-to-water	Heating	R-290	<1	5.15	4.54	A++	Europe
Stiebel Eltron & Denso	LWZ 604	Air-to-air	Heating, hot water production, ventilation	R-744	1	2.51	4.52	unknown	Europe
Quantum Energy	150l solar heat pump, 150-08AC6-290	Air-to-water	Hot water production	R-290	<1	3.61	4.3	unknown	Australia
Heliotherm	SNTM3-10	Ground-to-water	Heating, hot water production	R-290	<1	10	6.15	A +++	Europe
alpha innotec	LWDV 91-1 / 3 -HDV 9-1 / 3	Air-to-water	Hot water, heating	R-290	<1	5.08	4.61	A +++	World
Novelan	LADV 9-HDV 12	Air-to-water	Hot water, heating	R-290	<1	5.08	4.61	A +++	Austria/Germany
Hoval	Belaria pro compact (13/100/270)	Air-to-water	Heating, Cooling, hot water	R-290	<1	5.3	4.6	A +++	Europe
LAMBDA	EU13L	Air-to-water	Hot water	R-290	<1	12	5.1	A +++	Austria

Updated building regulations emphasising efficiency and green credentials to decarbonise heating will spur the heat pump market. To facilitate this roll-out globally, heating installers will require training to become competent in installing heat pumps, particularly natural refrigerant heat pumps.

Commercial and industrial heat pumps

Is this sector on the pathway to net-zero emissions?

The product list covers heat pumps with heating capacities ranging from 4-49kW, covering a range of temperatures. Many of the heat pumps featured here can be adapted for both commercial and industrial use. The list includes air-source, ground-source and water-source products for a range of applications covering hot water production, space-cooling and heating. The list features products available in North America, South Africa, parts of East Asia and Europe.

EcoCute CO2 heat pumps have had enormous success in Japan, with several manufacturers now producing them and Japanese sales of EcoCute units exceeding six million as of 2018.[113] Unfortunately we were unable to obtain detailed information to feature Japanese products on this list.

Further indirect emission reductions can be gained by using onsite renewable electricity production in combination with a heat pump system.

HFOs, hydrocarbons and water are being investigated as options for heating applications in the industrial subsector for delivery temperatures higher than 100°C.[114] Other industrial applications use hydrocarbons because of the wide availability of compressor technologies.[115]

Heat pumps are increasingly being used in district heating and cooling networks, especially in Scandinavia, and can reach capacities of several megawatts. Ammonia is often used for large scale industrial heat pumps, particularly for district heating and cooling.

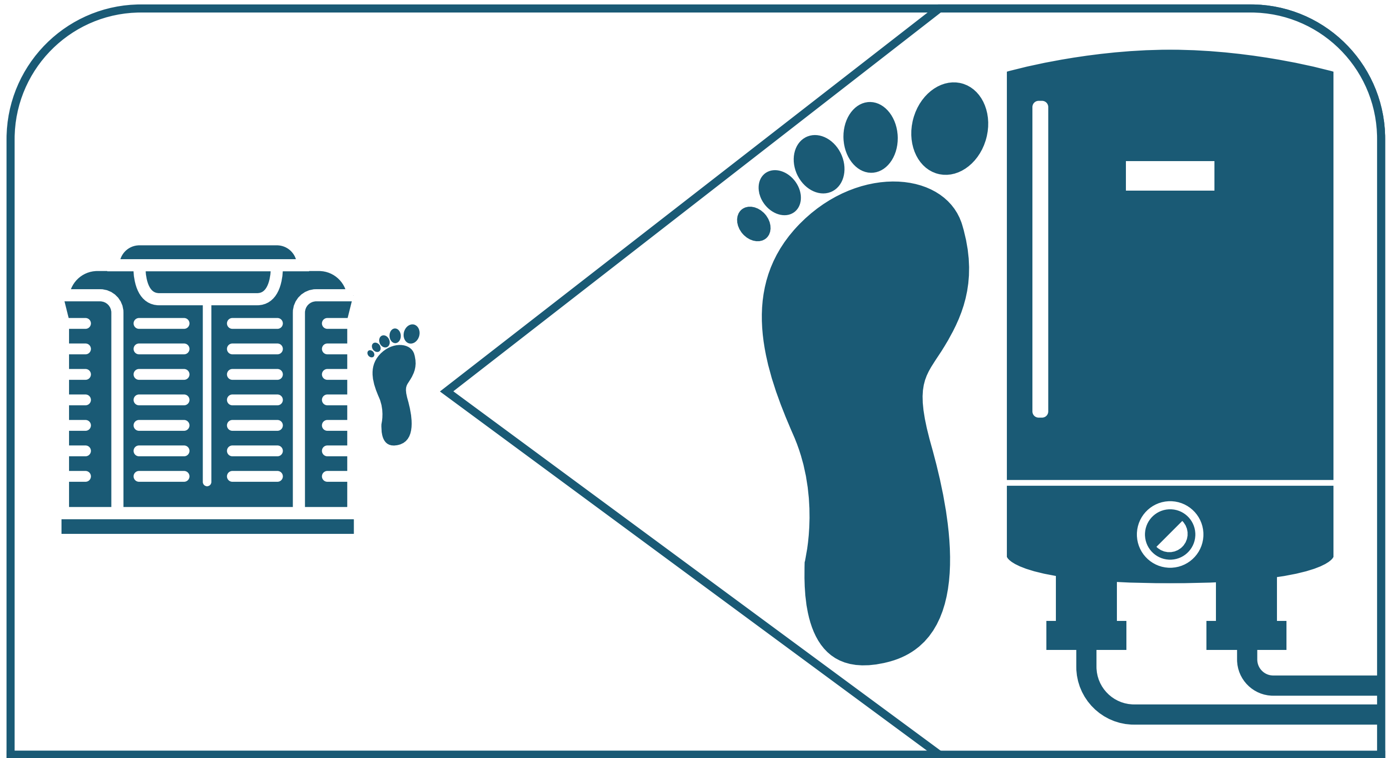
The Heat Roadmap Europe estimated that district heating could provide 50 per cent of the entire heat demand by 2050, with approximately 25-30 per cent of it being supplied using large-scale electric heat pumps.[116]

COMMERCIAL AND INDUSTRIAL HEAT PUMP PRODUCT LIST

CRITERIA

- F-gas free
- Products chosen to showcase a range of refrigerants, geographic availability and capacities

The list features COP for each product. As the temperature ranges at which the COPs are tested for commercial and industrial heat pumps differ more than for domestic heat pumps, COP does not always provide a reliable comparison of energy efficiency.



Heat pumps have a 66-80% lower carbon footprint than boilers

European Heat Pump Association (2020) 'European Heat Pump Market and Statistics: Report 2020.

Table 6: *Commercial and industrial heat pump product list*

Manufacturer	Product name	Type of heat pump	Application	Refrigerant	Refrigerant GWP	COP	Geographical availability
Auer	Communal hot water heat pump (Reference 151622)	Air-to-water	Hot water production	R-290	<1	4.1	Europe
Frigopol	Energy Station for heating and cooling 40F1	Air/water/ground-to-water	Heating, cooling	R-290	<1	4.3	Europe
Enerblue	Purple HP 22.1	Air-to-water	Heating, cooling	R-290	<1	3.70	Europe
CRS	Ruby Heat Pump (RHP-500)	Air-to-water	Heating	R-744	1	3.7	South Africa
Eco2 Systems	R744 water heater	Air-to-water	Hot water production	R-744	1	4.2	North America, Caribbean
Hautec	Carno HCS Premium	Ground-to-water	Heating, hot water production	R-290	<1	>5	Europe
Felzer	Nordic Green P22.2	Water-to-water	Heating, hot water production	R-290	<1	3.74	Europe

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Domestic refrigeration

Definition and scope of sector

When electricity becomes available to households, one of the first electrical appliances purchased is a refrigerator. **Almost every household in developed countries has a refrigerator and in developing countries the number of households with a refrigerator is expected to double to almost two billion over the next 15 years**. Globally, there are an estimated 2-2.3 billion domestic refrigerators already installed, with 170 million produced annually.[117]

The most environmentally friendly, commercially available refrigerant option for domestic refrigeration today is isobutane with a GWP of less than one. Isobutane is cost-competitive and energy efficient (roughly five per cent more efficient than HFC-134a), with lower annual running costs and lifetime costs than alternatives.[118] Today, more than one billion domestic refrigerators use isobutane and 75 per cent of new refrigerator production uses this natural refrigerant.[119]

Current emissions from the sector

The refrigerator is the second highest energy-consuming appliance in most households (after a domestic air-conditioner), with the typical fridge using 13.7 per cent of residential energy.[120]

The energy efficiency of this equipment has been increasing steadily since its inception and average energy consumption has dropped by about 65 per cent in the past 15 years.[121]

The transition to natural refrigerants is essentially complete in Europe and other regions. Emerging markets, where the transition to climate-friendly, energy-efficient refrigerators can achieve energy savings of more than 60 per cent, are following suit.[122] North America has historically lagged in its adoption of natural refrigerants for domestic refrigeration. While **North American industry has announced a voluntary goal to phase out HFCs in this equipment after 2024, it can be argued this is too late for a sector with widely available net-zero alternatives**.[123]

Greenfreeze improves the domestic refrigeration sector

The almost wholesale transition away from climate-damaging refrigerants in this subsector was made possible by the introduction of Greenfreeze technology in 1992.

Greenpeace and German manufacturer DKK Scharfenstein created new refrigerators using a mixture of propane and isobutane as well as using hydrocarbons for the blowing of the insulation foam inside the appliance.[124] These units used 38 per cent less energy than HFC models at the time.[125]

Greenfreeze technology was made available worldwide and has been adopted by most manufacturers in this sector. In 2018, Greenfreeze technology avoided emissions of approximately 9MtCO$_2$e compared to the use of HFC-134a.[126]

The WWF Topten product lists were used to produce this list to ensure that only products meeting their energy efficiency standards were included. Products for South America, Europe and China were taken from the appropriate Topten websites, while the US products were sourced from EIA's US HFC-free Fridge Buyers Guide, which uses energy efficiency information from the US Energy Star database.[127]

We have attempted to include products that cover a broad range of regional availability across various price points and capacities to highlight the accessibility of net-zero products for this subsector. The list contains domestic refrigerators, freezers and fridge-freezers.

Is this sector on the pathway to net-zero emissions?

Concerns about the flammability of hydrocarbon refrigerants in domestic environments have been assuaged through appropriate design and construction features.[128]

Hydrocarbons are expected to increase their share of the market as HFCs are phased down under the Kigali Amendment. The application of n-butane (R-600) is also being explored and has been found to reduce energy consumption by 14 per cent compared to isobutane for small domestic refrigerators.[129]

As a reduction in demand for fridges seems unlikely, a reduction in energy consumption of these appliances is of utmost importance for lowering the emissions from this sector.

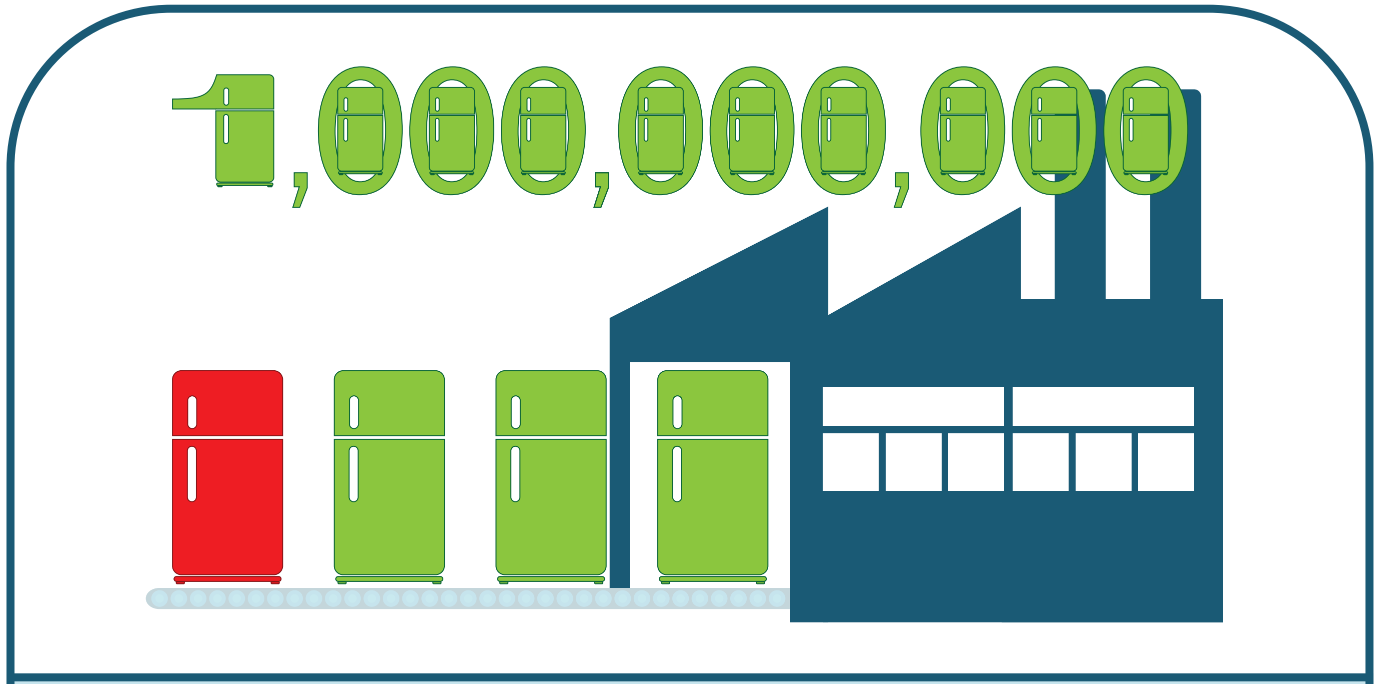
DOMESTIC REFRIGERATION PRODUCT LIST

CRITERIA

- F-gas free
- EU A+ energy label or equivalent (US Energy Star, China Grade 1)
- Range of sizes and function, i.e. fridge/freezers and fridge only options with one freezer only product
- Range of geographic availability
- Commercially available

Table 7: *Domestic refrigeration product list*

Manufacturer and model number	Product type	Refrigerant	Refrigerant GWP	Geographical availability	Refrigerator capacity (litres)	Freezer capacity (litres)	Regional energy label	Cost
Mabe RMF02LRX0	Refrigerator	R-600a	<1	Chile	45		A++	$ 89,990
SAMSUNG RT46K6361	Refrigerator/freezer	R-600a	<1	Brazil	342	111	A+	R $ 2,900
Atma HNT45300X	Refrigerator/freezer	R-600a	<1	Argentina	233	60	A++	$Arg 19,620
LG GW-F439BLFZ	Refrigerator/freezer	R-600a	<1	Argentina	221	93	A++	$Arg 15,999
Peabody PE-FV90	Freezer	R-600a	<1	Argentina	0	81	A+	$Arg 15,750
Electrolux IK2581BNR	Refrigerator/freezer	R-600a	<1	Europe	185	61	A+++	€ 360
Liebherr BP2850	Refrigerator	R-600a	<1	Europe	157	0	A+++	€ 186
Bosch B36CT80SN	Refrigerator/freezer	R-600a	<1	US	total capacity 594	total capacity 594	US Energy Star certified	$2874
Haier - HRQ16N3B	Refrigerator/freezer	R-600a	<1	US	316	157	US Energy Star certified	$1599
Hisense - HBM17158	Refrigerator/freezer	R-600a	<1	US	344	140	US Energy Star certified	$999
Midea BCD-230WTPZM	Refrigerator/freezer	R-600a	<1	China	156	74	Grade 1	RNB 2099
Haier BCD-225WDGK	Refrigerator/freezer	R-600a	<1	China	121	71	Grade 1	RNB 2599
Homa BCD-327WFJA/B	Refrigerator/freezer	R-600a	<1	China	261	116	Grade 1	RNB 4299
Wanbao BC-92D	Refrigerator	R-600a	<1	China	92	0	Grade 1	RNB 539



Today, natural refrigerants are used in more than one billion domestic refrigerators, and 75% of new refrigerator production

Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee of Montreal Protocol on Substances that Deplete the Ozone Layer, (2018). '2018 Assessment Report'. UN Environment.

Options for improving energy efficiency of domestic refrigerators identified by the Montreal Protocol's Refrigeration Technical Options Committee (RTOC) include:[130]

- high efficiency heat exchangers
- improved low thermal loss cabinet structures and gaskets
- intelligent controls
- efficient variable speed compressors
- advanced insulation
- demand side management initiatives.

RTOC warns that despite their commercial availability, the additional cost of some of these measures has curtailed widespread adoption of more efficient refrigerator technology.[131]

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Commercial refrigeration

Definition and scope of the sector

Commercial refrigeration is an integral part of the cold chain as it enables produce to be kept fresh before it reaches the consumer. **Products include refrigerated display cabinets and freezers used in supermarkets, shops, offices, hospitality and other commercial spaces**.

This product list features centralised systems, condensing units, stand-alone units and vaccine coolers.

Current emissions

Emissions from commercial refrigeration have a huge climate impact. **The use of high-GWP HFCs combined with high leakage rates has resulted in commercial refrigeration accounting for about 40 per cent of total annual refrigerant emissions**.[132,133]

Global annual emissions associated with commercial refrigeration are 474 MtCO2e, of which approximately 36 per cent are direct emissions (i.e. from refrigerant leakage), with the remaining 64 per cent associated with energy use.[134] Refrigeration systems are the biggest source of energy demand in supermarkets, accounting for approximately 60 per cent of store energy use.[135]

Tackling energy usage in this sector is key and the net-zero products featured here can help address this. However, **one of the easiest and most cost-effective way to reduce energy consumption is by using doors on fridges and freezers**. A recent study by Imperial College London found that doors can reduce energy consumption by up to 40 per cent.[136]

In recognition of the huge climate impact commercial of refrigeration, EIA began its Chilling Facts campaign in 2009 which called for supermarkets in Europe to phase-out HFCs.

Our initial market survey revealed a lack of investment in HFC-free alternatives by supermarkets. Key barriers cited by retailers were cost, energy efficiency and access to skilled engineers.[137] However, growing public awareness of the carbon footprint of HFC cooling led to increased adoption of natural refrigerant technologies.

In 2010, members of the Consumer Goods Forum agreed to a resolution to begin phasing out HFC refrigerants and replacing them with natural refrigerant alternatives.

In 2014, Europe revised its F-gas Regulation, which would not only phase down the use of HFCs but set specific product bans within the commercial refrigeration sector outlined in Figure 1.

The widespread roll-out of natural refrigerant commercial refrigeration products in Europe is testament to the initial work done by EIA and subsequent ambitious regulatory measures.

Progress in the US has been much slower; EIA's recent assessments of the US commercial refrigeration sector show increasing adoption in recent years, particularly dominated by a small group of retailers. Nevertheless, most US retailers have yet to achieve widespread uptake of natural refrigerants.[138]

Figure 1: *Commercial refrigeration product bans outlined in the EU 2014 F-gas Regulation*

1 January 2020	Stationary refrigeration equipment that contains, or whose functioning relies upon, HFCs with GWP of 2,500 or more except equipment intended for application designed to cool products to temperatures below 50 °C.
1 January 2020	The use of HFCs with a GWP of 2,500 or more to service or maintain refrigeration equipment with a charge size of 40 tonnes of CO2e or more is prohibited.
1 January 2022	Refrigerators and freezers for commercial use (hermetically sealed equipment) that contain HFCs with GWP of 150 or more.
1 January 2022	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.

Centralised systems

The dominant system choice for many supermarkets is a centralised system where the compressor units are installed in a machinery room away from the display cabinets.

These systems often have very large refrigerant charges and long piping circuits and, as a result, conventional systems using HFCs often experience high leakage rates. For example, in the US a typical supermarket system holds about 2,000kg of HFC, of which about 25 per cent is leaked each year, equating to almost 2,000 tonnes of CO_2e emissions per system per year for a system using HFC-404A (GWP 3,922).[139]

Is this sector on the pathway to net-zero emissions?

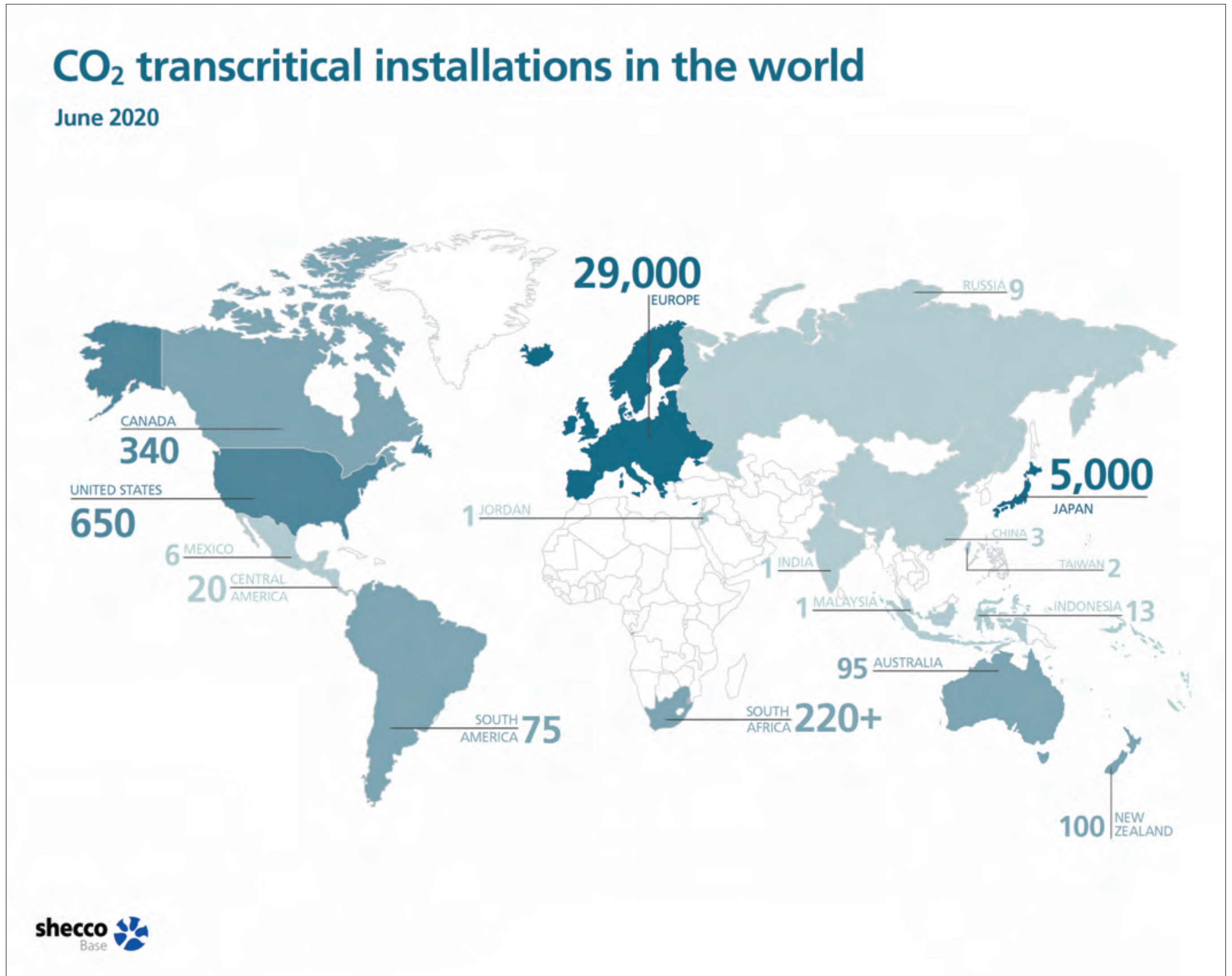
Legislative measures to restrict the use of HFCs in centralised systems in Europe have accelerated the development of natural refrigerant based centralised systems. CO_2 is the most popular of these, although indirect systems using low charge ammonia, hydrocarbons and CO_2 cascade systems are also being adopted.

As of 2020, there were more than 35,000 transcritical CO_2 centralised systems in use. Figure 2 shows their geographic spread.[140]

Given the huge number of centralised CO_2 systems in operation today and the often bespoke nature of the systems, it is not possible to produce a product list for this subsector.

Instead, we have produced a simple guide to highlight some elements of best practice in a centralised CO_2 commercial refrigeration system and how to ensure that the system achieves optimal energy efficiency.

Figure 2: *Number of CO_2 transcritical installations across the world as of June 2020.*



Having doors on fridges in supermarkets can reduce energy usage by up to 40%

Hart et al, (2020). 'Impact of a warming climate on UK food retail refrigeration systems: Recommendations for industry'.

Guide to net-zero CO_2 centralised systems

System choice may depend on the local ambient temperature of the installation. To achieve higher energy efficiencies, many centralised systems use CO_2 in a transcritical cycle. In cold to medium climates, the use of boosters and parallel compression can represent a cost effective and energy efficient solution.[141]

The benefit of using CO_2 is that it enables heat recovery which can be used to cover a store's hot water and space heating needs. A case study from a Danish supermarket has shown that by replacing the gas heating system with heat recovery from a CO_2 system, it was able to provide the entire heating demand of the supermarket with a payback period for the heat recovery of less than five months.[142]

The energy efficiency of CO_2 systems in warm climates can be improved through the use of ejectors and adiabatic cooling. Ejectors help reduce expansion losses and adiabatic cooling helps decrease the effect of ambient temperature on hot days by absorbing heat from the air to help the system run in optimal conditions.[143] A CO_2 system with adiabatic cooling was used in a Carrefour Express store in Kurtköy, Turkey, with reported energy efficiency gains of 15 per cent.[144]

The pace of innovation in CO_2 centralised systems, especially those suited to hot climates, is rapid. Refrigeration equipment manufacturer Epta has recently added a mechanical sub-cooler to its existing centralised CO_2 system, claiming this will allow end users to efficiently run their CO_2 refrigeration systems in all types of climates, even at temperatures higher than 40°C (104°F).[145]

Supermarket cooling needs can be complex and vary widely between region and individual stores. Not all options can be included in this short guide; for more detailed information and an array of case studies, please refer to EIA and shecco's technical report on energy efficiency in HFC-free supermarket refrigeration.[146]

Condensing units

Condensing units are typically found in medium and small stores such as convenience stores, forecourt sites, cold stores, fast food outlets, bars and restaurants.

They enable a smaller number of display cabinets to be connected to the system compared to a centralised system, require less space and are typically easier to install. Historically, though, they can suffer from similar leakage rates to centralised direct systems.

CONDENSING UNIT PRODUCT LIST

CRITERIA

- **F-gas free**
- **Products for both low temperature and medium temperature applications**
- **Regional availability was prioritised**
- **The most energy efficient products that meet the UK's Energy Technology List criteria are highlighted, although more products are featured to factor in greater accessibility.**
- **Commercially available**
- **One product per manufacturer**

Is this sector on the pathway to net-zero emissions?

Two CO_2 products from Carrier and Panasonic meet the UK's Energy Technology List efficiency requirements, which stipulate high minimum Energy Efficiency Ratios depending on the capacity and operating temperature of the product. Other CO_2 condensing units are also featured.

CO_2 is proving to be a popular alternative to HFC-based condensing units and Japan leads the way with this technology. As of 2017, more than 8,500 CO_2 condensing units were in use across the country.[147]

Japanese convenience store retailer Lawsons has reported energy efficiency gains of 27 per cent over HFC units.[148] Lawsons has helped roll-out this technology in Indonesia as well by assisting with the installation of CO_2 condensing units in Jakarta.[149] Since 2017, European companies have also begun to adopt this technology; equipment producer Panasonic has reported sales of 600 CO_2 condensing units in the past two years.[150]

The list also features hydrocarbon condensing units. Flammability concerns have led to the development of indirect condensing units using propane (R-290) or propene (R-1270) in Europe, with reported energy efficiency increases of up to 30 per cent.[151]

Net-zero condensing units are gaining popularity in Europe and Japan and some manufacturers are willing to export globally. Access may be affected by the higher initial costs of CO_2 condensing units.

Table 8: *Condensing unit product list*

Name of the company	Name of the product	Temperature application	Refrigerant	Refrigerant GWP	COP/SEPR MT	COP/SEPR LT	Geographical availability	Training availability
Carel	HECU	Medium temperature	R-744	1	1.76	1.54	Worldwide	Physical in any region where a Carel subsidiary is present, and virtual by remote
Panasonic	OCU-CR200VF5 & OCU-CR200VF5SL	Medium and low temperature	R-744	1	3.83	1.92	At least Europe, Japan	unknown
Danfoss	Optyma™ NL9CNXN0	Medium temperature	R-290	<1	Not available	1.25	Worldwide	unknown
Emerson	Copeland™ EazyCool CO_2 Unit	Medium temperature	R-744	1	unknown	Not available	At least Europe, but potentially worldwide	Can provide training at their laboratory in Aachen or on locally on request.
Mitsubishi Heavy Industries	C-puzzle HCCV2001M	Medium and low temperature	R-744	1	1.85	0.96	Japan	They hold seminars for services and maintenance in Japan.
Huayi	Cubigel® CNPT 14RA_N	Medium temperature	R-290	<1	3.08		At least Europe	unknown
Tecumseh	HBP AE4460UH-FZ	Medium temperature	R-290	<1	1.38		Worldwide	They have held many training seminars on R-290 both physical and virtual as part of a Tecumseh University training program.
Carrier	QuietCO2OL 2S	Low temperature	R-744	1	3.41	1.46	Worldwide	On site in their factory in France or in the field
Embraco	UNT6222U	Medium temperature	R-290	<1	1.66		Europe	unknown

STAND ALONE REFRIGERATION UNIT PRODUCT LIST

CRITERIA

- F-gas free
- As the featured products cover different temperature ranges, it is not possible to set a baseline for energy consumption
- Commercially available
- One product per manufacturer

Stand-alone refrigeration units

Stand-alone refrigeration units are self-contained systems. This subsector covers a variety of products such as ice-cream freezers, ice machines, vending machines and display cases.

As sealed systems, they do not require extensive installation hence they are often referred to as 'plug-in units'.

A main benefit of these systems is that the initial costs are lower and maintenance is easier than with centralised systems, with the option to replace a single stand-alone cabinet upon failure.

On the other hand, the main disadvantage is that the condenser heat is released directly to the sales area, creating an additional heat load for the supermarket, potentially increasing costs and emissions associated with any air-conditioning required to mitigate this. This can be overcome with a water circuit and stand-alone water-cooled units, as discussed in the next subsection.

EIA consulted WWF's EU Topten lists to identify the most energy efficient F-gas free vertical and horizonal stand-alone equipment for both medium and low temperature applications.

Our own research supplemented these lists to show broader regional accessibility of products. Energy usage is expressed as kilowatt hours consumed per day (kwh/day). While this can help compare the products, energy usage is also affected by the temperature at which the cabinet is running and the dimensions of the unit.

Is this sector on the pathway to net-zero emissions?

Hydrocarbons such as propane (R-290) and isobutane (R-600a) are net-zero compatible alternatives to HFC-based systems. Accessibility is good, with net-zero products available across the globe. **In 2019, there were more than three million hydrocarbon display cases on the global market.**[152]

Progressive updates to commercial refrigeration product standards for flammable refrigerants (IEC 60335-2-89) passed in May 2019 allow an increase of charge size for A3 flammable refrigerants (such as hydrocarbons) in commercial refrigeration from 150g to 500g. This is expected to have a positive impact on the range of hydrocarbon models available on the market.

Table 9: *Stand-alone refrigeration unit product list*

Manufacturer	Product name	Type of product	Refrigerant	Refrigerant GWP	Temperature range	Energy (kWh/d)	Geographic availability
Vertical units							
Staycold International	HD1140-HC	Double hinged door upright cooler (plug-in)	R-290	<1	+1°C - +5°C	3.18	Worldwide
Novum Overseas Ltd	Panama Green	Door upright cooler (plug-in)	R-290	<1	-25°C - -18°C	12.52-18.78	Europe, Japan, South Africa, U.S., Canada
Carrier Commercial Refrigeration	Optimer® 1348 LG Chiller	Plug-in vertical display refrigerator	R-290	<1	-1°C - +5°C	12	Europe, Middle East, Africa
JBG 2	Garmo Multideck / RDGA-1250-L4 3M1-I-R600A-DVO-I3Z	Vertical display refrigerator	R-600a	<1	0°C - +2°C	4.90	Worldwide
Docriluc	HM-6-100	Vertical display refrigerator	R-290	<1	-1°C - +5°C	4.54	Worldwide
Liebherr	SFT 1223	Vertical display freezer	R-290	<1	-23°C to -18°C	8.90	Europe
Horizontal units							
Carrier Commercial Refrigeration	EasyCube Chiller	Plug-in service counter (horizontal)	R-290	<1	-1°C - +5°C	3.81	Europe, Middle East, Africa
Novum Overseas Ltd	Grand Cayman	Open shelf cabinet (plug-in)	R-290	<1	-25°C - -18°C	4.15	Europe, Japan, South Africa, U.S., Canada
Arneg	Sendai 2 Island	Island, plug-in (horizontal)	R-290	<1	0°C- +2°C	8.95- 8.77	Worldwide
Liebherr	STs 872	Universal chest	R-290	<1	-18...- 23°C/+1...+7°C	4.44	Europe
Novum	601L (no lighting)	Horizontal display freezer	R-290	<1	−18...−23°C	3.19	Europe
AHT Cooling systems	MONTREAL 250 (U)	Universal chest	R-290	<1	-18 ... -23°C / -1 ... +2°C	6.60	Europe

Water-cooled stand-alone refrigeration units

Water-cooled stand-alone refrigeration units tackle the problem of excess heat from conventional stand-alone systems being ejected into the store area by using a chilled water circuit to carry the heat to the outside.

The water in the pipes can be kept cool by a chiller or dry cooler located outside the store. Hydrocarbon refrigerants can be used to cool the stand-alone units and the chiller.

The benefit of this technology is that it combines the flexibility and low maintenance of conventional stand-alone units without the excess heat they generate, thus allowing it to be applied in larger stores as well as having better efficiency by achieving lower heat rejection temperatures.

This is a relatively new approach to retail cooling. As of 2019, more than 2,500 systems using hydrocarbon water-cooled systems were in use globally.[153]

The availability of products was limited. Some products on the list are just the water-cooled stand-alone refrigeration unit, while others feature the entire integrated system. This list aims to show a range of F-gas free product options across the globe.

WATER-COOLED STAND-ALONE REFRIGERATION UNIT PRODUCT LIST

CRITERIA

- F-gas free
- Commercially available
- A comparison of energy efficiency is not possible due to the range of temperatures, construction of units and capacities covered.

Is this sector on the pathway to net-zero emissions?

While the range of options available on the market is limited, access is good with units available in most regions, except Africa.

A 2019 survey by shecco found this water circuit technology is growing in popularity in Asia due to its suitability for warm climates, fast installation and lower maintenance costs.[154]

Equipment producer Carter's water-cooled system has been used by UK retailer Waitrose since 2011, where the waste heat from the cooling circuit is used for space heating, reducing operating costs by £65,000 per store per year.[155] Additionally, the manufacturer has reported about 16 per cent better energy performance with hydrocarbon water-cooled stand-alone refrigeration units used in Australia compared to similar HFC models.[156]

Unfortunately, we were unable to obtain detailed information about the product, so is not featured in the list.

Table 10: *Water-cooled stand-alone refrigeration unit product list*

Manufacturer	Product name	Refrigerant	Refrigerant GWP	Temperature application	Geographical availability	Training availability
Carel	HEOS	R-744	1	Medium and Low Temperature	Worldwide	Physical in any region where a CAREL subsidiary is present, and virtual by remote
Carel	HEOS	R-290	<1	Medium and Low Temperature	Worldwide	Physical in any region where a CAREL subsidiary is present, and virtual by remote
Hussmann	microDS	R-290	<1	Information not found	At least in North America	Unknown
Freor	Hydroloop	R-290	<1	Medium and Low Temperature	Europe, Aruba, Azerbaijan, Philippines	No
Epta	GranVista Integral Waterloop	R-290	<1	-1°C - +5°C	Europe, Asia Pacific and Latin America	Unknown

VACCINE COOLER PRODUCT LIST

CRITERIA

- F-gas free
- Commercially available
- Solar powered and mains powered
- A range of sizes

Vaccine coolers

Keeping vaccines and certain medication at exact refrigerated temperatures is essential to ensure their efficacy.

Vaccine coolers can be plugged in or, where there is limited access to reliable power supplies, solar powered refrigerators can offer an essential lifeline.

Currently most vaccine coolers chill to about +2°C to +8°C, although some models vary to meet the specific temperature needs of certain vaccines and medications.

Is this sector on the pathway to net-zero emissions?

Many of the products featured use Solarchill technology developed by Greenpeace and UNEP 20 years ago using isobutane (R-600a) as the refrigerant and solar power as the energy source.

Allowing free access to the technology has enabled the deployment of more than 100,000 units in off-grid locations around the world.[157] Some Solarchill products continue to operate even when the solar panels are not able to harvest energy, for example the B medical system vaccine cooler can work for up to a month without being recharged. Surechill systems are also able to stay cool for significant periods without access to power. When plugged in, the cooler freezes water which is then used to keep the medications cool even when not plugged in. More recently, Coolar has developed a new solar powered evaporative vaccine cooler, using water as a refrigerant.[158]

Table 11: *Vaccine cooler product list*

Manufacturer	Product name	Type of product	Refrigerant	Refrigerant GWP	Power source	Volume in litres	Energy consumption in kWh/d	Geographic availability
B Medical Systems	Ultra16 SDD	Vaccine cooler - SolarChill	R600a	<1	Solar powered - Autonomy: 20 days at +43°COver one month at +25°C	16	Not found	Worldwide
Coolar	Coolar	Domestic refrigerator; vaccine cooler	R718	1	Solar powered	90	Not found	Prototype available worldwide
Dulas Limited	VC88SDD	Vaccine cooler	R600a	<1	Solar powered; Freeze Protection and a +5C to +43C extended temperature operating range.	88	3.5kWh/m2/d	Worldwide
Godrej Appliances	GVR 50 DC	Laboratory refrigerator (incl. vaccines), SureChill	R600a	<1	Mains powered but 'Approved by the WHO to provide active cooling without power, for over 12 days in an ambient climate of 43°C.'	50	0.85 kWh/24 hours	India, Fiji, Niger, Nigeria, Cameroon, PNG
Haier	HTCD-90	SolarChill Vaccine cooler with freezer combination	R600a	<1	Solar powered	37.5	3.5kWh/m2/d	Not found
PHC Holdings Corporation (PHCbi)	MPR-S300H-PA	Pharmaceutical refrigerator	R600a	<1	Mains powered	345	Not found	At least U.S.; other models in Japan
Sure Chill license (various companies)	SureChill GVR99 Lite	Laboratory refrigerator (incl. vaccines), SureChill	R600a	<1	Mains powered but 'Approved by the WHO to provide active cooling without power, for over 12 days in an ambient climate of 43°C.'	99.5	1.220 kWh/24h	Worldwide
TemPure Scientific	15³ Vaccine Refrigerator 40°F R290 HydroCarbon Refrigerant & Hinged Glass Door	Vaccine cooler	R290a	<1	Mains powered	424.75	Not found	At least U.S.
Vestfrost Solutions	VLS 024 SDD	SolarChill Vaccine cooler	R600a	<1	Solar powered	25.5	3.5kWh/m2/d	Africa, South East Asia and Latin America
Zero Appliances	SDD Ref. Zero ZLF30DC E003/055	SureChill vaccine cooler	R600a	<1	Solar powered	27	3.5kWh/m2/d	Not found

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Industrial refrigeration

Definition and scope of the sector

Industrial refrigeration includes refrigeration for food processing, environmental testing of products and cold storage. It is integral to the cold chain and is the fastest growing cooling sector.[159]

The food and beverage sector is the biggest end user of industrial refrigeration, followed by pharmaceutical companies as many medications require specific temperature ranges during production and storage. Other uses include in gas liquefication and ice rinks.

Industrial refrigeration systems often have specific design requirements, such as the need for uninterrupted service and cooling for highly temperature-sensitive processes. Industrial refrigeration systems often use chillers. According to the Montreal Protocol's Refrigeration Technical Options Committee, ammonia has been the refrigerant of choice for many years due to its low flammability and superior energy efficiency.[160]

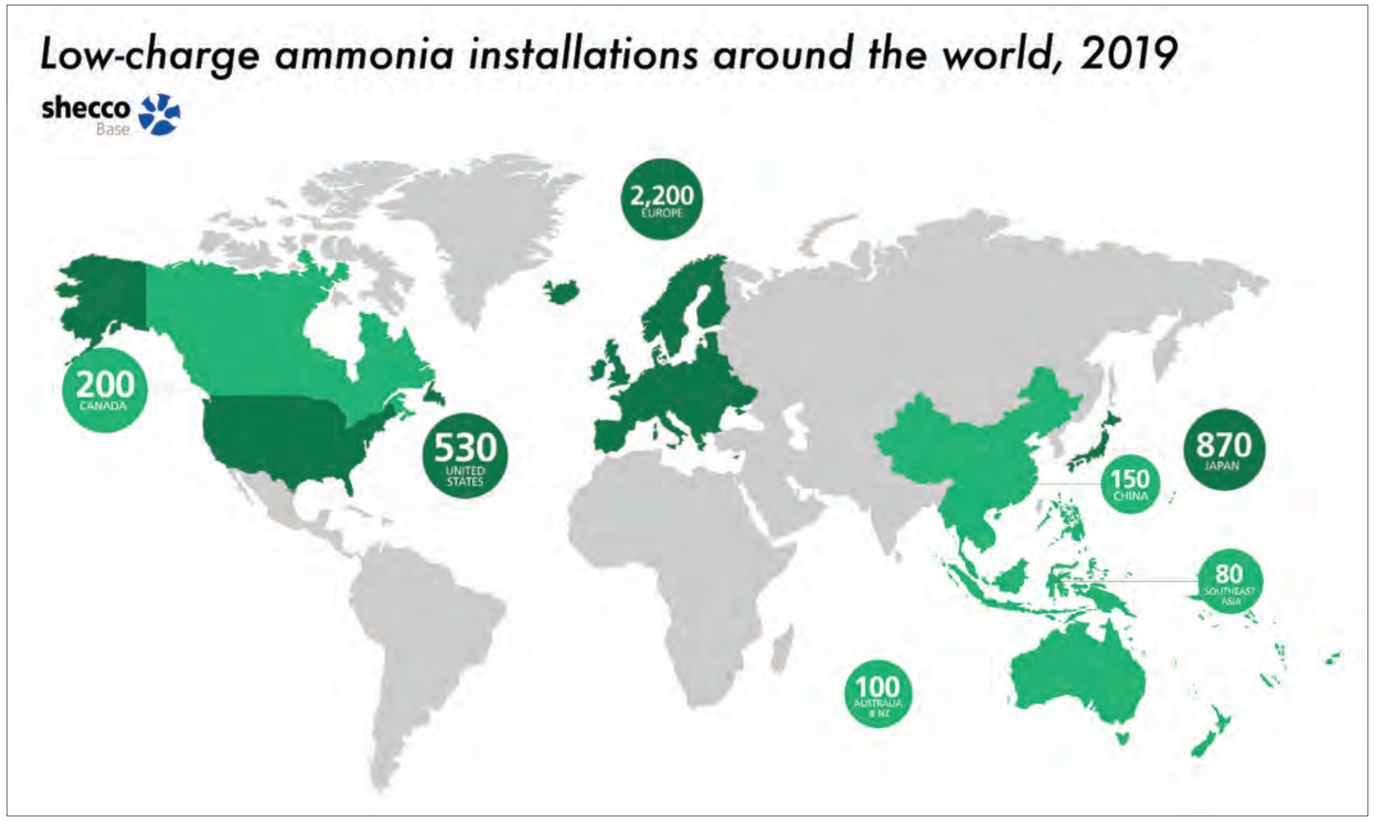
To minimise the safety obligations due to the toxicity of ammonia, low charge ammonia systems have been developed and interest in CO_2 based systems has grown. In 2019, there were more than 4,000 low charge ammonia installations; figure 3 shows their geographic distribution.

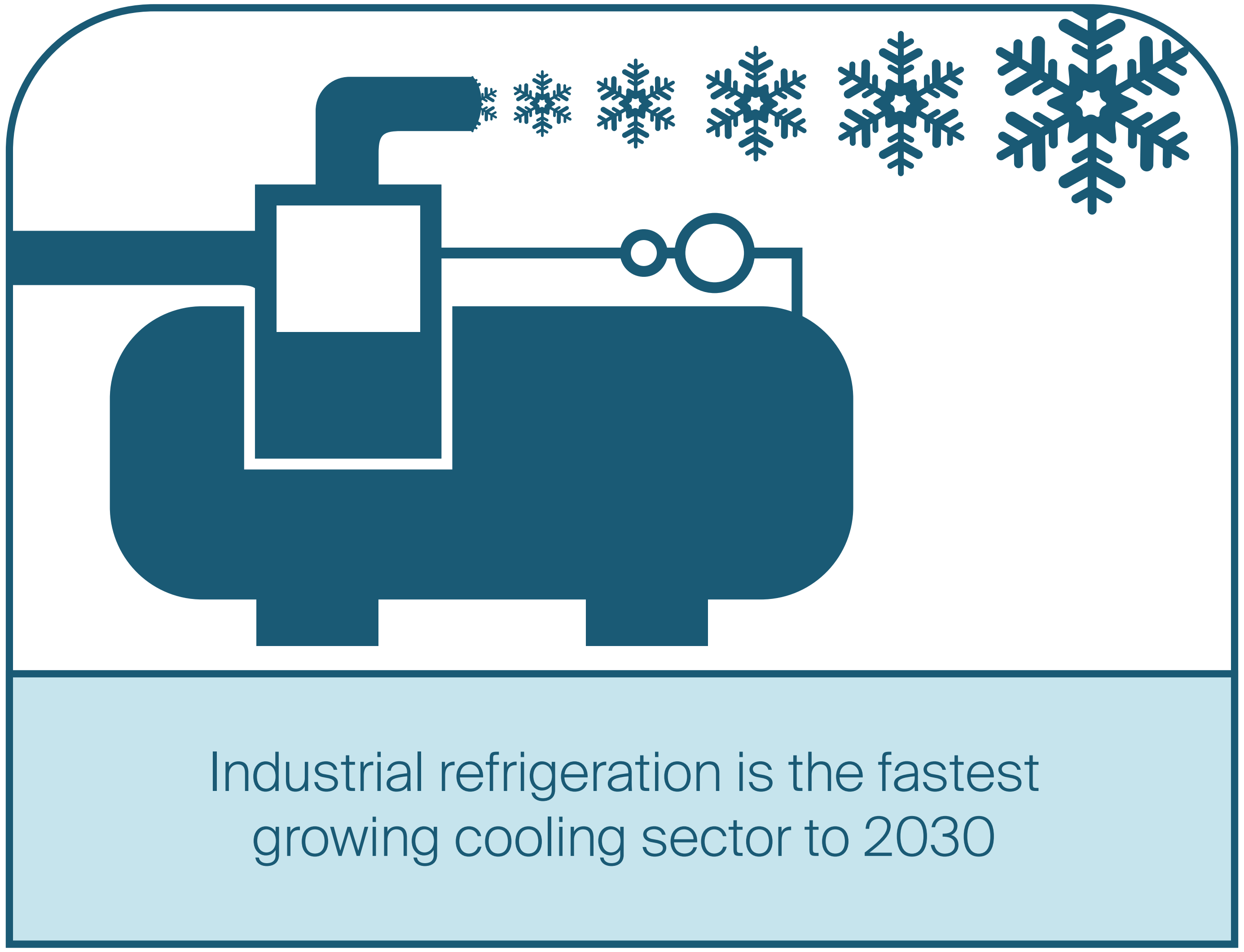
Combining ammonia with CO_2 in a cascade system can allow for a reduction of the ammonia charge to about 10 per cent or less of the original charge.[161]

There is significant overlap between chillers used in industrial refrigeration and commercial and industrial air-conditioning, with the key distinction being the operating temperature of the chillers.

> The cold chain ensures food is preserved from farm to fork, characterised by a network of refrigerated warehouses.
>
> Cold chains are essential to avoid food waste, with about 13 per cent of food lost globally as a result of inadequate cold chains, reaching higher percentages in developing and emerging economies.[162]
>
> Demand for cold chain services is booming, particularly in developing countries. For example, China's cold chain sector is reported to be growing at 25 per cent per year and was worth an estimated $75 billion in 2017.[163]

Figure 3: *Low-charge ammonia installations around the world in 2019. Courtesy of shecco*





The Economist Intelligence Unit, (2019). 'The Cooling Imperative: Forecasting the size and source of future cooling demand'.

Above: Cooling units on a food processing factory roof.

INDUSTRIAL REFRIGERATION PRODUCT LIST

CRITERIA

- F-gas free
- Commercially available
- One entry manufacturer

Many systems are bespoke and the specific cooling requirements of each application can have significant impacts on each system's coefficient of performance.

Standardised information about energy efficiency ratios (EER, COP) of products was often unavailable. As such, this product list strives to show the breadth of F-gas free alternatives available across a range of cooling capacities. All chillers made in Europe must comply with the Ecodesign directive.

Is this sector on the Pathway to net-zero emissions?

The product list features water and air-cooled chillers using a variety of compressor types for medium temperature (process cooling above -25°C) and low temperature (process cooling below -25°C) applications. Ammonia is the most popular refrigerant, although carbon dioxide and hydrocarbons are also used. For low temperature applications, chillers use propane and ammonia. Equipment using carbon dioxide in a booster system and with ammonia in a cascade system is also featured.

Accessibility to net-zero industrial refrigeration cooling systems is good, with many manufacturers able to supply products internationally.

Ammonia is efficient in large systems and has been used for many years. Ensuring the systems are maintained by skilled engineers who adhere to safety standards is critical to ensure health and. More than of half the manufacturers on the list provide training sessions, either online or in person.

Table 12: *Industrial refrigeration product list*

Manufacturer	Product name	Type of product	Refrigerant	Refrigerant GWP	EER/ COP	Cooling capacity (kW)	Temperature application	Geographic availability	Training availability
Advansor	SteelXL	CO_2 Booster	R744	1	Not found	Up to 700kW	-30°C to -8°C	Europe	On-site, Online or at Advansor Training Centre
Aqua	R290 Hydrocarbon Propane chillers	Air-cooled chiller	R290	<1	Not found	20-210	-40°C to +25°C	UK but open to other markets	unknown
Azane	Azane Freezer AF290E	Direct ammonia system	R717	0	EER:1.551	289.2	-22°C	Worldwide	Can be provided locally or at their facility in Scotland. Online training material is also under development.
CIMCO	EcoChill	Screw chiller	R717		COP:4.0	280-3500	-40°C to +7°C	Worldwide	Yes
Compact Kältetechnik	CombiChiller MCL 100-10E	Water-cooled chiller	R290, R600	<1	EER:2.96	45.2	-10°C to +20°C	At least Europe	Unknown
Enex	Yukon Ejector 4-230	Air-cooled, reciprocating chiller	R744	1	EER:1.73	185.4	-25°C - +10°C	Worldwide	Yes
Frick (JCI)	PowerPac packaged ammonia chiller PAC 316	Water-cooled, rotary screw chiller	R717	0	COP:4.1	664.3TR (2335.2 kW)	-8°C - +4.4C	Mainly Americas	Yes
GEA	BluGenium 900	Water-cooled, piston chiller	R717	0	EER:5.5	810	-15°C - +18°C	Worldwide	?
Intarcon SL	Ammolite MWW-MPM-41801	Air-cooled semi-hermetic screw chiller	R717	1	EER:4.75	362.9	-30°C to 0°C	Europe, South America, Africa	Yes
Mayekawa	NewTon R-8000	Cascade	R717, R744	0,1	EER:2.25	270	-30°C to -20°C	Japan & Asia Pacific, North America, Latin America, Europe, Middle East	Japan & Asia Pacific, North America, Latin America, Europe, Middle East
Sabroe (JCI)	ChillPac 116 E-C	Water-cooled, reciprocating chiller	R717	0	COP: 3.3	729	-25°C - +7°C	Worldwide	No
SCM Frigo	Booster Industrial MWT	CO_2 Booster	R744	1	Not found	Up to 450	Various	Worldwide	Unknown
Secon	STRATOS VP4-2-2070-I2-LN_LT	Air-cooled semi-hermetic screw chiller	R290	<1	EER:1.53	80	-25°C	Worldwide, if suitable partners are found	Training programs in German and English
Teko	ROXSTAindustrial	CO_2 Booster	R744	1	Not found	Up to 490	-30°C to -5°C	Worldwide, if suitable partners are found	Physical at headquarter, otherwise virtual
Zudek	airmatik® air5	Air-cooled, screw chiller	R717	0	EER:2.88	750	-35°C - +7°C	Worldwide	Unknown

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Transport refrigeration

Definition and scope of the sector

Transport refrigeration is an integral part of the cold chain moving products between any two points within a temperature-controlled environment.

Transport refrigeration systems are designed to keep perishable products cool, such as vaccines, medications, blood, food, beverages, and flowers. They need to be reliable to ensure the safety and shelf-life of the products being transported. Subsectors covered in this list are road transport, which includes refrigerated trucks and trailers, and shipping transport refrigeration, which includes refrigerated shipping containers and refrigeration units onboard shipping vessels.

There are currently about 2.7 million transport refrigeration units and some 1.1 million refrigerated containers in use globally. These figures are expected to rise to about 3.5 million and 2.8 million units respectively by 2050, although the figure could be significantly higher, with both figures tripling according to some estimates.[164]

Given the significant growth in future demand for transport refrigeration, urgent action to develop net-zero compatible products is needed.

The most common transport refrigeration system is the vapour compression cycle system powered using an auxiliary diesel engine.[165] These systems have high energy consumption, high leakage rates, poor end-of-life refrigerant recovery and low average lifetimes of about five to seven years.[166]

REFRIGERATED TRUCK AND TRAILER PRODUCT LIST

CRITERIA

- **F-gas free**
- **Commercially available**

The dominant refrigerant used in truck and trailer systems is HFC-404A (GWP 3,922), although HFC-134a (GWP 1,300) and other HFC/HFO blends including R-452A (GWP 2,000) are also used widely, especially in the EU due to legislation to reduce refrigerant emissions.[167] While new ships in Europe are increasingly using ammonia and/or CO_2 to meet their cooling needs, the majority of ships and fishing vessels worldwide continue to use the ozone-depleting HCFC-22 (GWP 1,760).[168]

Cooling systems for refrigerated transport are constrained by available space and weight as well as the flexibility required to transport different products at different temperatures and loads. These constraints mean that current transport refrigeration equipment tends to have lower efficiencies than their stationary counterparts.[169]

Emissions from transport refrigeration systems can account for as much 40 per cent of a vehicle's total emissions, half of which can be due to refrigerant leakage.[170] **The use of poorly regulated diesel engines to power transport refrigeration units makes them particularly polluting, emitting up to six times more nitrogen oxide (NOx) and up to 30 times more particulate matter (PM) than a similar non-refrigerated vehicle**.[171]

Refrigerant leakage is a major challenge for transport refrigeration since this equipment is expected to operate in much harsher conditions than stationary equipment.

Refrigerant leakage rates can be as high as 165 per cent of the original charge over a 10-year period.[172] The short lifespan of these systems means that emissions at the end of their life are also a significant problem. Direct emissions could be virtually eliminated with a switch to ultra-low GWP refrigerants. However, using ultra-low GWP alternatives often adds complexity to these systems, thus driving up costs and requiring better skilled technicians to undertake the work.[173] Both of these barriers need to be addressed in order to set this subsector onto the pathway to net-zero emissions.

Is this sector on the Pathway to net-zero emissions?

The truck and trailer product list contains four products, two of which use cryogenic liquid nitrogen and two using CO_2 in either a cryogenic system or in a refrigeration cycle.

Cryogenic systems use ultracool liquid CO_2 or nitrogen to cool the air within the truck which is then released to the atmosphere. Thermo King has more than 600 CO_2 CryoTech units in operation, which reportedly reduce carbon emissions by 90 per cent during the cooling cycle compared with traditional systems.[174]

Additional benefits of this system are the reduced noise level and faster temperature recovery, plus it can be retrofitted to existing vehicles.[175] Linde's Frostcruise system reportedly improves mileage by one to three miles per gallon over a typical air-cooled diesel system.[176] The Dearman engine goes a step further and uses the liquid nitrogen to power a refrigeration cycle, offering further cooling without the use of a diesel engine. However, current versions of this technology use HFCs to power the refrigeration cycle so are not included in this list. Greencold offers cooling as a service by renting out mobile trailers which are cooled with CO_2 systems when static.

Our research found multiple units in development and at the prototype stage, including one using propane, but we have chosen to feature only those that are already commercially available.

Some manufacturers stated that prototype development had been paused due to a lack of market interest and would be re-evaluated when this picks up. There is a large ongoing research and development effort towards mitigating the safety concerns of using flammable refrigerants in this equipment but mass production has not yet been introduced, although some companies are trialling this technology.[177]

Given the limited number of net-zero compatible products found in our research in this subsector, we have chosen to feature several products using cryogenic technology. More research is needed to fully evaluate the green credentials of this technology – a large amount of energy is required to compress the CO_2 or nitrogen that is used and if this gas is being compressed using renewable energy, then it is a favourable technology.

As supermarkets look to address their carbon emissions, they will have to scrutinise the emissions from their deliveries and logistics, which are responsible for a up to quarter of their total emissions.[178]

Energy efficiency of road transport refrigeration systems can be improved through better logistics efficiency (streamlining routes and timings to avoid traffic), improved monitoring and controls such as two-stage refrigerant circuits (depending upon temperature level), optimised components and inverter technology.[179]

Further emissions reductions can be gained through better route planning and strip curtains and/or air curtains to reduce infiltration of ambient air during the opening and closing of doors along a delivery route.[180]

Shifting to electric vehicles will reduce transport emissions, but the energy consumption of the refrigeration unit will impact the range of the vehicle so this is currently most useful for relatively short distances, such as last mile delivery services, where electric drive compressors are a suitable solution.[181] Other technologies being explored to reduce the emissions from transport refrigeration are fuel cells, electric standby and alternative fuels.[182]

Table 13: *Refrigerated truck and trailer product list*

Manufacturer	Product name	Type of product	Refrigerant	Energy efficiency information	Geographical availability
Air Liquide	CRYOGEN®-Trans	Refrigeration system for truck	Cryogenic liquid nitrogen	No information supplied	Worldwide
Greencold	Greencold CO_2 Cold Chain Condenser Unit (for mobile trailers)	Refrigerated trailer	R-744	Manufacturer report 16% energy savings for refrigeration, and a 25% saving for freezing applications, compared to traditional units using R404A	UK but available for hire outside UK if there is interest
Linde	Frostcruise™	Refrigeration system for truck	Cryogenic liquid nitrogen	Manufacturer reports improved mileage of 1–3 miles per gallon over a typical air-cooled diesel system	Worldwide
Thermo King	Thermo King CryoTech	Refrigeration system for truck and trailer	R-744	Manufacturer reported reduced carbon emissions of up to 90 per cent during the cooling cycle compared with traditional systems	Worldwide

Innovation

There are some significant innovations in the transport refrigeration subsector, including moving away from vapour compression.

Portable solar powered cool boxes for medical supplies could save millions of lives and offer emission savings if using ultra low GWP refrigerants in the cooling process.[183] Other innovations designed as off-grid solutions using solar power are being trialled worldwide.[184] Ice packs for supermarket home delivery transport fleets are being rolled out in the Netherlands.[185] Fleets of trucks cooled by liquid nitrogen are rising in popularity as are electric delivery vans.[186] However, the key challenge for both of these innovations is the lack of underlying infrastructure necessary for charging of electric vehicles and transport and manufacture of liquid nitrogen.

Harnessing the 'cold energy' of the production of liquified natural gas is being explored as an alternative fuel for refrigerated transport, with one estimate claiming that the wasted cold energy from this process in the EU in 2014 could have supported the cooling demand for 210,000 refrigerated vehicles.[187]

Eutectic systems are being rolled out in tandem with existing vapour compression systems to provide efficiency savings. The beams that contain the eutectic (phase change material) are frozen at night when electricity prices are lower and then provide reliable and silent cooling. These systems are more suited to shorter, direct deliveries with fewer door openings.[188]

The shipping product list covers containers and larger scale systems for shipping and some of the product ranges featured can also be used on trawlers and for fish processing and cold storage on commercial fishing vessels.

Is this sector on the pathway to net-zero emissions?

Carbon dioxide is increasingly being favoured for reefers and shipping. **In 2018, Carrier leased 2,000 CO_2 NaturalLine units to a Mediterranean Shipping company**.[189] The efficiency of systems using CO_2 varies with the climatic conditions; in moderate ambient temperatures they show better efficiency than HFC systems, although this drops in high ambient temperatures.[190]

The Montreal Protocol's Refrigeration Technical Options Committee found average usage patterns show the overall energy efficiency of CO_2 in containers is about equal to that of HFCs.[191]

There is interest in the use of propane (R-290), as this maintains efficiency in warm climates and manufacturers are working to mitigate safety concerns due to its flammability through design and servicing procedures. HFO-HFC blend R-513A (GWP 631) is being adopted in some container systems, however concerns over the lower energy efficiency of HFO-HFC blends in containers remain.[192] HFO-HFC blends are not considered to be net-zero compatible and are not included in this product list.

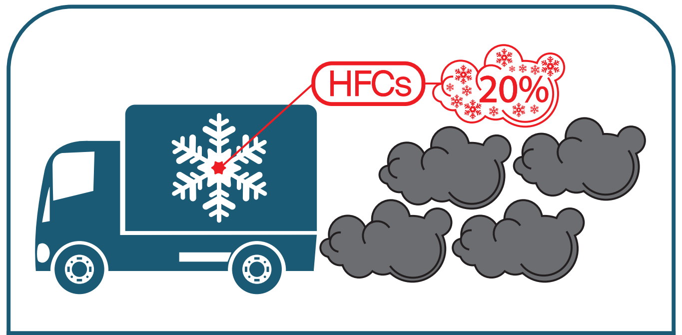
The energy use of reefers can be significant, with as much as 40 per cent of energy consumption of ports being used to cool these units.[193] Innovation to reduce their indirect emissions is urgently needed.

This product list does not specifically cover fishing vessels but the 2018 RTOC report states that ammonia has a significant presence in this subsector and CO_2 cascade and transcritical systems are also in use.[194]

REFRIGERATED SHIPPING PRODUCT LIST

CRITERIA

- **F-gas free**
- **Commercially available**



Leaking HFCs from transport refrigeration systems account for around 20% of the vehicle's total greenhouse gas emissions

Green Cooling Initiative 'Global greenhouse gas emission from RAC sector' and H Stellingwerf et al (2018) 'Reducing CO_2 emissions in temperature-controlled road transportation using the LDVRP model', Transportation Research PartD: Transport and Environment vol 58.

The role of transport refrigeration in the coronavirus vaccine role out

The COVID-19 pandemic is shining a light on the shortcomings of global refrigerated transport systems.

While the primary race was to create a vaccine, a secondary challenge has also emerged – how to transport the billions of vaccines required globally, with some vaccines requiring cooling temperatures of approximately -70°C. Effective delivery of the vaccine will require an extensive and reliable cold chain that currently does not exist. The World Health Organisation estimates that 50 per cent of vaccines are ruined each year, partly due to transportation issues.[195]

The cold chain, including refrigerated transport, will have to develop rapidly to meet the challenge of equitable distribution of a COVID-19 vaccine. However, given the current state of refrigerated transport technology, there is a great risk of locking in inefficient and climate-damaging equipment. Solving one crisis must not be allowed to lead to another greater crisis.

This cold chain will have far more wide-reaching benefits post-pandemic as it can be used for the transport of other vaccines and medications as well as fresh food and other perishables in the future.

Refrigerated transport is a core part of the global cold chain vital to human health, nourishment and prosperity. With the expected expansion of the cold chain, the shift away from the current climate-damaging equipment must be achieved immediately as a key element in the urgent fight against the climate crisis.

Table 14: *Refrigerated shipping product lis*

Manufacturer	Product name	Type of product	Refrigerant	Energy efficiency measures	Geographical availability
Carrier	Transicold NaturaLINE®	Container refrigeration unit	R-744	The Montreal Protocol's Refrigeration Technical Options Committee found average usage patterns show the overall energy efficiency of CO_2 in containers is about equal to that of HFCs.	Worldwide
DSI	DSI plate freezer V20 38/75B	Plate freezer	NH3/R744 cascade	COP: 1.78-2.18	Worldwide
Everflo	Everflo SuperFreeeze Plate Freezer	Plate freezer	R-717	Not supplied	Europe, South America, Africa, Asia South Asia (India, etc.), Australia & New Zealand
GEA	GEA HGX46/345-4 S CO_2 T (one capacity size out of the HG CO_2 T range)	Cascade plant on-board a trawler	NH3/R744 cascade	EER: 1.90 - at evaporating -10°C, gas cooler outlet 35°C/90 bar, superheat 10 K)	Worldwide
Johnson Controls	SAB 110 screw compressors	Compressor	NH3/R744 cascade	Not supplied	Worldwide

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Training and servicing

Importance of servicing cooling products and training technicians to handle them safely

Good service and maintenance practices are essential to ensure the efficient and safe use of all cooling products, regardless of refrigerant used. Openly available and accessible training on handling natural refrigerants will be imperative to the widespread adoption of net-zero cooling products.

Safety concerns about natural refrigerants have posed a barrier to their adoption. These can be mitigated through equipment design and proper handling by technicians. All refrigerants require proper handling to mitigate hazards and natural refrigerants are no exception. Natural refrigerants possess characteristics that differ in some ways to HFCs and require specific safety and handling knowledge to use, e.g. flammability, toxicity and high pressure. Workforces must be prepared now to facilitate the roll-out of these refrigerants.

Refrigerant safety and handling training is essential for all refrigerants, including F-gases. Improved servicing can significantly reduce emissions by reducing leakage rates and improving energy efficiency.[196] Regular cleaning and maintenance of cooling equipment can avoid reduced energy efficiency and can therefore lower emissions over product lifetimes.

A lack of adequately trained technicians is a key barrier to the uptake of natural refrigerants. This is particularly problematic in domestic air-conditioning as manufacturer servicing networks are not always available. Hydrocarbons are subject to strict safety requirements, but uniform comprehensive training for personnel handling hydrocarbons is currently lacking in many parts of the world.[197] A survey by the European refrigeration and air-conditioning contractors' body AREA revealed that only 5.3-7 per cent of technicians certified under the EU's F-gas Regulation have received training on natural refrigerants.[198]

Low uptake of formal certification or qualification among cooling product technicians is driven by two key factors:

- globally, a large share of personnel working on equipment belong to an informal workforce who learn on the job rather than undergo training. This is especially prevalent in developing countries;
- lack of regulatory support for natural refrigerant training exacerbates this. Even the EU's F-Gas Regulation currently fails to specify mandatory training for natural refrigerant alternatives to F-gases.[199]

Solutions to barriers

Despite poor regulatory support for natural refrigerant training qualification schemes, significant efforts are happening globally to train technicians. Germany's development agency (GIZ) has led the way by providing training in countries including Ghana, the Philippines, Costa Rica, Brazil, Grenada and Thailand.[200] Ghana is developing a certification system for technicians which encompasses skills needed to work with flammable refrigerants.[201]

REAL Alternatives 4 LIFE provides free, multilingual online learning materials and training on natural refrigerants, HFOs and HFC-32.[202]

Why does the servicing sector need natural refrigerant specific training?

Natural refrigerants have characteristics which require specialised knowledge to be handled safely.

Hydrocarbons are classified as A3 flammable refrigerants. They can be applied safely if the units are designed correctly and to the appropriate standards and if the installation, servicing and decommissioning is carried out by trained technicians adhering to relevant standards.[203] For more detailed information on training on hydrocarbons, please see GIZ Proklima's Cool Training Website.[204]

CO_2 has an A1 safety classification and is therefore not flammable; however, it operates at higher pressures and can be toxic at high concentrations.[205] Technicians therefore require specific training in order to adhere to safety procedures when handling CO_2 systems.[206] CO_2 system components, pipework and tools must be rated to safely operate at these higher pressures and technicians must be aware of additional safety precautions when working with this refrigerant).[207] Training on CO_2 should cover the various system types (cascade, secondary, transcritical and direct expansion.)[208]

Ammonia holds a B2L classification with higher toxicity and lower flammability and must be handled with care to mitigate hazards.[209] Ammonia has been used in cooling systems since the 1800s and, with the appropriate training and procedures, can be used safely.

Technician training for ammonia systems is relatively well established, as many systems are large and bespoke the manufacturers often offer their own specific training and installation workforce.

©Godrej Appliances

Manufacturer Godrej takes the lead

Leading Indian domestic air-conditioning manufacturer Godrej and Boyce has demonstrated how a manufacturer can overcome the servicing challenges associated with natural refrigerants in residential cooling.

With 22 trainer centres across India, it has successfully rolled out more than 600,000 propane (R290) split air-conditioners across India without any safety issues. Here it shares some insights into its success:

- use of targeted training module on hydrocarbons
- combining theoretical and practical training
- trainers accompany technicians during initial installations.
- technician evaluation through various performance index such as First Time Fix, repeat failure and Star Rating.
- ongoing training of technicians at regular intervals
- free installation for all propane air-conditioners
- service management systems which ensure that installation and repair of propane air-conditioners are only assigned to trained and certified engineers
- knowledge sharing and joint learning, for example Godrej has also carried out training programmes in Costa Rica.

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References

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