MGM Innova Capital

Kigali Cooling Efficiency Program Window 3 – Finance Technologies Review Report

SEPT 2019

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Abbreviations and acronyms

ABNT	Brazilian Association of Technical Standards
AHRI	Air Conditioning, Heating, and Refrigeration Institute (USA), formerly ARI
ANSI	American National Standards Institute (USA)
ARI	Air Conditioning and Refrigeration Institute. Since 2007, it is AHRI
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEPS	Building energy performance standards
BM	Build Margin (emissions factor)
CAF	Latin America Development Bank, formerly Corporación Andina de Fomento
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism (of the Kyoto Protocol of the UNFCCC)
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CFC	Chlorofluorocarbon
CHP	Combined heat and power
CM	Combined Margin (emissions factor)
CONUEE	Comisión Nacional para el Uso Eficiente de la Energía (National Commission for Energy Efficiency, Mexico)
COP	Coefficient of performance (dimensionless)
DEVap	Desiccant-Enhanced eVaporative air conditioner
DOE	US Department of Energy
DU	Dobson Unit
EER	Energy Efficiency Ratio
EF	Emissions factor for electricity generation (also for consumption)
EN	European Standard ratified by one of the three *European* Standardization Organizations: CEN, CENELEC or ETSI
EPA	Environmental Protection Agency
EPM	Empresas Públicas de Medellín (public utility)
ESCO	Energy service company
ETSI	European Telecommunications Standards Institute (not cited in this report)
EV	Electric vehicle
GABC	Global Alliance on Buildings and Construction
GEF	Global Environment Facility
GHG	Greenhouse gas
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IEC	International Electrotechnical Commission
IEA	International Energy Agency
IIEC	International Institute for Energy Conservation
IPCC	Intergovernmental Panel on Climate Change
IRAM	Argentine Institute for Standardization and Certification (Instituto Argentino de Normalización y Certificación)
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
K-CEP	Kigali Cooling Efficiency Program
kWh	Kilowatt hour
LAC	Latin America and the Caribbean
LED	Light emitting diode

LEED	Leadership in Energy and Environmental Design
LT	Low temperature (for refrigeration systems)
MEPS	Minimum energy performance standards
MRV	Measurement, Reporting and Verification
MSEF	*MGM* Sustainable Energy Fund
MT	Medium temperature (for refrigeration systems)
MWh	Megawatt hour
NAMA	Nationally Appropriate Mitigation Actions
NASA	National Aeronautics and Space Administration (USA)
NDC	Nationally Determined Contributions (country commitments on climate change, reported to the UNFCCC)
NIST	US National Institute of Standards and Technology
NOM	Normas Oficiales Mexicanas (Mexican National Standards)
NREL	US National Renewable Energy Laboratory
ODP	Ozone depletion potential,
ODS	Ozone depleting substances
OM	Operating Margin (emissions factor)
OTEC	Ocean Thermal Energy Conversion
PoA	Programme of Activities, a set of climate change mitigation projects, within the CDM (see above) and Gold Standard (voluntary market)
PV	Photovoltaic
PROCEL	Programa Nacional de Conservação de Energia Elétrica (National Electricity Conservation Program, Brazil)
RACHP	Refrigeration, air conditioning, and heat pump
RETIQ	Reglamento Técnico de Etiquetado (Energy efficiency labeling requirement, Colombia)
RT	Refrigeration ton, a measure of cooling capacity = 12,000 Btu/h
RTQ-C	Requisitos Técnicos da Qualidade para o Nível de Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos (Minimum energy efficiency standards for commercial and public buildings, Brazil)
SIDS	Small Island Developing States
SWAC	Sea water air conditioning
TEAP	Technology and Economic Assessment Panel. Montreal Protocol on Substances that Deplete the Ozone Layer
TEWI	Total equivalent warming impact
TDL	Transmission and distribution losses
TR	Tons of refrigeration, a measure of cooling capacity = 12,000 Btu/h = 3.5 kW
TRL	Technology readiness level
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIT	Instituto Uruguayo de Normas Técnicas (Uruguayan Institute for Technical Standards)
UPB	Universidad Pontificia Bolivariana
VRF	Variable refrigerant flow
WMO	World Meteorological Organization

Glossary[1]

APF: Annual Performance Factor (see Seasonal Energy Efficiency Ratio). Represents heating and cooling capacity per kilowatt hour (kWh) over one year of use of an air conditioner under specific conditions.

Central chiller: A type of cooling equipment that is centrally located and that produces chilled water in order to cool air. Performance indicator: EER, kW/ton, COP.

Coefficient of performance (COP, sometimes CP or CoP): For a heat pump, refrigerator or air conditioning system, this is a ratio of useful heating or cooling provided to work required. Higher COPs equate to lower operating costs. It is the ratio of the heating/cooling capacity to the effective power input to the device at any given set of rating condition (ISO 5151:2017-7). It is expressed in Watts divided by the power input in Watts (unit-less measure), or BTU per hour divided by power input Watts (BTU/h/W).

Cooling capacity: A measure of a system's ability to remove heat. Measured in kW, BTU/h, or refrigeration ton (RT), where 1 RT = 3.5 kW = 12,000 BTU/h.

Cooling/heating load: The amount of energy needed to heat or cool to a desired level of service. Improving insulation in a building is a strategy for reducing heating and cooling load while providing the same level of comfort to the occupant. One measure of cooling/heating load is cooling/heating degree days. A degree day measures how cold or warm a given location is, by comparing the mean of the high and low outdoor temperatures recorded each day (daily mid-range temperature) to a standard temperature (for example, 18°C).

Cooling degree days (CDD): CDDs measure how much the daily mid-range temperature exceeds the standard or reference temperature each day over a given period, which can be any period of interest (e.g. a measurement period) or the whole year.

CSPF: Cooling season performance factor (see **Seasonal Energy Efficiency Ratio**).

Design efficiency: The energy performance of equipment as designed or as shipped, same as nameplate efficiency.

District chilled water: see District cooling.

District cooling: Water chilled outside of a building in a central plant and piped into the building as an energy source for cooling.

Dobson unit (DU): One Dobson Unit (DU) is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature

[1] Based on UNEP/TEAP, 2019. Also USDOE (http://web.archive.org/web/20130214012615/http://buildingsdatabook.eren.doe.gov/Glossary.aspx) Additional terms added.

of 0 degrees Celsius and a pressure of 1 atmosphere. The "Dobson Unit" is named after professor G.M.B. Dobson (1889-1976), who started studying the ozone layer in the 1920s.

Energy Efficiency Ratio (EER): Ratio of the cooling output divided by the electrical energy input when measured at full load (i.e., at the maximum cooling capacity or the design point) and is measured in W/W or Btu/h/W (1 W = 3.412 Btu/h).

Energy performance: The amount of energy consumed for a piece of equipment or system to perform a specific level of service.

Energy service company (ESCO): A company that offers energy services which may include implementing energy-efficiency projects (and also renewable energy projects) and in many case on a turn-key basis. ESCOs may finance or assist in financing these projects. Sometimes, ESCOs provide energy savings guarantees, and/or their revenues depend on energy savings actually achieved.

Energy Star ®: A program run by the U.S. Environmental Protection Agency and U.S. Department of Energy that promotes energy efficiency.

Evaporative cooler: A type of cooling equipment that turns air into moist, cool air by spraying cool water into ducts and cooling the air as the spray evaporates.

Geothermal heat pump: A central heating (and/or cooling system) that “pumps” heat from the ground for use as household heating. Performance indicator: EER.

Heat pump (air source): A heat pump used for cooling moves, or “pumps”, heat from the indoor environment and rejects the heat to the outdoor environment. An air source heat pump can also move, or “pump”, heat from outside air and use this heat to provide hot water or household heating. Performance indicator for heating is HSPF, and for cooling SEER.

HSPF: Heating Seasonal Performance Factor (see Seasonal Energy Efficiency Ratio).

Installed efficiency: The energy performance of equipment as installed.

Kilowatt-hour (kWh): A measure of energy, measured as 1 kilowatt (1,000 watts) of power expended for 1 hour. One kWh is equivalent to 3,412 British Thermal Units (Btu).

Manufacturing cost: cost to manufacture the equipment.

MGM Sustainable Energy Fund (MSEF): a private equity fund that invests in energy efficiency and renewable energy projects in Latin America and the Caribbean.

Million tonnes oil equivalent (Mtoe): 1 Mtoe = 11.63 billion kWh

Nominal design point: represents the set of conditions (e.g. indoor and outdoor temperatures) used to design the system

Operating cost: The cost to the equipment user to operate the equipment.

Packaged A/C: A type of heating and/or cooling equipment that is assembled at a factory and installed as a self-contained unit. Performance indicator: EER, SEER.

Part-load operation: condition that happens when the system has to face a load lower than nominal (nominal conditions are used for the design of the system). Refrigeration, air conditioning and heat pump (RACHP) systems usually operate at part-load conditions for most part of their life cycle.

Peak load: The highest electricity demand occurring within a given period on an electric grid.

Percent energy efficiency improvement: percent change in energy consumption of an efficient unit compared with a base unit.

Refrigeration ton (RT): Measure of cooling capacity, where 1 ton refers to 3.5 kW (12,000 Btu). More often called TR (Ton of refrigeration).

Retail price: Price to purchase the equipment.

Seasonal Energy Efficiency Ratio (SEER): Ratio of cooling output divided by the electrical energy input, measured at full and part-load, and weighted to represent the overall performance of the device for the weather over a typical cooling season in each given location. An alternative name to SEER is the Cooling Seasonal Performance Factor (CSPF). Heating Seasonal Performance Factor (HSPF) is used for heating mode. Annual Performance Factor (APF) is a metric used for reversible heat-pump room air conditioners that heat and cool.

Transmission and distribution losses (TDL): Average proportion of electricity lost from generation to the point of use.

Ton of refrigeration (TR): Measure of cooling capacity, where 1 ton refers to 3.5 kW (12,000 Btu).

Technology readiness level (TRL): Originally defined by the National Aeronautics and Space Administration (NASA), but has since been applied to other technology areas. Higher TRL numbers indicate more mature technologies. NASA' original definition went from TRL Level 1 – Basic Principles Observed and Reported to TRL Level 7 – System Adequacy Validated in Space. Higher TRL numbers indicate more mature technologies. In this report, for more terrestrial applications, three additional levels have been added: TRL 8 - Product Developed; TRL9 - In Production; TRL10 - Mature Offering.

Total equivalent warming impact (TEWI): TEWI adds direct GHG emissions (refrigerant and other GHG gas leaks) and indirect emissions (CO_2 emissions from electricity generation).

Unit energy consumption: The amount of energy consumed by a unit of equipment, usually over one year.

Urban heat island: An elevation in urban air temperatures compared to surrounding rural areas.

Variable speed drives (VSD): A type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor, also known as inverter.

Variable refrigerant flow (VRF): AC units that are typically more complex units which generally have a compressor, and condensing unit, but multiple evaporating units in separate conditioned spaces, employing a complex control system. The control system adjusts the refrigerant flow to achieve the desired air-conditioning for each of the different spaces being conditioned.

"Muchos años después, frente al pelotón de fusilamiento, el coronel Aureliano Buendía había de recordar aquella tarde remota en que su padre lo llevó a conocer el hielo." Primera frase del libro **Cien años de soledad,** de Gabriel García Márquez (1967).

"Many years later, as he faced the firing squad, Colonel Aureliano Buendía was to remember that distant afternoon when his father took him to discover ice." First sentence of the book, **One Hundred Years of Solitude,** by Gabriel García Márquez (1967)**.**

Report perspective

This report presents a review of refrigeration and air conditioning technologies that would reduce the emissions of greenhouse gases, comprising both "direct emissions" through the release of refrigerants with high global warming potential as well as "indirect emissions" as CO_2 emissions in electricity generation.

The subject matter is very extensive. This report reduces the focus (a) by limiting the geographical area to Latin America and the Caribbean (LAC), and (b) by considering the perspective of an energy service company (ESCO), i.e. a private company that would invest in projects with the goal of energy savings and emissions reduction as defined in the previous paragraph.

The geographical limitation to the LAC takes into consideration that:

- the climate is mild or hot, with only a small population in very cold climates;
- solar resources are excellent in many countries;
- electricity generation is largely from renewable sources (historically hydro but extending to solar and wind in recent years); and
- technological alternatives are limited in some countries, because the market size is small.

The ESCO perspective focuses on areas where investment and market opportunities exist, and includes:

- cooling in commercial and public buildings, e.g. hotels, hospitals, office buildings;
- commercial refrigeration, e.g. supermarkets, food and beverage display cases, ice and cold water dispensing equipment, ice cream refrigerators, etc.;
- food and beverage distribution centers;
- industrial process cooling, e.g. for conserving fish;
- financing replacement of refrigerators and air conditioners in households; etc.

The ESCO perspective focuses on the near term, i.e. investments in the next few years, and thus focuses on technologies that are already mature, perhaps in other regions but not in LAC. Thus, an ESCO does not consider relatively new technologies that have not been commercially demonstrated, or any alternative, however promising, that is in an early stage of development.

ESCO investment opportunities generally exclude the following types of activities that would be complementary in moving towards reducing emissions in refrigeration and air conditioning, but beyond the scope of an ESCO:

- government initiatives, including laws, regulations and fiscal incentives;
- residential buildings, except where they are grouped, e.g. public and private housing estates;
- building construction;
- equipment manufacture, though an ESCO may be involved in demonstration and pilot projects to help bring to market specific promising technologies;
- projects that require very large investments, say more than 10 million dollars.

Background

The World Bank has identified four elements of sustainable cooling[2]. These are commented below:

1. *Cooling is vital for both health and prosperity*.
2. *Business-as-usual cooling will be a disaster for the planet*. Cooling contributes to climate change by increasing demand for electricity, much of which is still generated from fossil fuels, and through leakage of refrigerants, which have a much higher global warming potential than CO_2 emission. Conventional cooling devices – such as refrigerators, room air conditioners, industrial scale chillers, and other devices – account for as much as 10% of all global greenhouse gas emissions. Furthermore, if left unchecked, emissions from cooling are expected to double by 2030 and triple by 2100, driven by heat waves, population growth, urbanization, and a growing middle class. Business-as-usual cooling generates a vicious cycle: as the world gets hotter, increased demand for cooling drives up levels of greenhouse gas emissions that, in turn, drive up temperatures and make access to cooling even more critical, all while endangering human safety and livelihoods.
3. *Getting cooling right is a major opportunity*. Affordable and sustainable cooling in developing countries can help alleviate poverty, reduce food loss, improve health, manage energy demand, and combat climate change
4. *Asia will be key for the development of sustainable cooling technologies*. MGM comment: Asian mega cities are vulnerable to urban heat island phenomena. While Latin America hosts some of the largest metropolitan areas, notably Sao Paulo, Mexico City, Buenos Aires, Rio de Janeiro (all exceeding 10 million), with Lima and Bogotá (each exceeding 8 million), they are mostly *not* in hot climates. Moreover, may Latin American countries have relatively low emissions factor for electricity generation, further reducing the impact of cooling electricity use on climate change. There are, of course, many people in hot climates and several countries have relatively high emissions from electricity generation, for example, the Caribbean islands, Central America (except Belize, Costa Rica and Panamá), which generate electricity principally using fuel oil.

The International Energy Agency (IEA) has been Tracking Clean Energy Progress (https://www.iea.org/tcep/). Technologies that are on track are marked in green, while those that are not on track are marked in red. Between them (yellow) are "cooling" and "Appliances and equipment". This review focuses on clean cooling technologies as applied to refrigeration and air conditioning. However, we also keep in mind that the IEA marked in red three categories, "Building envelopes", "Heating", and "Heat pumps". All three are related to air conditioning and are also discussed within this report.

The report has been organized as follows:

- **Section 1** presents a brief introduction to refrigeration and air conditioning, noting the prevalence of vapor compression systems, which traditionally used refrigerants.

[2] http://www.worldbank.org/en/news/feature/2019/05/23/four-things-you-should-know-about-sustainable-cooling

- **Section 2** reviews refrigerants used in vapor compression systems, including their properties, environmental impact, with a focus on alternatives that are not ozone depleting substances (ODS) and have low global warming potential (GWP).
- **Section 3** reviews alternatives to vapor compression systems, especially since these do not require refrigerants that are ODS nor that have significant GWP.
- **Section 4** notes that heating and air conditioning often involve similar technologies, and that there are opportunities for GHG emissions reduction by including heating in the discussion.
- **Section 5** briefly notes that energy efficient lighting favors energy efficiency in air conditioning and refrigeration.
- An ESCO or other investor faces choices for specific applications. Thus an application-specific focus is the basis for **Section 6**.
- **Section 7** reviews technologies on the basis of manufacturer product offerings, focusing on two global manufacturers, and summarizing the remainder.
- **Section 8** presents a few comments on the measurement of energy savings and emissions reduction**.**
- Finally, **Section 9** provides conclusions and major recommendations based on the previous sections**.**

1. Introduction to refrigeration and air conditioning

Most refrigeration and air conditioning systems involve mechanical and/or electrical energy. The way cooling is achieved can be broadly classified into the five categories shown in Table 1. The most common system comprises a vapor compression refrigeration cycle, explained simply in Figure 1.

Table 1. Categories for providing cooling, with suitability for cooling people and objects

#	Category and brief description	Suitable for cooling	
		People	**Things**
1	*Fans*. Mechanical devices that cool persons and not spaces. While these have been widely used, especially in poorer countries, they are not relevant to ESCO activities and are not discussed further.	Yes	No
2	*Evaporative cooling*. Most air conditioning systems cool spaces, by lowering both temperature and humidity in order to achieve thermal comfort. However, the temperature can be lowered by evaporating water, which increases humidity. In dry locations, the humidity increase does not lead to discomfort. Large parts of LAC, especially along the Pacific Coast, and often reaching far inland are dry, so that evaporative cooling is relevant to ESCOs, and will be discussed in this report.	Yes	No, although earthenware pots are used to keep water cool
3	*Absorption cooling*. A heat activated cooling system based on solution absorption. Though nominally less efficient than vapor compression, the heat source can be waste heat from electricity generation, other waste heat, or solar energy. Typical refrigerants are a combination of water and ammonia, which are neither ozone depleting nor have high	Yes, air conditioning	Yes, refrigeration equipment

	global warming potential (GWP).		
4	*Vapor compression cooling*. This is the basis for most mechanical refrigeration and air conditioning systems. They involve a refrigerant and many refrigerants were ozone depleting substances (ODS) until their use was banned by the Montreal Protocol. Other refrigerants still in use have high global warming potential. A review of refrigerants that are not ODSs, have low GWP, while providing energy efficiency requires an extensive study of alternatives. A review of refrigerants forms a substantial part of this report.	Yes, air conditioning	Yes, refrigeration equipment
5	*Solid-state cooling*. Solid-state cooling, as the name suggests, does not require the movement of any fluid nor have any moving parts. There are four types: **thermoelectric** (based on the Peltier effect) has been known for a long time; **magnetic** (based on the magnetocaloric principle), **thermoacoustic**, and **thermoelastic**.	Not yet	Yes, e.g. thermoelectric cooling

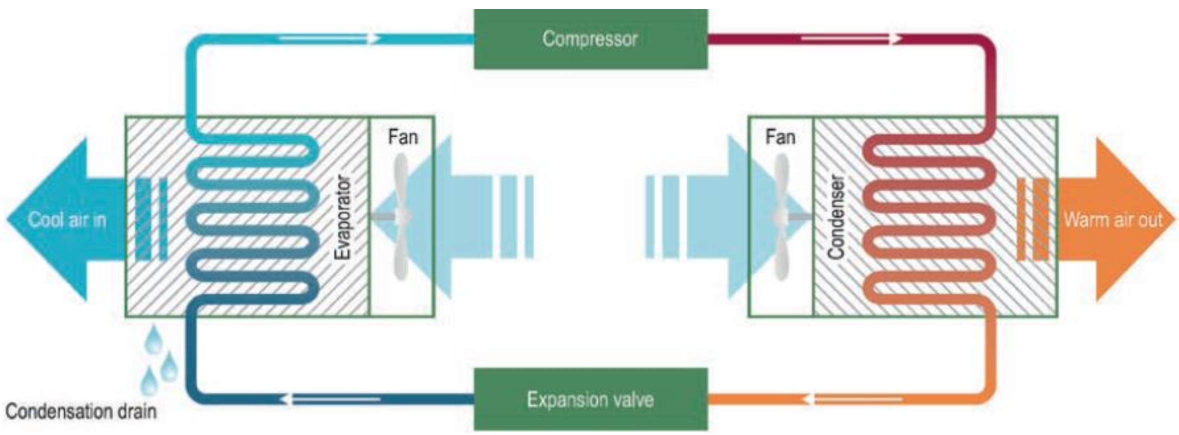


Figure 1. How a standard vapor compression refrigeration cycle works. In a refrigerator, the fans are not needed.
Source: IEA, 2018, Figure 1.1

In this technology review, with a focus on options that are already commercial or are likely to be so in the short term, we focus on Options 2, 3 and 4 from the table above. We do not consider Option 1 (fans), since the technology is already widely used and moreover, since fans do not require third party investment. Option 5 is discarded for different reasons, as will be discussed in a section on Solid-state cooling.

Technologies under Options 2, 3 and 4 all require refrigerants, which are reviewed in the following section.

Another way of classifying refrigeration and air conditioning equipment is by configuration, which is often dictated by application. Household refrigerators and small commercial refrigerators are unitary, while larger commercial refrigeration systems are made up of connected components. A classification of air conditioning configurations is shown in Figure 2, with details shown in the box further below. All except room (or through-the-wall) air conditioners are relevant for this technology review. Room (wall) air conditioners are currently in disuse, with mini-split A/Cs taking over those market segments.

Vapor compression systems (Option 4) as well as solid-state systems (Option 5) can also be used for space, water and other heating. Such systems are an alternative to and much more energy efficient than heat generated by fuel burning or by electric resistance heating. Thus clean cooling can be extended to heating, to further reduce CO_2 emissions. The properties of any refrigerant used need to be taken into consideration.

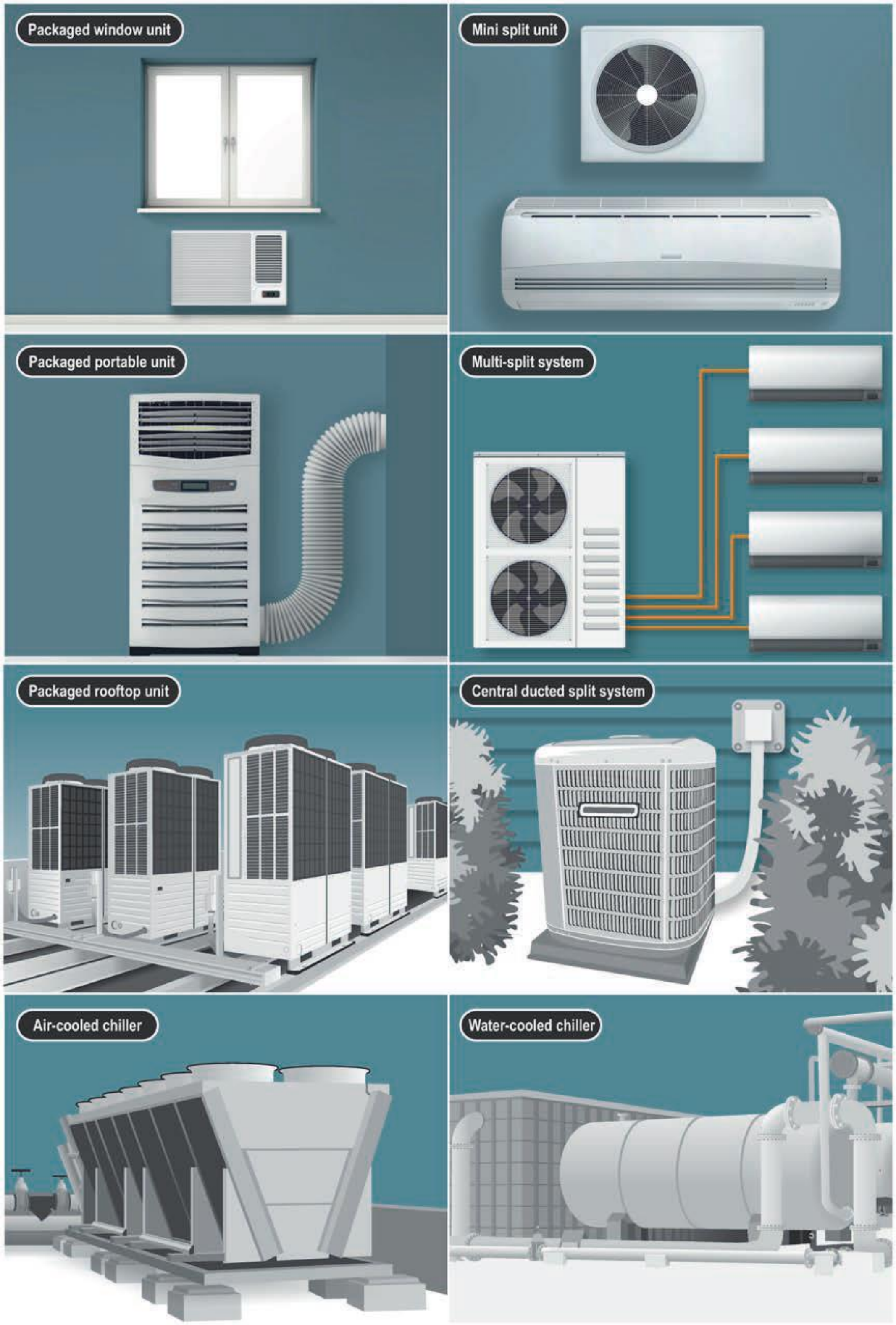


Figure 2. Configurations for air conditioning systems
Source: IEA, 2018, Fig. 1.2.

Types of air conditioning in use today (Source: IEA, 2018, Box 1.1)

Packaged ACs range from small window units that cool a single room to large rooftop units that are capable of cooling an entire building (often as part of an overall HVAC system). All packaged ACs, also known as unitary systems, contain both the condenser and evaporator in a single box that moves hot air out of the building and cool air inside. The main types of packaged ACs are as follows:

• *Window units* that are small enough to fit into a standard window frame. They are sometimes referred to as "through-the-wall" units when sold to fit through a hole in a wall.

• *Packaged terminal ACs*, common in hotels, are characterized by a large unit under a window with a grilled opening passing through the wall connecting the condensing unit on the outside to the evaporative unit on the inside.

• *Packaged portable units* are designed to be easily transported inside a building from room to room, with a hose to evacuate the hot air from the unit to the exterior.

• *Packaged rooftop units*, also known as outdoor packaged units, are larger packaged chiller systems that deliver cooled air into the building through ducts.

Split-system ACs range from small room units to large systems that can cool a large complex of buildings. In all cases, the condenser is located outside the building and is separated through piping that carries the refrigerant to the evaporator, or air handling unit, on the inside of the building.

• *Ductless mini-split systems* deliver cooling to a building through refrigerant that is piped from the outdoor condensing unit to the indoor evaporator mounted on a wall or ceiling. Ductless systems have advantages over ducted systems, including lower distribution losses, increased energy efficiency and increased control of temperature in each room.

• *Ductless multi-split systems* allow multiple rooms to be cooled from a single outdoor unit, with a separate indoor evaporator unit(s). The main advantage of this system is the reduced number of outdoor units while retaining the flexibility for cooling individual rooms. Variable refrigerant flow systems are a variant of multi-split systems, which have been developed to deliver variable refrigerant quantity depending on the cooling needs of each evaporator.

• *Central ducted split-systems* deliver cooling through ducted air, whereby the evaporator is placed in a single central location, providing cooling for an entire residential or commercial building through a system of ducts. The temperature in each zone can be controlled separately.

Chillers are large ACs that produce chilled water and distribute it throughout a building or cooling network through pipes to an indoor system that cools the air. Compression cycle chillers can be centrifugal, reciprocating or screw driven. Absorption cycle chillers can be fueled by electricity, natural gas or even solar heat. There are three main types of chillers:

• *Water-cooled chillers* use a condenser and refrigerant to reject heat to water, which is pumped to a cooling tower and circulated using fins to expel heat to the atmosphere (typically through evaporation). In certain cases, cooling towers can be replaced by ground heat exchangers, which can reduce the amount of water to be evaporated.

• *Air-cooled chillers* have condensers in which the refrigerant rejects heat directly to the outside air using one or more fans to cool the heat exchange coils.

• *Evaporative-cooled chillers* involve the use of a water spray to reject heat use more efficiently. Such chillers can make use of natural gas or co-generated sources of heat to drive the refrigeration cycle. This can be particularly useful in buildings with large cooling needs or with a concurrent need for both air conditioning and heating. They also alleviate overall electricity load.

As noted above, refrigerants are needed for several types of refrigeration and air conditioning systems. Since refrigerants can be flammable, toxic, can damage the ozone layer and can have high global warming potential, they are discussed in detail in the following section.

2. Refrigerants for vapor compression systems

Vapor compression systems used for cooling (and heating) require the use of a refrigerant. In an excellent review of the evolution of refrigerants, James Call (2008) divided the progression of refrigerants into four generations as shown in Figure 3.

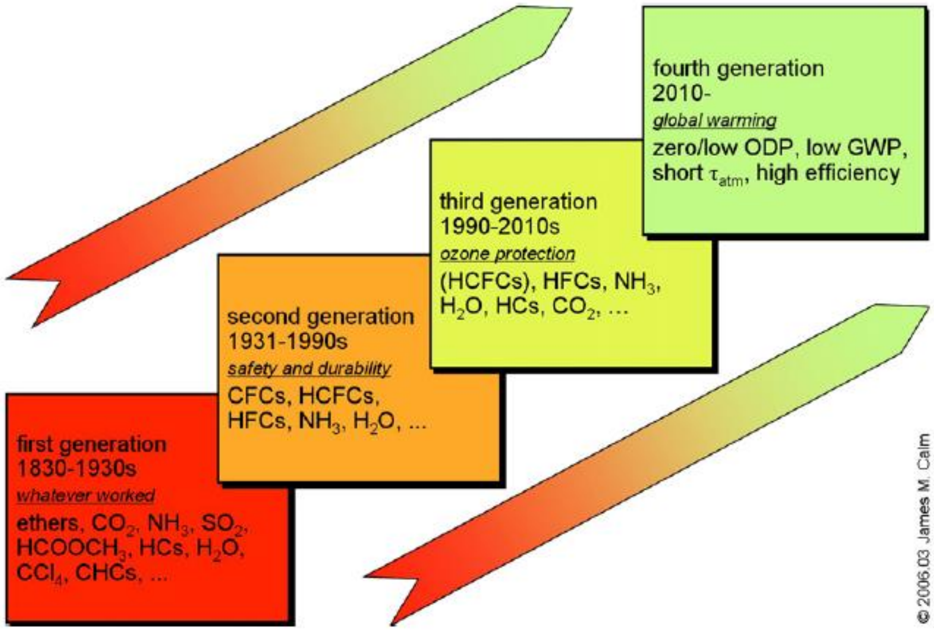


Figure 3. Progression of refrigerants.
Source: Calm, 2008, Fig. 1

In summary, safety and durability concerns led to the evolution of man-made refrigerants CFCs and HCFCs to replace refrigerants previously in use. In the second generation, common refrigerants used in refrigeration and air conditioning were chlorofluorocarbons (CFCs), the most common being R-12 or CFC-12.

The third generation focused on ozone layer protection. Following the Montreal Protocol on Ozone Depleting Substances (ODSs), the manufacture and use of CFCs and HCFCs were progressively banned, and in many cases, they were replaced by HFCs, with no Ozone Depletion Potential (ODP).

Because alternative refrigerants for air conditioning in particular were not as available, R-22, an HCFC, with a small ODP (0.055 compared to CFC 12 considered to be one), continued to be used. R-22 is currently being replaced by HFCs and other gases in air conditioning systems being sold and installed in LAC today. However, refrigerants that replaced R-12, both R-22 and HFCs, have a relatively high Global Warming Potential (GWP). Recognizing these greenhouse gases (GHG), and others produced in the manufacture of HCFCs, led to the development of a number of climate change mitigation projects involving the reduction or elimination of emissions of these gases. There were also national and regional initiatives, e.g. in the European Union, to replace HFCs with other refrigerants for some applications. These comprise the fourth generation of refrigerants. This generation was formalized in the first international agreement applicable to the GWP of all refrigerants as the Kigali Amendments to the Montreal Protocol.

2.1. Protecting the ozone layer

We know that certain refrigerants, together with foam blowing agents, and other gases containing chlorine, have been responsible for the depletion of the ozone layer. The production/ consumption of ozone depleting substances has decreased following the Montreal Protocol on Ozone Depleting Substances (signed 1987), see
Figure 4.

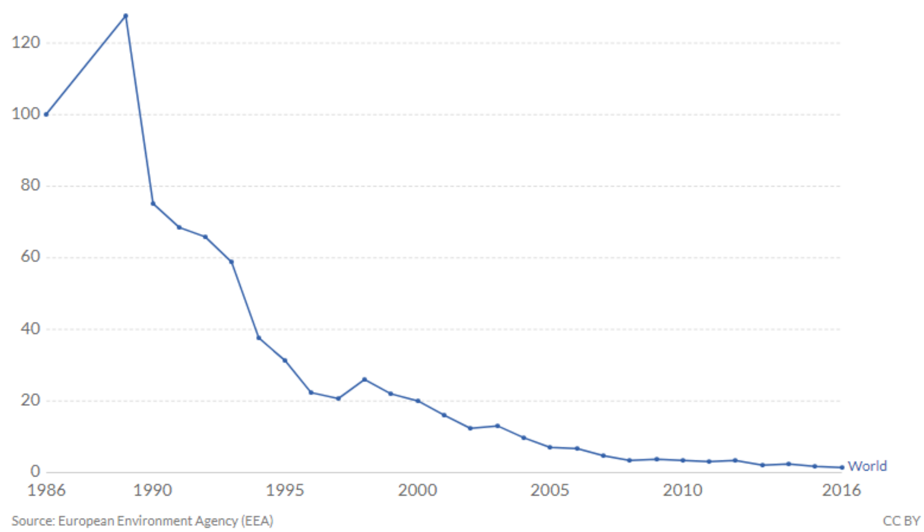


Figure 4. Global consumption of ozone depleting substances, relative to year 1986 (=100)
Source: https://ourworldindata.org/ozone-layer, from European Environment Agency (EEA) compilation

It is important to note that *production/consumption* of ozone depleting substances (ODSs) is not the same as ODS *emissions*, each as defined below:

> ***Production/consumption*** *of ozone-depleting substances refers to the primary production of new materials or products containing any of the halogen gases noted as ODS. The important aspect to note here is that this relates to the production or release of new/recent substances.*
>
> ***Emissions*** *of ozone-depleting substances can be natural or man-made. Small, relatively consistent levels of ozone-depleting substances are emitted through natural processes. Most discussion in relation to ODS emissions therefore focuses on man-made emissions which can be controlled.*

While consumption has decreased substantially, emissions have not, through leakage of refrigerants and other ODS, as well as when equipment containing these ODS reach the end of their useful life, without appropriate ODS recovery and recycling. One consequence of continued emissions is that the stratospheric ozone concentration remains low in the Southern Hemisphere (Figure 5), which includes the Southern Cone of South America.

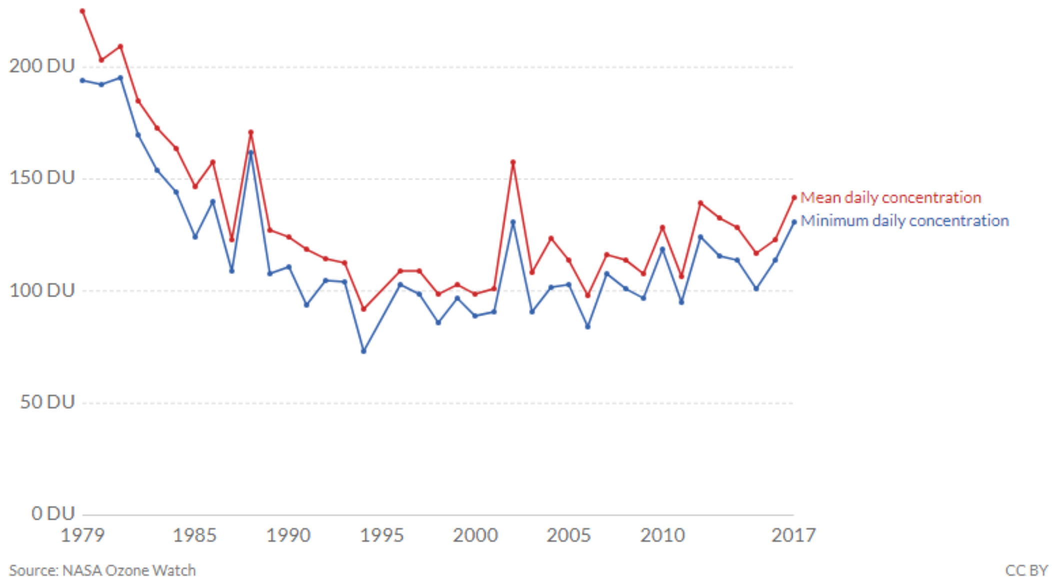
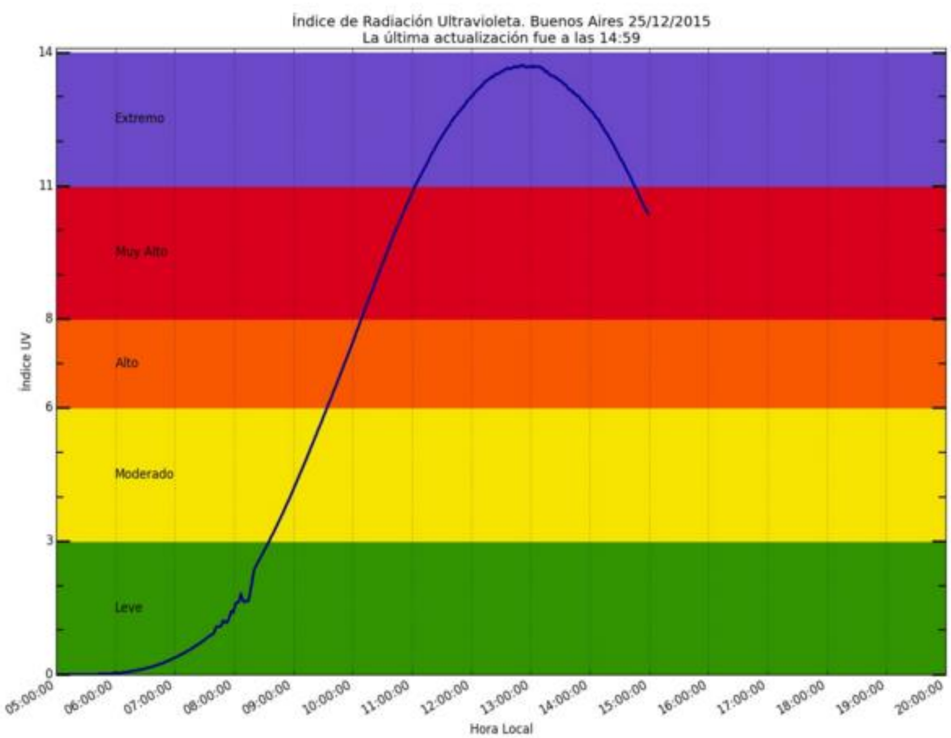


Figure 5. Stratospheric ozone concentration in the Southern Hemisphere, in Dobson Units, 1979-2017. One Dobson Unit (DU) is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere.

Source: https://ourworldindata.org/ozone-layer, taken from NASA Ozone Watch

A depletion of the ozone layer means that more harmful, ultraviolet radiation reaches the surface. Figure 6 shows the hourly variation in the ultraviolet index on Christmas Day, 2015[3].



[3] In recent years, the maximum levels have fallen somewhat, e.g. reaching a maximum value of only 12 on Dec. 31, 2018.

Figure 6. Ultraviolet radiation index in Buenos Aires, on Dec. 25, 2015.
(Source: Servicio Meteorológico Nacional, Argentina)

Measurements such as those shown in
Figure 6, following guidelines of the World Meteorological Organization (WMO) and reported globally, are made on a *horizontal surface*. The solar radiation measured on a horizontal surface peaks at solar noon. However, total solar radiation received on East-facing *vertical surfaces* can be high early in the day (and West facing vertical surfaces late in the day), as shown in Figure 7 for a clear day on Sept. 21 at a latitude roughly corresponding to Santiago (Chile), Buenos Aires and Montevideo. Therefore, vertical facing surfaces, such as people's faces, can be exposed to high levels of radiation in the morning and afternoon as well.

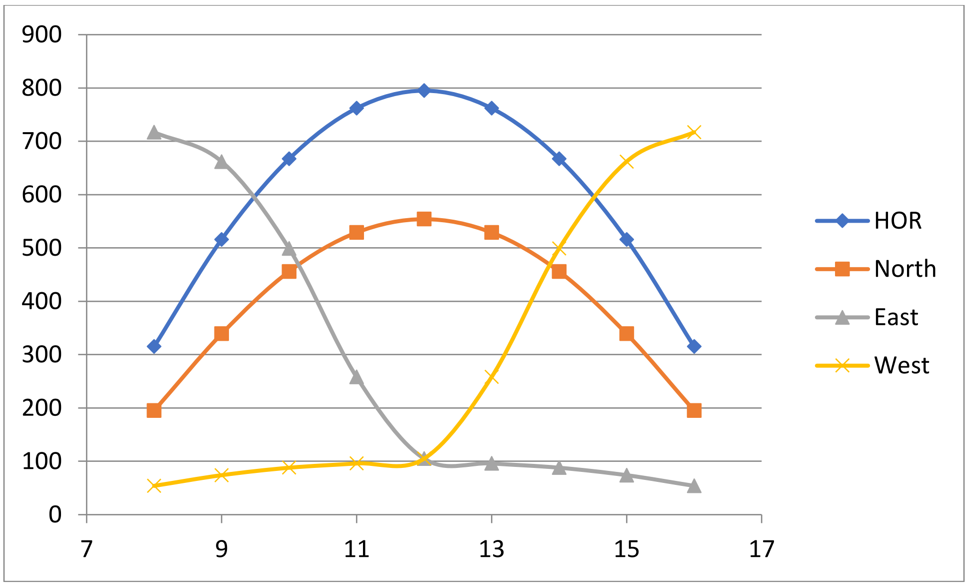


Figure 7. Solar radiation on a clear day on September 21, at a latitude of 32° South
Source: Adapted for Southern Hemisphere from *ASHRAE Handbook HVAC Fundamentals Spanish Edition*, 1985, Table 22

One consequence of high exposure to UV radiation is skin cancer. In Argentina some 130,000 cases of melanoma (an aggressive form of skin cancer) are diagnosed annually and despite treatment, almost 600 persons die each year [4].

While the depletion of the ozone layer is supposed to be centered on the South Pole, UV radiation levels are higher at smaller latitudes (e.g. Buenos Aires) compared to Ushuaia. The same is observed in New Zealand, where northern cities such as Auckland register higher UV levels than southern locations[5].

[4] https://www.infobae.com/salud/2019/05/23/en-la-argentina-se-diagnostican-por-ano-cerca-de-130-mil-casos-de-melanoma/
[5] https://www.niwa.co.nz/sites/niwa.co.nz/files/sites/default/files/import/attachments/Web_plots.pdf

The UV radiation levels increase in the Spring of the Southern Hemisphere, and peak around year end (see, e.g.
Figure 6). Thus, the UV hazard situation has not yet advanced much at the time of the writing (Sept. 2, 2019). Starting this year, the Argentina Meteorological Service provides one-day-ahead, UV radiation maps covering the whole country (
Figure 8). It is noteworthy that exposures are almost unchanged on cloudy days (although the cloudiness level is not indicated). Moreover, the projection not only shows higher UV levels in *lower latitudes* but also higher UV levels at *higher altitudes*. Of course, UV levels have always been high at high latitudes, because there is less atmosphere to protect us. Many large LAC cities are located at higher altitudes[6] (La Paz, 3690 m; Quito, 2850 m; Bogotá, 2640 m; Mexico City, 2300 m). These and many smaller cities are exposed to increased levels of UV radiation from the ozone layer depletion adding to the already high levels from their altitude. For instance, maximum UV levels in Bogotá in the first week of September 2019 are expected to be 12 using the same WMO UV index as in Figure 6. UV index for the whole world and by regions are available from https://www.woespana.es.

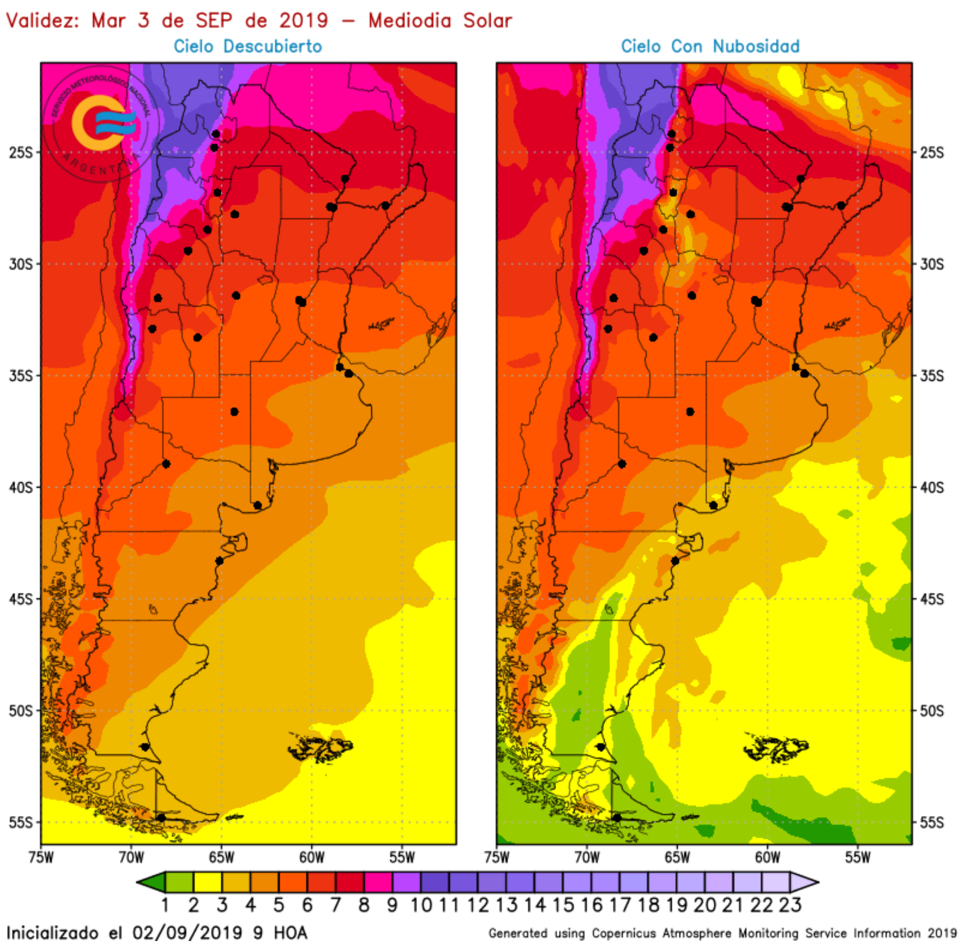


Figure 8. Projected UV levels on a clear day (left) and a cloudy day (right) in Argentina.
Source: https://www.smn.gob.ar/radiacionuv. accessed 2 Sep. 2019

[6] https://en.wikipedia.org/wiki/List_of_South_American_cities_by_elevation

Of course, ozone layer depletion is a consequence of global emissions of ODS. Nevertheless, since the LAC region includes some of the largest victims, one important objective of clean cooling in LAC is, not only to reduce the consumption of ozone depleting substances, but to reduce their emissions, e.g. including through refrigerant recovery and improved maintenance techniques to reduce leakage.

2.2. Refrigerants in terms of their Ozone layer protection and global warming

Table 2 lists some common refrigerants, with their ODP and 100-year GWP, the latter values as published in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC); Working Group 1 (WG1).

Table 2. Ozone Depletion Potential (ODP) and 100-year Global Warming Potential (GWP)

Source: ODP based on UNEP (2006) report, using R-12 as reference with a value of 1, and GWP based on IPCC Fourth Assessment Report, WG 1 (IPCC, 2007)

Product information (sorted by Product Type and Name)

Type	Product R- Number	ODP[1]		GWP[2]	
CFC	12	1	High	10900	High
	502	0,33	High	4657	High
HCFC	22	0,055	Medium	1810	Medium
	123	0,060	Medium	77	Low
	401A	0,033	Medium	1182	Medium
	401B	0,036	Medium	1288	Medium
	402A	0,019	Medium	2788	High
	402B	0,030	Medium	2416	Medium
	408A	0,024	Medium	3152	High
	409A	0,046	Medium	1909	Medium
HFC	23	0	Zero	14800	High
	32	0	Zero	675	Medium
	134a	0	Zero	1430	Medium
	404A	0	Zero	3922	High
	407A	0	Zero	2107	Medium
	407C	0	Zero	1774	Medium
	407F	0	Zero	2088	Medium
	417A	0	Zero	2346	Medium
	422A	0	Zero	3143	High
	422D	0	Zero	2729	High

	423A	0	Zero	2280	Medium
	424A	0	Zero	2440	Medium
	427A	0	Zero	2138	Medium
	428A	0	Zero	3607	High
	434A	0	Zero	3245	High
	437A	0	Zero	1805	Medium
	438A	0	Zero	2265	Medium
	442A	0	Zero	1888	Medium
	507A	0	Zero	3985	High
	508B	0	Zero	13396	High
	M089	0	Zero	3805	High
HFO	1234yf	0	Zero	4	Low
	1234ze	0	Zero	6	Low
Natural/Not in Kind	170	0	Zero	6	Low
	290	0	Zero	3	Low
	600a	0	Zero	3	Low
	717	0	Zero	0	Zero
	744	0	Zero	1	Low
	1150	0	Zero	4	Low
	1270	0	Zero	2	Low

As knowledge of how gases interact with the atmosphere to cause global warming improved, IPCC revised its estimates of GWP in its Fifth Assessment Report (or AR5, IPCC, 2013). The values are slightly different for the refrigerants of interest, with a comparison of AR4 and AR5 shown in Table 3, which also includes some so-called "natural" refrigerants: propane (R-290), ammonia and carbon dioxide. On the other hand, R-170 (ethane) and R-1150 (ethylene) are used in very low temperature applications, not relevant to this review. R-1270 is propylene, which has not been found in any equipment or system under consideration. While these gases are not listed in Table 3, it may be noted that they are not ODSs and have essentially zero GWP.

Table 3. Comparison of 100-year GWP of common refrigerants used in air conditioning, as per IPCC Fourth Assessment Report and Fifth Assessment Report.

Source: IPCC (2007, Table TS-2 or

Table 2, above), IPCC (2013, Table 8.A.1) and other sources

Refrigerant	Family	AR 4 100-year GWP	AR 5 100-year GWP
R-12	CFC	10,900	10,200
R-22	HCFC	1,810	1,760
R-134A	HFC	1,430	1,120
R-410A (See Note 1)	HFCs	2,088	Not listed
R-32	HFC	675	677
R-125	HFC	3500	3170
R-290 (See Note 2)	C_3H_8	3	Not listed
R 600 A (See Note 3)	HC	3	Not listed
R-1270 (See Note 3)	HC	2	Not listed
Ammonia (See Note 4)	NH_3	0	0
R-744 (Carbon dioxide)	CO_2	1	1

Notes:

a. R-410A is a mixture of R-32 and R-125. IPCC does not provide GWP values for HFC mixtures. The value shown above for R-410A (2088) is taken from

b. Table 2.

c. R-290 is propane, a hydrocarbon. Again, IPCC does not provide GWP values for this gas, since hydrocarbons other than methane are not considered to be GHGs. The value shown above (3) is taken from Table 2. Similarly, R-1270 is propylene, another hydrocarbon. The value shown above (2) from Table 2.
d. R 600A is isobutane, a hydrocarbon. As above, value from Table 2, not IPCC
e. Ammonia is not considered to be a GHG, hence we have assigned a value of zero.

The US National Institute of Standards and Technology provides a web-based database with the thermophysical *properties* for several fluids, including many refrigerants[7].

Transition from current refrigerants to low GWP refrigerants

While ozone depleting refrigerants, such as R-12, continue to be in use in old refrigeration and A/C equipment, most new equipment transitioned to R-410A in Latin America, although some R-22 continued to be used in South America until recently (Figure 9).

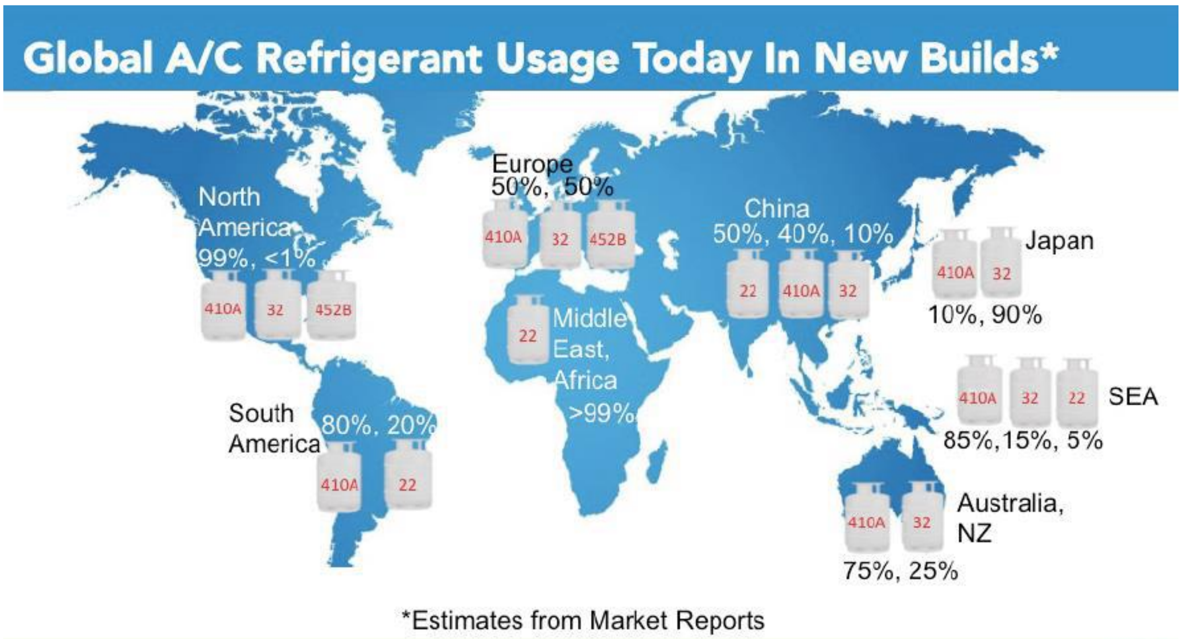


Figure 9. Global AC refrigerant usage in new unitary HVAC equipment.
Source: (©ASHRAE, www.ashrae.org, ASHRAE Webcast April 2019.). Cited in UNEP/TEAP, 2019, Figure 2.3.

Data often indicate the consumption of refrigerants, which are in fact not "consumed" in the sense of being used up. Here, as elsewhere, consumption is defined as:
Consumption = Production + Importation – Exportation

It can be assumed that, except for illegal transfers, the consumption of CFCs has been eliminated in LAC countries. Below we consider the consumption of HCFCs in selected countries:

[7] https://webbook.nist.gov/chemistry/fluid/

Argentina

According to the Ozone Office of the Argentina Secretary of Environment and Sustainable Development, the production and use of HCFCs for use in residential air conditioners were eliminated from mid 2013[8].

However, official statistics from the same organization shows that HCFCs continued to be "consumed" at least up to 2015, as shown in Figure 10.

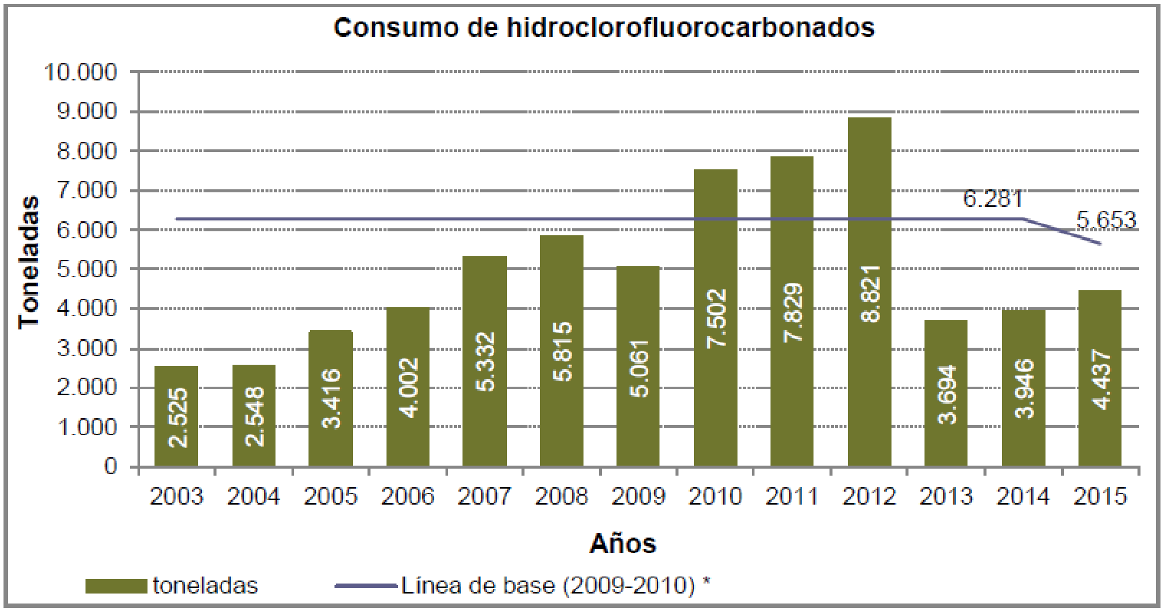


Figure 10. Consumption of HCFCs in Argentina, 2003-15.
Source:
http://estadisticas.ambiente.gob.ar/archivos/web/Indicadores/file/SIDSA%202016/textopdf/36_%20Consumo%20de%20HCFC.pdf

The same source also noted that from Jan. 2015, consumption would be reduced by 10% compared to a baseline. Accordingly, the maximum annual consumption of HCFC would reach 5653 tonnes on Jan. 1, 2020, following which further reduction would be required. However, more recent statistics on HCFC production or use in Argentina are not available.

Brazil

The consumption of HCFCs (ozone depleting substances) in Brazil, from 2010-15, is shown in Figure 11. Note that the units are in tonnes of Ozone Depletion Potential, not absolute consumption in tonnes. Considering that the ODP of HCFCs is substantially smaller than one (e.g. the ODP of HCFC-22 is 0.055, see

[8] https://www.argentina.gob.ar/ambiente/sustentabilidad/cambioclimatico/comunicacionnacional/capa-de-ozono/aireacondicionado

Table 2), the absolute tonnes are substantially larger. Nevertheless it remains clear that in 2015, there was substantial consumption of HCFCs in Brazil.

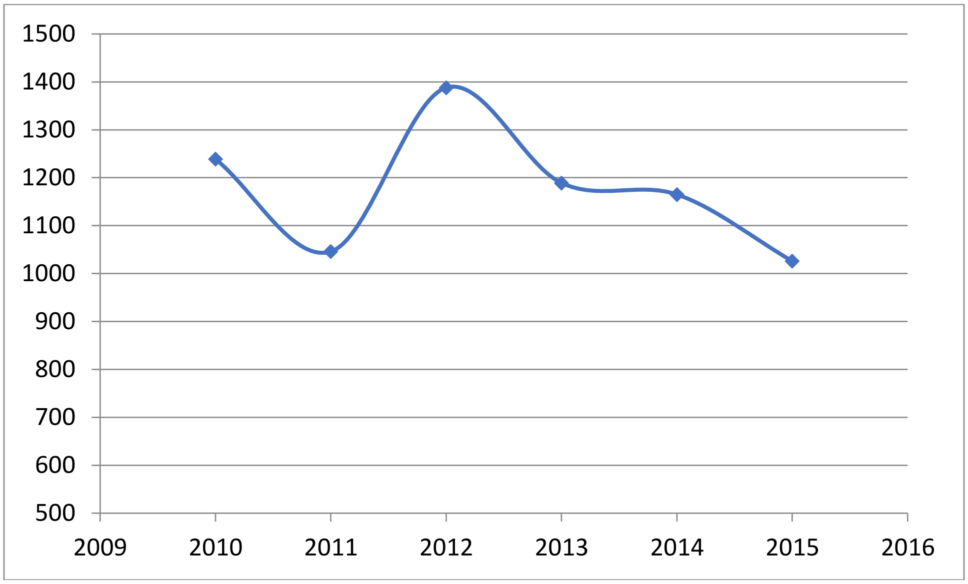


Figure 11. Historical consumption of HCFC in Brazil, 2010-15, in tonnes of Ozone Depletion Potential
Source: Data from https://www.mma.gov.br/publicacoes/item/587-consumo-de-sdos.html

Brazil has committed to reduce the consumption of HCFCs, ozone depleting substances used for refrigeration as well as for foam blowing. The Brazilian program starts by freezing consumption in 2013, with respect to a baseline consumption of 2009-10, with progressive reduction to -67% of baseline in 2025, -97.5% in 2030, and complete elimination by 2040[9].

Colombia

In Colombia, refrigerants HCFC and HFC were used for refrigeration, air conditioning and as a foam blowing agent in 2015 (Figure 12 left). There was substantial use of HCFC-22, an ozone depleting substance (ODS), in new equipment still being installed in 2015 (Figure 12 right).

[9] Source: https://www.mma.gov.br/clima/protecao-da-camada-de-ozonio/acoes-brasileiras-para-protecao-da-camada-de-ozonio/programa-brasileiro-de-eliminacao-dos-hcfcs-pbh

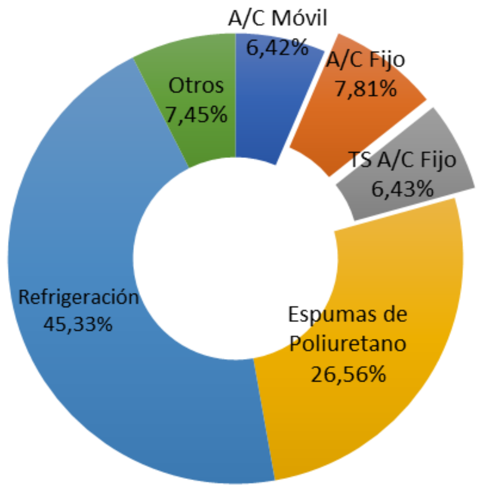


Figure 12. Left. Contribution of HCFC and HFC in Colombia by refrigeration, air conditioning and another uses in 2015. Right. Share of different refrigerants in 2015.
Source: MGM Innova, 2019. Deliverable 1, Fig. 21, based on CAEM, 2016.

Figure 13 shows the evolution of the consumption of HCFC-22 and different HFCs, from 2008-15 in Colombia. Total consumption of these refrigerants doubled in this period, although the proportion of HCFC-22 fell during this period, it remained substantial in 2015, with substantial increase in the consumption of R-410A, which is not an ODS, but with substantial GWP. These two figures are based on a major study undertaken in 2016 (CAEM, 2016). Since then, the consumption of HCFC-22 has fallen to zero.

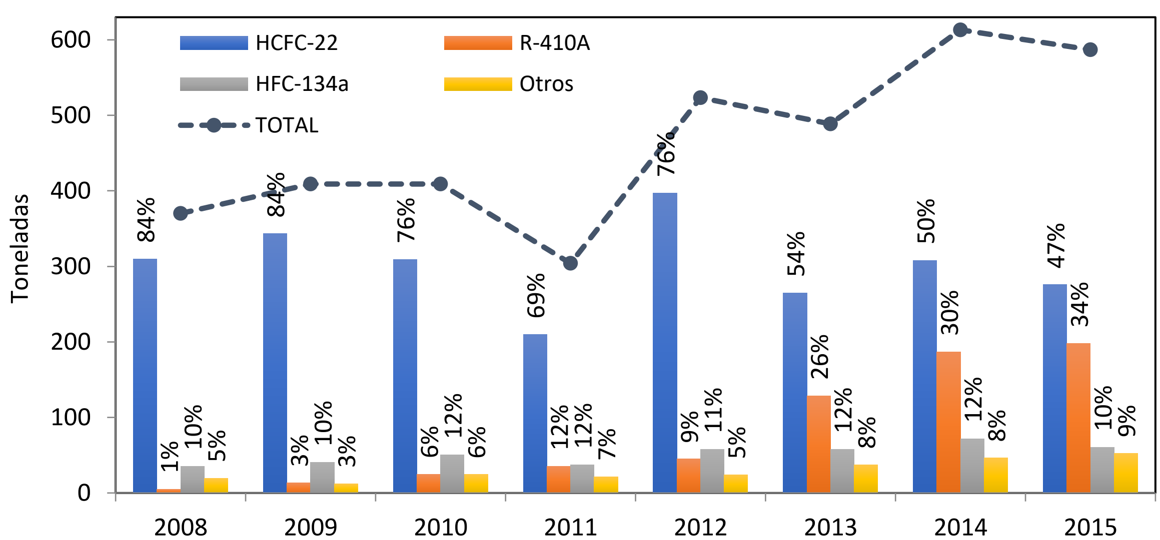


Figure 13. Consumption of refrigerants in stationary air conditioning in the period 2008-2015
Source: MGM Innova, 2019. Deliverable 1, Fig. 22, based on CAEM, 2016.

Mexico

A 2017 press release from the Mexican Secretary of Environment and Natural Resources indicated that the consumption of HCFC in 2017 was 7109 tonnes[10]

Mexico also has a substantial program for the destruction of ozone depleting substances. By 2017, 113 tonnes ODP had been destroyed[11].

Another source provides data on the *production* of HCFCs among "Annex 5" countries (to the Montreal Protocol) for the year 2017, showing substantial decrease in production in the three LAC countries, see Table 4. Note that the data are shown in equivalent ODP, not actual quantities.

Table 4. Production of HCFCs in Article 5 countries in 2017, compared to baseline. (Tonnes of ODP)
Fuente: Del Valle Méndez, 2019, cuadro 1

País	Consumo de 2017	Nivel base	% de reducción
Argentina	100.3	224.6	55,4
China	21.670.5	29.122.0	25,6
República Popular Democrática de Corea	24.8	27.6	10,1
India	1.789.5	2.399.5	25,4
México	190.1	697.0	72,7
República de Corea	305.6	395.1	22,6
Venezuela (República Bolivariana de)	15.0	123.1	87,8
Total	**24.095.8**	**32.988.9**	**27,0**

Another issue with ozone depleting substances is the continued illegal production and use. To this end, The Ozone Action office of UNEP issued a editorial on HCFC trade control (UNEP/Ozone Action, 2019). Illegal production of CFC-11, which is used as a foam blowing agent and not as a refrigerant recently caused a stir in the environmental community[12].

Health and safety of alternative refrigerants

As shown in Figure 3, the second generation of refrigerants were developed focusing on health and safety, mainly toxicity and flammability. The third generation mainly comprised refrigerants that were all safe, and with no flammability (HCFCs and HFCs) or low flammability (small quantities of hydrocarbons used in household refrigerators sold in

[10] https://www.gob.mx/semarnat/prensa/mexico-ha-eliminado-el-99-de-las-sustancias-agotadoras-de-la-capa-de-ozono Press release, 15 September 2017
[11] https://www.gob.mx/semarnat/prensa/mexico-cumple-con-el-manejo-y-destruccion-de-sustancias-que-danan-la-capa-de-ozono Press release, 22 March 2017
[12] For example, the journal Nature noted "Rogue emissions of ozone-depleting chemical pinned to China." 22 May 2019. https://www.nature.com/articles/d41586-019-01647-z

Europe and other countries). The fourth generation includes some refrigerants that were used in the first generation, but where there are issues on toxicity and flammability.

Table 5 summarizes information on safety and flammability of GWPs for selected alternative refrigerants for use in stationary[13] air conditioning. This list excludes CFCs as no longer in use in new equipment, but retains HCFC 22, the only refrigerant with any ODP, as noted above. In most LAC countries, the transition away from HCFC-22 is in progress. However, this refrigerant remains in use in some equipment and systems so that final disposition is important for the protection of the ozone layer. None of the other refrigerants listed in Table 5 is an ozone depleting substance. Two HFCs still in extensive use and in equipment being installed (HFC-410A and HFC-134A) have high GWP, and the K-CEP program seeks to promote alternatives that have lower GWP. However, these two high-HWP HFCs are both in the highest safety class (A1) and lowest flammability class (1). Except for two "natural" refrigerants (water and carbon dioxide), HFO-1336mzz(Z), and three HFO/HFC blends (R450A, R513A, and R513B), none of the other refrigerants are at the same class as the two aforementioned HFCs.

Table 5. Properties of Low-GWP Alternatives for Stationary ACs

Source: Park et al., 2019.

[13] As opposed to mobile applications. Include unitary equipment such as split ACs as well large systems used for commercial and other buildings.

Type	Chemical	Safety Class[a]	GWP[b]	Flamma-bility[c]	Comments
HCFCs	HCFC-22	A1	1,760	1	
HFCs	HFC-410A	A1	1,900	1	
	HFC-134a	A1	1,300	1	
Low-GWP Alternatives					
HFCs	HFC-32	A2L	677	2L	Small self-contained AC systems available. Small split AC systems also available in parts of Asia, India, and Europe.
HFOs	HFO-1234yf HFO-1234ze	A2L A2L	< 1 < 1	2L 2L	Considered for ducted and rooftop units, subject to safety standards and codes.
	HFO-1336mzz(Z)	A1	2	1	U.S. EPA SNAP approved in 2016 for use in industrial process AC (new equipment).
HFO/HFC Blends	R-446A R-447A R-452B R-454B	A2L A2L A2L A2L	460 570 680 470	2L 2L 2L	Newly developed blends being developed for small split ACs. Also for multi-splits, VRF systems, and ducted systems subject to safety standards and codes.
	R-450A R-513A R-513B	A1 A1 A1	550 570 540	1 1 1	Possible alternatives for ducted and packaged rooftop units.
Hydrocarbons (HCs)	HC-290 HC-1270	A3 A3	3 2	3 3	Limited availability for small split ACs in Europe and parts of Asia owing to flammability concerns.
Ammonia	R-717	B2L	0	1	Used only for chillers with small capacities owing to costs.
Water (H_2O)	R-718	A1	N/A	1	Limited to special applications for chillers.
CO_2	R-744	A1	1	1	Limited applicability for stationary AC systems and chillers based on reduced efficiency in high ambient temperatures. Market may not support development cost of components.

Notes:

a. ASHRAE Standard 34 (ASHRAE 2019B) safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 is higher toxicity/higher flammability.

b. 100-year time horizon GWP relative to CO_2 from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change.

c. Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Among the refrigerants compared in Table 5, ammonia is “worst” in the safety class with a “B2L” rating, meaning high toxicity and low flammability.

In terms of flammability, the two hydrocarbons listed in Table 5 are clearly flammable: HC-290 (propane) and HC-1270 (propylene), in the highest flammability class, 3. They are both in the safety class A3 corresponding to lower toxicity and higher flammability.

The classification “safety class” considers both toxicity and flammability. Table 6 shows another representation of flammability and toxicity classes.

Table 6. Combinations of inflammability and toxicity

Source: adapted from Sallent, 2018

	Low toxicity	High toxicity
No flame propagation	A1	B1
Low flammability	A2L	B2L
Flammable	A2	B2
High flammability	A3	B3

While "safety class" considers both toxicity and flammability, it is convenient to evaluate flammability separately. Flammability is a property of a mixture in which a flame is capable of self-propagating for a certain distance. Generally speaking, flammability of a refrigerant is its ability to burn or ignite, causing fire or combustion. The flammability depends on the amount of refrigerant in air (kg/m³), and the mixture is flammable when it is between the lower and upper flammability limits.

The flammability classes of refrigerants may also be represented as in Figure 14.

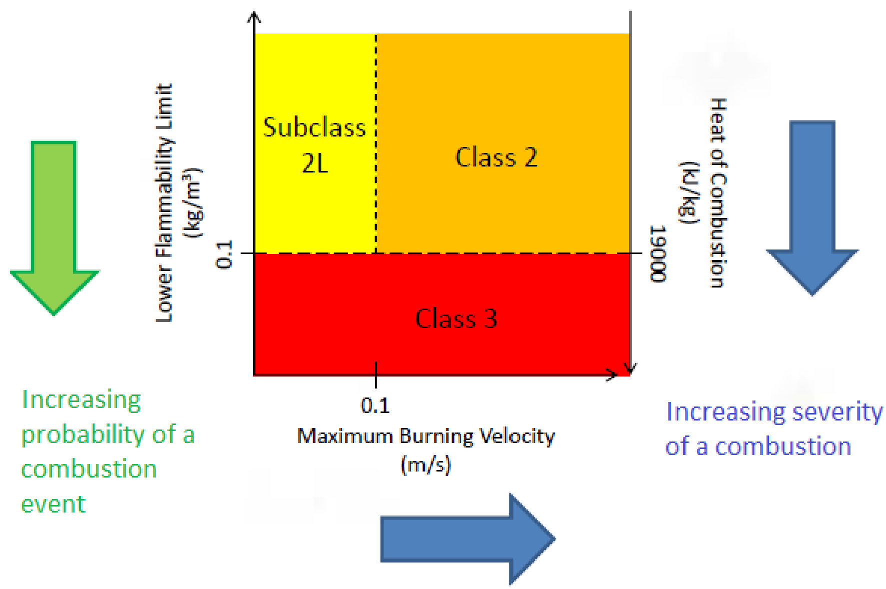


Figure 14. Flammability classes of flammable refrigerants according to ASHRAE standard 34

Source: Makhnatch, 2015B, Figure 3. Note that the Standard was updated in 2019 (ASHRAE, 2019B), to make 2L a separate flammability classification of refrigerants, as well as other changes.

According to one study by the Air-conditioning, Heating and Refrigeration Institute (Amrane 2013), most alternative refrigerants are flammable, as shown in Figure 15. Note, however, that the recent review shown in Table 5 includes some alternative refrigerants that are not combustible.

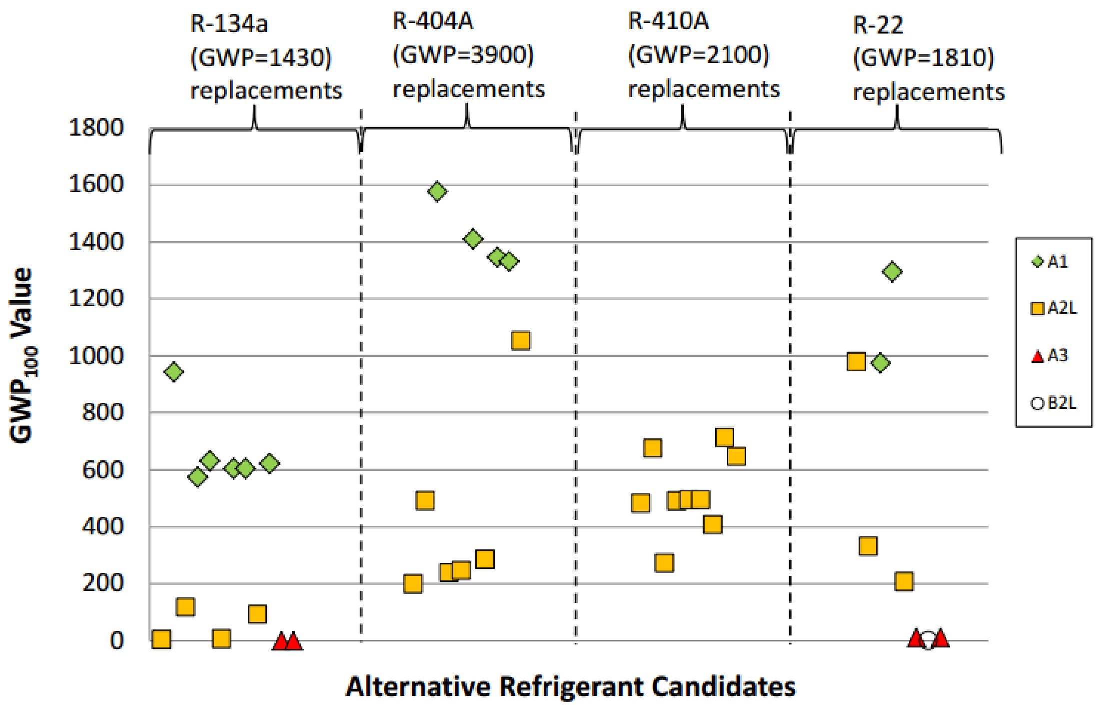


Figure 15. Overview of alternative low GWP refrigerants
Source, Amrane, 2013, as cited in Makhnatch (2015B, Figure 4)

Standards related to refrigeration flammability and safety

- ASHRAE Standard 34: Designation and Safety Classification of Refrigerants (ASHRAE, 2019B)
- ISO 817 "Refrigerants -- Designation and safety classification" provides an unambiguous system for assigning designations to refrigerants and its flammability on international levels;
- European Standard EN 378 "Safety and Environmental Requirements for Refrigeration Systems and Heat Pumps";
- ASHRAE Standard 15: "Safety Code for Mechanical Refrigeration"; updated to "Designation and Safety Classification of Refrigerants" (ASHRAE, 2019A)
- ISO 5149 "Refrigerating systems and heat pumps -- Safety and environmental requirements"; and
- European standards EN 60335-2-34 and EN 60335-2-40.

The American Heating and Refrigeration Institute (AHRI) has been conducting an extensive evaluation of Low-Global Warming Potential Alternative Refrigerants. The list of reports issued, and their relevance of an ESCO is discussed in Appendix H. In general, these reports are more relevant to equipment and component manufacturers, and some to service personnel, but not to a company investing in energy efficiency and low GWP cooling equipment and installations.

Generally, an ESCO has to choose from available equipment for a given application. Because of safety and flammability of some refrigerants, they can be used as long as the refrigerant quantity is below certain limits, determined by refrigerant mass (kg) per volume of space (m^3) where equipment is to be installed. Table 7 lists the safety class and refrigerant limits for four low-GWP refrigerants: carbon dioxide, ammonia, isobutene, and propane.

Table 7. Safety and flammability of selected alternative refrigerants
(Source: Sallent, 2018, slide 6)

Refrigerant	Safety class	Lower flammability limit (kg/m^3)	Ignition temperature (C)	Charge limit (kg/m^3)
R 744 (CO_2)	A1	N.A.	N.A.	0.1
R 717 (NH_3)	B2L	0.116	630	0.00035
R 600 a (isobutene)	A3	0.043	460	0.011
R 290 propane, C_3H_8)	A3	0.038	470	0.008

Table 8 presents requirements for refrigerants under safety standards for air conditioning, refrigeration and heat pump systems, according to international standards: IEC 60335 and ISO 5149.

Table 8. General technical obligations under safety standards for ACR&HP systems
Source: GIZ, 2018, Table 2.

Category	IEC 60335-2-24	IEC 60335-2-89	IEC 60335-2-40	ISO 5149-1, -2, -3, -4
	EN 60335-2-24	EN 60335-2-89	EN 60335-2-40	EN 378-1, -2, -3, -4
Scope	Domestic refrigerators, freezers and ice makers	Plug-in commercial appliances and cabinets with a condensing unit and single compressor	Factory-made whole air conditioners, heat pumps, dehumidifiers and partial units	All commercial and industrial refrigeration, air conditioning and heat pump systems
Limits on refrigerant charge amount	150 g flammable refrigerant No limits for R744 R717 is out of scope	150 g flammable refrigerant No limits for R744 R717 is out of scope	Approx. 1 kg of HC in a direct system inside (depending upon room size) and 5 kg outside or special enclosure No limits for R744 R717 is out of scope	1 kg, 1.5 kg, 5 kg, 10 kg, 25 kg of HC and no limit, depending upon type of system and/or room size No limits for R744 or limited by room size No limits for R717 if located outside or in machinery room
Marking	Requires flammability or high pressure warning symbols, as appropriate			
Strength pressure	Specifies pressure tests for systems and components (where applicable)			
Electrical equipment	Specifies design, construction and test requirements			Refers to appropriate standards
Sources of ignition	Describes what to consider and how to avoid a potential source of ignition, including a test method option (applies to all these standards except ISO 5149)			
Information & instructions	Details concerning the installation, use, service, maintenance, and disposal of the equipment so that users, operators and technicians are aware of how to handle flammability hazards			
System tightness	Systems generally have to be constructed as "sealed" or "hermetically sealed" systems if they are to use flammable refrigerants indoors (e.g., no or limited number of reusable mechanical connections or fittings)			
Pressure limiting/ relief devices	The need for additional devices to limit or relieve excess pressure may apply to smaller systems if flammable refrigerants are used			
Secondary/ indirect systems	Additional components for secondary or indirect circuits (such as those using water or brine) are required to vent a leak that has occurred from the evaporator into the secondary circuit if the primary refrigerant circuit exceeds a certain charge size			
Gas sensors	n/a	Gas sensors may be mandated to initiate mitigation measures such as ventilation, alarms, terminating electrical supplies, etc. These may be applicable to systems using flammable refrigerants in machinery rooms or even for systems in occupied spaces		
Construction of machinery rooms or ventilated enclosure	n/a	Machinery rooms or special enclosures may have certain requirements if flammable refrigerants are used, such as number and opening of doors, fire resistance of walls, tightness and minimum airflow rates, etc.		

The standard IEC 60335-2-89 of the International Electrotechnical Commission (IEC) establishes refrigerant limits depending on type of application. These include absolute limits (kg) as well as limits per room volume. The values applicable for flammable A3 refrigerants (hydrocarbons) until recently are shown in Table 9, showing a limit of 0.15 kg (total charge) for several applications, which was raised to 0.5 kg for A3 refrigerants (and to 1.2 kg for A2/A2L refrigerants) at an IEC meeting in May 2019[14].

Table 9. Charge limits for flammable (A3) refrigerants according to IEC 60335, prior to the 2019 increases in charge limits

(Source: GIZ, 2018, Table 3)

Equipment/ application	Vertical (60335-2-24, -40, -89)		Horizontal (ISO 5149-1, EN 378-1)	
	Maximum charge	Allowable charge	Maximum charge	Allowable charge
Domestic refrigeration	0.15 kg	0.15 kg		
Commercial refrigeration				
• Stand alone	0.15 kg	0.15 kg	1.5 kg	0.008× *Vrm*
• Condensing units	0.15 kg	0.15 kg	1.5 kg	0.008× *Vrm*
• Centralised systems			1.5 kg	0.008× *Vrm*
Transport refrigeration			1.5 kg; 2.5 kg	1.5 kg; 2.5 kg
Large size refrigeration			2.5, 10, 25 kg, no limit	0.008× *Vrm*
Air conditioner & heat pumps				
• Small self-contained	0.3 kg	0.01× *Vrm*	0.3 kg	0.01× *Vrm*
• Mini-split	1 kg		1.5 kg	
• Multi-split	1 kg		1.5 kg	
• Ducted split	1 kg		1.5 kg	
• Ducted commercial	1 kg		1.5 kg	
• Hot water heating heat pumps	1 kg, 5 kg	$0.04 \times h \times A_{rm}$	1.5 kg, 5 kg, 10 kg, 25 kg, no limit	
• Space heating heat pumps	1 kg, 5 kg	$0.04 \times h \times A_{rm}$	1.5 kg, 5 kg, 10 kg, 25 kg, no limit	
Chillers				
• Positive displacement	1 kg, 5 kg	1 kg, 5 kg	1.5 kg, 5 kg, 10 kg, 25 kg, no limit	
• Centrifugal			1.5 kg, 5 kg, 10 kg, 25 kg, no limit	

where: Vrm = room volume (in m³); A_{rm} = room area (in m²) and = unit installation height (in m)

The total amount of refrigerant charge depends on the cooling capacity of the equipment, as well as its COP or EER. Figure 16 gives an example of the relationship for air conditioners using R-290 as refrigerant.

[14] See, e.g. https://www.achrnews.com/articles/141742-iec-approves-higher-charge-limits-for-flammable-refrigerants?v=preview, accessed 14 August 2019.

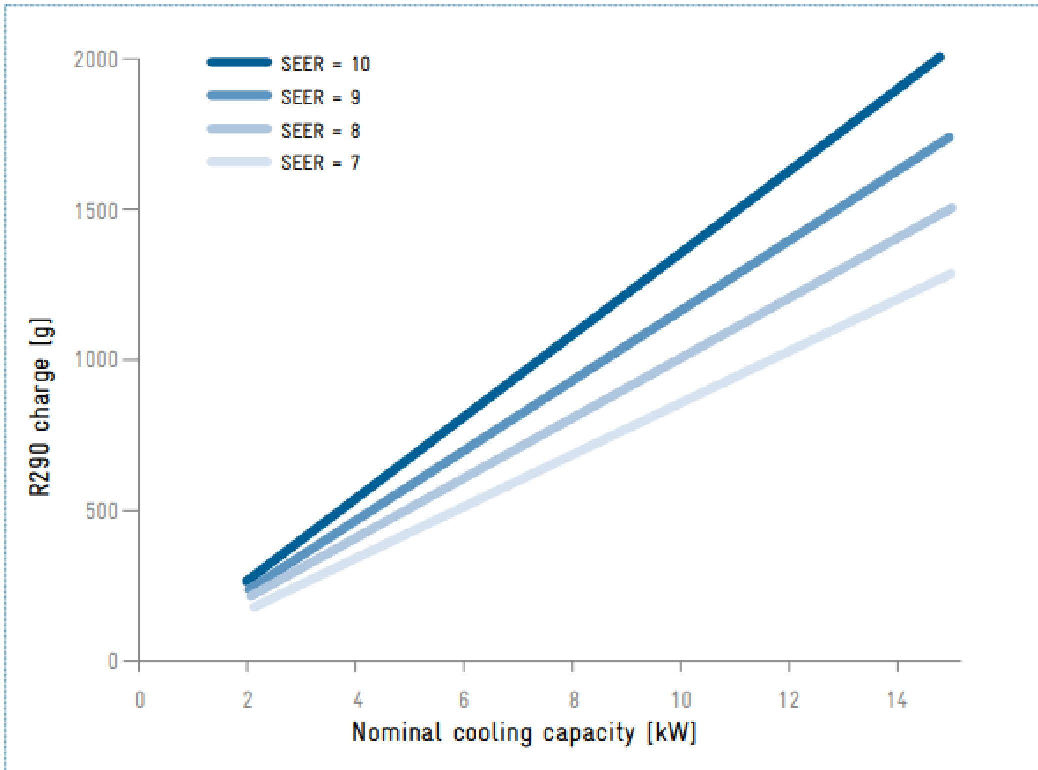


Figure 16. Example relationship between refrigerant charge and cooling capacity as a function of seasonal efficiency of an air conditioner (SEER) with R290
Source: GIZ, 2018, Figure 1

Approximate maximum capacity range for different applications using alternative refrigerants is shown in Table 10.

Table 10. Approximate capacity range for different types of applications using HC (hydrocarbons), R744 (carbon dioxide) or R717 (ammonia)
Source: GIZ, 2018, Table 4.

Equipment/application	Approximate maximum capacity with alternative refrigerant (kW)[3]		
	HC (R290, R600a, etc.)	R744*	R717
Domestic refrigeration	No limit	No limit	No limit (sorption type)
Commercial refrigeration			
• Stand-alone equipment	1 to 15	No limit	Not permitted
• Condensing units	5 to 10	No limit	Not permitted
• Centralised systems	2 to 4	No limit	Not permitted
Transport refrigeration	6 to 15	No limit	n/a
Large size refrigeration	60 to no limit	No limit	No limit
Air conditioner & heat pumps			
• Small self-contained	4 to 10	No limit	Not permitted
• Mini-split (non-ducted)	up to 10	No limit	Not permitted
• Multi-split	3 to 6	No limit	Not permitted
• Ducted split	10 to 20	No limit	Not permitted
• Ducted commercial	10 to 20	No limit	Not permitted
• Space/hot water heat pumps (domestic)	10 to 50	No limit	Not permitted
• Heat pumps (commercial)	50 to no limit	No limit	Not permitted
Chillers			
Positive displacement	150 to no limit	No limit	No limit
Centrifugal	25 to no limit	No limit	n/a

** Degradation of capacity and efficiency at moderate to high ambient temperatures must be considered.*

In conclusion we may note that hydrocarbons, though flammable, can be as safe as conventional refrigerants, as long as design and refrigerant quantities adhere to applicable standards. Leaks should be avoided for any refrigerant. However, the effort needs to be greater for toxic or flammable refrigerants. In general, much smaller quantities of hydrocarbons are needed compared to their HFC counterparts. Moreover, many refrigeration equipment using hydrocarbon refrigerants are very energy efficient, so that indirect emissions in electricity generation are small and this is an important consideration.

The USA has much more stringent rules on the use of flammable refrigerants. This is more for legal (manufacturer liability) reasons than for absolute technical factors, since global manufacturers offer their products both in the USA as well as in Europe and elsewhere, where hydrocarbon use is common. This was noted by Calm (2008, p. 1130). The special case of US refrigerant flammability is discussed in Appendix G.

Costs for the manufacture and use of flammable refrigerants

There are substantial additional costs for *manufacturing* facilities to change from a high-GWP refrigerant to *flammable* low-GWP refrigerants, see for example, UNEP/TEAP (2019, Table 3.1). UNEP/TEAP (2019, p. 49) further notes *"… that the distinct cost increase associated with the use of HC-290 over HCFC-22 or R-410A is in the order of €105,000 to €200,000 (24.4% to 25.3%) and is primarily due to the need for additional safety equipment associated with handling flammability. They also estimate that this results in an additional cost per unit output of €0.20 at most assuming 250,000 units produced annually. There may be additional costs related to production line machinery."*

In other words, once a production line has shifted over, the additional cost per unit is negligible.

As far as the refrigerant charge itself, conventional refrigerants account for about 1% of the total A/C cost. Indicative prices of refrigerants commonly used in air conditioning in China are shown in Figure 17.

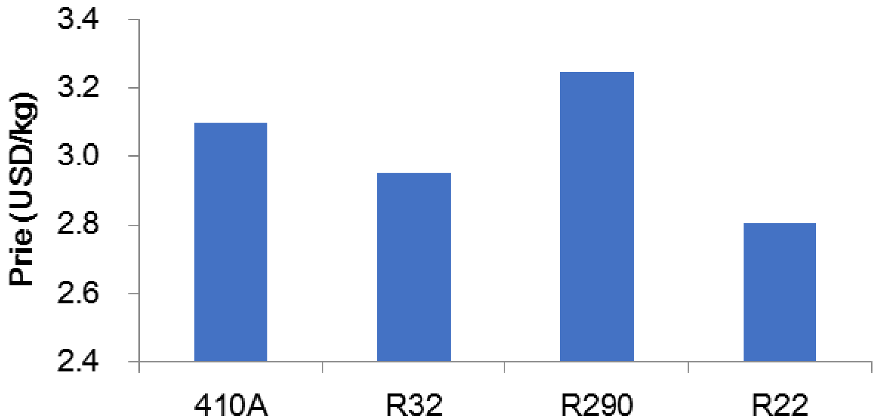


Figure 17. Estimates of refrigerant prices in China
Source: UNEP/TEAP (2019, Figure 3.2)

With respect to the price of refrigerants in the United Kingdom, UNEP/TEAP (2019) noted:

> *It is worth noting that in UK, the bulk HC (HC290, HC-600a, HC-1270) price varies between USD 1 to USD 1.5 per kg. Furthermore, the average HCFC-22 price is USD 6/kg.*
>
> *[In the UK] The general price range of refrigerants is low, around 3 USD/kg +/-10%. At an early stage, new refrigerants are more expensive, and difficult to get a foothold in the market. For example, HC290 is a by-product of the liquefied natural gas (LNG) industry. Its production process is simpler than HFC-32, but its current price is slightly higher than HFC-32. However, when buying in bulk quantities, refrigerant-grade propane can be as low as $1 per kg. The cost of high-GWP HFCs will rise with the implementation of the F-gas regulation and Kigali amendment, both of which impact the competitiveness of products containing HFCs. For example, the quoted price of R-410A in Europe went up tenfold over 2017, and in 2018 is ~ 20 Euro/kg, which far exceeds the material cost of the refrigerant itself (Figure 3.3). This increases the competitiveness of medium- and low-GWP alternative*

refrigerants and greatly promote the commercialization of environmentally friendly refrigerant technologies.

Two observations can be made on the relative price of refrigerants:

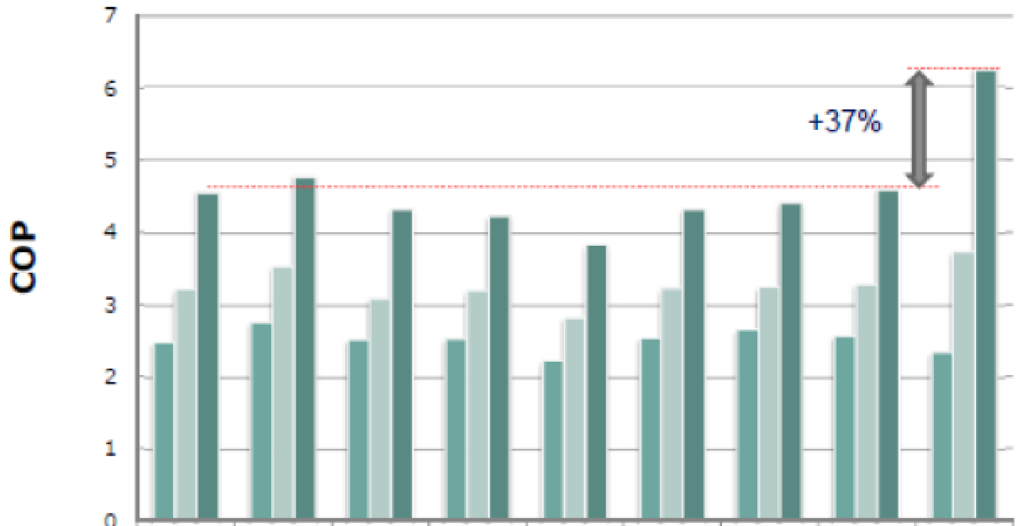
1. Refrigerant price is a very small part of equipment cost;
2. Fiscal incentives, e.g. taxes on high GWP refrigerants can make these much more expensive.

Below we discuss several specific refrigerants.

Carbon dioxide

Carbon dioxide has a GWP of 1 (one) by definition, which is the lowest of all refrigerants available. It is also not flammable and largely non-toxic. Compared to an atmospheric concentration of 380 ppm, an indoor concentration of 800 ppm is still considered to be good quality, with an 8-hour average concentration of 5000 ppm allowed for working environments, according to ASHRAE Standard 34 (ASHRAE, 2019B).

According to information we have received, systems using CO_2 as a refrigerant are generally not more efficient than current technologies for most applications. However, there are certain applications, including industrial refrigeration and supermarket refrigeration, where CO_2 and blends including CO_2 can be efficient. Figure 18 shows the results of modeling eight different systems using CO_2 and blends against a reference system with R-404A as refrigerant. At an ambient temperature of 20 C, none of the alternatives are more efficient than the reference system (see left bar of each of the 9 alternatives, and the top row of the results below the figure). However, the value improves with lower ambient temperatures, e.g. 10 C (middle bar and middle row), and especially at an ambient temperature of 0 C, (right bar and lowest row, highlighted in figure below).



	1. 2 x R404A	2. NH3 | CO2 + CO2	3. R134a | CO2 + CO2	4. NH3 + PG | CO2	5. R404A + PG | CO2	6. R290 + CO2 | CO2	7. R134a | CO2	8. R404A | CO2	9. CO2 Booster
tamb = 20 ºC	2.469	2.752	2.510	2.521	2.214	2.532	2.655	2.553	2.335
tamb = 10 ºC	3.209	3.529	3.077	3.191	2.817	3.226	3.243	3.279	3.727
tamb = 0 ºC	4.545	4.762	4.317	4.225	3.822	4.317	4.412	4.580	6.250

Figure 18. COP of different types of refrigerant systems using CO_2 against a reference system using R-404ª, as a function of ambient temperature

Source: Presentation: "Diseño de sistemas de CO_2 aplicados a la refrigeración industrial", slide 36.

It is our conclusion that CO_2 systems are generally not currently more efficient for many applications. However, this refrigerant may be suitable for certain applications. For example, CO_2 may be preferable for achieving low temperatures (-50 C) with quicker freezing times and improving productivity.

Below we note a few suppliers of equipment using CO_2 as refrigerant:

Daikin (Japan, global) offers variable refrigerant volume (VRV) heat pump systems using carbon dioxide as a refrigerant[15]. The outdoor unit **RXYN-AY1** has a cooling capacity of 28 kW with a COP of 2 (and heating capacity of 31.5, with a COP of 3). The indoor units **FXSN-AV1** are offered in cooling capacities from 20 to 100 kW.

Arneg (global, with plants in Argentina, Brazil, Colombia, USA, Italy, and elsewhere) manufactures transcritical CO_2 refrigeration units for medium and low temperature[16], "ideal for small store applications", according to the manufacturer. We were not able to find COP data in the specifications provided. Arneg also manufactures other refrigeration systems, where also technical specifications were scarce.

[15] https://my.daikin.eu/dam/document-library/catalogues/ac/vrv/bevn-a/CO2-based%20VRV%20-%20ECPEN09-207_Catalogues_English.pdf

[16] https://www.arneg.com.ar/en/products/refrigeration-systems/condensing-units/hcp-co2

Enex (Italy) lists a number of RAC products using CO_2 as refrigerant[17]. However, we could not find COP data in the specifications provided. A compilation undertaken by IIEC[18] also does not include efficiency information, but notes the following:
Enex offers a wide array of products:

- Refrigeration units for commercial applications
- Brine/water chillers;
- Heat pumps (for sanitary water)
- Industrial refrigeration systems (for distribution centres or groups of refrigerated cells)
- Refrigeration systems for freezing tunnels

Green and cool (Sweden) lists a number of RAC products using CO_2 as refrigerant[19]. However, we could not find COP data in the specifications provided. A compilation undertaken by IIEC[20] also does not include efficiency information.

Mayekawa (Japan, global) offers heat pumps using CO_2 as refrigerant. Improving upon its EcoCute model, it now offers UNIMO A/W heat pump system. The system provides hot water and can also provide chilled water. The brochure[21] currently lists only heating COP.

Ammonia

In the history and future of refrigerants, Calm (2008) noted:

> "*One of the oldest refrigerants, ammonia remains the refrigerant of choice in industrial systems and especially so for food and beverage processing, which often require large internal volumes and flexibility in system modification, as well as storage*."

Ammonia is a refrigerant in two ways. First, ammonia can used as a refrigerant in a compression refrigerant cycle, typically for industrial refrigeration. Ammonia can also used in an absorption cycle, where a heat source is used to provide cooling. Reindl (2014) provides a general introduction to ammonia and some applications in compression type refrigeration.

GEA Group AG (Germany) manufactures several families of chillers operating on ammonia as refrigerant, including:

- GEA BluAir
  - 370 - 1,270 kW cooling capacity (R717, 12/6 °C)
  - Ambient temperature max. -15/40 °C
  - Secondary refrigerant outlet temperature -15/18 °C
- GEA BluAstrum
  - Cooling capacity 390 - 1,730 kW (R717, 12/6 °C)

[17] http://www.enex-ref.com/eng/download.aspx
[18] http://www.iiec.org/coolingdemo-technologies/711-commercial-refrigeration/692-refrigeration-systems
[19] https://www.greenandcool.com/en/products-overview/
[20] http://www.iiec.org/coolingdemo-technologies/711-commercial-refrigeration/691-transcritical-refrigeration-systems
[21] https://www.mayekawausa.com/pdf/brochures/Unimo-AW.pdf

- o Secondary refrigerant outlet temperature -15/18 °C
- GEA BlueGenium
    - o Excellent part load efficiency, ESEER above 9
    - o 280 - 1,210 kW cooling capacity (R717, 12/6 °C)
    - o Secondary refrigerant outlet temperature -15/18 °C

The Energy Efficiency Ratio versus operating load of typical models in each family against "standard" models, as reported by the manufacturer is shown in Figure 19. Specifically, the GEA models show improved part-load performance compared to the standard models.

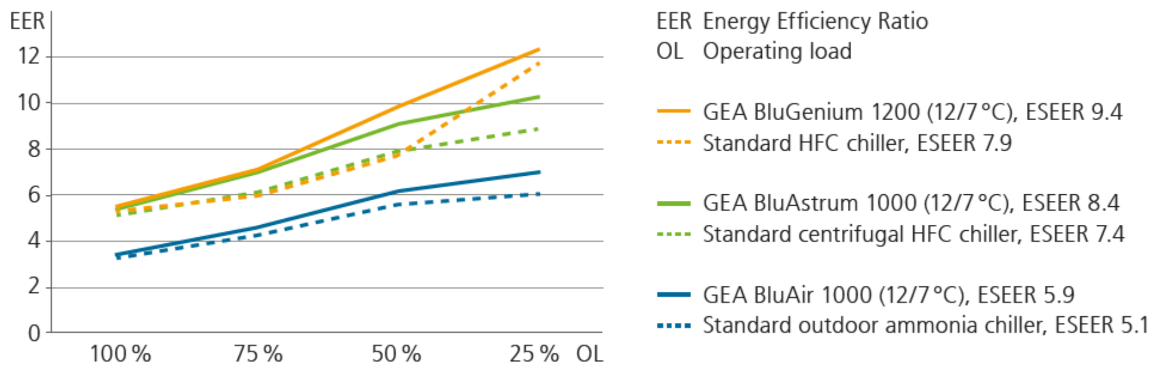


Figure 19. Performance of GEA BluAir and BluAstrum and BluGenium chiller models compared to standard HFC and ammonia chillers.

(Source:)

REFTECO (Italy) also offers ammonia chillers CHA in a wide cooling capacity range of 80 to 950 kW[22].

Azane (USA) also offers ammonia chillers:

- Azanechiller 2.0[23]. Manufacturer (Azane) claims 20% improved efficiency compared to HFC chillers, and low refrigerant charge, as low as 0.64 kg/TR. Note that Star Refrigeration (United Kingdom) lists Azanechiller 2.0 among its "Products"[24].
- Azanefreezer 2.0[25]. Manufacturer reports large energy savings compared to "European Average" for commercial freezers (-22 C), see Figure 20 and associated footnote.

[22] https://www.refteco.com/chillers/ammonia-chiller-cha/
[23] http://www.azane-inc.com/media/39191/ac_20_tri_compressed.pdf
[24] https://www.star-ref.co.uk/our-products/azanechiller-20.aspx
[25] http://www.azane-inc.com/media/39192/af_20_tri_compressed.pdf

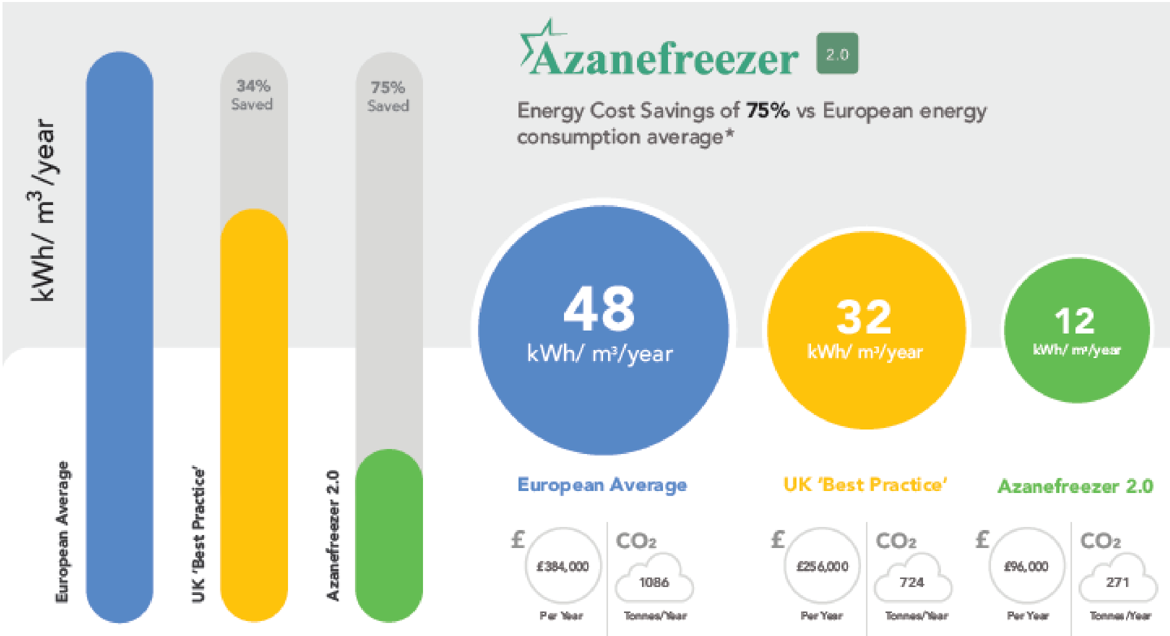


Figure 20. Energy consumption of Azanefreezer 2.0 compared to European Average and UK "Best practice"[26]
Source:

Note that the Azanechiller and Azanefreezer performance data reported by Star Refrigeration and in Figure 20 correspond to the United Kingdom, with an annual average outdoor temperature of only 12 C. For Azanechiller 2.0, Star Refrigeration claims "*With COPs up to 3.63 at 100% load and 35°C ambient, increasing to 11.9 at 50% load and typical UK ambient temperatures of 10°C, the new Azanechiller 2.0 is 15% more efficient than its screw compressor counterparts at design conditions.*" Ambient temperature is very important for any refrigeration and air conditioning system, and should be taken into account to ensure that any system and the reference are tested under the same conditions.

Mayekawa (Japan, global) offers a Slurry Ice system producing ice at 0 C, using ammonia as a refrigerant. A 20% energy savings is claimed compared to the Stick Ice system. Possible applications include[27]:

- Dairy plants – for cooling milk, cheese, yogurt, butter, etc.
- Beverage plants – for pasteurization of milk/beverages
- Food plants – for noodles, tofu, bread, fish and brewing
- HVAC

Ammonia can also be used in *absorption* refrigeration systems, as discussed in a section on this subject later.

[26] The manufacturer provides the following footnote to the figure : Figures based on an 80,000 m freezer volume. European Average figures based on Evans et al (2015). UK 'Best Practice' based on ETSU UK (1994). Azanefreezer 2.0 based on Star Refrigeration Data (2018) of a modern, well managed cold store at -22C and 10p/kWh. CO emissions are calculated using UK government conversion factors for 2018. (Source references not available.) Note that data correspond.

[27] Source: https://www.mayekawausa.com/industrial-refrigeration/products/cooling-system/slurry-ice-system/

Carbon dioxide with other refrigerants

Carbon dioxide can be used with another refrigerant in two-stage cascade refrigeration systems, which involves two refrigerants in each of two refrigerant cycles that share a common heat exchanger. The two refrigerants have different boiling points, and one is used for the initial cooling stage, with the other for the final cooling. Cascade cooling is most used in low temperature industrial and food storage applications, such as (Visser, 2002, p. 22):

1. Cold storage plants
2. Large scale blast freezing and plate freezing systems
3. Other freezing equipment - spirals, IQF, etc.
4. Ice cream plants
5. Dairy plants with cold storage and freezing facilities.
6. Fish processing plants
7. General food processing plants manufacturing frozen food.

The upper stage refrigerant can be a low-GWP HFC or ammonia, while the lower stage refrigerant is CO_2. Visser (2002) suggested a cascade system with CO_2 at say -55 to -8ºC and NH_3 at say -10ºC/+35ºC. Peterson (2016) claims a number of advantages to a CO_2/ammonia system compared to a system using only ammonia, including:

1. "*Lower operating costs. A CO_2/NH_3 cascade system uses less energy per ton of refrigeration than a typical two-stage ammonia system operating at evaporating temperatures of -35 F (-37 C) to -60 F (-51 C)*
2. *Lower capital costs. Using CO_2 instead of ammonia takes advantage of CO_2's unique physical properties, resulting in smaller pipes, smaller pumps, less insulation and less installation labor compared to a two-stage ammonia system*
3. *Ammonia charge reduction*."

These advantages could need to be verified and quantified in actual installations.

Below we consider some products using CO_2 with another refrigerant in cascade systems:

Kuroshiho (Japan). Kuroshiho has developed a cascade system for ultra-low temperatures of -40 C to -80C[28]. The refrigerants would be R-407E for the high pressure stage and R-32 for the low pressure stage. The reference system uses R-404A and R-23. The GWP of the Kuroshiho system is 894 compared to 8000 for the reference system. Kuroshiho claims lower initial cost and lower operating cost compared to the reference system, as well as reduced GWP.

Hillphoenix (USA, global). Hillphoenix offers low temperature industrial refrigerant systems using CO_2 in combination with an HFC. Its Second Nature® Low Temperature Direct Expansion Cascade (SNLTX2) system (Figure 21) allows a 70% decrease in HFC refrigerant charge.

[28] Source: http://www.nissin-ref.co.jp/english/product_blog/1-2.html, accessed 17 August 2019

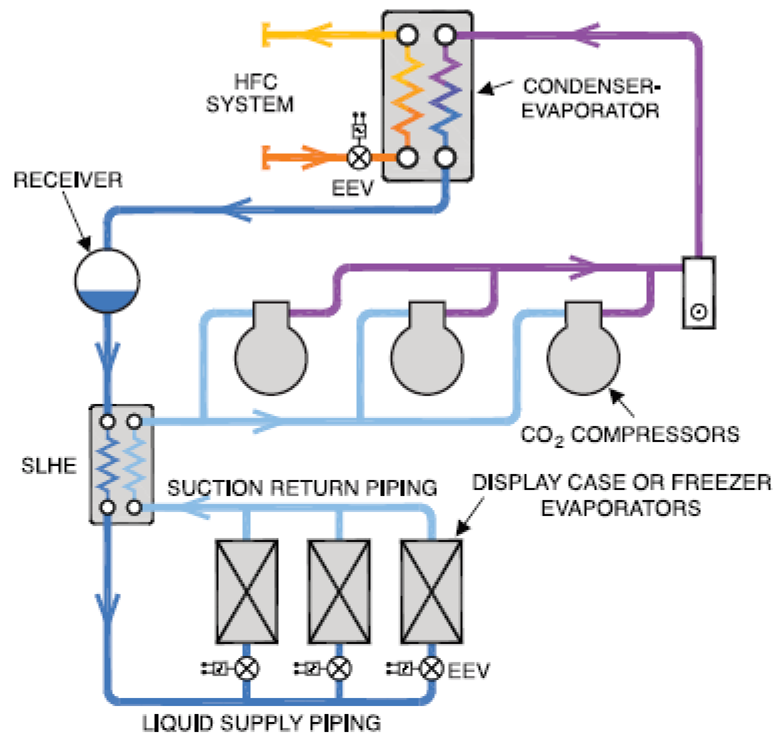


Figure 21. Hillphoenix Second Nature® Low Temperature Direct Expansion Cascade (SNLTX2) system, using CO_2 as well as an HFC
Source:

Mayekawa (Japan) also offers ammonia / CO_2 industrial refrigeration systems, including NewTon 3000, 6000, and 8000. Mayekawa reported energy savings[29]:

- Cold storage, 39,200 m^3: Using NewTon 3000, the factory saved 27.8% electricity for all uses (including lights and elevators). Reference system not specified.
- Freezers: 20% energy savings compared to a reference system using R-22.

Moreover, the system configuration allows for ammonia to be confined to the machine room, limiting exposure to this toxic gas (Figure 22).

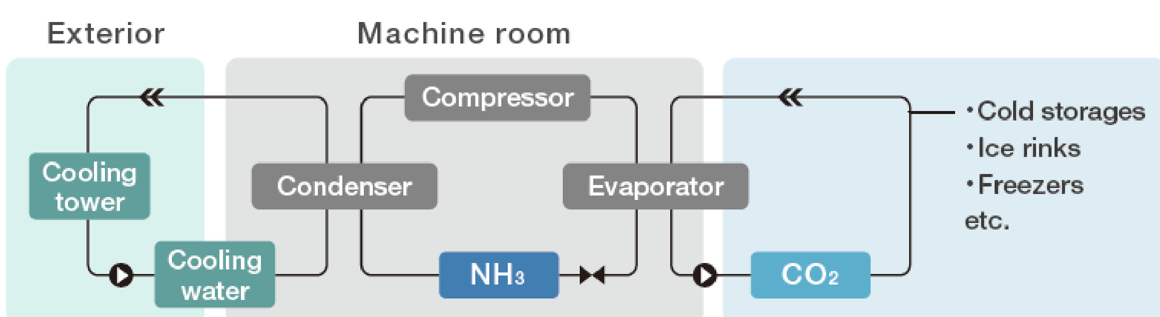


Figure 22. Configuration of Mayekawa NewTon refrigeration uses ammonia, CO_2 and water.
Source:

[29] Source: https://www.mayekawausa.com/pdf/brochures/Newton_Brochure.pdf

Air as refrigerant

Air can also be used as a refrigerant.

Mayekawa (Japan, global) offers its Pascal Air system for generating ultra-low temperature (-50 C-100 C), which can also be used for freeze drying applications (Figure 23).

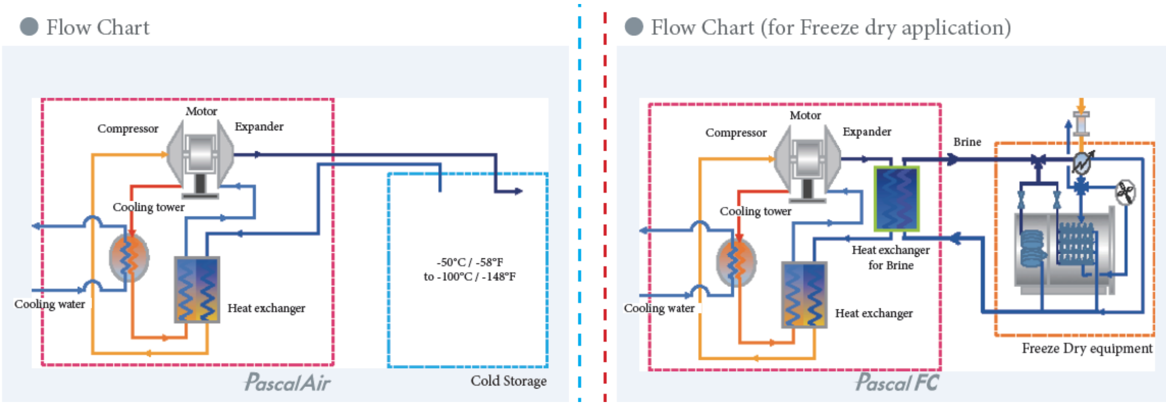


Figure 23. Flow chart to Mayekawa Pascal Air that uses as refrigerant for generating ultra low temperatures (left) and for freeze drying (right)

Source: https://www.mayekawausa.com/pdf/brochures/Newton_Brochure.pdf

Refrigerant R1234ze

R1234ze is a hydrofluoroolefin (HFO) developed by Honeywell, for a variety of possible applications including foam-blowing agent, aerosol propellant, as well as a refrigerant. The two isomers of HFO-1234ze are shown in Figure 24. Despite the presence of fluorine atoms, this refrigerant has a GWP below 1. This refrigerant has potential applications in commercial as well as in industrial refrigeration. However, the COP of HFC-1234ze to replace HFC refrigerants needs to be determined. At least one study indicates that "*a simple replacement of R134a refrigerant with R1234ze into existing chiller systems, the COP will be reduced by 16-18%*" (Di Bella, Weaver, and Osborne, 2017).

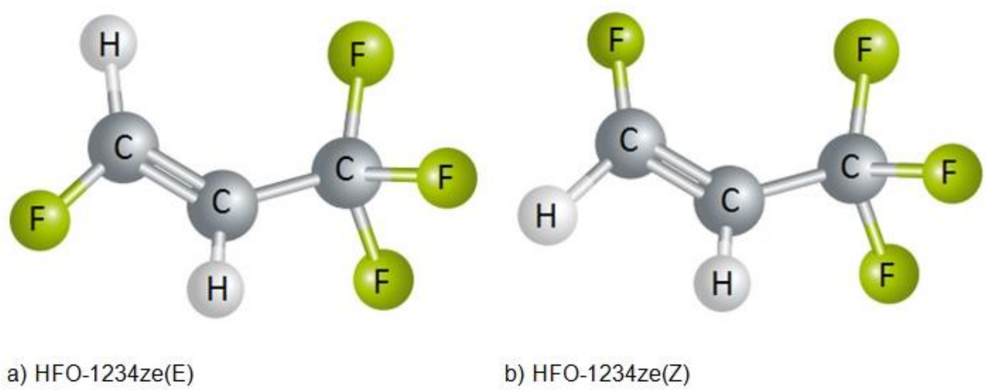


Figure 24. The HFO-1234ze isomers

Source: Makhnatch, 2015A, Fig. 1

Schneider Electric (Global) manufactures a wide range of cooling equipment in the Aquaflair Series[30], using R-410A and R-134A refrigerants. However, they also offer two models of chillers using refrigerant R1234ze (BREC and BREF), each with cooling capacities in the range 300 to 1000 kW. The product brochure cited here includes detailed performance specifications for all models, including R-410A, R-134A and R1234ze, so that a comparison of R1234ze with alternative systems may be made by the system designer. Schneider Electric also offers a great deal of control options to further optimize energy use.

Daikin (Japan, global) launched a new generation of inverter driven air-cooled and water-cooled screw chiller series with refrigerant R-1234ze in Feb. 2018[31]. They noted the future availability of models as follows:

- *The Air-cooled chiller range (TZ series) will be available from 130 kW up to 830 kW cooling capacity.*
- *The Water-cooled chiller range (VZ series) will be available from 340 kW up to 1600 kW cooling capacity.*

Moreover, the DZ chiller series would also be available on an "R-1234ze platform" as well as with the "R-134A platform"[32].

Refrigerant R-32

The above discussion indicates that, in a transition to low-GWP refrigerants, there are a number of refrigerants to choose from, depending on the application. We agree with the manufacturer Daikin in its assessment (Daikin, 2016, paragraph 2):

> *The main tenet of Daikin's policy is "diversity of refrigerants." And there is no ideal "one-size-fits-all" refrigerant solution for all applications, because many criteria need to be assessed such as the ODP and GWP value of the refrigerant and safety, energy consumption, availability, affordability, resource efficiency, recyclability, recoverability and total global warming impact of the equipment.*

To this effect, this particular company has suggested the following:

> *Daikin has identified R32 as a very beneficial refrigerant for single and multi-split type air conditioners and heat pumps based upon the above criteria. Daikin believes that the transition to R32 will help to meet both the HFC phase down schedule and the HCFC phase out schedule.*

As we have noted above (Table 3), R-32 is an HFC with a GWP of 675, much lower than other HFCs currently in use (R-134A: 1430; R-410A: 2088). Since 2012, Daikin and other manufacturers have commercialized RAC equipment using R-32 as refrigerant, as shown in

Figure 25. Daikin offers free access to patents for equipment using R-32 (Daikin, 2018B, slide 26).

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[30] FFAI-9CHEMJ_R5_EN.pdf available at https://www.schneider-electric.com/en/product-range-download/62213-aquaflair-df/#tabs-top.

[31] https://www.daikin-ce.com/en_us/press-releases/2018/new_chiller_ranges_R-1234ze.html

[32] https://www.daikin.eu/en_us/product-group/chillers/dz-chiller.html

Figure 25. Equipment manufacturers using R-32 as refrigerant in split-system A/Cs and associated infrastructure
Source: Daikin, 2018B, slide 18

The importance of R-32 as an intermediate refrigerant has also been formalized in policies defined by Colombia, and included in the NAMA for air conditioning (designed by MGM Innova). A number of activities within the NAMA indicate a refrigerant GWP cut off value of 1000. A GWP of below 1000 includes R-32 (GWP 675) as well as all natural refrigerants. The following NAMA activities would be directly affected by the condition on refrigerant GWP:

- A pilot project at the Universidad Nacional de Colombia (Medellín) to replace mini-split A/Cs using R-410A and R-22, with energy efficient mini-splits using R-32 as refrigerant.
- The introduction of standards so that public buildings acquire efficient air conditioners, using a refrigerant with GWP < 1000.
- Restriction of the sale of air conditioners that are less efficient or have refrigerants with GWP > 1000

2.3. Refrigerant recovery and treatment

Chile

In 2014, the Environment Ministry of Chile compiled the experience with refrigerant recovery, recycling in a number of LAC countries as well as the USA in order to design its national program (MMA, 2014). Since then, Chile has started a program of its own[33].

Colombia

[33] http://regenerchile.cl/

Decree 1076 (2015) compiles previous laws and decrees related to post-consumer treatment of hazardous wastes (MADS, 2017). The *Red Verde* (Green Network) program, started in 2014, deals with the recycling of electric appliances, including refrigerants and foam-blowing agents. However, the program has had limited success, with only 8609 items recovered so far[34].

Mexico

Mexico has 14 Refrigerant Recycling Centers (Centros de Reciclado de Refrigerantes, CRR) in various States of the country, operating since 2008, as shown in Figure 26.

Figure 26. Refrigerant Recycling Centers (Centros de Reciclado de Refrigerantes, CRR)
Source: adapted from https://www.andira.org.mx/2017/01/02/red-nacional-de-centros-de-reciclaje-2/

It is our conclusion that, except for Mexico, refrigerant recycling is far from its potential in LAC and, as a result, large quantities of ODSs and GHGs are being released to the atmosphere.

[34] http://www.redverde.co/index.php, consulted 22 September 2019.

3. Alternatives to vapor compression systems

3.1. Evaporative cooling

Evaporative cooling reduces temperature by the evaporation of a liquid, which removes latent heat from a surface where evaporation takes place. For practical purposes, an evaporative cooler cools air by the evaporation of water. Water absorbs a relatively large amount of latent heat as it evaporates: 2,260 kJ/kg. There is no mechanical energy input as in vapor compression refrigeration nor is any heat source needed as in absorption refrigeration. In the simplest systems, a direct evaporative cooler, (outside) air passes through a wet media, gaining moisture and falling in temperature in the process (Figure 27). In an indirect evaporative cooler, there is a heat exchanger to transfer the cold to the supply air. There are also passive systems, where a building element, such as the roof, contains water that is exposed to the air at night. This process of roof ponds with movable insulation was first applied by Hay and Yellott (1969), and was called Sky-therm cooling[35].

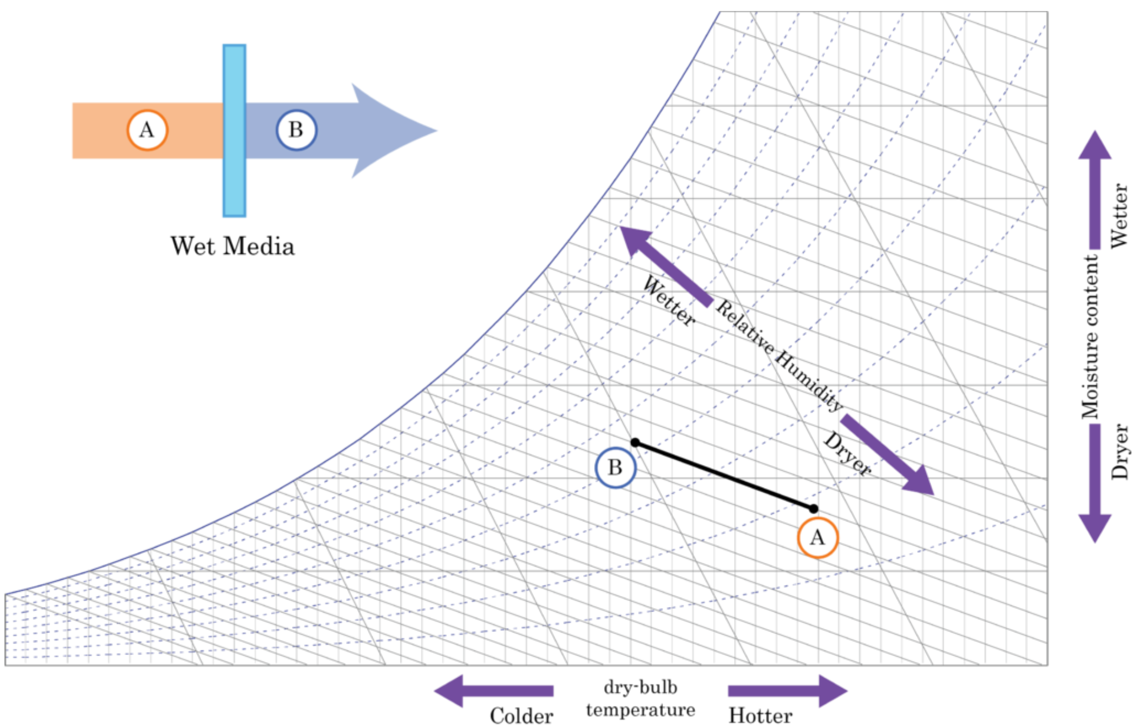

Figure 27. Schematic psychrometric chart showing the operation of a direct evaporative cooler. Hot and dry air (condition A) passes through wet media and reaches condition B, with lower dry-bulb temperature, but higher relative humidity.

Source: Hootman, 2013

[35] Movable insulation is not practical for larger buildings and the design of an enclosed, water-filled roof, that depended on night-sky radiation cooling was explored by Prasad et al. (1979).

For evaporative cooling to work, the ambient air needs to be fairly dry. Hence, evaporative coolers are also called desert coolers. In extremely dry climates, evaporative cooling adds moisture to indoor air, improving comfort. Figure 28 shows a world map of Köppen climate classification, indicating areas suitable for evaporative cooling in red. Within the LAC region, this includes northern and Western Mexico, some parts of the Pacific coast of Central and South America, and Western Argentina.

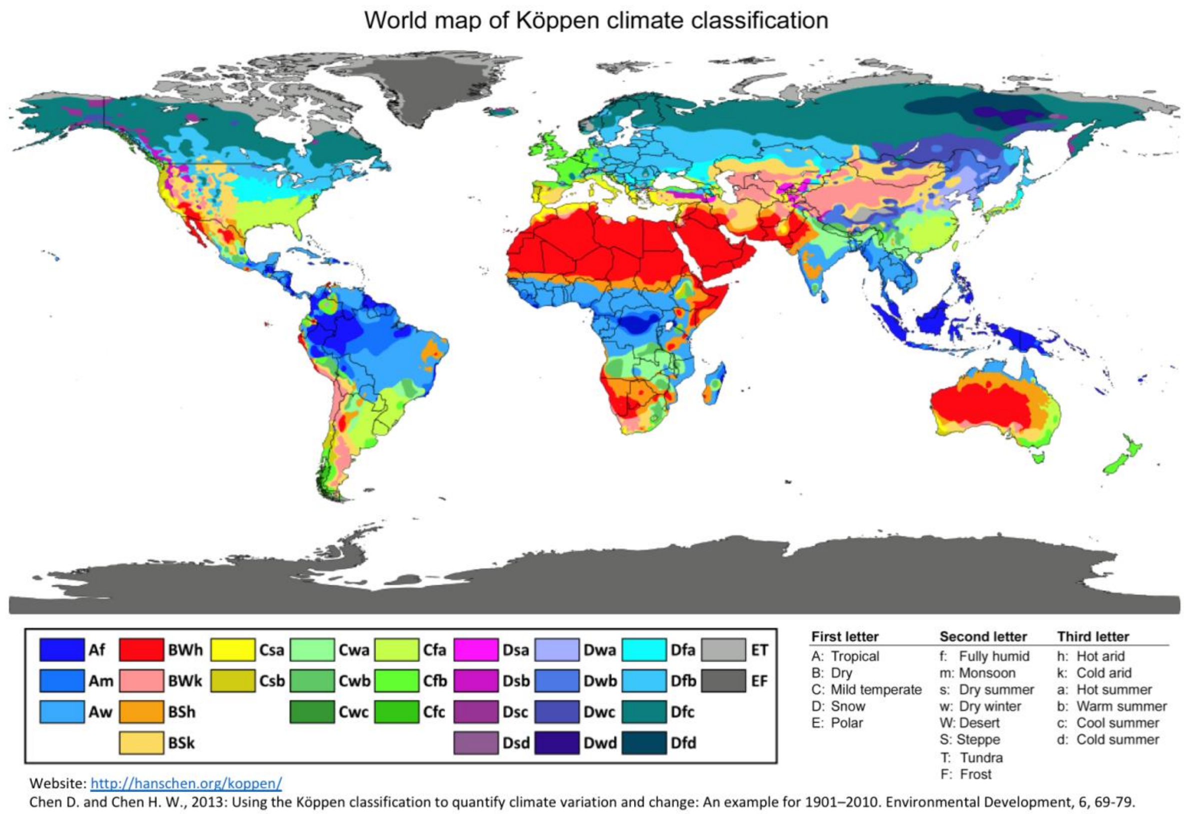

Figure 28. World map of Köppen climate classification. Evaporative cooling is most effective in Dry hot locations, specifically BWh, shown in red in the map.
(Source: http://hanschen.org/koppen/, as cited in https://d-lab.mit.edu/research/food/post-harvest-storage-processing/evaporative-cooling-weather)

Figure 28 shows a highly aggregated map. However, considering large local variations in climate as well as large variations in altitude, especially along the Pacific coast of LAC, more local studies are needed. One such study found that evaporative cooling was practical for residential, commercial and public buildings and even for data centers in Colombia, above an altitude of 1400 m (Air Caribe, 2018). Given the number of cities at altitudes above this level, the study noted a potential for this technology in Colombia.

One obvious limitation of evaporative cooling is clear from a look at the map in Figure 28: regions where evaporative cooling would work are likely to be short of water. In coastal desert regions (e.g. Baja California as well as coastal areas of the interior of the Gulf of California and the Pacific Coast of Mexico in general), seawater desalination provides a source of fresh water. However, the most common process for desalination is by reverse osmosis, which is very electricity intensive. The electricity consumption for desalination of water lost from an evaporative cooling process needs to be taken into account.

In recent years, there have been a number of studies on hybrid systems for evaporative cooling and desalination. Many of these involve solar energy. We do not believe that these processes have reached a commercial scale. However, given the large areas along the Pacific Coast of LAC as well as in Caribbean islands, they are worth detailed review in the future. Kabeel et al. (2018) present the results of hybrid system of indirect evaporative air cooler and humidification-dehumidification desalination system assisted by solar energy for remote areas. Byrne et al. (2015) note that separate cooling and desalination processes are energy intensive. They provide an extensive review of coupled cooling, desalination and solar photovoltaic systems, showing that such coupled systems lead to energy and environmental benefits.

One technology for overcoming the limitation of water shortage and reduce water demand, as well as to extend evaporative cooling to humid climates is Desiccant Enhanced Evaporative Air Conditioning (DEVap), developed by the US National Renewable Energy Laboratory (NREL). According to NREL (2010), this process has the potential to reduce energy use by 50 to 90% compared to the most efficient units available. It uses membranes, evaporative cooling and liquid desiccants. Since the desiccant removes moisture from the air, this kind of evaporative cooling would also work in humid climates. The process uses salt solutions, so no refrigerants are involved.

Figure 29 shows how the "*DEVap cooling core uses water and liquid desiccant to draw in outside air, exhaust some of that air and return cool, dry air to the area being cooled. DEVap's integrated evaporative component and its desiccant drying process offer improved dehumidification and, thus lower costs and much lower energy usage*"[36].

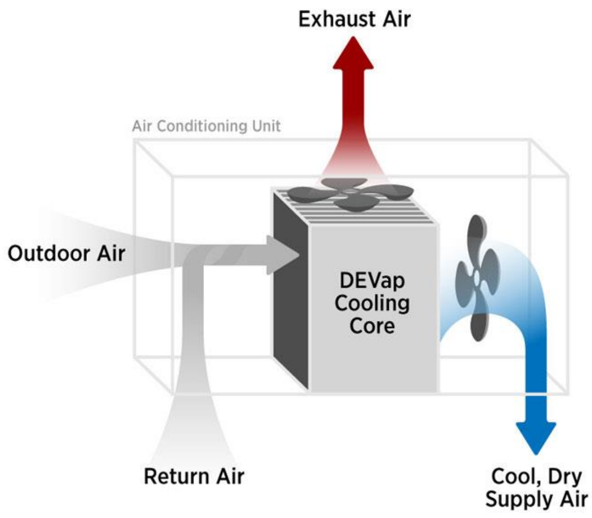

Figure 29. Desiccant-Enhanced eVaporative air conditioner (DEVap)
Source: US National Renewable Energy Laboratory (NREL), 2010.

[36] https://www.nrel.gov/news/features/2010/1531.html

More details can be found in Kozubal et al. (2011). However, as far as we can tell, this technology is not commercially available.

3.2. Absorption refrigeration systems

An absorption refrigeration system, as in the case of evaporating cooling, does not depend on refrigerant (vapor) compression. The absorption cooling system is a heat-activated cooling system that uses absorption of a solution. The difference between the vapor compression system and an absorption cooling system can be seen in Figure 30.

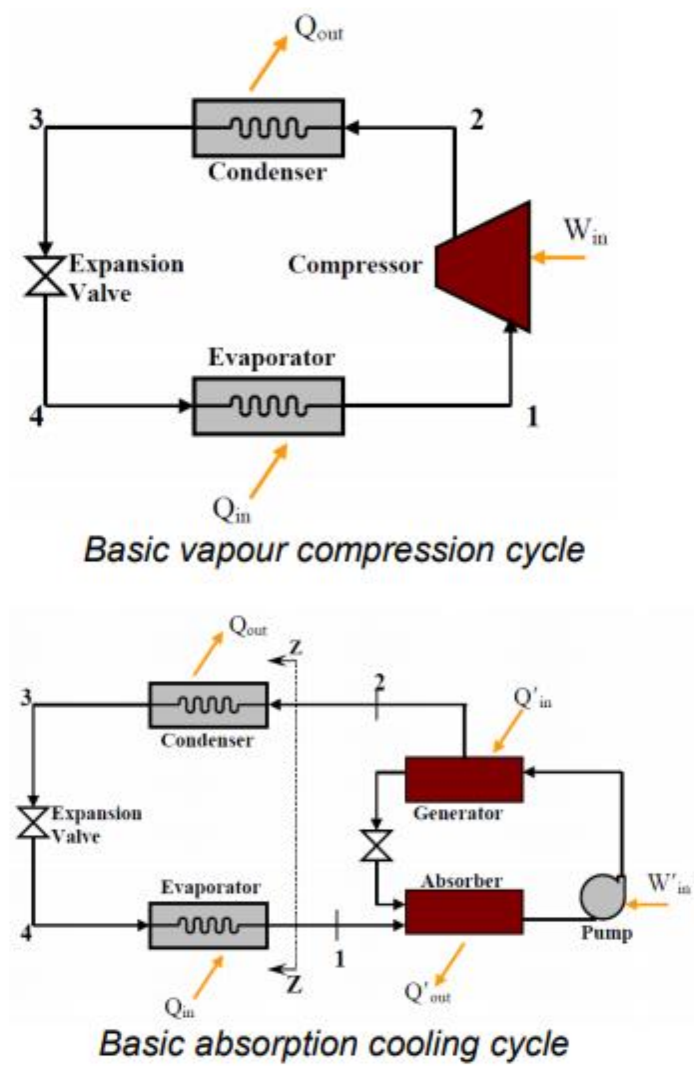

Figure 30. Basic vapor compression cycle (top) and a basic absorption cooling cycle (bottom)
(Source: CIBSE, 2012)

Vapor compression systems depend on electrically powered compressors, while absorption cooling uses a source of heat to produce cold. Basic absorption cooling systems need no electricity at all, while more complex systems require electricity for pumping (as shown in Figure 30 bottom). As explained by CIBSE (2012): *instead of compressing refrigerant* *vapor, the absorption cycle dissolves this vapor in a liquid (called the absorbent), pumps the solution to a higher pressure (with much less work input than required by a compressor) and then uses heat input to evaporate the refrigerant vapor out of the solution.*

Common absorption cooling systems use lithium bromide (LiBr), while others use ammonia and water.

Broad USA is a manufacturer of absorption chillers using lithium bromide. The company offers a wide range of products, including gas fired, steam driven, exhaust driven, and hot water driven. Some systems use multiple heat sources, e.g. gas as well as exhaust. There are also solar powered absorption chillers[37]. Case studies include hotels, schools/universities, and hospitals[38].

Ammonia an also be used in *absorption* refrigeration systems. Wu et al. (2017) provide an excellent overview, whose abstract is copied below:

> *The use of ammonia-based working fluids for absorption prevails in a wide range of applications due to the low freezing temperature of the refrigerant and the absence of crystallization as well as the lack of problems under vacuum conditions. This paper presents a comprehensive overview on the use of ammonia-based absorption chillers and heat pumps. The thermodynamic and physical properties of pure ammonia and binary and ternary ammonia mixtures are presented in correlation formulas. Developments and applications in subfreezing refrigeration, heating/domestic hot water, renewable energy utilization, waste heat recovery, thermal energy storage and miniaturization of absorption systems are presented and summarized. In subfreezing refrigeration, the evaporation temperatures for single-stage absorption lie mainly between −30 C and −5 C, and they can reach as low as −70 C in advanced absorption systems. Air-source and ground-source absorption heat pumps are suggested for heating/domestic hot water applications in cold regions. For renewable energy uses, ammonia-based solar absorption applications with various working fluids are quite popular, whereas geothermal and biomass energy systems are less studied. In thermal energy storage, ammonia-based working fluids are not advantageous for storage capacity or cycle efficiency, but they prevail for subfreezing energy storage. Additionally, ammonia-based fluids are also attractive options for the miniaturization of absorption systems due to the absence of crystallization.*

An example of ammonia and water as refrigerants for an air conditioning system based on absorption is the EPM District Cooling project, discussed later in this review.

Xu and Wang (2016) provide an excellent review of solar powered absorption cooling systems. The abstract of the paper is copied below:

> *The absorption cooling system is a heat-activated cooling system based on a solution absorption process. It is a good choice for solar cooling. Various kinds of absorption cooling systems are available for various working conditions. In this chapter, the fundamentals of absorption cooling technology are introduced, including the working principle and working pairs. These are followed by an introduction to various absorption cooling systems. These systems are categorized by coupled solar collectors, thermodynamic cycles, and working*

[37] Source: https://www.broadusa.net/en/products-line/

[38] https://www.broadusa.net/en/case-studies/

pairs. Five low-temperature solar power-driven systems and five medium-temperature solar power-driven systems are introduced. Four other kinds of absorption cooling systems designed specifically for solar cooling are also introduced. The schematics, parameters, and solar-powered cases of these absorption cooling systems are presented. This information presents sufficient choices for solar-powered absorption cooling systems.

The design of solar powered absorption air conditioning system is described below, with details in Appendix G. The case study refers to a building of the Universidad Pontificia Bolivariana (UPB) in Medellín, Colombia. The building (Rectory in "Bloque 3") was previously cooled by a 50 TR chiller using R-22 as refrigerant[39]. The chiller was moved to another building and replaced by mini-split A/Cs, room air conditioners using R-22 or R-410A (with an average EER estimated to be 2.3, or 1.5 kW/TR), and a chiller with a total cooling capacity of 108.4 TR.

The new solar powered absorption cooling system has a design cooling capacity of 165 TR, intended to provide air conditioning to all needed parts of the building. The system comprises the following main components:

- *Absorption chiller*. The absorption unit has a cooling capacity of 580 kW (165 TR), with a design hot water flow rate of 67.5 m^3/h, with hot water entry/exit temperatures of 95 C/85 C, providing chilled water at entry/ exit temperatures of 12 C/ 7 C. Electric power input is 1.5 kW.
- *Cooling tower*. Nominal water flow rate of 101 liters /min with entry/exit temperatures of 35.8 C / 31.8 C.
- *Solar collectors*. Evacuated tube collectors would be installed on the building roof.
- *Hot and cold water tanks* Each tank has a capacity of 1000 liters.
- *Auxiliary heater.* Gas-fired heater with an input power of 40 kW.
- *Water pump.* Two pumps would be installed in parallel, so that their use could be alternated, as well as to provide redundancy. Each pump will have a design flow rate of 167 liters/min.
- The air handling system and ducts of the previous central chiller will continue to be used.

3.3. Sea water air conditioning

The temperature at the sea bottom is low, and pumping sea water can provide a source of air conditioning in islands and other coastal areas.

There are basically two types of sea water air conditioning (SWAC) systems, "pure" and hybrid" as summarized in a report by the Latin American Development Bank (CAF, 2015a):

"In "pure" SWAC, the intake pipe must acquire water cold enough to supply all cooling customers with adequately cold chilled water after all heat gains in pipes have been accounted for. In hybrid SWAC, seawater that is warmer than required is obtained. This results in chilled water coming out of the heat exchanger that is too warm to meet cooling

[39] Carrier Model 30GT-050-510KA

customer temperature requirements. An auxiliary chiller downstream of the heat exchanger is used to drop the chilled water to the required temperature. In doing so, the chiller is absorbing some of the cooling load coming from the distribution system."

Figure 31 shows a schematic of pure SWAC, and Figure 32 shows a schematic of hybrid SWAC.

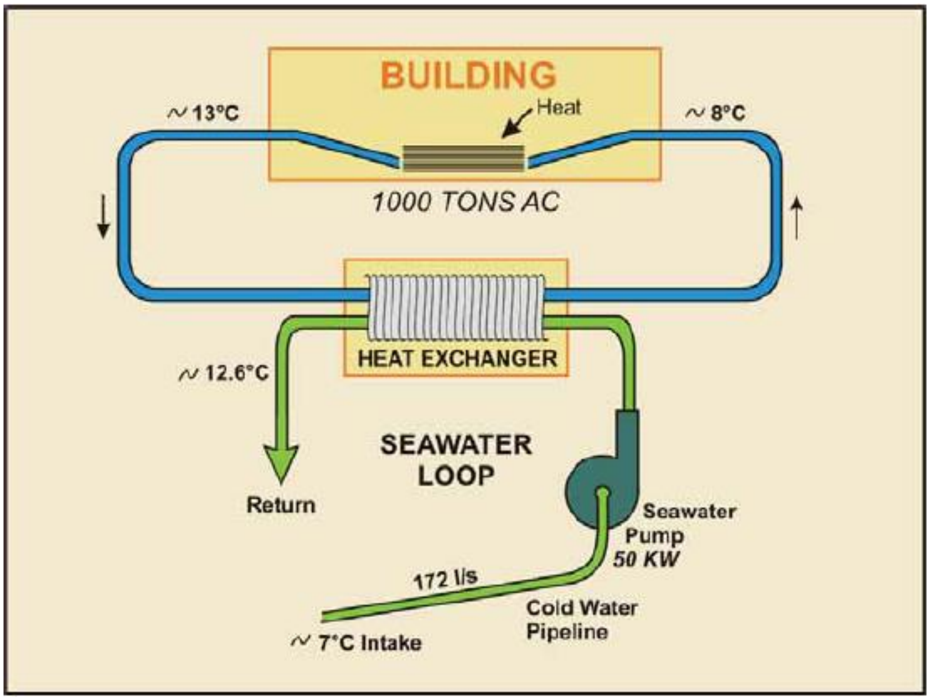

Figure 31. Schematic of pure sea water air conditioning system

Source: CAF, 2015a, Figure 5.3, from Makai (2004)

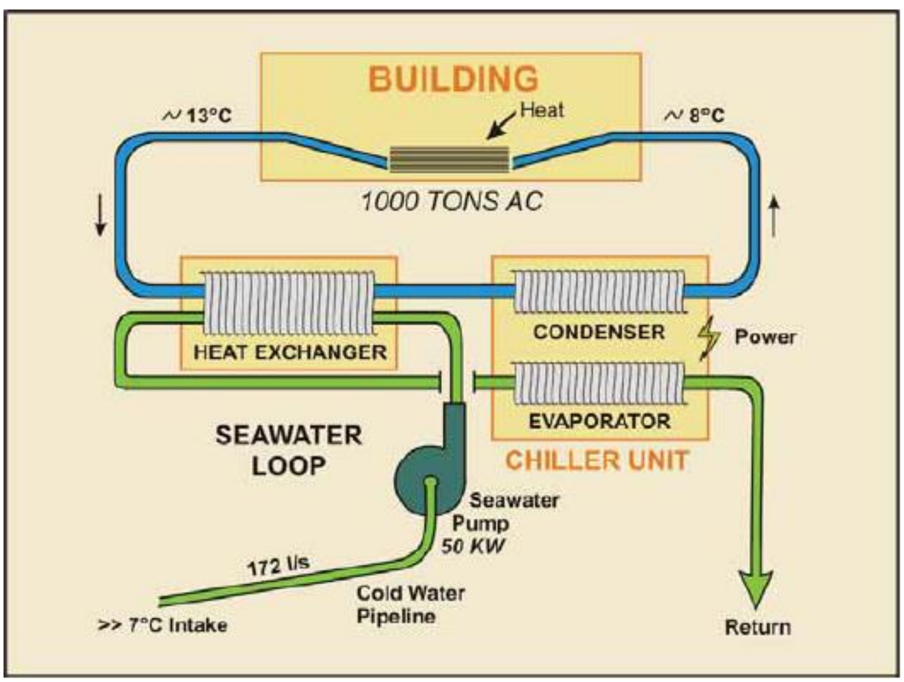

Figure 32. Schematic of a hybrid sea water air conditioning system
Source: CAF, 2015a, Figure 5.4, from Makai (2004)

In the pure SWAC system, water is the refrigerant so that there is no ODS nor high-GWP refrigerant involved. In the hybrid system, the auxiliary chiller would include a refrigerant, and the design of this chiller should require consideration of both efficiency and refrigerant GWP.

Figure 33 shows a global map of potential locations where sea water air conditioning (SWAC) may be feasible. The figure has been published by a SWAC technology provider[40], and is therefore generous. It shows all the coastal areas of Latin America and all of the Caribbean to be potential SWAC locations.

Figure 33. Potential locations for the application of Sea water air conditioning includes coastal areas of Latin America and all of the Caribbean.
Source: https://www.bardotocean.com/collections/all

Capital costs of SWAC systems are high, with low operating cost, so that ideal locations where year-round average temperature is high (e.g. 28 C), "in the inter-tropical regions and where seafloor bathymetry allows a reasonably short cold seawater intake pipeline" (Hunt et al., 2019).

To narrow the geographical focus, the Latin American Development Bank evaluated eight sites in four islands, see
Figure 34 (CAF, 2017).

[40] Bardot Ocean. https://www.bardotocean.com/pages/otec-ocean-thermal-energy-conversion-by-bardot-group.

Figure 34. Eight locations on four Caribbean islands evaluated by CAF in 2014
Source: CAF, 2017, slide 17.

The initial CAF evaluation reached the following conclusions:

- French Islands: small loads, large distribution system, low electricity rates
- Kingston and Santo Domingo: complex onshore network, long offshore pipes
- Montego Bay, Jamaica and Puerto Plata, Dominican Republic: selected for further analysis

Subsequently, the Latin American Development Bank conducted a pre-feasibility study of deep seawater air conditioning systems at Montego Bay, Jamaica and Puerto Plata in the Dominican Republic (CAF, 2015a). Both cases studied considered district cooling systems, i.e. the same network cooling several buildings. Their main conclusions were the following (CAF, 2017, slide 26):

- Both Puerto Plata and Montego Bay are excellent candidates for SWAC development
- Other Caribbean sites may also be good candidates if economic conditions are right
- Developers need to work closely with local stakeholders to be successful
- Next step: hi-resolution seafloor survey to support more detailed SWAC design.

Meanwhile, one technology provider (Makai Ocean Engineering) has already installed SWAC systems at several Caribbean locations: Curacao, Netherlands Antilles and Nassau, Bahamas, besides installations in Hawaii, and Reunion Island in the Indian Ocean[41]. Another technology provider is Bardot Ocean[42].

[41] https://www.makai.com/sea-water-air-conditioning/, accessed 22 July 2019
[42] https://www.bardotocean.com/pages/otec-ocean-thermal-energy-conversion-by-bardot-group

Devis Morales et al. (2014) studied Colombia's ocean thermal resources mainly with a view to electricity generation based on Ocean Thermal Energy Conversion (OTEC). However, the ocean temperature measurements are also useful to quantify the potential for seawater air conditioning in San Andres island and coastal areas of Colombia. One Brazilian study considers cooling off-shore oil platforms, which is a rather limited application (Miranda, 2008).

Arias Gaviria et al. (2018) modeled the potential of sea water air conditioning in the Caribbean, using Jamaica as an example with the most important potential. They noted that the start of SWAC is limited by a threshold, i.e. investing in a system that is cost effective without a guarantee that the number of buildings needed to join the system would agree to be connected to the system.

The most recent technical and economic evaluation of SWAC has been conducted by Hunt, Byers and Santos Sánchez (2019). They considered existing installations as well as those proposed by CAF and others for Latin America and the Caribbean. They conclude that (Hunt et al., 2019):

> *SWAC has large potential in intertropical ocean temperatures regions, especially in small tropical islands with high electricity costs and with a favorable seafloor bathymetry that allows the cold seawater inlet pipeline to be reasonably short. The world potential for SWAC presented in this paper focuses on four main aspects, the pipeline length, the estimated capacity factor of the SWAC project, the depth to reach seawater at 5 C and the cost estimates. According to Figs 12 and 13* [of source paper], *possible viable locations for the construction of SWAC projects, with a cost lower than $0.04 kWht, are the* ***intertropical islands in the Caribbean****, Pacific and Indian Oceans, and Fernando de Noronha, Sao Tome and Principe in the Atlantic Ocean. Hawaii's potential is limited to few locations due to the low SWAC capacity factor. The continental and medium sizes islands potential for SWAC can be seen in the* ***West Coast of Mexico, Colombia, Northeast of Brazil****, Togo, Yemen, Madagascar, Sri Lanka, Indonesia, Philippines and Papua New Guinea.* (Emphasis added)

Extracts of the Hunt et al.'s two figures (noted above), limited to the Latin America and Caribbean are presented as Figure 35 and Figure 36 below.

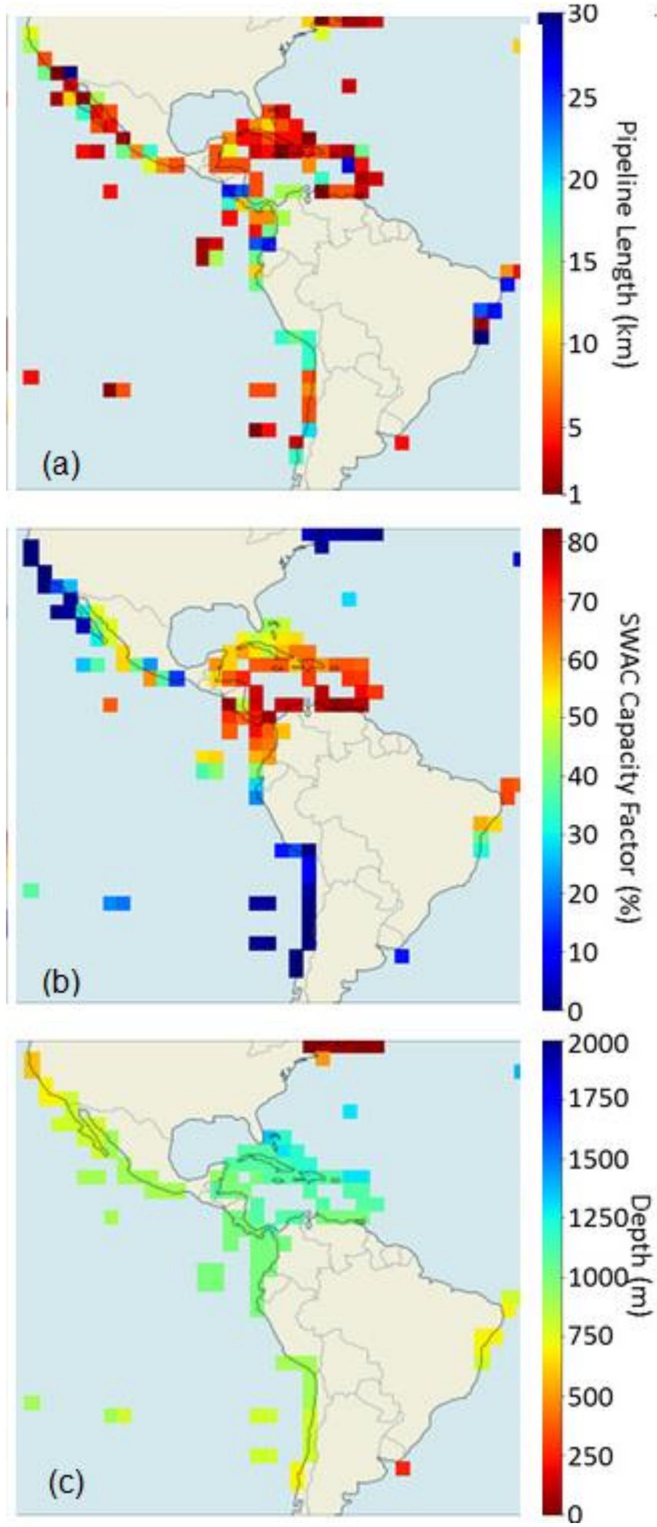

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Figure 35. Maps of SWAC in LAC represented by the (a) length of the pipeline, (b) capacity factor and (c) depth where the seawater is extracted.

Source: Extracted from Hunt, Byers and Santos Sánchez, 2019, Figure 12.

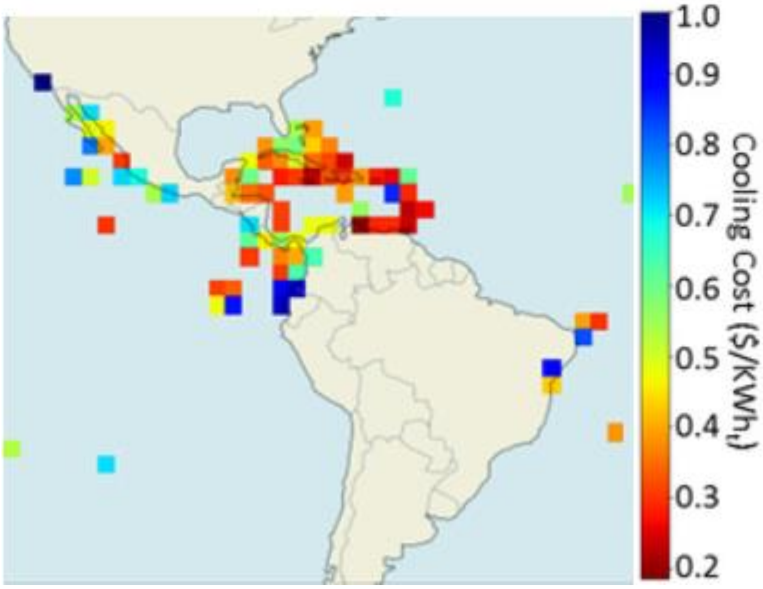

Figure 36. Potential SWAC projects in LAC: cost estimate in dollars per kWh of cooling.
Source: Edited from Hunt, Byers and Santos Sánchez, 2019, Figure 13.

Figure 36 shows relatively low cooling cost at several locations in the Caribbean and the northern part of South America. However, there are large variations among locations that are close to each other, so that localized demand studies are required for project selection. Indeed, cooling demand locations, as determined by population density and the demand for cooling were not considered in the Hunt et al. (2019), and any feasibility study would need to consider specific demand centers.

3.4. Solid-state cooling

In the introductory section on refrigeration and air conditioning, we mentioned a category "Solid-state cooling". They do not require any refrigerants. So their GHG emissions depend on energy efficiency. As noted there, there are four types of solid-state cooling, briefly discussed below:

Thermoelectric cooling. This process is based on the Peltier effect, which has been known for a long time. It is not as energy efficient as conventional cooling technologies, so that their use is limited to specific applications where space is a premium, e.g. for cooling microprocessors. We do not expect this technology to be relevant for most cooling investments.

Magnetic refrigeration is based on the magnetocaloric principle, where certain materials change temperature when subjected to a changing magnetic field. It can be used to achieve extremely low temperatures. One company, Cooltech appears to offer a magnetic refrigeration system. However, the product may not be commercially available yet[43].

[43] http://www.cooltech-applications.com/our-solution.html

Thermoacoustic cooling. Thermoacoustic devices produce or absorb sound power, rather than the "shaft power" characteristic of rotating machinery. They may have no moving parts or have few, in which case they are not strictly solid-state devices. Garrett and Backhaus (2000) provided an extensive review of thermoacoustic devices. We do not believe that thermoacoustic cooling is commercially mature[44].

Thermoelastic cooling, also known as elastocaloric cooling uses martensite-austentite phase transition found in shape memory alloys. It is a recent invention by the University of Maryland. An overview can be found in Qian et al. (2015) with recent developments reported by Takeuchi (2017). A prototype was under construction. The technology is not commercial.

[44] Sound Energy BV, a Dutch company offers A/C with electroacoustic technology. However, installations are not currently known. One company Cooltech Applications offered magnetic refrigeration equipment in 2016, but do not have a working website. http://www.cooltech-applications.com/our-solution.html

4. Heating and air conditioning

Although this technology review focuses on clean cooling, there are strong links between heating and cooling, in the sense that some equipment used for space cooling can also help reduce emissions in space heating. Moreover, there are many situations where there is a demand for both heat and cold, and there are systems that can provide them simultaneously.

4.1. Air conditioners and heat pumps

In terms of thermodynamics, refrigerators and air conditioners, that move heat from a cold space to a warmer space, fall into a category of device called heat pumps. (This is in opposition to a *heat engine* that produces "work" in a thermodynamic sense taking heat from a source at a higher temperature and discharging it at a lower temperature).

One characteristic of heat pumps is that their performance is defined by a coefficient of performance (COP), rather than efficiency, since the value can be greater than one. The fact that the COP of a heat pump is higher than one means that it can be used for space or water heating, consuming less electricity than an electric resistance device, which is limited by an efficiency of one, or a fuel-based heating system whose efficiency is substantially below one.

According to the IEA, 90% of global heating demand in buildings could be met by heat pumps[45]. Of course, most of the demand for space heating is in the colder climates.

In the Southern part of South America, there is a seasonal demand for space heating and cooling. In these climates, considerable energy can be saved by the use of heat pumps that provide both space heating and space cooling. In fact the growth of mini-split air conditioning systems has been accompanied by a similar growth in mini-split systems that can be used for either space heating or space cooling. Moreover the heat-cool devices are only slightly more expensive than the cooling-only systems. For example, the most energy efficiency mini-split heat pumps available in Argentina had a COP of around 3.3 for both heating and cooling (see Appendix E). Thus, this equipment would use less than a third of electricity compared to electric resistance space heating. Typical gas space heaters have an efficiency of about 65%, so that energy savings are even larger. Although natural gas is less expensive than electricity on a per-energy-unit basis, the energy savings are so large that substantial cost savings are also possible. A study for residential space heating in Argentina showed a potential for net natural gas savings of 5,000 million m^3 and a GHG emissions reduction of 9 million tCO_2-eq., up to 2030, starting from a baseline of 2010 (Nicchi, Tanides and Lavoria, 2015). While the study did not consider refrigerant emission, it has already been emphasized that GHG emissions are dominated by energy use.

[45] IEA Webinar "Tracking clean energy progress". 13 June 2019.

The application of heat pumps for space heating and cooling is not limited to mini-split systems. Thus, heat pumps can provide heating and cooling in central systems in commercial and public buildings as well.

It is important to keep in mind that heat pumps are much more energy efficient, and their GHG emissions are lower than fuel-based heating anywhere, and especially in countries with lower emissions factor for electricity generation, which is the case in many LAC countries. Therefore, there are substantial GHG emissions reductions in the use of mini-split systems and heat pumps in general for space heating wherever such systems would be used for space cooling. In heat pump system selection for heating and cooling, the choice of refrigerants would be as important as for cooling-only equipment.

Heat pump water heaters (HPWH) are an alternative to conventional water heaters, saving large amounts of energy compared to fuel-powered water heaters, as well as of course electric resistance water heaters. For residential use, HPWH remain expensive in terms of the initial cost. However, for certain applications, such as pool heating, they are an excellent choice and are increasingly used, e.g. in Medellín. In these applications, heat pump water heaters are less capital intensive compared to solar water heaters, and do not require any significant amount of space.

Since there are few locations in LAC with a demand for space heating and cooling (e.g. the Southern Cone), annual variations in outdoor air temperature are generally small, especially in the inter-tropical regions. Thus, there is little potential for ground source heat pumps, also called geothermal heat pumps.

5. Lighting, air conditioning, and refrigeration

Lighting inside buildings adds heat, equivalent to its electricity consumption. Thus, lighting use adds to the building cooling load. The Sears Tower in Chicago, once the world's tallest building, was designed without any space heating system, since all space heating would be provided by the lighting energy used.

The last few decades have seen a revolution in energy efficient lighting. The emergence of compact fluorescent lamps in 1982 provided an alternative to traditional incandescent lamps, with later models providing around five times the luminous efficacy (lumen/W) and with lifetimes up to 15 times more. Electronic ballasts and high efficiency phosphors allowed fluorescent lamps to be more efficient, while improving color rendition compared to traditional fluorescent lamps. See, e.g. Dutt (1994) and Dutt (2002, revised 2005).

While light emitting diodes existed since the 1960s, their cost reduction over the years, and finally the invention of blue light LEDs allowed LEDs to be available in all colors. The blue LED invention was so important that their inventors were awarded the Nobel Prize in Physics in 2014[46]. Now LEDs are not only efficient but also can have very long life, making them suitable for all applications including commercial and public buildings. Thus an ESCO often includes energy efficient lighting together with energy efficiency improvements in air conditioning and refrigeration. Since energy service companies do not limit themselves to refrigeration and air conditioning, it is natural that lighting energy efficiency measures are included in the investment package.

It is important to note that energy efficiency improvements in lighting reduce building cooling load. For an energy savings in lighting of, say 1 kWh, there will be cooling electricity savings of 1/COP kWh, where "COP" is the coefficient of performance of the cooling system in use. [47]

It is also worth noting that many refrigeration equipment, e.g. beverage dispensers, or food display units, include lights within the enclosure. These lights add heat into the interior of the equipment, and increase their cooling load. Where this equipment does not always have high-efficiency lighting, typically LEDs, an ESCO should include such lighting wherever possible.

[46] https://www.nobelprize.org/prizes/physics/2014/press-release/

[47] Of course there would be a similar increase in space heating demand, where this is present. In most cases, the benefits of energy efficient lighting are large enough that they are cost effective at all climates, even where there is a substantial space heating demand. In any case, space-heating dominated climates are scarce in LAC.

6. Application-specific alternatives

Refrigeration and air conditioning system selection depends on the application. Below we consider the following categories:

- Building air conditioning
- District cooling
- Commercial refrigeration, including supermarkets, food and beverage storage, etc.

6.1. Building air conditioning

As commented early in this review, the World Bank identified four elements of sustainable cooling[48]. In a short video, the World Bank makes the following four recommendations:

1. Improve thermal efficiency of buildings
2. Improve urban planning and the use of green spaces in cities
3. Set temperature limits in buildings
4. Government policies to reduce cooling demand in buildings

Only the first item is potentially within the reach of an ESCO and is discussed below.

Building thermal envelope

Key to improving the thermal efficiency of buildings is the building thermal envelope. Energy consumption for building cooling (and heating) depends on the performance of the building thermal envelope.

IEA's Tracking Clean Energy Progress (https://www.iea.org/tcep/) identified a few technologies that were on track to meet climate goals. Specifically, the IEA "*included the most up-to-date information for where technologies are today and where they need to be according to the IEA's Sustainable Development Scenario, a pathway to reach the Paris Agreement well below 2°C climate goal, deliver universal energy access and significantly lower air pollution*." They further noted the following: "Some technologies have made tremendous progress in 2017 – particularly solar PV, LEDs and EVs – but most are not on track". In a table comparing the technologies, those with good progress were marked in green, others in yellow, while the remaining were in red. Buildings as a whole were considered "Not on track", while the categories, "Building envelopes", "Heating", and "Heat pumps" were marked in red, while "Cooling" and "Appliances and equipment" were marked in yellow (see Figure 37). In an earlier edition, there was an annotation next to "Cooling" as "one to watch". Therefore, before we review cooling technologies as those "to watch", we briefly comment on some issues that should not be forgotten while we move towards cleaner technologies for space cooling as well as for refrigeration, which would be within the IEA "Appliances and equipment" category.

[48] http://www.worldbank.org/en/news/feature/2019/05/23/four-things-you-should-know-about-sustainable-cooling

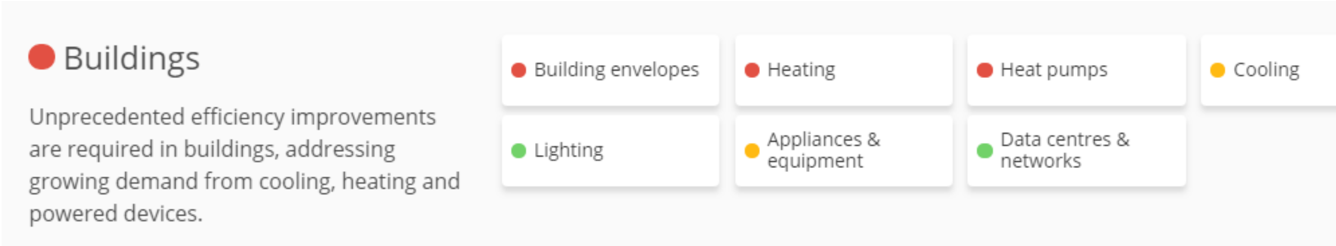

Figure 37. Tracking Clean Energy Progress: Buildings.
Source: International Energy Agency, https://www.iea.org/tcep/, accessed 28 May 2019

The International Energy Agency, in its Energy Technology Perspectives (IEA, 2017, most recent edition, as of 9/2019), noted that the building thermal envelope has not improved much, noting (IEA, 2017, p. 62):

> *"Global annual average building envelope energy intensity improvements of 1.4% have been achieved since 2010. Building envelope intensities need to improve by 30% by 2025 to keep pace with growth in floor area and the demand for greater comfort."*

To remedy this situation, the IEA recommends:

> *Global co-operation should seek to ensure that all countries implement and enforce building energy codes and standards for both new and existing buildings, with improvement in enforcement and verification of codes and standards to overcome barriers to their implementation.*

The thermal envelope of buildings can be improved to reduce both heating and cooling loads, correspondingly reducing energy needed for heating and cooling. Many countries have established Building Energy Performance Standards (BEPS) that set minimum efficiency levels or upper limits on specific energy use. Other countries have limited themselves to building energy consumption labels, informing potential buyers and renters of the energy consumption and associated expenses. Appendix A lists Building energy efficiency labels and standards in Latin America and the Caribbean. Mexico and Brazil are the LAC countries with the strongest requirements on building thermal performance, especially for commercial and public buildings, most relevant for MSEF and other ESCOs: Other countries with relevant requirements are Argentina, Colombia, and Costa Rica.

The IEA recommends a transition to Zero Carbon Buildings and Low-Carbon Communities, noting (IEA, 2017, p. 142).

> *Building envelope improvements and rapid deployment of energy efficiency measures across the global buildings sector are essential to meeting B2DS[49] objectives, but these alone are insufficient to achieve the energy transition to low-carbon buildings by 2060. The B2DS also requires a critical shift away from fossil fuels, moving beyond the measures prescribed in the 2DS (e.g. mandatory condensing boiler technology) to cut fossil fuel consumption in buildings by an additional 75% by 2060. This effectively means that nearly all coal and oil*

[49] This is the most ambitious (or optimistic) of IEA scenarios, which are: the Reference Technology Scenario (RTS) and the 2°C Scenario (2DS), and the Beyond 2°C Scenario (B2DS)

use in buildings would be eliminated over the next 40 years, while natural gas use in the B2DS would be reduced by an additional 70% compared with the 2DS in 2060.

In the same vein, the Global Alliance for Buildings and Construction (GABC, 2016) has concluded:

Energy use in buildings and for building construction represents more than one-third of global final energy consumption and contributes to nearly one-quarter of greenhouse gases (GHG) emissions worldwide. A growing population, as well as rapid growth in purchasing power in emerging economies and developing countries, means that energy demand in buildings could increase by 50% by 2050, while global building floor area is expected to double by 2050, driving energy demand and related GHG emissions for construction.

Green buildings

As defined by the World Green Building Council[50]:

A 'green' building is a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment. Green buildings preserve precious natural resources and improve our quality of life.

Green building considers many other aspects besides energy efficiency. There are Green Building Council chapters in most LAC countries, see list in Appendix A. Green Building Councils promote green buildings in different ways and provide voluntary certification of energy efficiency and other parameters of building sustainability. The best known one is Leadership in Energy and Environmental Design (LEED) developed by the US Green Building Council.

An ESCO generally does not have opportunity for improvements in building thermal envelopes, since the ESCO is either operating on an existing building or a new building that has already been designed and built according to prevailing norms and practices. A possible exception could be roof insulation, e.g. in flat-roof commercial buildings. Specifically, in Colombia, there is a plan to remove asbestos incorporated into roofing systems. The asbestos removal process may present an opportunity to add roof insulation at a relatively small marginal cost.

Cooling demand in LAC

The population density of LAC is generally low compared to Asia or Europe, except for Mexico, Central America and the Caribbean (see Figure 38). However, the population is largely urban, especially in the lower-density countries (see Figure 39). Another feature of the population distribution is that much of the population is located in areas (e.g. medium altitude locations in Mexico, and the Andean region) that have relatively low cooling load (see Figure 40). However, through a combination of urban heat islands and global

[50] https://www.worldgbc.org/

warming, the cooling demand is increasing. In its baseline scenario, IEA projects an increase in CDDs, 2016-2050 (see Figure 41).

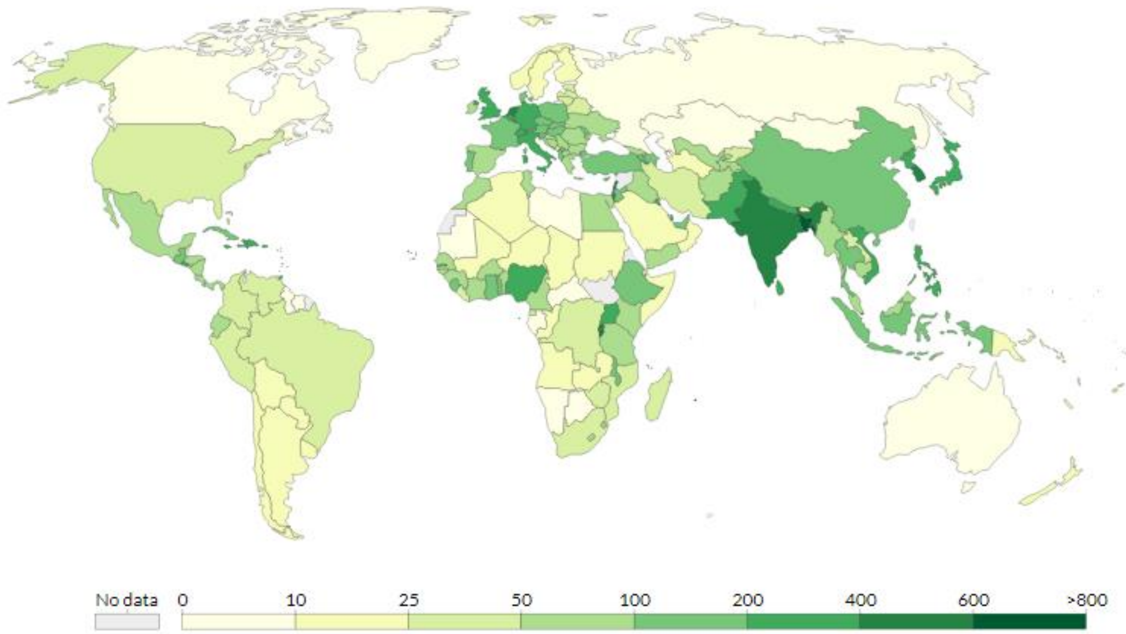

Figure 38. Population density, people per km², 2017:
Source: Compiled by *Our World in Data* from World Bank data. https://ourworldindata.org/world-population-cartogram

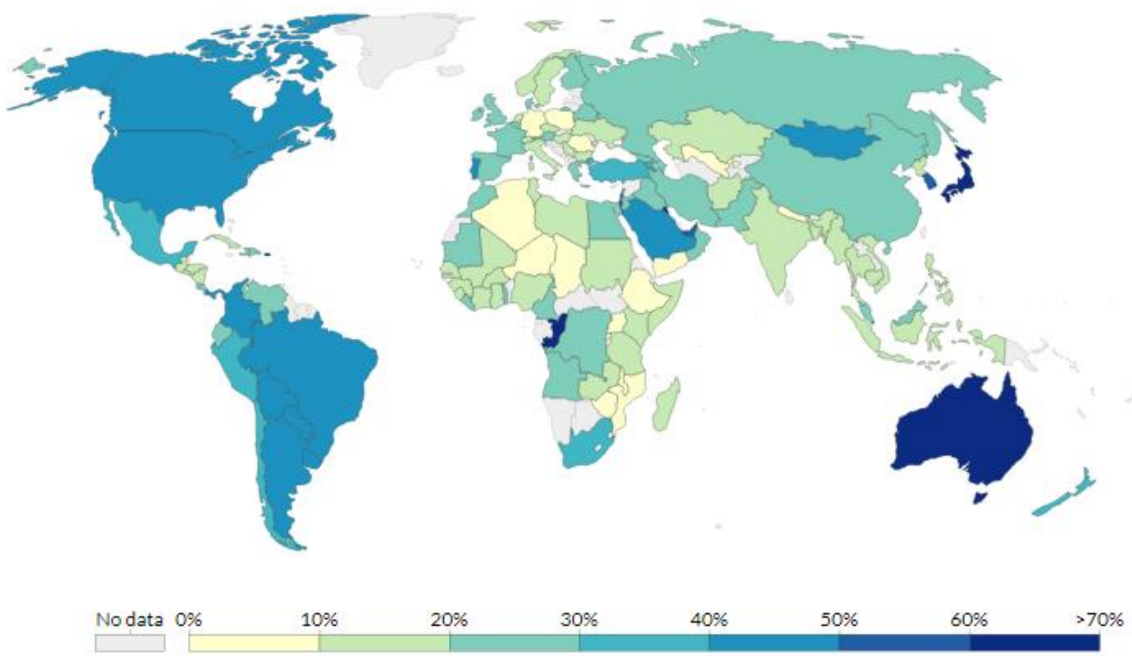

Figure 39. Share of the total population (%) who live in urban settings with a population of more than 1 million people, 2017.
Source: Compiled by *Our World in Data* from World Bank data. https://ourworldindata.org/urbanization

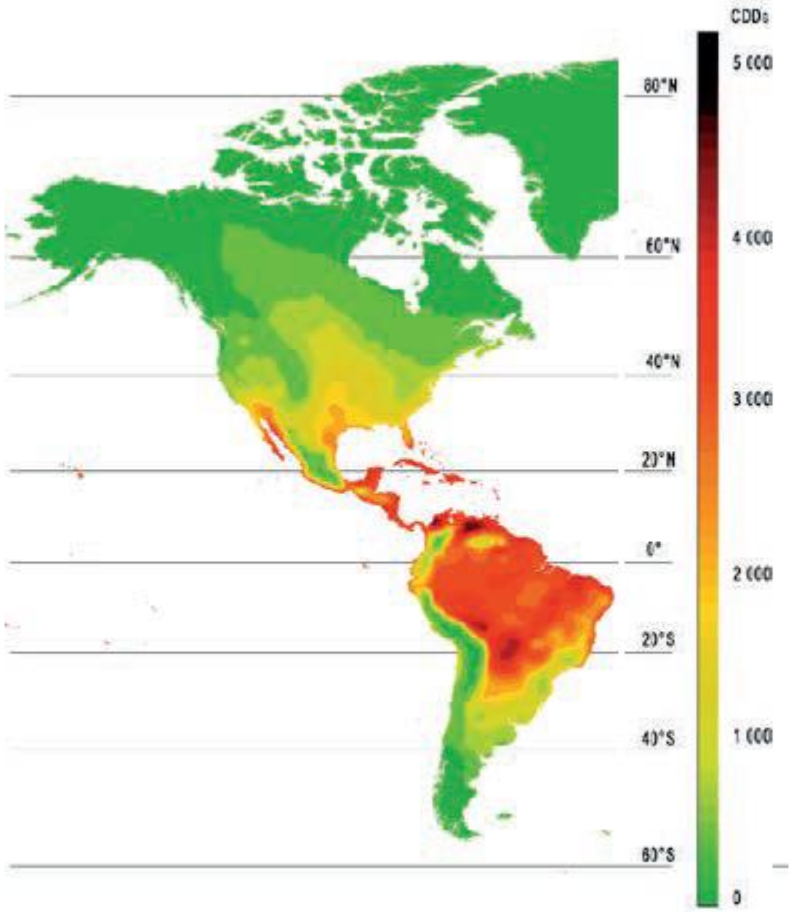

Figure 40. Cooling demand as determined by cooling degree days (CDD), base 18 C.
(Source: Americas region selected from IEA 2018, Map 2.1)

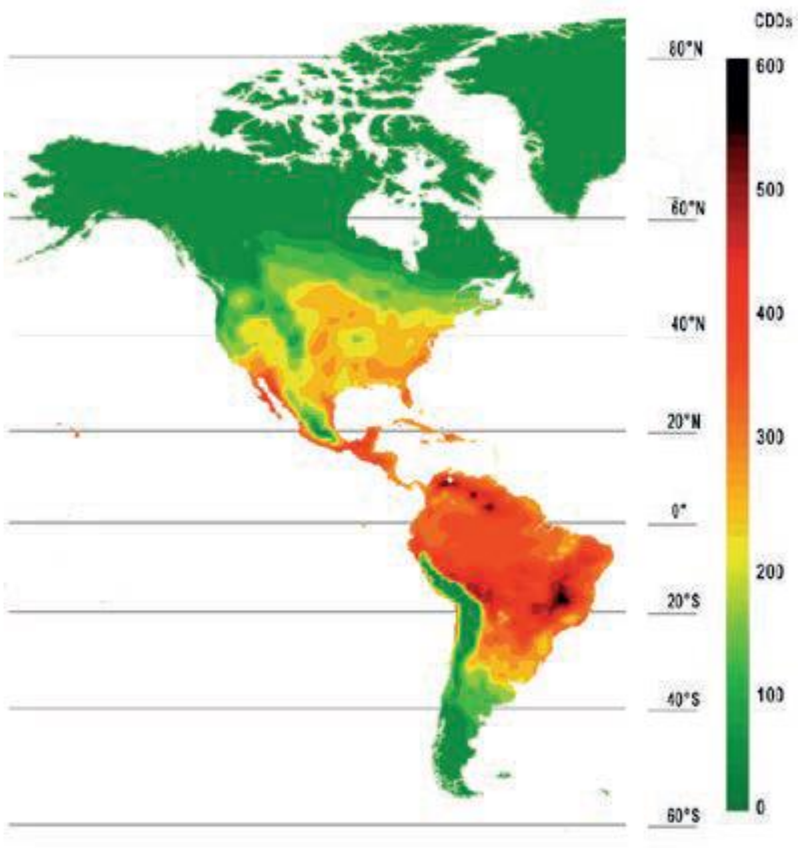

Figure 41. Increase in cooling degree days (CDDs) in the IEA Baseline Scenario relative to historical CDDs, 2016-50

Source: Americas region selected from IEA 2018, Map 2.2

The heat island effect means that urban areas are warmer than surrounding areas, as depicted in Figure 42. As noted by the Heat Island Group, Lawrence Berkeley National Laboratory[51]:

> *"On a sunny summer afternoon, urban air can be 1-3°C (2-5°F) warmer than nearby rural air. The elevated air temperatures associated with this summer "urban heat island" (UHI) make air conditioners work harder to keep buildings cool…"*

A part of the urban heat island is caused by heat generated in urban areas, and one of the heat sources is, in fact, air conditioning. Thus, as the demand for cooling increases, so will the heat island effect, in an undesirable positive feedback loop. There are ways of mitigating the heat island effect, e.g. through lighter color surfaces (pavements and roofs) that absorb less solar radiation. While an urban planning policy is beyond the scope of an ESCO, it can modify roof surface color at the time of installation and modifications to roof-top air conditioning equipment or at the time roof insulation is added, and such measures would reduce the cooling demand of the building in question, while making a minor contribution to the urban heat island effect.

[51] https://heatisland.lbl.gov/coolscience

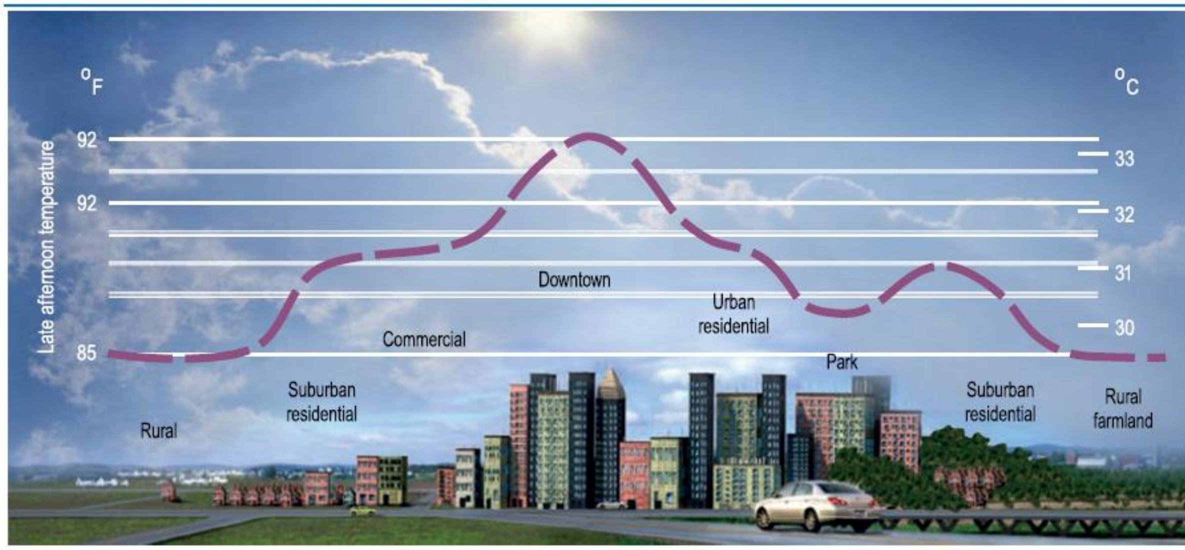

Figure 42. The urban heat island effect.
Source: IEA (2018, Fig. 2.2), citing LBNL (2013)

There are limited options for improvements in the thermal envelope of existing buildings. Moreover, buildings have long life. Therefore, most available options, especially from an ESCO perspective, are related to more efficient equipment, which are discussed below.

More efficient equipment

Below we consider the two main configurations for building air conditioning systems:
- Mini-split A/C systems
- Centralized A/C systems

Mini-split A/C systems

As noted in IEA (2018, p. 19):

> *Between 1990 and 2016, annual sales of ACs nearly quadrupled to 135 million units. The bulk of the units sold are packaged and split-system ACs for residential and smaller commercial buildings, though the typical size of commercial ACs, including chillers, and their associated energy use are generally much larger.*

In LAC countries, the sales and installations of mini-split A/C systems have increased considerably. For new installations, one can choose models that are energy efficient and, if possible, with a low-GWP refrigerant. In the lower lying tropical and equatorial regions of LAC, there is a year-round demand for cooling, which means that typical mini-split systems have a relatively short life, estimated to be only four years in Colombia (earlier MGM Innova study). Thus, remaining equipment life is not a major issue, and even for existing installations, equipment replacement with energy efficient, low GWP models can be a viable option.

An IEA review has shown that there is a large range in efficiency not only across countries, but also within countries, as shown in Figure 43. The comparison does not include any LAC countries. However, even energy-efficient countries such as South Korea show a large range in values. Figure 44 shows how A/C efficiency increased over time, with sharp increases in recent years. It is also noteworthy that the price of A/Cs fell compared to the general consumer price index (CPI) over the years, indicating that, historically, improved energy efficiency has not been accompanied by a corresponding increase in equipment price, a phenomenon that was noted early for US refrigerators (e.g. Meier, 1993; Sachs, 1994; as cited in Dutt, 1995) and other equipment in many countries.

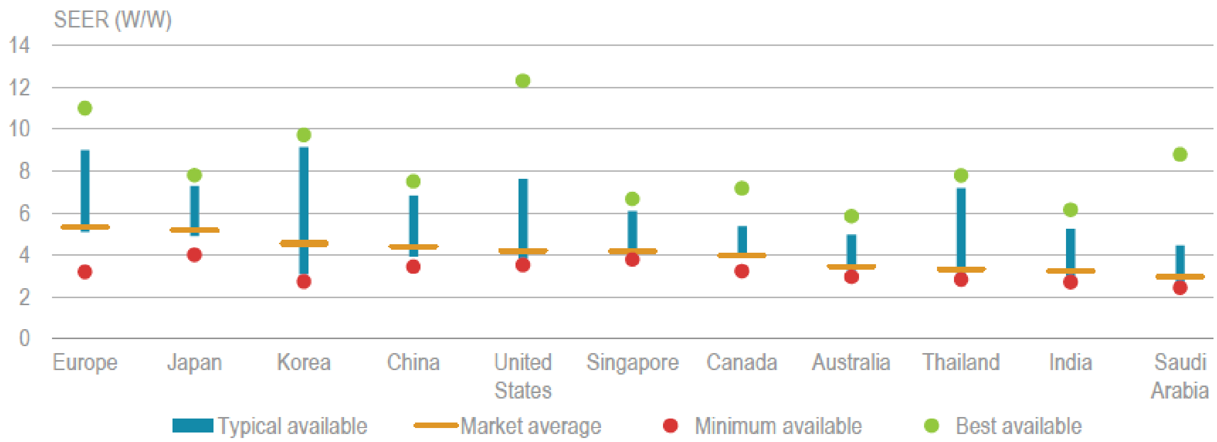

Figure 43. Seasonal energy efficiency ratios (SEERs) of available residential ACs in selected countries/regions, 2018

Source: IEA, 2018, Fig. 2.3.

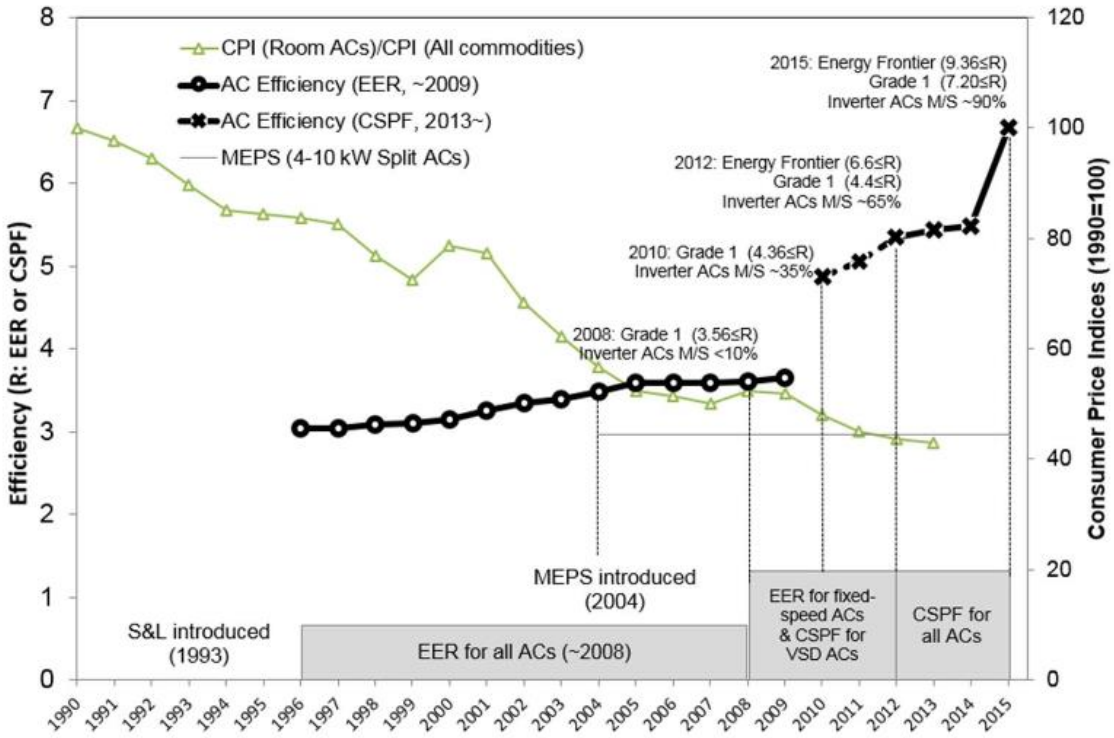

Figure 44. Trends in room AC efficiency and price indices in South Korea

Source: Abhyankar et al., 2017, Fig. 6.

The IEA (2018) report focuses on energy efficiency, notes the importance of refrigerants but does not provide any quantitative information on refrigerant use. Below we consider the availability of mini-split A/Cs in LAC, considering both energy efficiency and refrigerants.

In all the large LAC countries and many others, the efficiency of air conditioners has improved in recent years, because of labeling and minimum energy performance standards. Thus, for new installations, the values indicated in red in Figure 43 are too low. However, in replacement options the existing unit may be very inefficient, especially in milder climates where the cooling season is short, and equipment can be quite inefficient, with large potential for energy savings.

In LAC, mini-split A/Cs are manufactured by two Chinese companies (Midea and Gree) and later imported and sold under a variety of brand names, including their own. As far as we know, all models currently use R-410 A as refrigerant. Figure 45 shows how the efficiency of air conditioners has improved in recent years in Argentina, where a standards upgrade in 2019 requires a minimum efficiency class of A for cooling, and all models sold meet this requirement, with a COP of around 3.3. Wall and split system air conditioners sold in Brazil fall into efficiency classes A to D, according to a national standard, with models in the A class with COP around 3.3, while those in the D class around 2.8 (with a few around 2.66). Mexico has minimum efficiency performance standards for split air conditioners, with minimum seasonal EER from 3.28 to 3.37, depending on cooling capacity (SE-NOM-023-ENER, 2018).

Chile offers at least one model of A/C, a multi-split model, with an efficiency class A++ in cooling mode, with a COP of 7.2 (and class A+ in heating mode with a COP of 4.12)[52].

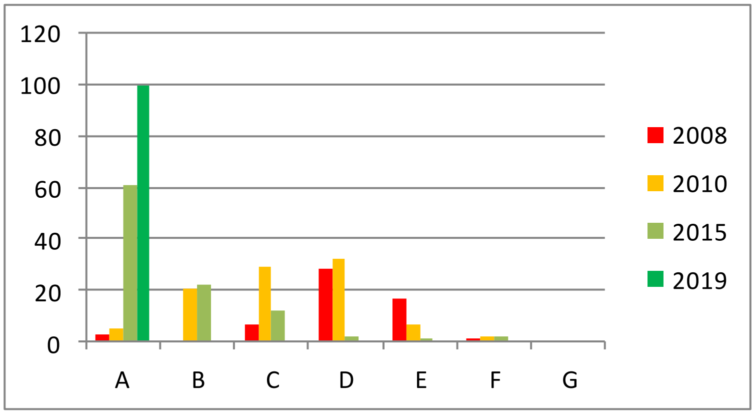

Figure 45. Argentina: Percent of mini-split A/C models in cooling mode, according to efficiency class, showing shift from 2008, before the labeling program was implemented, when models were estimated to be in the D and E classes, to the first year following labeling (2010) with most models C or D, to 2019, where all models are A.
(Source: Based on AES/CLASP, 2008, Fig. 16 and Tanides, 2017, slide 8, updated with current information)

Colombia has initiated the efficiency labeling process, and much higher levels of efficiency levels for each efficiency class A to E, see Appendix E. The average efficiency class for models commercialized in 2015 was in the Colombian D category, roughly equivalent to the B category in Argentina and Brazil.

One difficulty in the comparison of efficiency labels in LAC countries stems from the varying definitions applicable in different countries. Moreover, as IEA (2018, p. 46) has noted:

> *Most of the major cooling markets today have mandatory MEPS, although the required efficiency levels are typically far below those of the most efficient products available.*

While test protocols, e.g. outside temperature and humidity for testing are not uniform across countries, nor are the rating classes for labels similar to the EU label, a comparison of efficiencies of LAC A/Cs with
Figure 43 indicates that there is further room for improvement in energy efficiency. A look at the most efficient air conditioner models in the EU as listed in Top Ten, shows a large number of high efficiency models. For instance, at least 25 A+++ A/C models are available in Portugal, with seasonal COP (SCOP) of 5.1 to 5.9, and seasonal EER (SEER) of 8.5 to 10.5[53]. Moreover, most of the models (from Daikin and Mitsubishi Electric) use R-32 as refrigerant, while a few use R-410A.

Important observations for the LAC are that manufacturers generally do not offer (a) models with a lower GWP refrigerant such as R-32, nor (b) the most efficient models, e.g. those available in the EU.

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[52] https://top-ten.cl/aire-acondicionado/view?id=52
[53] https://topten.pt/private/products/aircon

A demonstration project involving the manufacturer Daikin and the Mexican Institute of Clean Electricity and Energy (Instituto Nacional de Electricidad y Energías Limpias, INEEL) comprised the replacement of conventional (on-off) mini-split systems using R-22 by inverter systems using R-32 refrigerant. Over a 30 day monitoring period, energy savings of 66% was recorded. The conventional system consumed 72 kWh while the R-32 inverter system consumed only 24 kWh (Daikin, 2018B, slide 29).

Daikin (2018B) indicated a number of other demonstration projects and other initiatives in progress in LAC (Daikin, 2018B, slides 32 to 37; MGM Innova, 2019):

- **Mexico**: replace conventional R-410A on-off system with inverter R-32 system in five cities: Tijuana, Monterrey, Guadalajara, Mexico City and Cancun;
- **Brazil**: as above, in three cities: São Paulo, Florianópolis, and Rio de Janeiro;
- **Colombia:** a large-scale replacement of conventional split systems with efficient, R-32 systems would be part of a NAMA developed by MGM Innova (2019). The Colombian government would provide a tax incentive to energy efficiency projects in air conditioning that use refrigerants with low GWP (<1000)

Centralized A/C systems

While room air conditioners were common in the past, and installations of mini-split systems have proliferated in recent years, an alternative is a central system where the cold is generated at a single location and distributed to each conditioned space as chilled water or cold air. Figure 2 showed different configurations for air conditioning systems including packaged window unit, mini-split unit, and various configurations of central A/C systems. Many centralized A/C systems are already installed, especially in commercial and public buildings. Figure 46 shows the comparative performance of all these systems as evaluated in Colombia, using the energy efficiency labeling system “RETIQ”.

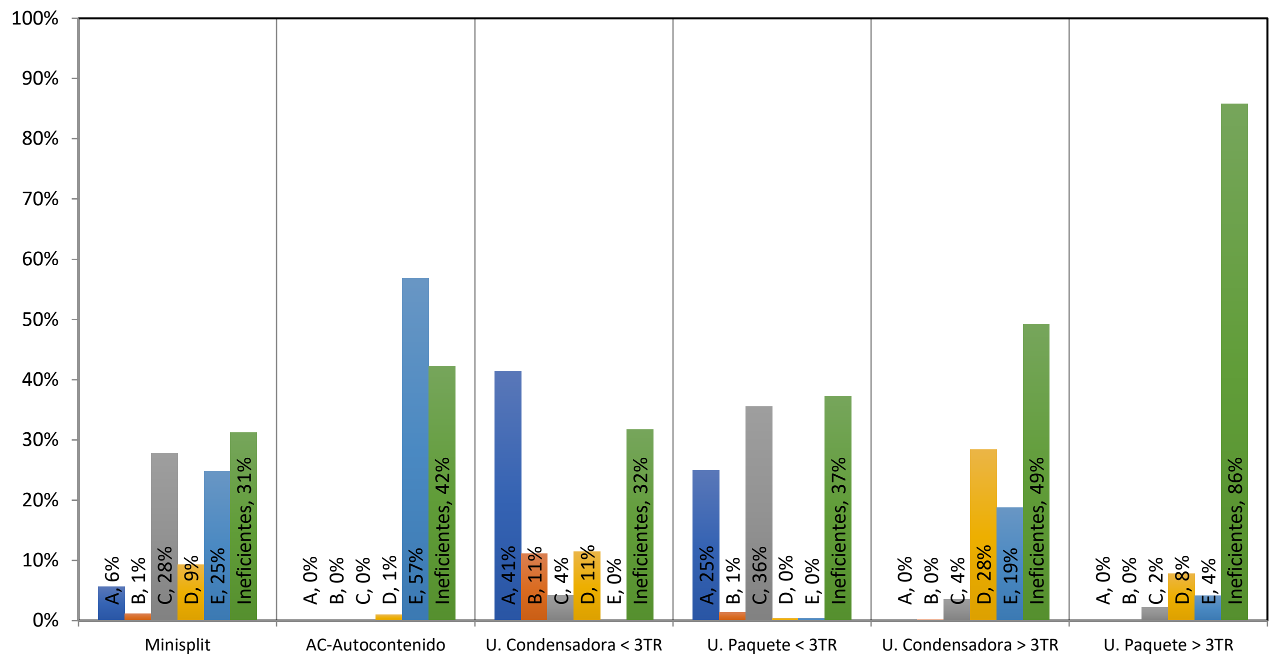

Figure 46. Efficiency of different types of air conditioning systems, including mini-split, room air conditioners and various configurations of central air conditioning systems.

Source: MGM Innova, 2019. Deliverable 1, based on Resolution 41012, 2015; UTO; MADS, 2017

In the previous section, we considered the one-to-one replacement of mini-split systems with more efficient models, preferably with lower-GWP refrigerants. An alternative to the one-to-one replacement of mini-split systems is their replacement with a central system. Moreover, Figure 46 shows, for Colombia, that many existing central A/C systems are also inefficient. Thus, there are many opportunities for energy efficiency improvement in central A/C systems, both as a replacement for mini-split A/C units, as well as replacement for existing central A/C systems. Each such system replacement would also allow a low-GWP refrigerant choice.

Besides equipment efficiency, advanced control systems permit energy savings. These are considered below.

Advanced control systems

Centralized building air conditioning systems provide an opportunity for energy savings through improved control systems, including:

- *Variable refrigerant flow (VRF) systems*. Also called variable refrigerant volume (VRV). VRF systems may be used to adjust total building cooling supply according to outside temperature. Variable refrigerant flows allow temperatures in each room to be controlled as required, thus conserving the individual control that is possible with mini-split systems that only cool one room. Either permits better regulation and energy savings. The VRF/VRV system was invented by Daikin in 1982, and "duplicated by many", according to the company[54]. Already by 2007, in Japan, VRFs were used in 50% of midsize office buildings (up to 6,500 m^2) and 33% of large commercial buildings (more than 6,500 m^2), according to (Goetzler, 2007). Hillphoenix conducted a 12-month study in a commercial building (a store), which was operated on alternate weeks in fixed and variable refrigerant flow modes. The results are illustrated below (Figure 47). As noted by Hillphoenix[55], "For the month, constant speed power consumption reached a high of nearly 3000 kWh but variable speed power consumption never exceeded 2600 kWh."

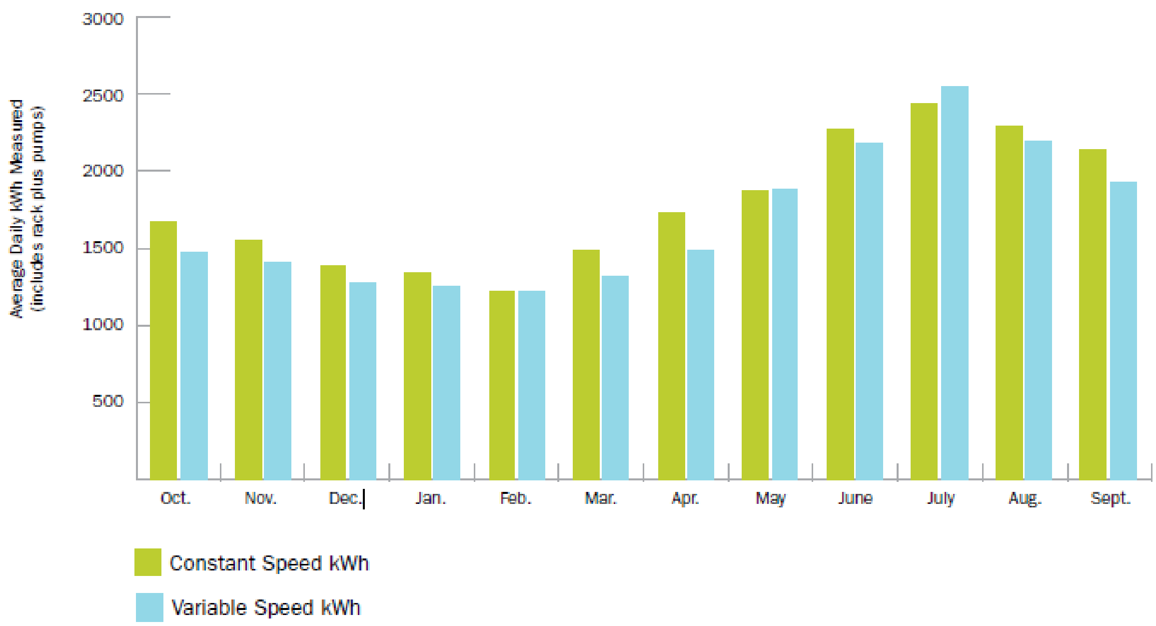

Figure 47. Energy consumption of a building cooling system operated, alternately at constant speed (and constant refrigerant volume) and variable speed (VRV)

Source: https://www.hillphoenix.com/wp-content/uploads/2018/02/Case-Study-Refrigeration-Variable-Speed-12-12.pdf

- *Dual path air handler*. Typically, an air conditioning system is required to both reduce temperature as well as remove humidity. Khattar and Brandemuehl (2002) proposed "Separating the V in HVAC" with a "dual-path approach" to building ventilation, where the provision of the temperature and humidity conditions could be separated. Commercial systems are offered by Toro Water Air Thermal Technologies Corp. The company claims 50% energy efficiency[56]. Given that LAC includes climates that go from dry to very humid, this technology is worth consideration. However, energy savings would need to be verified from actual case studies.
- *Ice energy storage.* Cooling energy demand is highest during mid day, adding to peak electricity demand, which often requires a higher tariff. One way to reduce

[54] https://www.daikin.eu/en_us/about/daikin-innovations/variable-refrigerant-volume.html
[55] https://www.hillphoenix.com/wp-content/uploads/2018/02/Case-Study-Refrigeration-Variable-Speed-12-12.pdf, page 7.
[56] http://www.torowatt.com/

peak demand is to generate cold during off-peak periods and use the stored cold for cooling during peak periods. The simplest form of storing cold is as ice, where the latent heat of ice melting allows additional cooling beyond what is available in temperature difference alone. One company offering ice storage systems is IceEnergy[57].

- *Energy storage using other phase-change materials*. Ice is not the only phase-change material for storing cold. However, we do not believe that other phase-change materials for cold storage are currently commercially viable.

Going beyond centralized A/C systems at a building level, there are district cooling systems that provide cooling to a group of buildings. These district cooling systems are discussed below.

[57] https://www.ice-energy.com/commercial-industrial/

6.2. District heating and cooling

Centralized generation and distribution of heat as hot water or steam has been extensively used for many years in cities in temperate countries where there is a substantial heating demand. The first district heating system distributed hot water from a geothermal, source to some buildings in Chaude-Aigues, France in 1334 (Collins, 1959). In "modern" times, district heating started to be installed in the 1870s. District heating is common in cities in Denmark and other northern European countries, Canada, China, and South Korea. With the exception of a few southern cities in LAC (Buenos Aires, Montevideo, Santiago de Chile), there is little demand for space heating, and there are no known installations of district heating in LAC..

According to a recent review of district heating and cooling (Werner, 2017):

> *The fundamental idea of district heating is 'to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place'.*

While the idea is to use fuel or heat resources that would otherwise be wasted, the reality is different. Figure 48 shows that (in 2014) almost all district heating and cooling was provided by fossil fuels, with a small participation of biomass and geothermal energy.

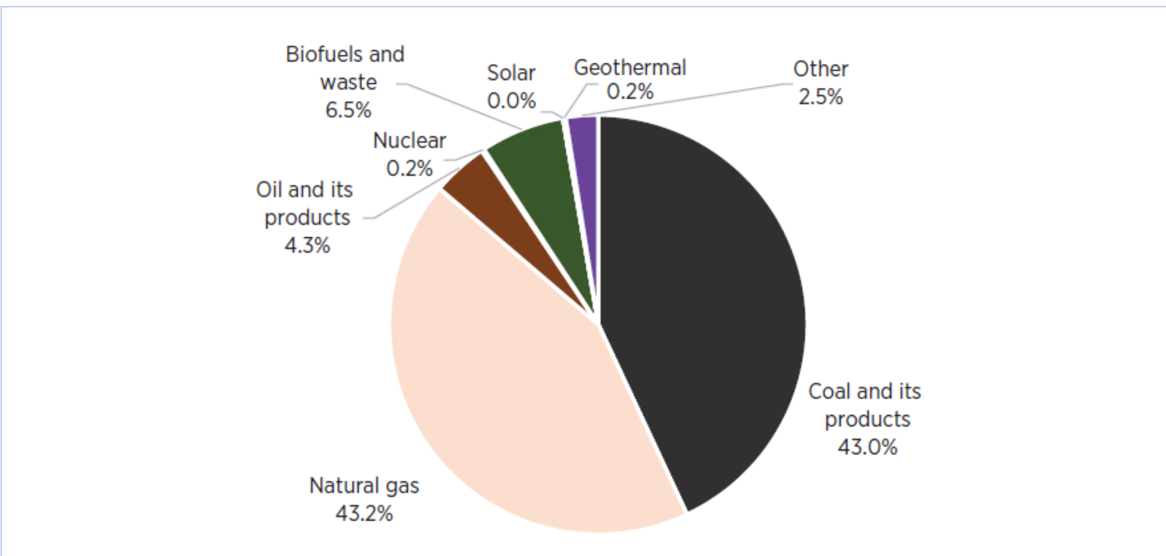

Figure 48. Breakdown of fuel use in district heating and cooling systems worldwide in 2014
(Source: IRENA, 2017a, Fig. ES-2)

Some of the district heating and cooling systems in temperate climates are very complex. For instance, MGM Innova developed a new CDM methodology, NM 336 "Introduction of a new, natural gas fired combined cycle power plant for supplying heat and cold to a district heating system and electricity to a power grid". The project activity comprises a combined-cycle power plant which would generate electricity all year long, using some of the waste heat to provide district heating (winter) and to provide district cooling (summer).

Subsequently, the CDM approved (2016) the methodology AM117: "Introduction of a new district cooling system". There are no registered CDM project using this methodology. One CDM Programme of Activities: PoA 0519, was submitted in Dec. 2018. According to Version 1 of the PoA DD (Design Document), "The typical project will employ a new energy efficient district cooling plant(s) (*water cooled electric driven centrifugal chillers*) with thermal energy storage. The baseline system is described as "less efficient *air-cooled reciprocating chiller systems*". The CPA DD (CDM Project Activity Design Document) for any specific project is not available on the UNFCCC website. There is no quantification of the performance of the technology to be used by the proposed project cooling system, so that neither the energy efficiency nor emissions reduction can be determined. Neither the methodology AM 0117 nor the PoA DD restricts the use of refrigerants, though GHG emissions from refrigerant leaks are accounted for in the calculations.

The methodology AM 0117 was used in the MRV procedure for Colombian NAMA on Air Conditioning, developed by MGM Innova during 2017-19.

IRENA published a number of case studies on district heating and cooling using renewable energy (IRENA, 2017b). Most studies were based in industrialized countries, and some included cooling as well as heating. However, they noted that "So far no district energy system has been built to incorporate solar cooling." Three case studies considered Arizona, Singapore and Saudi Arabia. Seawater cooling, which we have discussed above, comprised case studies in Bahrain and Hawaii.

Werner (2017) noted:

> "*Established expertise of district heating has paved the way for introduction and deployment of district cooling systems, mainly for covering space cooling demands in buildings. However, this district cooling development has been more recent compared to the development of district heating. District cooling systems are therefore neither as common nor as extensive as district heating systems*."

The United Nations Environment Programme (UNEP) launched the District Energy in Cities Initiative. It includes three countries in South America: Argentina, Chile, and Colombia. These three countries are discussed further below.

Argentina. District heating and cooling in the context of cogeneration was proposed and studied for Argentina by the late Alberto Fushimi, cogeneration expert and professor at the National University of La Plata. In 2019, two UN supported plans for district energy systems were announced in Argentina: one in General Alvear, Mendoza province; the other in Ubajay Entre Ríos province. Both would be biomass based and are expected to provide heat only.

Chile is one of three LAC country included in the UNEP District Energy Initiative[58]. District energy is a part of the Chilean government program to reduce air pollution in Southern Cities. Biomass is used for space heating, and a GEF-funded initiative is supporting the District Energy System (DES) to southern Chile (UNEP/GEF, 2018). However, the Chilean DES will be limited to providing *space and water heating*. No HFC emission reduction involved in the project. Tractebel and ENGIE have conducted pre-feasibility studies of district heating in Chile[59]. As far as we know, there are no initiatives to promote district cooling in the country, probably because the low population of northern Chile, which has a hotter climate.

Colombia. The National University of Colombia reviewed the potential for district cooling in the country. They noted that, as an equatorial country, there was no seasonal temperature variation, and that cooling was needed year-round in low altitude locations (see Figure 49 and Figure 50).

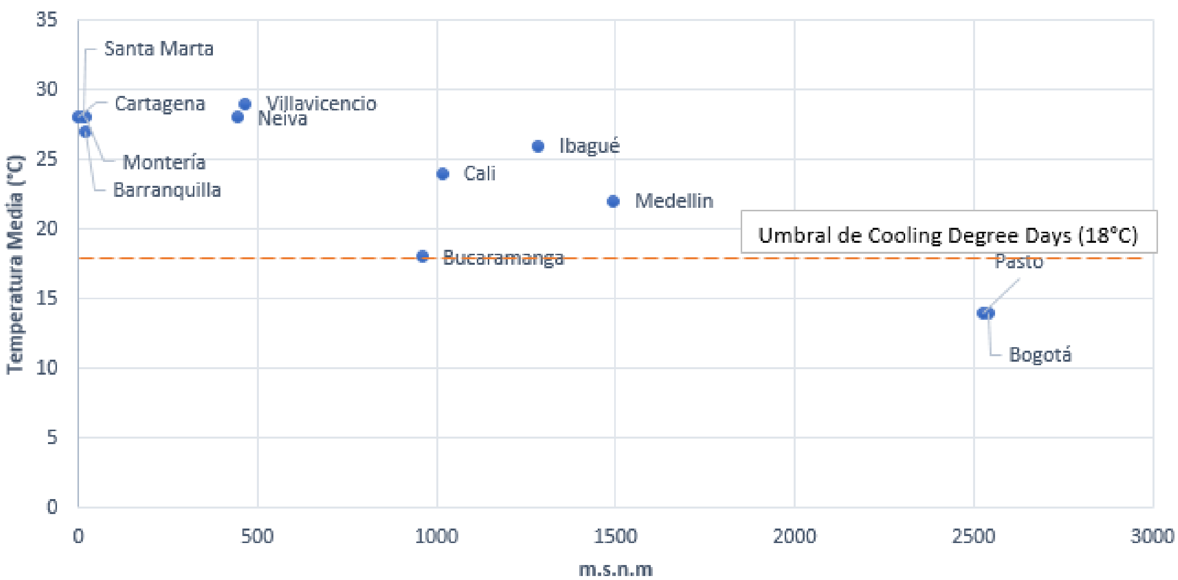

Figure 49. Altitude and annual mean average temperature of main Colombian cities
Source: González Martínez, 2018, Figure 1.

[58] http://www.districtenergyinitiative.org/chile
https://www.unenvironment.org/news-and-stories/story/district-energy-secret-weapon-climate-action-and-human-health.
[59] http://www.agrificiente.cl/tractebel-esta-desarrollando-estudios-de-perfectibilidad-sobre-distritos-termicos-en-chile/

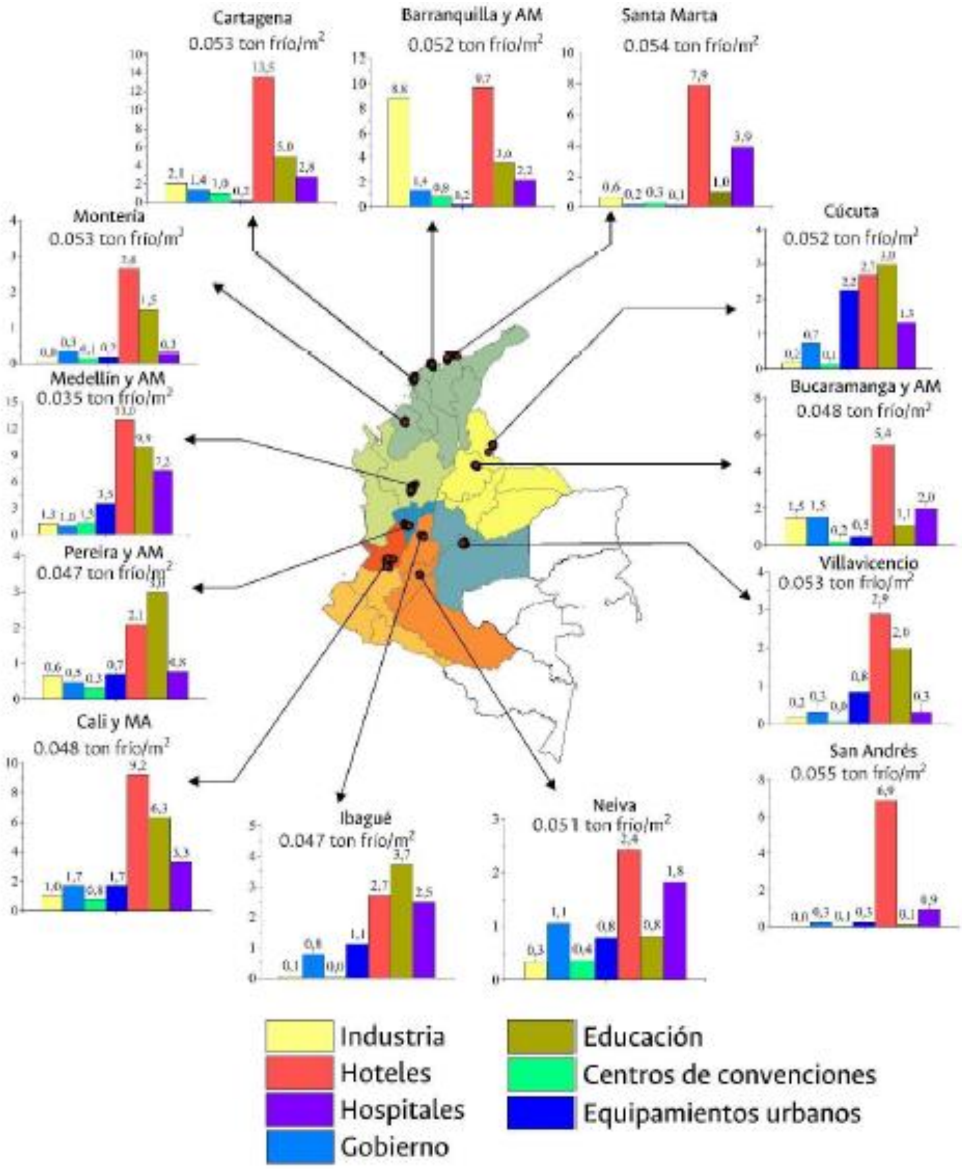

Figure 50. Geographical distribution of refrigeration potential by sector, in thousands of tons of refrigeration
Source: Smith Quintero et al., 2017, Figure 5.

The UNEP program, mentioned above, proposed a district cooling system for the city of Cartagena, Colombia, which is part of a NAMA prepared by MGM Innova for the Colombian government (MGM Innova, 2019).

In 2015, Latin America Development Bank (CAF) launched a district cooling program for cities in Latin America and the Caribbean (CAF, 2015b). Most of this involved sea water air conditioning in coastal areas, discussed in an earlier section. The program would also include cities away from the sea[60]. The first city in the region with a district cooling system is Medellin, Colombia, discussed below.

[60] http://scioteca.caf.com/handle/123456789/807 accessed 23 July 2019.

6.2.1. District cooling project in Medellín, Colombia

The utility Empresas Públicas de Medellín (EPM) commissioned the first district cooling system to be installed in LAC. The project comprises the central source of cold to be distributed to a number of buildings as shown in Figure 51.

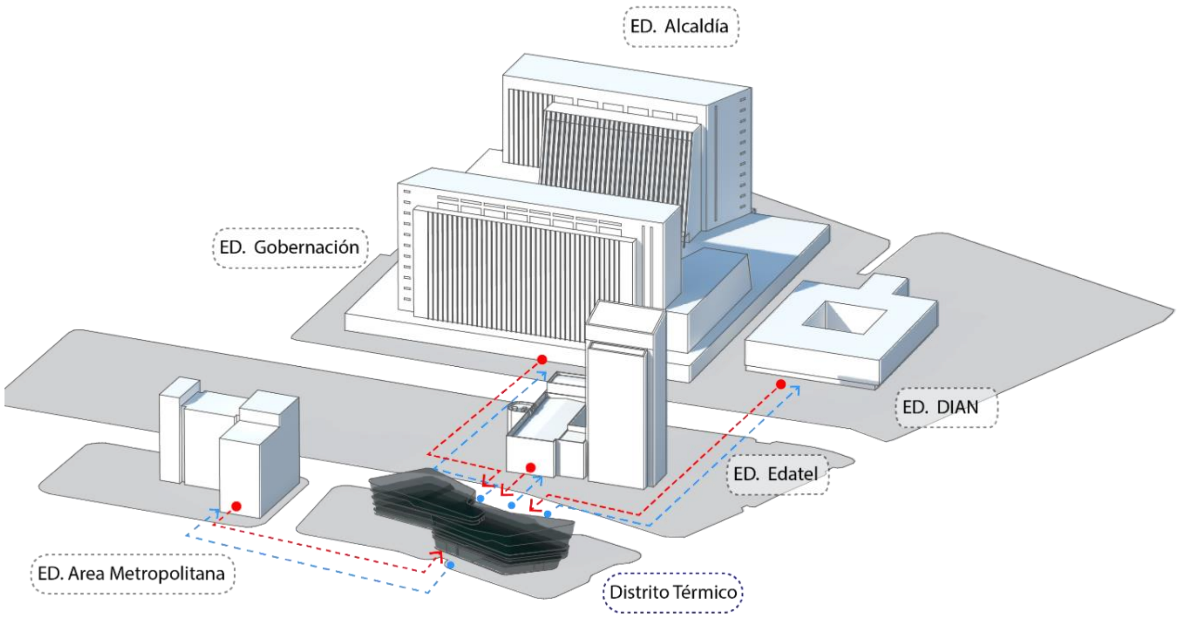

Figure 51. General scheme for EPM district cooling system in Medellín, Colombia
Source: EPM, 2016, slide 6

The process for the production of chilled water is shown in

Figure 52. There are two sources for the production of cold:

1. An absorption chiller, with a cooling capacity of 510 TR, operating on waste heat from a 1 MW natural gas powered gas turbine power plant;
2. Three electric chillers each with a cooling capacity of 1038 TR.

A cooling tower, pumps, piping, measurement and control equipment made up the system.

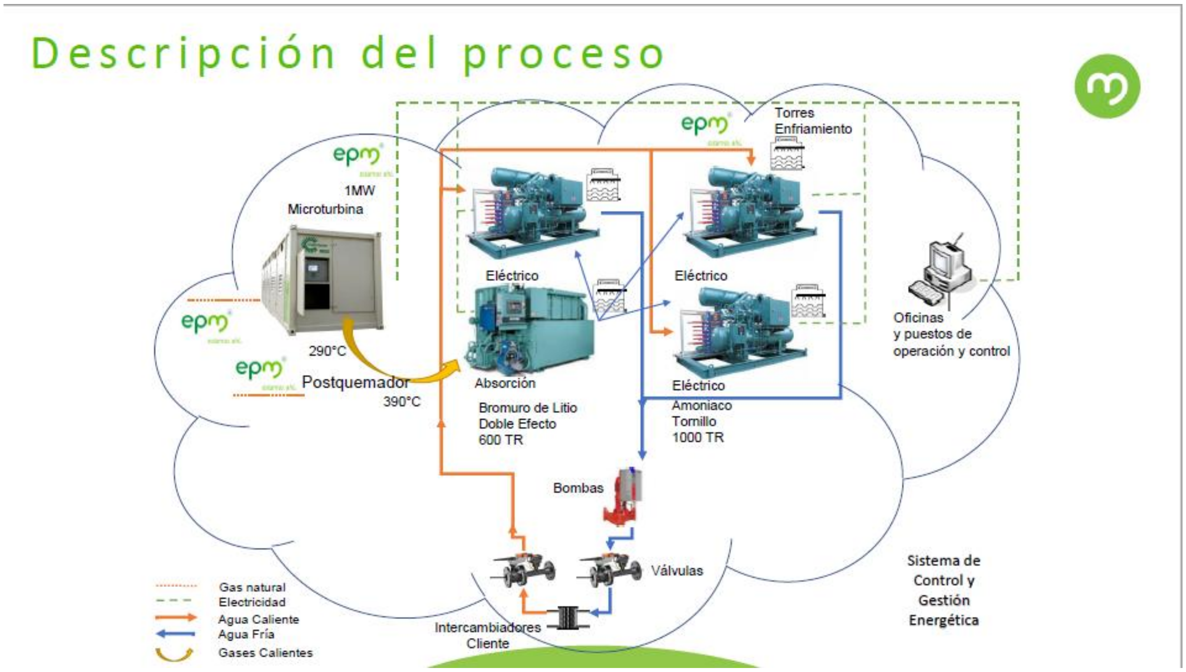

Figure 52. Process for the production of cold for La Alpujarra district cooling project.
(Source: EPM, 2018, slide 13)

The bird's eye view of the installation where cold is generated is shown in Figure 53, while an exterior ground view is shown in Figure 54.

Figure 53. Aerial view of EPM district cooling system in Medellín, Colombia, showing the cold production plant at the center
Source: EPM, 2018, slide 27.

Figure 54. Exterior ground view of the La Alpujarra district cooling plant
Source: EPM, 2018, slide 25.

A few technical details are given in Table 11. The only refrigerants are water, ammonia and lithium bromide, including both the absorption chiller as well as the centrifugal electric chillers. There are no chlorinated or fluorinated refrigerants, thus not ozone depleting nor of high-GWP, so that overall GHG emissions are determined by electricity consumption and the emissions factor of the Colombian electricity system.

Table 11. Key technical parameters for the EPM La Alpujarra district cooling system
(Source: EPM, 2018)

Current cooling capacity	3600 RT
Refrigerant in absorption cooler	Water and lithium bromide
Refrigerant in chiller	Ammonia
Estimated energy efficiency	0.54 kW/RT
Estimated COP	6.5
Estimated GHG emissions reduction	30%

The NAMA on air conditioning in Colombia recently drafted includes a pilot district cooling project in Cartagena. The proposed project would provide cooling to nine buildings, including six hotels three of which currently use R134A, two use R-22 while the last uses R123A, with GWPs of 1.430, 1.810 and 77 respectively. The remaining three buildings are shopping centers, two of which use R134A, while one uses R410A. The proposed cooling capacity would be 9270 TR (32.4 MW), comprising an absorption chiller based on waste heat from a gas turbine power plant, and five centrifugal chillers, with key parameters summarized below.

Table 12. Cooling capacity of central chillers for the proposed Cartagena district cooling Project
(Source: Hinicio-Tractebel, 2018, cited in MGM Innova, 2019)

Equipment	Number	Cooling capacity	COP	Energy source
Centrifugal chiller	5	1770 TR (6.2 MW)	6.5	Electricity
Absorption chiller	1	1285 TR (4.5 MW)	0.8	Gas turbine waste heat

The refrigerants are likely to be hydrocarbons, HFO 1234yf, or ammonia. Details of the proposed project can be found in Hinicio-Tractebel (2018), and in MGM Innova (2019, Deliverable 5).

6.2.2. District heating and cooling

In the Southern Cone, where there is a demand for both space heating as well as cooling, a district heating and cooling system may be appropriate. Major cities in the Southern Cone include Montevideo, Buenos Aires, Rosario, Córdoba, Santiago, as well as the South of Brazil. An example of a district heating and cooling is provided by a project in South Korea, whose CDM methodology was developed by MGM. The project comprises a Combined Cycle Natural Gas power plant that generates electricity at high efficiency. However, operation can be adapted seasonally, so that waste heat is available for space and water heating in the winter, and for space cooling in the summer, through a district heating and cooling system. The following figures show the main three operating modes, according to the season and heating needs (Source: KDHC, 2010):

- Mode 1: Operation during winter.
- Mode 3: Summer operation.
- Mode 5: Spring and fall operation

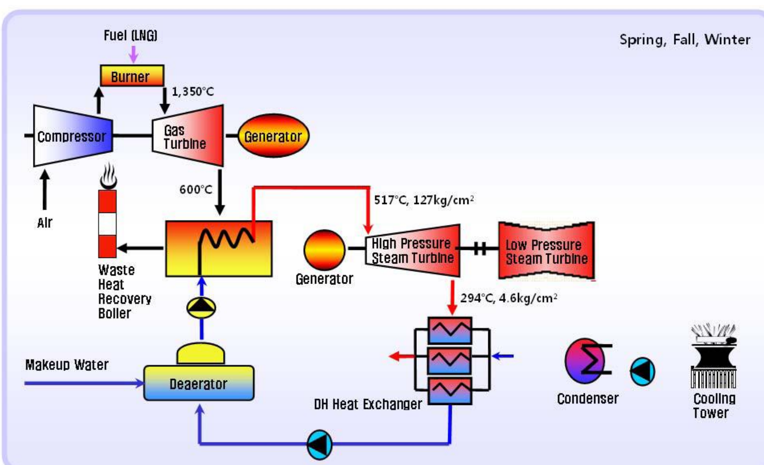

Figure 55. Operation Mode 1: Winter. Waste heat from gas turbine passes through heat recovery steam generator, with the steam passing only through the high-pressure (HP) turbine stage. Steam exits the HP turbine at 294 C and enters the district heating heat exchanger.
Source: KDHC, 2010

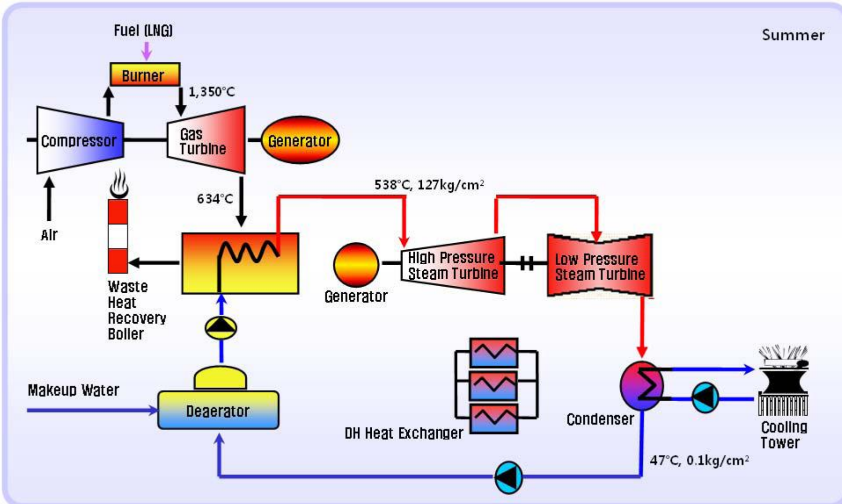

Figure 56. Operation Mode 3: Summer. All heat recovered from the gas turbine is sent to both stages of the steam turbine to maximize electricity generation. However, since some heat is needed for water heating and some for cooling, the system is operated in Mode 1 and Mode 3, alternately, as needed.

Source: KDHC, 2010

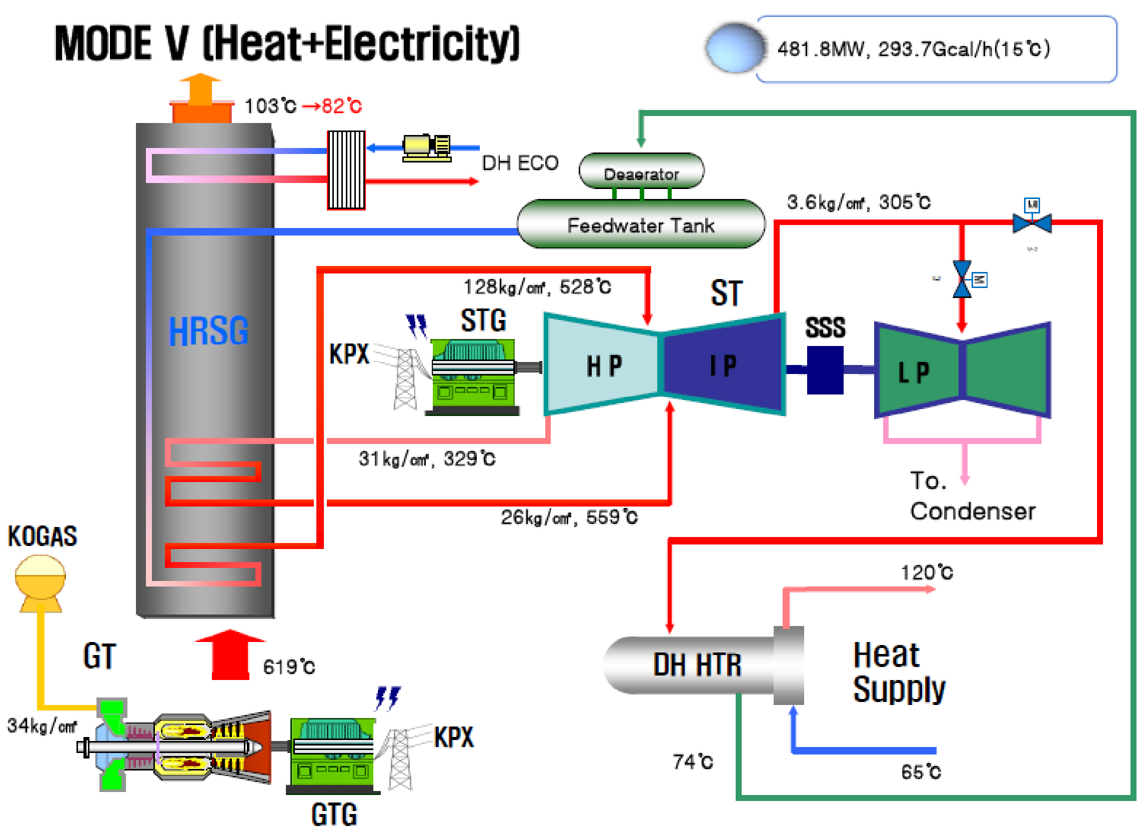

Figure 57. Operation Mode 5: Spring and Fall. This is between Modes 1 and 3: some heat goes to the low-pressure steam turbine depending on heat demand.

Source: KDHC, 2010

6.3. Commercial refrigeration

The US Department of Energy provides a classification of commercial refrigeration, shown in Table 13.

Table 13. Classification of commercial refrigeration
Source:
http://web.archive.org/web/20130214012615/http://buildingsdatabook.eren.doe.gov/Glossary.aspx

Technology	Definition
Supermarket Refrigeration	The complete supermarket refrigeration system including display cases, compressor racks, condensers, and walk-ins.
Walk-Ins	A refrigeration or freezer unit (within a building) that is large enough to walk into.
Reach-Ins	Upright, self-contained refrigerated cases with solid or glass doors whose purpose is to hold frozen and/or refrigerated food products.
Refrigerated Vending Machines	Upright, refrigerated cases whose purpose is to hold cold beverages and/or food products and vend them in exchange for currency or tokens.
Ice Machines	Machines used to provide a variety of ice types used in the food service, food preservation, hotel, and healthcare industries.
Beverage Merchandisers	Self-contained, upright, refrigerated cabinets that are designed to hold and/or display refrigerated beverage items for purchase without an automatic vending feature.

Some commercial refrigeration systems comprise stand-alone refrigerators for beverages and ice-machines. These cases are similar to the case of mini-split A/C systems where a one-to-one replacement with more efficient equipment using low-GWP refrigerants is a relatively simple option.

6.3.1. Supermarket refrigeration

Refrigeration and air conditioning in supermarkets comprise a major component of commercial refrigeration, and often include some of the other categories listed in Table 13: "**Reach-Ins"** and **"Beverage Merchandisers".** Energy use intensity in supermarkets is high compared to retail buildings due to the refrigeration needed for the conservation of chilled and frozen products (Mylona et al., 2017).

One important consideration in supermarket refrigeration is the climate. In warm climates, such as most of LAC, the supermarket may require air conditioning all or most of the year. In such cases, the cold "lost" from open display cases may contribute to space cooling. In temperate climates, space cooling is needed only a part of the year, or not at all. Therefore experience in energy efficiency from temperate climates may not be relevant in many parts of LAC. We need to keep this in mind in reviewing the literature from studies in temperate climates.

Mota Babiloni et al. (2015) reviewed food freezing and conservation in retail stores and supermarkets. They expect that because of global warming considerations, HFCs such as R404A and R507 would be phased out. They conclude that "*Besides hydrocarbons and HFO, CO_2 appears as one of the most promising HFC replacements because its low contribution to global warming and high efficiencies when used in transcritical and low-stage of cascade systems*".

Islam et al. (2017) assessed the total equivalent warming impact (TEWI) of supermarket refrigeration systems. TEWI considers both direct and indirect global warming. They considered refrigeration systems for low temperature (LT) evaporation and medium temperature one (MT) at 0 C with condensation at 40 C. They considered various refrigerants such as HFC 134a, HFC blend 507A and their combinations are as working fluids for catering to a LT load of 50 kW and MT load of 250 kW. They observed that HFC 134a for LT and MT provided the best combination, suggesting that low GWP alternatives to this HFC refrigerant may be less efficient. They concluded that HFC blend 507A refrigerant has the highest TEWI and system costs are also the highest. However, they also evaluated transcritical CO_2 refrigeration systems and found they could "conceivably" have higher COP in the relevant operating conditions, which would be best from the TEWI perspective with minimum economic loss due to refrigerant leakage because of its abundance availability.

Karampour and Sawalha (2017) also evaluated integrated CO_2 trans-critical system in supermarkets. Their study included field measurements as well as modeling. However, their study was undertaken in Sweden, the system provided space and water heating as well as refrigeration and air conditioning. They concluded that the "integrated CO_2 system used about 11% less electricity than stand-alone HFC solutions for refrigeration, heating and AC in Northern Europe. Because of differences in climate, their conclusions may not be valid in most of LAC.

Similarly, the results and conclusions of a study by Sawalha et al. (2017), with field measurements of supermarket refrigerant systems, comparing HFC with transcritical CO_2, may not be valid in LAC. However, the methodology of this study and an earlier study

(Sawalha et al., 2015) would provide useful methodological procedures for evaluating conventional (HFC based), transcritical CO_2 and other systems.

By contrast, the study by Antunes and Bandarra Filho (2016) was conducted in Brazil, so that there are no uncertainties from regional extrapolation. They conducted an experimental evaluation of a 5-ton refrigeration system involving the "drop-in" replacement of refrigerant R-22, with a variety of halogenated refrigerants such as HFC-438A, HFC-404A, HFC-410A and HFC-32, as well as hydrocarbons HC-290 and HC-1270. They concluded that the natural refrigerants presented the best coefficient of performance and that results for HFCs, excepting the HFC-32, remained below those of HCFC-22. Environmental impact was evaluated using the parameter TEWI, and again the best results were reached with hydrocarbons, while refrigerant HFC-404A presented the highest environmental impact.

Food and produce display

A number of cooling technologies are available for food and produce display, as illustrated below. Some use hydrocarbon or CO_2 as refrigerant, while one appears to be solid-state. No performance information is available. Open display cabinets are not energy efficient, so that an important energy efficiency measure would be placing doors in display cabinets, where feasible.

Figure 58. Food display unit by De Rigo Refrigeration uses R-290 (hydrocarbon) refrigerant
Source: DeRigoRefrigeration.com

Figure 59 shows the first installation of a Panasonic condensing unit using CO_2 as refrigerant at a location outside Japan.

OCU-CR2001MVF Jaya Grocer Mutiara Tropicana store

Figure 59. Panasonic CO_2 condensing unit (left) installed in a Malaysia grocery store (right)
https://news.panasonic.com/global/press/data/2017/05/en170509-3/en170509-3.html

One technology provider (Grener Systems) does not give details of their technology. However, the limited product literature suggests that it is a solid-state cooling system, using a coolant that is a "biodegradable additive".[61]

Figure 60. Produce display system based on Coolplates, Grener Systems Nederland BV
Source: https://www.coolplates.nl/en/applications

[61] https://www.coolplates.nl/en/about-coolplates

7. Review of manufacturer technology offerings

7.1. Introduction

As a starting point for a review of manufacture technology offerings, we considered two sources:

1. A number of cooling technologies were compared in an Excel sheet "181204_Technology list from 29oct workhsop_review CF.xlsx", prepared for a workshop held on October 29, 2018[62]. It provides a brief review of the most relevant technologies. All companies and technologies were evaluated, in order to prepare a shorter list of relevant technologies, as detailed in Appendix C.
2. The International Institute for Energy Conservation (IIEC) also prepared a list of clean and efficient cooling technologies[63]. The list of companies and technologies is much shorter than the Excel compilation noted above and reviewed in Appendix C. The IIEC list is reviewed in Appendix D.

The above compilations were supplemented by our own review of manufacturer offerings. The results are summarized by manufacturer, refrigerant, application, etc. in an Excel Workbook, a part of which is extracted in Table 14 later in this section.

Table 14 considers mostly commercial and industrial applications. It does not include mini-split A/Cs common in residential and small commercial applications. As noted earlier, two Chinese companies, Midea and Gree, manufacture most mini-split A/Cs sold in LAC, under a variety of brand names, including their own. Some are inverter models, so that they are likely to be more efficient than constant power models[64]. Currently, none of the models they offer in the LAC market use low-GWP refrigerants[65]. However, in some countries there are high efficiency models on the market, e.g. with the efficiency category A, according to the Argentina energy efficiency label, see Appendix E.

Both companies as well as many others offer mini-split A/Cs using R-32 refrigerant in other markets. In fact, Panasonic offers mini-split A/Cs with R-32 refrigerant in Panamá. We can expect that, with suitable policy encouragement, energy efficient mini-splits with R-32 should be available in all LAC countries in the medium term.

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[62] The exact details of the workshop are not available. It was likely a K-CEP workshop. The Excel file was made available to MGM Innova as part of background documentation for the K-CEP grant.

[63] http://www.iiec.org/coolingdemo-technologies

[64] For model offerings of Midea and Gree in the global market, see http://www.midea.com/global/products/air_conditioning/residential_air_conditioner/ac_split/ http://global.gree.com/ywb/productsservices/residentialairconditioner/guaji_e/index.shtml

[65] As an example, for Argentina, see https://www.midea.com.ar/producto/climatizacion-residencial/aires-acondicionado/

For the commercial market, Gree offers a number of multi-split models with variable refrigerant flow (VRF), where the manufactures claims: "*Its energy efficiency is improved by 78% compared with conventional multi VRF*".[66] Details are not clear.

Also for commercial refrigeration, Gree offers a number of chiller models. There is no mention of the refrigerants used, so one can assume that they are conventional. While there is insufficient information in the website to evaluate most of the models, the following appear interesting[67]:

- *CVE Series Permanent Magnet Synchronous Inverter Centrifugal Chiller*. Permanent magnet suggests more efficient electric motor, while inverter indicates improved efficiency.
- *Photovoltaic Direct-driven Inverter Centrifugal Chiller*[68]. This allows the equipment to operate using combinations of grid electricity and on-site PV generation, exchanging energy with the grid as needed.

Below we provide details of two major manufacturers (Daikin and Mayekawa) which have a significant presence in the LAC market. Daikin is poised to offer efficient air conditioning equipment using R-32 and other low-GWP refrigerants. Mayekawa offers equipment with a variety of low-GWP refrigerants.

Further below, we provide a summary table (Table 14) based on MGM Innova review of manufacturer offerings. Many of the products and systems in the table are not offered in LAC yet, or have a very limited presence in the region. However, they all represent interesting opportunities for clean cooling in the region.

[66] http://global.gree.com/ywb/productsservices/commericalairconditioner/light_commercial_ac/index.shtml
[67] http://global.gree.com/ywb/productsservices/commericalairconditioner/chiller/index.shtml#product_menu
[68] http://global.gree.com/ywb/productsservices/commericalairconditioner/chiller/detail-1983.shtml

7.2. Daikin

Daikin is a Japanese manufacturer supplying the global market. Its innovations since 1980 are shown in Figure 61. They have developed systems using all of the refrigerants discussed earlier, and for a wide variety of applications.

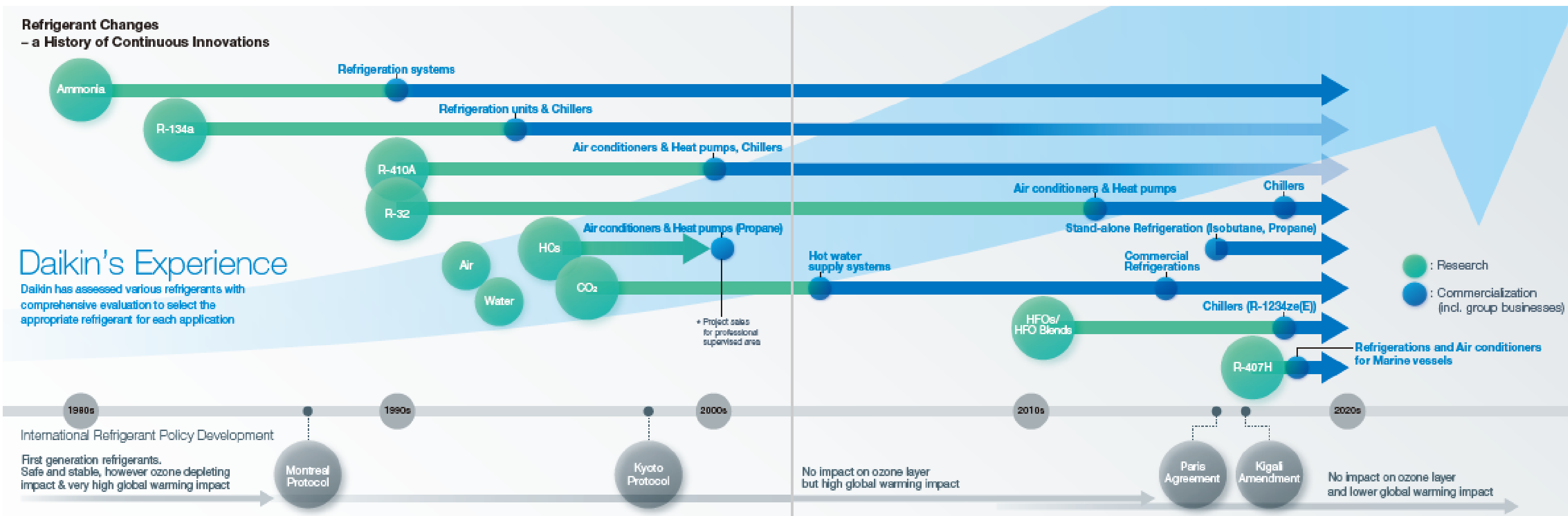


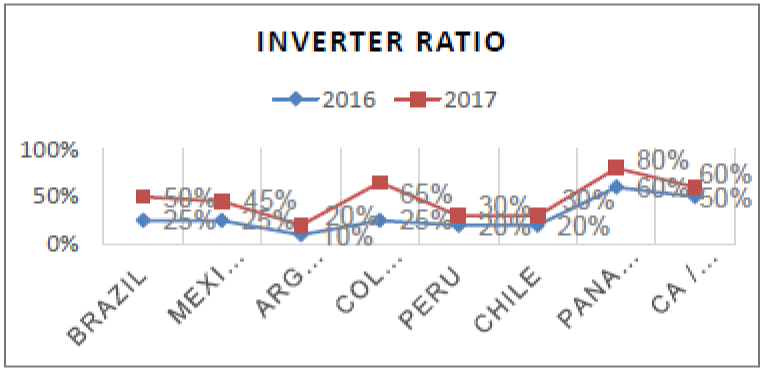
Figure 61. Daikin's experience in the development of refrigeration, air conditioners and heat pumps
Source: Daikin, 2018A

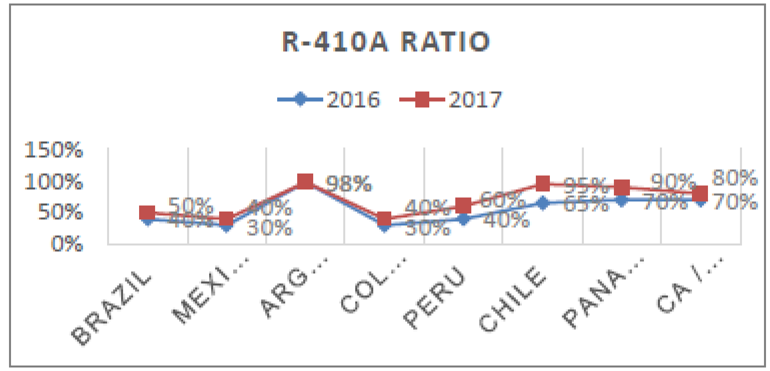
Daikin's presence in LAC is somewhat limited, but with an interest in expansion (Figure 62). Daikin made a presentation to MGM Innova in August 2018 (Daikin, 2018B).

Figure 62. Daikin in Latin America and the Caribbean
Source: Daikin, 2018B, slide 5

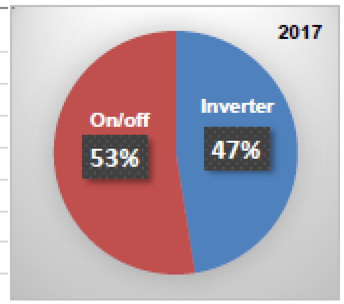
Daikin has already increased the share of inverter type air conditioners as well as R-410A to replace R-22 in the region as shown in Figure 63, noting the following (Dakin, 2018B, slide 6):

- Inverter ratio has increased from 32% to 51%. Brazil, Mexico & Colombia with the highest growth.
- R-410A ratio has increased from 49% to 65%. Peru & Chile with the highest growth. Argentina at 98%.
- Central America & The Caribbean at 60%/80% achievement. Panama at 80%/90%.





	UNITS (K)	2016	2017	Growth (%)
BRAZIL	2,000	25%	50%	100%
MEXICO	817	25%	45%	80%
ARGENTINA	1,100	10%	20%	100%
COLOMBIA	254	25%	65%	160%
PERU	57	20%	30%	50%
CHILE	126	20%	30%	50%
PANAMA	242	60%	80%	33%
CA / CARIB.	447	50%	60%	20%



	UNITS (K)	2016	2017	Growth (%)
BRAZIL	2,000	40%	50%	25%
MEXICO	817	30%	40%	33%
ARGENTINA	1,100	98%	98%	0%
COLOMBIA	254	30%	40%	33%
PERU	57	40%	60%	50%
CHILE	126	65%	95%	46%
PANAMA	242	70%	90%	29%
CA / CARIB.	447	70%	80%	14%

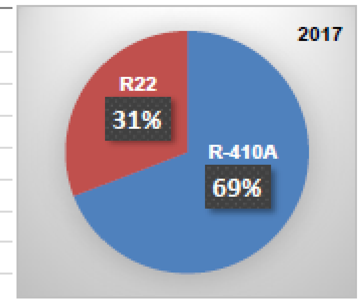


Figure 63. Daikin has increased its proportion of inverter units as well as the use of R-410A in LAC in split-system ACs in recent years

Source: Daikin 2018B, slide 6.

The next step for Daikin is to promote low-GWP efficient equipment. As noted earlier, Daikin has chosen R-32 as a medium-GWP HFC refrigerant as an interim refrigerant with inverter technology to promote energy efficiency. Between 2012 and 2017, Daikin sold 32 million RAC units with R-32 (Daikin, 2018B, slides 16 and 17).

7.3. Mayekawa

Mayekawa, founded in Tokyo in 1924, has developed equipment for a wide range of cooling and heating applications. In the search for alternatives to refrigerants that are ozone depleting and/or have high GWP, they have developed equipment using what they call "NATURAL FIVE" refrigerants: ammonia (NH_3), carbon dioxide (CO_2), water (H_2O), hydrocarbons (HC) and air. Applications include heating, drying, hot water supply, air conditioning, cooling, chilling and freezing over a multitude of temperatures from 200 C to -100 C[69], as illustrated below.

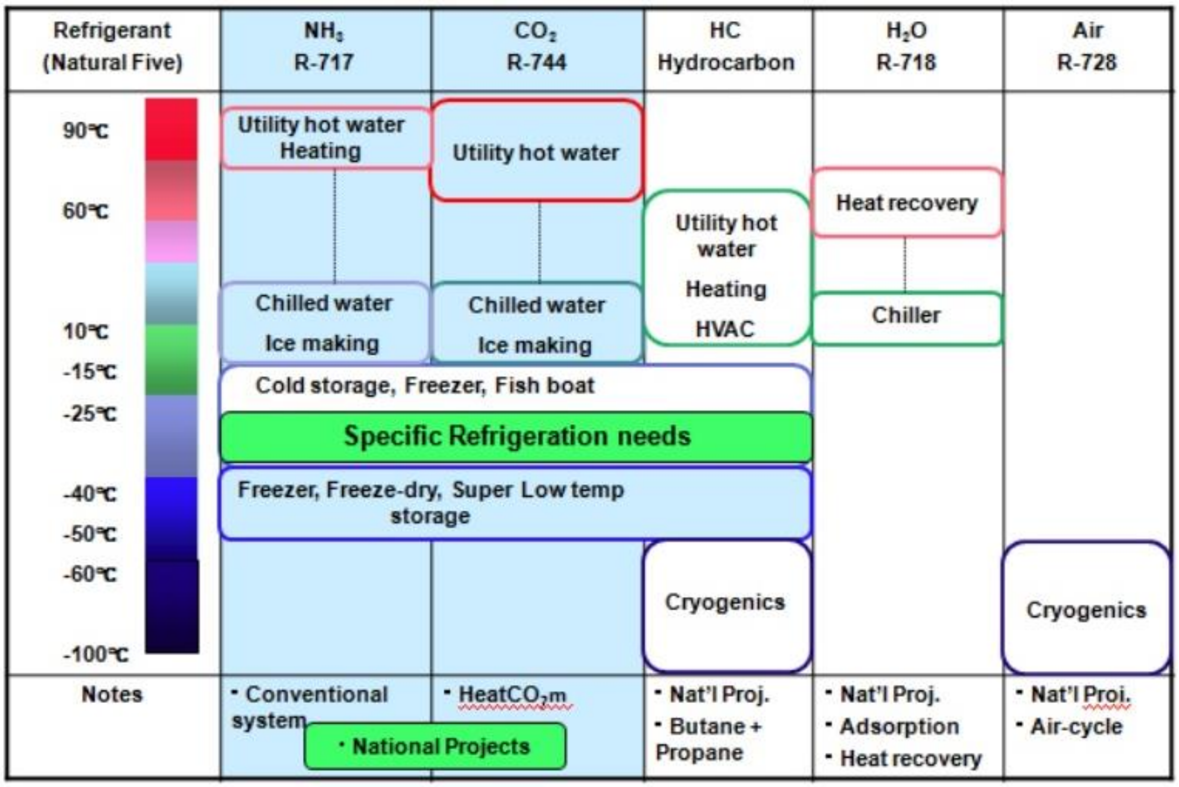


Figure 64. Mayekawa equipment based on natural refrigerants
(Source: Mayekawa, 2013, slide 5)

For the LAC market[70], Mayekawa offers Eco Cute, heat pumps that use carbon dioxide as a refrigerant. Within the Eco Cute line, they offer Unimo Transcritical CO_2 heat pumps[71]. The Air/Water version (Unimo A/W) provides hot water at 65 to 90 C, with a COP of 4.2. The water/water version (Unimo W/W) also provides cold water as cold as 9 C, with a combined COP of 8.0 (adding the heating and cooling COP). According to their calculation, the replacement of an electric chiller and a steam boiler with their Eco Cute system would have a simple payback of 1.7 years, at an electricity cost of US$ 0.13/kWh.

[69] http://www.mayekawa.com/activities/natural5/
[70] Information in this section is based on a Mayekawa presentation to MGM Innova.
[71] http://www.mayekawa.com/products/features/eco_cute/

Mayekawa also offers the Plus Heat model heat pump using ammonia as refrigerant.

Their slurry ice system produces cold water also using ammonia as a refrigerant. This system can be used for ice making as well as for food conservation. For a cooling capacity of 187 kW, their slurry ice system would require 77.6 kW compared to 93.1 kW for a conventional stick ice system. They estimate a simple payback period of 5 years, perhaps not attractive in the LAC market, without additional benefits.

Mayekawa's Pascal Air system for generating ultra-low temperatures was mentioned in the discussion on the use of air as a refrigerant.

Mayekawa offers a number of industrial freezer models that can operate on natural as well as fluorocarbon refrigerants[72]:

- Thermo-Jack freezer: High-efficiency tunnel freezing using impinging jets from slit nozzles
- Slim-light freezer, similar to the Thermo-Jack
- Multi-layered freezer, for better use of space and continuous freezing
- IQF Line freezer, rapid freezing, ideal for freezing vegetables, fruit and fishery products without clumping
- Spiral freezer, also for space saving.
- Batch freezer, for rapid freezing of small amounts of different products

Mayekawa also offers an *adsorption* cooling system (a technology we did not review earlier). As in *absorption* refrigeration, the system uses waste heat as a source of cold. The refrigerant is water. For their system, Adref Noa, they claim a 50% energy savings compared to conventional chillers.

Mayekawa also offers high efficiency compressors for conventional refrigerants (R 22, R 507A) as well as ammonia.

Mayekawa has a global presence including LAC, as shown in Figure 65.

[72] Mayekawa General Freezer Catalog

Figure 65. Mayekawa presence in LAC includes factories in Cuernavaca (Mexico) and Arujá (Brazil), shown as blue stars in map

Source: Mayekawa general freezer catalog

7.4. Other manufacturers

Daikin and Mayekawa are only two global manufacturers featured here. Products from these and other manufacturers were mentioned above in relation to specific refrigerants. The manufacturer product offerings are summarized in the Excel table "Manufacturers and technologies 15sep19.xlsx", prepared to accompany this review. An extract of the Excel file is given in Table 14 below.

Table 14. Manufacturer or supplier of refrigeration and air conditioning technologies
(Source: Manufacturers and technologies 15sep19.xlsx, MGM Innova compilation)

Manufacturer / supplier	**Refrigeration, A/C, or heat pump**	**Refrigerant**	**Technology /Application**	**Models**
Daikin	A/C	HFC 32 or R-32	Mini-split systems for residential and small commercial	Many
Daikin		HFO - 1234ze	Chillers	DZ, TZ, and VZ chiller series
Daikin		CO_2	CO_2-based VRV System	Outdoor unit RXYN-AY1 ; indoor units FXSN-AV1
Daikin		Water, Lithium bromide	Absorption chiller	TSA-DC (direct-fired chiller/heater) TSA-NC (steam-fired chiller)
Panasonic	A/C	HFC 32 or R-32	Mini-split systems for residential and small commercial	Many models
Panasonic		Water, Lithium bromide	Absorption chiller	
Panasonic	R	CO_2	CO_2 Direct Expansion Refrigerating System	OCU-CR2001MVF (condensing unit)
Carrier	A/C	HFC 32 or R-32	Mini-split systems for residential and small commercial	Many models
Carrier		HFO - 1234ze	Chillers	Aquaforce chiller with PUREtec refrigerant
Carrier		Water, Lithium bromide	Absorption chiller	16TJ (100 to 700 tons)
Carrier	R	CO_2	Air-Cooled Gas Coolers for refrigeration	Many models
Johnson Controls	R	NH_3	Commercial refrigeration	Frick PowerPac
Johnson Controls	A/C	Water, Lithium bromide	Absorption chiller	YHAU-C Single Effect Steam Chiller YHAU-CG Direct Fired Chiller/Heaters YHAU-CW Double Effect Steam Chiller
FOGEL	R	CO_2	Commercial refrigerators	
		R-290		
EPTA	R	CO_2	Commercial refrigerators	
		R-290	Commercial refrigerators	
Zanotti	R	CO_2	Commercial refrigerators	
		R-290		

De Rigo	R	R-290	Commercial refrigerators	
Mayekawa	HP	CO_2	Hot and cold water	Unimo A/W
Mayekawa	R	NH_3	Slurry ice system	Slurry Ice system
Mayekawa	R	NH_3 / CO_2	Refrigeration industrial	NewTon 3000, 6000, and 800
Mayekawa		Air	Very low temperatura and "freeze drying"	Pascal Air
Hussmann	R	CO_2	Commercial refrigerators	Purity
		R-290	Self-contained food display	VRM MD4060DA
Hill Phoenix	R	CO_2 /HFC (cascade)	Low temperature industrial refrigeration	Second Nature® Low Temperature Direct Expansion Cascade (SNLTX2)
Arneg	R	CO_2	Refrigeration for supermarkets	HCP CO_2
Schneider		R1234ze	Air-cooled chillers for commercial use	Aquaflair BREC & BREF
GEA Group	R & A/C	NH_3	Chillers for commercial use	• GEA BluAir • GEA BluAstrum • GEA BlueGenium
REFTECO	R	NH_3	Chillers for commercial use	CHA
Azane	R	NH_3	Chillers for commercial use	Azanechiller 2.0
Azane	R	NH_3	Food freezing	Azanefreezer 2.0
Kuroshiho	R	R-407E/R-32 (cascade)	Very low temperatures	
Enex	R}	CO_2	Chillers for commercial use Industrial and commercial refrigeration	Yukon (chiller) Elba, Drava, Neva (Refrigeration)
Green and Cool	R	CO_2	Refrigeration and A/C	Many models, including Mistral, Crystal, Sirocco
Smartcool	R	N.A.	RAC Control system (retrofit)	Eco3
Ice Energy	R & A/C	N.A.	Ice energy storage	Many models
Cool plates	R	Solid-state?	Self-contained food display	

8. Measurement of energy savings and emissions reduction

This document is a review of clean cooling technologies. However, since the objective of clean cooling is saving energy and reducing greenhouse gas emissions, some comments on the measurement of this objective is in order.

Electricity savings lead to GHG emissions reduction insofar as a part of the electricity is generated using fossil fuels. The Emissions Factor to determine CO_2 emissions reduction from electricity savings is discussed in Appendix F, with special reference to data availability in LAC countries. Some LAC countries publish official data on emissions factor. For other countries, we recommend that the governments do so. Meanwhile, ESCOs will need to determine the emissions factor from the most recent electricity generation data available.

Most of the GHG emissions in refrigeration and air conditioning (RAC) are from CO_2 emissions in electricity generation. These emissions depend on electricity consumption and continue for the equipment life. Many refrigerants in use today have high GWP and also contribute to total GHG emissions. These emissions take place in refrigerant leaks while the RAC system is in use, during maintenance and at the end of equipment life, if the refrigerant is not recovered and destroyed. Thus reducing leakage, improving maintenance procedures to reduce leakage, extending equipment lifetime, as well as refrigerant recycling, all contribute to reducing GHG emissions from refrigerants. All these factors become less relevant with the use of very low-GWP refrigerants, both "natural" and synthetics such as HFOs. Meanwhile, monitoring procedures should include not only energy use, but also estimates of refrigerant leakage in use and maintenance and equipment lifetime.

9. Conclusions and major recommendations for action

This document attempts to review technologies and related issues from the point of view of investors in energy efficiency, with options that also reduce emissions of ozone depleting substances (ODS) and greenhouse gases (GHG).

Some of the conclusions of the review were known *a priori*, and confirmed in this review.

A. Recovery of refrigerants and foam blowing agents from equipment removed from service

Emissions of ODS have immediate health effects, and are therefore important to reduce urgently. Although the production of ODS for use in refrigeration has decreased substantially, some, especially HCFC-22 may be produced and installed in some LAC countries. Since alternative refrigerants for these applications with zero ODP exist, an ESCO should not incorporate ODSs in any installations.

While the production of ODS has fallen drastically, these gases remain within equipment that are currently in use. Without an adequate recovery and final disposition, these gases would be released at the end of useful life of the equipment or when they are replaced by other equipment during remodeling, for energy savings or for other reasons. The level of equipment recycling, including the removal and destruction of refrigerants and foam blowing agents, is relatively low in LAC. However, there have been initiatives in Mexico, Brazil, Colombia, Argentina, Chile and elsewhere to promote such recycling. Without economic incentives, the economic benefits of recycling are expected to be smaller than the additional cost. Thus, refrigerant recycling represents an additional cost to an ESCO.

Some countries, notably Colombia, have laws on post-consumer waste. However, the process has not matured substantially for the recovery and treatment of refrigerants.

There have been initiatives, such as the Climate Action Reserve (CAR) from California, where the removal of ODSs was economically compensated in a carbon market that applied not only to California but also to other areas. While it is not cost effective for an ESCO to recycle ODS, the additional cost of such removal could be paid for with a modest revenue in a carbon market, such as that of the CAR, since these ODS are also greenhouse gases. We believe that the climate change mitigation cost for this recycling would be small compared to many other mitigation options, also delivering ODS emissions reduction at no cost.

The carbon market approach to finance recycling could be extended to refrigerants and foam-blowing agents that have zero ODP but have high GWP. There are many HFCs that fall in this category. Besides any international carbon market that may emerge to allow refrigerant GHG emissions to be monetized, countries that already have national carbon markets, such as Chile and Colombia could consider extending their carbon markets to include refrigerants and foam-blowing agents.

Our review found that certain classes of refrigeration equipment, especially those used for cooling beverages and ice cream at point of sale, do not always receive adequate maintenance and are discarded at the end of their useful life. This equipment is generally relatively new and does not use any ODS. Nevertheless, some continue to be based on HFCs. In the medium term, this equipment would use refrigerants and foam blowing agents that have negligible GWP. However, in the shorter term, HFCs may continue to be used. To this end, we recommend that an ESCO choose one of the following alternatives:

1. Install only equipment that uses refrigerants with very low GWP, e.g. hydrocarbons. Equipment removed should be recycled where ODSs or high GWP gases are involved.
2. Provide the equipment on a lease basis with recovery of the equipment when it stops working. In this case, the ESCO may operate its own repair infrastructure to extend equipment life, and/or recycle end-of-life equipment.
3. Acquire equipment in use from their current owners with a lease back commitment to change and upgrade installed equipment during the contract period.

In the above cases, the ESCO would benefit from a financial incentive such as a carbon market for destruction of GHGs removed.

B. Energy efficiency is more important than refrigerants, from a global warming perspective

Another conclusion known *a priori* is that the global warming potential of refrigeration and air conditioning equipment is dominated by CO_2 emissions from electricity generation, even in the many LAC countries that have low-emission electricity generation. Thus, under no circumstance, the equipment installed by the ESCO should consume more energy than the alternative, even when the new equipment requires the use of an HFC. Principal in this category would be mini-split air conditioners, as discussed below.

Mini-split air conditioning equipment has become very popular in recent years. In LAC countries, most new equipment no longer uses HCFC-22. However, R-410A (an HFC with high GWP, 2088) remains the dominant refrigerant. At the present time, no mini-split A/Cs with very low GWP is commercially available anywhere, except for some models using R-32 in Mexico, Panamá, and possibly other countries in the region. However, Daikin and other manufacturers offer mini-split A/Cs using R-32, an HFC with relatively small GWP (675). Many of these models are energy efficient in design and moreover incorporate inverter technology that reduces seasonal energy use. Therefore, we would recommend that ESCOs install mini-split A/Cs, where they are appropriate from a design perspective, but always choosing high efficiency equipment, using inverter technology and R-32 as refrigerant.

The selection of high-efficiency mini-split A/Cs by ESCOs, and by individual purchasers of such equipment, would be greatly favored by the existence of national efficiency labeling and minimum energy performance standards. The larger LAC countries, and a few others, already have such programs, while others are in the process of developing them. However, there is often a range of equipment efficiencies in any country. An ESCO could choose among the most efficient available, provided they are cost effective.

Moreover, a proposed bulk-purchase agreement between the ESCO and manufacturers could permit a price reduction to improve cost effectiveness. Such price reduction may benefit other purchasers as well, if a general price reduction can be stimulated by the initial bulk purchase agreement.

While mini-split A/Cs using R-32 are widely available in Europe and elsewhere, they are generally not available in LAC countries. For example, while Colombia has announced ambitious plans to reduce GHG emissions in air conditioning, through a NAMA, including the extended use of mini-split A/Cs using R-32, the latter equipment cannot be used in Colombia, pending certification procedures. Even in large countries such as Colombia, the LAC market is considered small by manufacturers for them to make the effort to obtain the necessary certification. Thus there is a "Catch-22" situation: no R-32 A/Cs are installed since they are not yet certified, while manufacturers do not get certification since the market does not exist. We believe that this barrier would be removed once the NAMA becomes operational. In the meantime, an ESCO such as MSEF may be able to resolve this by simultaneously proposing installations and promoting certification.

Where the mini-split A/Cs to be installed are in replacement of existing A/C equipment based on HCFC-22 or R 410A, we again state the need and benefits of an effective recycling program.
This review also leads to tentative new conclusions, described below.

C. There is very little scope for ground source heat pumps in LAC countries

Much of LAC is in the inter-tropical region, where the annual (seasonal) variation in air temperature is relatively small, so that no thermodynamic benefit can be drawn from differences in air temperature and temperature a few meters below ground, the latter tending to remain close to the annual average above-ground temperature. The southern cone has temperate climate with substantial seasonal variations in air temperature. There are few ground-source heat pump installations so far, and it remains to be seen if the market can be large enough to justify the technical infrastructure for the large investments needed.

D. The market for evaporative cooling needs to be explored further

Evaporative cooling is a technology that has been available for a very long time, perhaps hundreds or thousands of years. A climate map shows that there are desert areas along the Pacific coast where evaporative cooling may be feasible. Given altitude variations, local studies would be needed to define technical and economic potential. A detailed study in Colombia indicated regions where this technology would work and there are a number of A/C installations in Medellin and Bogotá that use the technology with good results. Water shortage could be a problem in the dry climates where evaporative cooling would work. Some of these regions, e.g. Baja California, use sea water desalination to obtain fresh water, a very energy intensive process. There are a number of promising technologies that are not yet available commercially. These include hybrid systems for evaporative cooling and desalination and Desiccant Enhanced Evaporative Air Conditioning (DEVap), which could be applicable in humid climates as well.

E. Absorption cooling may be an attractive alternative for building A/C and industrial refrigeration

Absorption cooling is another alternative to vapor compression. It is a mature technology with a number of equipment suppliers. While it is less energy efficient compared to vapor compression, the cooling is provided by a heat source, which can be waste heat from an industrial process, from thermal power generation, or from solar energy. Using waste heat, absorption cooling requires little electricity so that it can be electrically efficient, in terms of cooling capacity per kW (electric). Another attractiveness of absorption cooling is that it uses refrigerants that are not GHGs: typically lithium bromide or ammonia/water. A recent installation of absorption cooling, together with electric chillers using ammonia, supply cold to the EPM District Cooling project in Medellín, Colombia.

A solar powered absorption A/C system has been proposed for a building in a university, also in Medellín, as part of the NAMA on air conditioning in Colombia. Investment requirements for absorption cooling systems for buildings are within the range accessible to ESCOs, so that the technology is promising.

Absorption cooling can be used to achieve very low temperatures, and there are equipment providers for such industrial applications, again within reach of ESCO investment capacity.

F. District cooling, including sea water air conditioning, has large potential in LAC

We noted a district cooling system based on absorption cooling installed by EPM in Medellín. There are other district cooling systems in Colombia: in Serena del Mar and CC Nuestro Uraba. These systems provide cooling to a number of buildings from a central system which includes a natural gas fueled power plant, as well as auxiliary chillers. The design of district cooling systems not only requires large investments but also the existence and interest of potential clients for the cooling. This is even more the case for sea water air conditioning systems. In this case, the demand needs to cover a larger number of buildings, and would likely require municipal or other state participation in such projects. However, a number of studies on sea water air conditioning systems have been conducted, including surveys of deep-sea temperatures, so that such systems may be installed in the Caribbean or in coastal LAC in the near future, as they have been elsewhere.

Limited district cooling systems, covering a few buildings belonging to a single owner, may be feasible for an ESCO.

G. Central cooling systems for buildings can be an alternative to a set of mini-split systems

Even more limited than district cooling is the provision of centralized cooling for a single building. In fact, MSEF already has experience in this regard, with the installation of a central cooling system in an office building, belonging to the Q-Office chain. The building is occupied by different companies. MSEF provides cooling to each, using a control and measurement technology that allows users to control their demand for cold, and for MSEF to charge users for the amount of "cold" consumed. In this case, the new technology comprised an improved control and monitoring system, accompanied by a different business model. In the future, the central cooling system could also include a different cooling technology, such as absorption cooling to further reduce the carbon footprint of building cooling. Even if the central cooling system is based on vapor compression, it could be based on a refrigerant other than any HFC, including R-32. Refrigerant 1234yf is another possible refrigerant. Moreover, the central system could have a higher COP compared to a set of mini-split systems.

H. There are many technologies for supermarket refrigeration and air conditioning

Supermarkets require refrigeration or freezing of many products sold, so that this commercial building sub-sector is one of the most energy intensive. Moreover, in lower altitudes, in the inter-tropical regions of LAC, large supermarkets would require air conditioning for all or most of the year. Smaller stores may not have air conditioning, while in the Southern part of South America, air conditioning would be needed for only a part of the year.

Unitary refrigeration equipment (e.g. stand-alone refrigerators and freezers) installed within supermarkets generate heat that is liberated within the conditioned space, adding to the air conditioning demand, where present, or overheated interiors where absent. Energy-efficient unitary equipment would reduce this cooling demand, thus providing an additional energy savings. Open display cases increase energy use of the equipment involved, leading to larger release of heat into the conditioned space. While some supermarkets use enclosed refrigerators and freezers, others continue to use open display cases, leading to additional energy consumption for refrigeration and for air conditioning. An ESCO cannot change real or perceived loss of sales from glass or other transparent doors to display cabinets. However, whenever possible, the ESCO should encourage the use of enclosed display cases and cabinets.

As far as equipment used for refrigeration and freezing, a wide range of refrigerants are available. A number of studies indicate that energy efficient equipment using hydrocarbons, trans-critical CO_2 and possibly R-290 (hydrocarbon) as alternative refrigerants may have the lowest total equivalent warming impact (TEWI). Note that the total quantity of hydrocarbons within a given space needs to be limited due to considerations on flammability. Moreover, since many of the studies were conducted in supermarkets located in temperate climates, where there is a greater demand for space heating, the results on optimal equipment choice cannot be assumed to be valid in LAC. Regional pilot installations and documented case studies would be needed to determine optimal technologies for supermarkets in the different LAC regions.

While open food display units are not encouraged, they are still widely used, and there are a number of manufacturers with equipment using hydrocarbon (De Rigo), CO_2 (Hillphoenix, Hussmann), and possibly even solid-state cooling equipment (Grener systems). Technology suppliers in Colombia include Imbera, Indufral and Inducol, all offering R-290 refrigerant for small retail equipment. Note that energy use of open display cases depends on ambient temperature, and no performance data are provided by manufacturers. Therefore, there would be a greater need to measure in-situ performance in test installations and determine not only direct energy use of the equipment, but also the energy impact on air conditioning.

For supermarket air conditioning, as in any air conditioning, the heat is rejected outside the building thermal envelope, e.g. through equipment mounted on the roof. Cold storage rooms in large food distribution centers keep food at refrigeration temperatures (4 C) or frozen (-18 C). Again, heat is rejected outside the refrigerated rooms. In other supermarkets, food display cases may also be cooled in this way, with heat rejected outside the building thermal envelope. In this case, any cold lost from the display units (e.g. through door openings or because there are no doors at all) will contribute to building air conditioning, without significant additional energy use, since the heat is rejected outside the building and does not add to the cooling load of the air conditioner. Energy efficiency of both food display units as well as supermarket air conditioning systems remains to be high so as to minimize electricity used for cooling.

Food display units that are centrally cooled, with heat rejection outside the building thermal envelope need to be site-built, and are most appropriate at the time of construction of new supermarkets and during major overhauls. Site-built refrigeration systems allow for a wider choice in component sizing as well as refrigerant compared to plug-in unitary cooling equipment.

I. Technology advances need to be tracked

Refrigeration technology has evolved over time, with the most recent advances motivated by climate change mitigation through improved energy efficiency as well as alternatives to high-GWP refrigerants. Thus, a review such as this report needs to be updated periodically, perhaps twice a year in order to ensure that new manufacturer offerings are incorporated in equipment and system choice. Moreover, some products may not be commercially available in the LAC region. Since these may be relevant to the region, manufacturers should be encouraged to expand their geographical coverage.

Some refrigeration technologies mentioned in this review were considered not commercially available. However, some of these technologies, especially desiccant enhanced evaporative cooling and solid-state cooling may become commercial in the near future, expanding the choice of cooling technologies.

J. Barriers to specific technologies need to be tracked

We have noted that certain technologies are not available in the LAC region, for a variety of barriers, including country regulations, e.g. restrictions on “new” refrigerants, such as R-32 in air conditioners, hydrocarbon refrigerants, etc. Manufacturers may limit their product offerings because historic demand for certain technologies has been limited. The existence of such barriers should be tracked with a view to encourage their removal when possible.

K. Review and update energy efficiency labeling and minimum energy performance standards in all LAC countries.

Building thermal performance is key to reduced air conditioning (and space heating) energy use. Some LAC countries have taken steps to improve building thermal performance, including energy efficiency labeling and minimum energy performance standards (MEPS). This report only included a brief review of country measures. Prior to investments in any country, these norms need to be reviewed in order to ensure that equipment are sized accordingly to be compatible with air conditioning demand.

L. Review and update emissions factors for electricity generation in each LAC country

The energy mix for electricity generation in each country and interconnected region is outside the scope of a review of technologies for refrigeration and air conditioning. However, the emissions reduction through reduced electricity use will depend on this energy mix, and especially the emissions factor for electricity generation, as well as transmission and distribution losses. The emissions factor for some LAC countries are included in this report. However, since the value changes as new generation plants are added to the grid and old plants removed, the emissions factor changes over time. The impact of these changes needs to be tracked annually. Moreover, one should keep in mind that clean cooling technologies would have a higher impact in countries or regions with a high emissions factor, where liquid petroleum fuels make up a significant part of power generation, such as in the Caribbean islands and in some parts of Central America.

M. Review and update electricity tariffs

Electricity tariffs are not a part of any technology review. However, the commercial viability of many energy efficient cooling technologies depends on electricity tariffs. Hence electricity tariffs need to be reviewed and updated, especially for those user groups with the largest potential for the application of clean cooling technologies, e.g. commercial and public buildings, commercial refrigeration, etc. New technologies may be most relevant for installations in countries with high tariffs. However, this experience would allow the technologies to be demonstrated and acquire maturity in the LAC region, permitting their application in other countries as well.

References and additional bibliography

Note: *This report was edited to be shorter and more readable. However, in the interest of completeness, all the references in the longer version have been maintained, since many of these provide additional information on the subjects discussed.*

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Appendix A. Building energy efficiency labels and standards

One way of promoting energy efficiency in buildings, especially in cooling and heating, is through energy efficiency labels and minimum energy performance standards.

Country	Standard	Name and/or brief description	Comments and relevance for ESCOs
Argentina	IRAM 11900/ 2017 y 2019	Prestaciones energéticas en viviendas. Método de cálculo	Application only to residential buildings, not very relevant for ESCOs
Argentina	IRAM 11507-6: 2018	Calificación y Etiquetado de Carpintería de Obra (Ventanas exteriores)	Only for windows. Under trial. Evaluation software: https://etiquetadoventanas.energia.gob.ar/
Brazil	RTQ-C, 2010, mod 2012, 2013, and 2014	Energy efficiency of commercial and public buildings. Labeling under development.	
Colombia	RITE 2017	Reglamento Técnico de Instalaciones Térmicas en Edificaciones	Limited to installations. Includes standards for piping insulation, but not for thermal envelope
Costa Rica	INTE 06-12-01:2014/Enm 1:2017	Construcción. RESET. Requisitos para Edificaciones Sostenibles en el Trópico.	Includes criteria for sustainability, where energy efficiency comprises some elements. Does not specify thermal insulation.
Mexico	**NOM-008-ENER-2001**	Eficiencia energética en edificaciones, envolvente de edificios no residenciales.	For building thermal envelope, not very relevant for ESCOs
Mexico	**NOM-011-ENER-2006**	Eficiencia energética en acondicionadores de aire tipo central, paquete o dividido. Límites, métodos de prueba y etiquetado.	Efficiency of air conditioners, central, packet and split.
Mexico	**NOM-018-ENER-2011**	Aislantes térmicos para edificaciones. Características, límites y métodos de prueba.	Only for materials, not relevant for ESCOs
Mexico	**NOM-020-ENER-2011**	Eficiencia energética en edificaciones, Envolvente de edificios para uso habitacional.	Applicable only to residential buildings, not relevant to ESCOs

Besides national mandatory standards, there are processes for the voluntary certification of energy efficiency and other parameters of building sustainability. The best known one is **Leadership in Energy and Environmental Design** (LEED) developed by the US Green Building Council, leading to the Green Building Certification Institute. LEED certification has extended to buildings in many Latin American countries, including Argentina, Brazil, Chile, Colombia, Mexico, Peru. Green Building Council chapters exist in most LAC countries, some of which are listed below.

Country	Local name	Website
Argentina	Argentina Green Building Council	https://www.argentinagbc.org.ar/
Brazil	Construindo um futuro sustentavel	
Chile	Chile Green Building Council (Chile GBC)	
Colombia	Consejo Colombiano de Construcción Sostenible (CCCS)	https://www.cccs.org.co/wp/
Costa Rica	Consejo de Construcción Verde de Costa Rica	https://www.gbccr.org/
Mexico	includes Sustentabilidad para México (SUMe), the Green Building Council for México, and the Green Business Certification Inc.	https://www.gbci.org/mexico,

Brazil

While there are building energy efficiency standards for residential buildings (RTQ-R), the most relevant here are those for commercial and public buildings: RTQ-C (Technical quality requirements for energy efficiency levels for commercial and public buildings)[73]. There is also an Application Manual for RTQ-C[74].

There is also a labeling program for building energy efficiency. An example of the label for commercial and public buildings is shown below[75].

[73] http://www.pbeedifica.com.br/etiquetagem/publica/regulamentos
[74] http://pbeedifica.com.br/sites/default/files/projetos/etiquetagem/comercial/downloads/manualv02_1.pdf
[75] A brief introduction can be found in http://pbeedifica.com.br/conhecendo-pbe-edifica

There is also a label "Selo PROCEL" (PROCEL seal) for energy efficient building, applicable to buildings that exceed a certain level of efficiency, including being in efficiency class A for the thermal envelope, lighting, and air conditioning[76]. An example of a PROCEL seal, accompanying the energy-efficiency label is shown below.

PROCEL seal for buildings

Example of Energy efficiency label for buildings

[76] Details in http://www.procelinfo.com.br/main.asp?View={E85A0ACC-8C62-465D-9EBD-47FF3BAECDAE}

Appendix B. Beyond the thermal envelope: other measures to reducing cooling energy demand in buildings

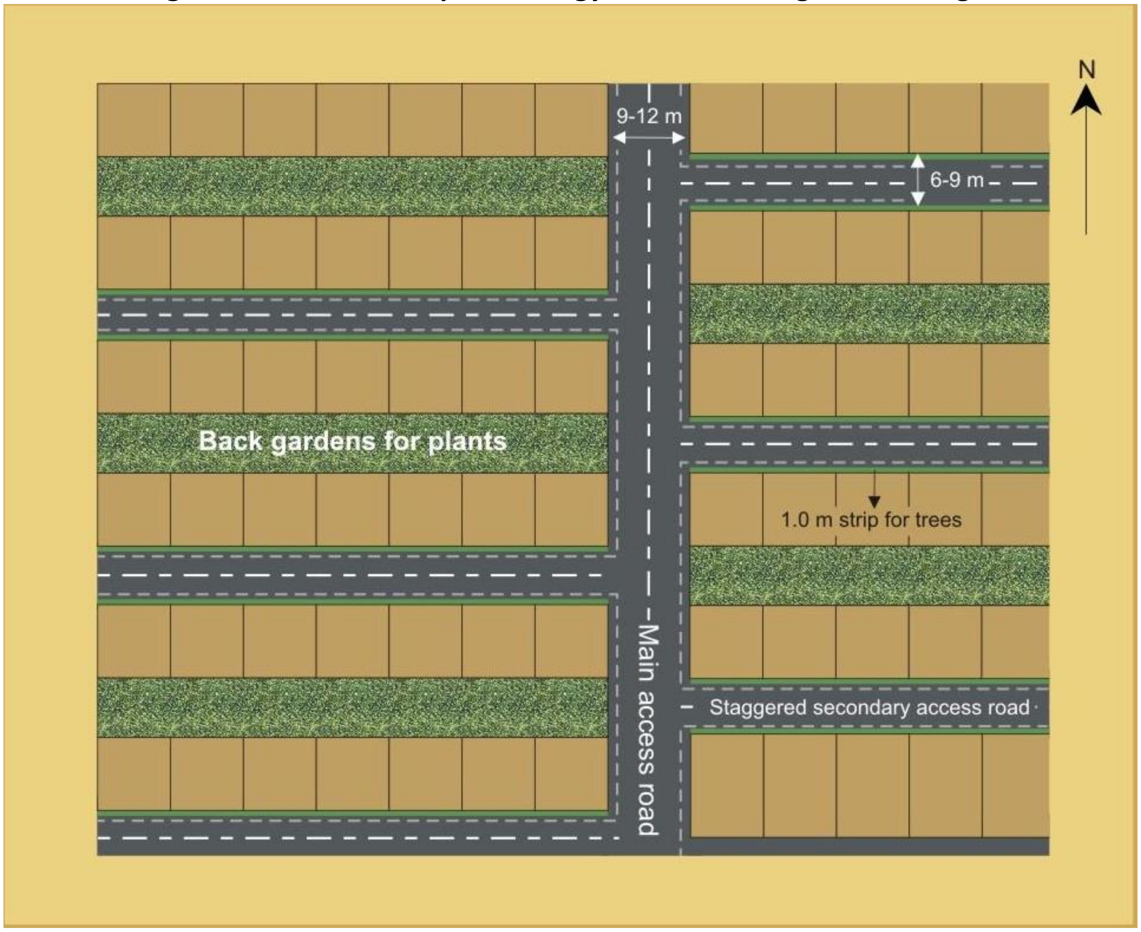
Building energy performance standards (BEPS), as described in Appendix A, are important in building energy consumption.

The Global Alliance for Buildings and Construction identified nine key priorities in a roadmap, (UNEP/IEA, 2017, p. 13), most of which with relevance to cooling energy use in buildings, including the buildings as well as the urban environment, as highlighted in the list below:

1. ***Use urban planning policies to impact the form and compactness of buildings to enable reduced energy demand and increased renewable energy capacity.***
2. ***Increase the rate of building energy renovation and increase the level of energy efficiency in existing buildings.***
3. ***Increase uptake of net-zero operating emissions for new and existing buildings, including through system-level solutions such as zero-carbon district energy.***
4. ***Reduce the operating energy and emissions through improved energy management tools and operational capacity building.***
5. ***Integrate renewable energy and reduce the carbon footprint of energy demand in buildings.***
6. *Reduce the environmental impact of materials and equipment in the buildings & construction value chain by taking a life-cycle approach.*
7. ***Collaborate with global initiatives to reduce the energy demand from appliances, lighting and cooking.***
8. *Reduce climate-change related risks of buildings by adapting building design and improving resilience.*
9. ***Support training and capacity building including educational and informative tools to make the case for sustainable buildings and construction.***

Passive cooling techniques, not covered by building energy performance standards, could include building orientation, urban space design, use of trees and other vegetation around buildings, as well as roof-tops. See Box below on how street and building orientation can reduce heating and cooling demand in houses.

Building orientation can help cut energy use for heating and cooling homes



The sun moves across the sky from east to west, and hangs lower in the sky in winter than in summer. Thus, in moderate to high latitudes, south-facing windows in the northern hemisphere allow the winter sun to heat a building, while the higher summer sun can be easily blocked by an awning on the southern windows. Even in low-altitude, tropical locations, with no requirement for space-heating and a reason to keep solar heat out, north- and south-facing windows are preferable to east- or west-facing ones. Opportunities to benefit from building orientation have no cost provided windows can be appropriately oriented. For houses on small plots of land, this requires streets to be oriented in certain ways. The illustration shows a highly desirable land sub-division plan for high-density low-rise houses. While the plan was proposed for tropical climates, the same orientation scheme would also be appropriate for higher latitudes in both northern and southern hemispheres.

Energy for Sustainable Development, vol. 11, no. 4, back cover illustration and text by Gautam S. Dutt, journal editor, based on paper by Halwatura and Jayasinghe, 2007.

Appendix C. Selected companies and cooling technology providers suitable for investments in Latin America and the Caribbean

A number of cooling technologies were compared in an Excel sheet "181204_Technology list from 29oct workhsop_review CF.xlsx", prepared for a workshop held on October 29, 2018[77]. It provides a brief review of the most relevant technologies.

The technologies listed in the Excel table included some applications (called "Primary segment" in the Excel table) that are not relevant for the present review. These include:

- Transport Refrigeration – Road
- Farm and Pack houses

The remaining applications are abbreviated as follows:

Com.	Commercial Refrigeration
CSFP	Cold Storage and Food Processing
CSPH	Cold Storage and Pack Houses
Dom.	Domestic Refrigeration
D, C and T	Domestic, Commercial and Transport Refrigeration
HMCM	Household, Medical, Commercial, Military
Ind.	Industrial Refrigeration
Unit.	Unitary Air Conditioners

Technologies listed have been labeled with a Technology readiness level (TRL), originally defined by the National Aeronautics and Space Administration (NASA), but which has since been applied to other technology areas. In general, higher TRL numbers indicate more mature technologies. NASA' original definition[78] went from Level 1 – Basic Principles Observed and Reported to Level 7 – System Adequacy Validated in Space. The Excel file cited above, provides its own definitions, as listed below.

Only TRLs 8 and above have been selected in the shortened list here, as sufficiently mature to represent investment opportunities in the near future, and comprise:

- TRL 8 - Product Developed
- TRL9 - In Production
- TRL10 - Mature Offering

Thus, the following categories were excluded:

- TRL1-3 - Theoretical Viability
- TRL4 - Lab Demonstrator
- TRL5-6 - First Field Tests
- TRL7 - Scale Trials

[77] The exact details of the workshop are not available. It was likely a K-CEP workshop. The Excel file was made available to MGM Innova as part of background documentation for the K-CEP grant.
[78] https://en.wikipedia.org/wiki/Technology_readiness_level

The Excel table, cited above, included many more columns, with information on company location, size of company defined by number of employees, and website. A number of companies clearly were limited to a single country (e.g. India or Kenya), so that they are also not relevant to LAC. Table 15 provides a short list of the remaining companies and technologies, with comments on each alternative, using the following color code:

Not relevant for Energy Service companies in LAC
Probably not relevant
Possibly relevant

As noted in the comments column of Table below, very few technologies are likely to be relevant for investment by MSEF or other ESCO operating in LAC. These include two providers of systems based on CO_2 as refrigerant (Green & Cool[79]; Enex[80]), a control system for A/C (Smartcool[81]), a mature company offering ice energy storage (Ice Energy[82]), and a product that provides cooling from below in open produce displays (Cool Plates from Grener Systems[83]). These companies/technologies are highlighted in green below and discussed in more detail in the main text of the review. A number of other companies and technologies could be relevant and are highlighted in yellow below.

79 https://www.greenandcool.com/en/products-overview/
80 https://www.enex.it/en/
81 https://smartcool.net/
82 https://www.ice-energy.com/commercial-industrial/
83 https://www.coolplates.nl/en/

Table 15. Selected list of companies and technologies for providing cooling and refrigeration.

No.	Company	Technology	Technology Type	Primary Segment	Dev. Status	Comments, including MGM Innova
2	Sure Chill	Sure Chill	PCM New Applications	Com.	TRL9	Recent investment of £5m. Provides cooling from "consistent power" using ice formation as regulation. Ice as phase change material.
3	Cold Hubs	Cold Hubs	VCC - Controls & Cycle Optimisation	Com.	TRL9	Nigerian company solar energy, for solar powered cold storage of food.
5	Optimised Thermal Systems	VapCyc	VCC - Controls & Cycle Optimisation	Com.	TRL9	Simulation tools and cycle design.
7	Polysolar	Building Integrated PV	Shade/Reduced Solar Gain	Other	TRL9	PV integrated windows & glass products.
9	Smartcool	EC03 & ESM	VCC - Controls & Cycle Optimisation	Unit.	TRL10	Control system with HVAC and refrigeration apps
10	Haier	SolarChill	PCM - New Applications	Com.	TRL10	Solar PV with Ice energy storage. For vaccine storage.
11	Palfridge (The Fridge Factory)	SolarChill	PCM New Applications	Com.	TRL10	Solar PV with Ice energy storage. South African manufacturer of small equipment.
12	Vestfrost	SolarChill	PCM New Applications	Com.	TRL10	Solar PV with Ice energy storage. Specialized equipment manufacturer.
13	Green & Cool	CO_2 Systems	VCC - Refrigerant Selection	Com.	TRL9	CO_2 cooling system manufacturer
14	Enex	CO_2 Systems	VCC - Refrigerant Selection	Com.	TRL9	CO_2 cooling system manufacturer
15	SolabCool	Solabcool	Absorption Chilling	Unit.	TRL 8	Heat to cold + water recovery
16	Purix	Purix	Absorption Chilling	Unit.	TRL 8	Solar powered, small size equipment
21	Cooltech	Magnetic Refrigeration System	Magnetic	Dom.	TRL 8	Magneto Caloric Effect, no refrigerant. Product may not be commercially available yet. http://www.cooltech-applications.com/our-solution.html
22	Enwave	Thermal Energy Storage	Heat Sinks (e.g. ground source, LNG)	Unit.	TRL9	District cooling system using lake water. Group focus is on district heating and cooling
23	Cristopia (ciat)	Cristopia	PCM New Applications	Chillers	TRL9	Phase change materials for storing cold.
24	GuardTop	CoolSeal	Shade/Reduced Solar Gain	Other	TRL10	Emulsion based sealant for asphalt and pavements
26	Ice Energy	Ice Bear	PCM New Applications	Unit.	TRL10	One of the original Ice/AC integration companies

28	Axiom Energy	Refrigeration Battery	PCM New Applications	Com.	TRL 8	Provides building management services and software.
29	Ecozen	Ecofrost	PCM - New Applications	Com.	TRL 8	Indian manufacturer of solar energy integrated cold room with eutectics for small scale farmers
33	Mitticool	Clay Refrigerator	PCM New Applications	Dom.	TRL9	Exploits evaporative cooling effect of water. Indian manufacturer of small refrigerators.
34	Aldelano	Aldelano Solar ColdBox	VCC - Controls & Cycle Optimisation	Ind.	TRL 8	PV integrated cold boxes - refrigeration cycle details unclear almost certainly VCC. For off-grid applications
36	Dulas	Freeze-Free	PCM - New Materials	Com.	TRL9	PCM alternative to water for solar freezers. Small size equipment.
37	Dulas	Solar Refrigerator	PCM - New Applications	Com.	TRL9	Solar refrigerator part of the WHO group of offerings, some development in evidence of PCM beyond basic ice. Small size specialized applications
40	Weltevree	Ground Fridge	Heat Sinks (e.g. ground source, LNG)	Dom.	TRL 8	Pre-fab root cellar
44	Emerald Environmental Technologies	Geo3	Heat Sinks (e.g. ground source, LNG)	Chillers	TRL9	Geo3: Modular geothermal heat pump system for chiller type applications. Other products are for specialized applications, e.g. ice rinks.
49	Ozefridge	Ozefridge	PCM New Applications	Dom.	TRL 8	Combination Eutectic and low voltage system for mobile applications. Small Australian manufacturer of small equipment
52	Monodraught	COOL-PHASE	PCM New Applications	Unit.	TRL9	PCM in room AC integration with proprietary controls https://www.monodraught.com/products/natural-cooling/cool-phase
53	PCM Products	PlusICE Eutectics	PCM - New Materials	Com.	TRL 8	PCM formulation company (controversial with Hubbard)
55	Yazaki Corporation	Absorption Chiller	Absorption Chilling	Chillers	TRL10	Group has interests in electrical systems (e.g. PV and automotive harnesses) as well as HVAC equipment

58	Toro Water Air Thermal Technologies Corp	Split path air conditioning	VCC - Air Handling	Unit.	TRL9	Operates by separating dehumidifying and cooling functions. Indian subsidiary of a Canadian business - but Indian business seems to predate
59	Hubbard	Simply Air	Heat Sinks (e.g. ground source, LNG)	Com.	TRL9	Rejects heat to outside not into store. MGM could not find much information on products.
60	Phoebus Energy	Hydrabalance	Heat Sinks (e.g. ground source, LNG)	Chillers	TRL9	Uses heat rejected from AC for water heating, also sub cools refrigeration cycle on AC system to reduce energy requirement
65	Phononic	Evolve	Peltier Effect	Com.	TRL 8	Peltier effect solid state cooling. MGM: For data centers and other specialized applications, probably because of small size. Peltier effect tends to be less efficient cooling.
69	Software Motor Company	Software Commutated Motors	VCC - Air Handling	Unit.	TRL9	Switched reluctance motor with efficiency improvements. Also integrates with building management systems.
70	Fahrenheit	Adsorption Chilling with Zeolite	Adsorption Chilling	Chillers	TRL9	Offers alternate adsorption materials for greater compactness. Waste heat to cooling. Combined heat and power. Solar heat for cooling.
71	Grener Systems Nederland BV	Cool Plates	New categories (e.g. micro-emulsions)	Com.	TRL9	Spot cooling of produce from below. Use in fruit/vegetable stores and supermarkets. Cooling process not explained in Dutch manufacturer information, perhaps thermoelectric cooling
73	MetaFridge Vaccine Refrigeration	MetaFridge	PCM - New Applications	Com.	TRL 8	Vaccine fridge designed to deal with extreme power fluctuations, hardened electronics and an integrated ice store. Being manufactured by Qingdao Aucma Global Medical Co Ltd of China

Appendix D. IIEC Efficient and Clean Cooling Technologies

The International Institute for Energy Conservation (IIEC)[84] listed a number of clean cooling technologies according to the following categories:

- Cold Storage and Food Processing
- Commercial Refrigeration
- Domestic Refrigeration. Not relevant
- Domestic, Commercial and Transport Refrigeration
- Farm and Pack Houses. Not relevant
- Household, Medical, Commercial and Military Refrigeration. Not relevant
- Unitary Air Conditioners

Some of the categories are not relevant for ESCOs operating in LAC, as noted above. The IIEC compilation included a brief description of the technologies. Those in the relevant categories are copied below. The brief description provided by IIEC in their compilation has been copied from company websites, and is not adequate for evaluation of the different technologies.

In our review of the list, we may exclude some companies because of (a) country focus, e.g. India or Kenya; (b) targeted for small businesses in poor countries; (c) small, solar powered cooling. The most relevant of the remaining technologies, shown in larger font in the description below, are:

- Cooling System for fresh produce and seafood (Cool Plates)
- CO_2 Systems - Refrigeration Units (Enex)
- Transcritical refrigeration systems - Cooling System (Green & Cool)
- Split path air conditioning - Air Handling (Toro Water Air Thermal Technologies Corp)

Cold Storage and Food Processing

Technology

Fresh box - Refrigerated storage (Solar option) (FreshBox)

FreshBox's flagship product is a large commercial cooling unit that can hold over two tons of fruits and vegetables and fits conveniently in a vendor space at fruit and vegetable markets across Kenya. Our unique pay-as-you-go model allows us to reach customers that previously have not had access to refrigeration services and allows us to help prevent the spoilage of fruits and vegetables.

READ MORE

[84] http://www.iiec.org/coolingdemo-technologies#catid720

Technology

Energy efficient refrigerated storage - Cycle Optimisation (InspiraFarms)

InspiraFarms supplies a highly adaptable energy-efficient refrigerated storage and food processing solution for agribusinesses that face problems of loss reduction, energy reliability and market access.

The technology provides 30m² – 120m² of 2-14 ºC, automated, controlled and remotely monitored refrigeration storage and food processing space that can be adapted in both size and specific layout to suit needs.

READ MORE

Solar cool cube - Off-grid Solar powered cold rooms (Dgrid Energy)

DGridEnergy is a US-based social benefit company. Our mission is to provide renewable energy solutions that expand businesses, enhance livelihoods and empower communities by developing a refrigerated supply chain for temperature-sensitive products in emerging markets.

Solar Powered Energy Efficient Walk-in Refrigerator that is expandable as your needs grow.

Ecofrost - Portable, solar powered cold rooms (Ecozen solutions)

Ecofrost is a portable, solar powered cold room with storage capacity of 5 metric tons that does works with an efficient thermal energy storage to provide backup of over 30 hours. It is meant to be used for on-farm cooling and storage of produce right after harvest. With a wide range of temperature control, it is ideal for storing fruits, vegetables, flowers and other perishable commodities.

READ MORE

Commercial Refrigeration

Technology

Low ammonia charge system (Association of Ammonia Refrigeration)

Industrial refrigeration using Ammonia is being used in many installations and is now poised to grow significantly in India. For the efficient use of ammonia refrigeration proper knowledge, safety and training is important for the people and organizations involved.

READ MORE

Technology

Cooling System for fresh product and seafood (Cool Plates)

The cooling system of Coolplates is a modular system that cools fresh produce, fresh seafood on flake ice from underneath. Products keep their optimal condition longer and remain freely accessible. The system is simple and quick to install in most store environments. All you need is 220/240 volt connection. The Coolplates system can be installed in existing store displays or in a seperate refrigerating presentation unit. Depending on the situation and the size of the display unit, the building-up of the systeem requires one or more hours. The modular construction of the system makes it possbile to align the position of the coolplates at your own desired height.

READ MORE

CO_2 Systems - Refrigeration Units (Enex)

Since Enex was founded in 2004, it has been designing and developing exclusively high-efficiency refrigeration systems, using natural refrigerating fluids, in particular the carbon dioxide (CO_2). Enex has been the first company ever with this mission and it succeeded in revolutionizing the entire refrigeration sector. For this reason, nowadays the company is considered a technological excellence and can boast a leadership role in the commercial and industrial refrigeration markets.

READ MORE

Transcritical refrigeration systems - Cooling System (Green & Cool)

Green & Cool is a world-leading supplier of transcritical refrigeration systems that uses environmentally-friendly carbon dioxide (CO_2) as a refrigerant. In addition to outstanding environmental performance, the Green & Cool units offer superior lifetime economy and high reliability, as well as being very user-friendly. Green & Cool has developed modern CO_2 refrigeration to be a commercially-attractive alternative. CO_2 systems are developed to provide businesses that have less-demanding refrigeration requirements, such as small shops and petrol stations, with an affordable and uncomplicated, but environmentally friendly, option.

READ MORE

Technology

Walk-in, solar-powered cold stations - Controls & Cycle Optimisation (Cold Hubs)

ColdHubs is a "plug and play" modular, solar-powered walk-in cold room, for 24/7 off-grid storage and preservation of perishable foods. It adequately addresses the problem of post- harvest losses in fruits, vegetables and other perishable food. ColdHubs is installed in major food production and consumption centers (in markets and farms), farmers place their produce in clean plastic crates, these plastic crates are stacked inside the cold room. This extends the freshness of fruits, vegetables and other perishable food from 2 days to about 21 days. The solar powered walk-in cold room is made of 120mm insulating cold room panels to retain cold. Energy from solar panels mounted on the roof-top of the cold room are stored in high capacity batteries, these batteries feeds an inverter which in turn feeds the refrigerating unit.
READ MORE

Cooling System - Phase Change Materials New Applications (Sure Chill)

Sure Chill is a brand new kind of cooling system. It doesn't need a constant power source. In an on-grid situation with intermittent power, it works perfectly well. In an off-grid situation, where a solar panel may be used, a Sure Chill powered refrigerator doesn't even need a rechargeable battery. It shouldn't work but it does. And it works beautifully.

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Domestic, Commercial and Transport Refrigeration

Technology

Thermal Energy Storage (TES) for low temperature applications (Kehems)

Optimal energy management is imperative in today's environment where there is a growing need to be eco-friendly and where energy costs run high. The Kehems's TES system serves this very purpose as it applies the concept of energy storage to all types of air-conditioning, refrigeration and low-grade heating requirements, thereby enabling efficient Energy Management.

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Unitary Air Conditioners

Technology

Split path air conditioning - Air Handling (Toro Water Air Thermal Technologies Corp)

TORO WATT – a Canadian HVAC technology company based in Ontario, is a signatory to the Advanced Cooling Challenge, an initiative of Clean Energy Ministerial where TORO WATT committed to introducing a 50% more energy efficient residential Air Conditioner. TORO WATT designed & developed the Room Air Conditioner based on Dual Path Technology using conventional refrigerants for the time being but reduced refrigerant charge by 50% for the given capacity. Mass production of these units requires minor changes to the current manufacturing processes. The outcome besides reducing the refrigerant emissions by 50%, will also reduce the carbon footprint of the air conditioner by 50% reducing strain on the already stressed ecosystem. This changeover will actually be an opportunity to achieve a leapfrog effect when integrated with natural refrigerants like hydrocarbons /ammonia in the residential air conditioning. This should happen as the next logical step and sooner.
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Technology

Cool Phase Ventilation System - Phase Change Materials New Applications (Monodraught)

COOL-PHASE is an award winning natural cooling and low energy ventilation system that creates a comfortable, fresh and healthy indoor environment that can significantly reduce the running costs of buildings. The system uses the concept of a 'Thermal Battery' to capture and store heat and cooling energy. The Thermal Batteries use the latent heat property of a Phase Change Material (PCM) to store large amounts of energy. This PCM changes phase at room temperature and is charged and discharged by passing air through its thermal batteries releasing the stored energy when it is required. The COOL-PHASE system monitors indoor and outdoor temperatures, internal CO_2 levels and humidity and automatically ventilates the space via the means of an intelligently controlled Air Handling Unit.

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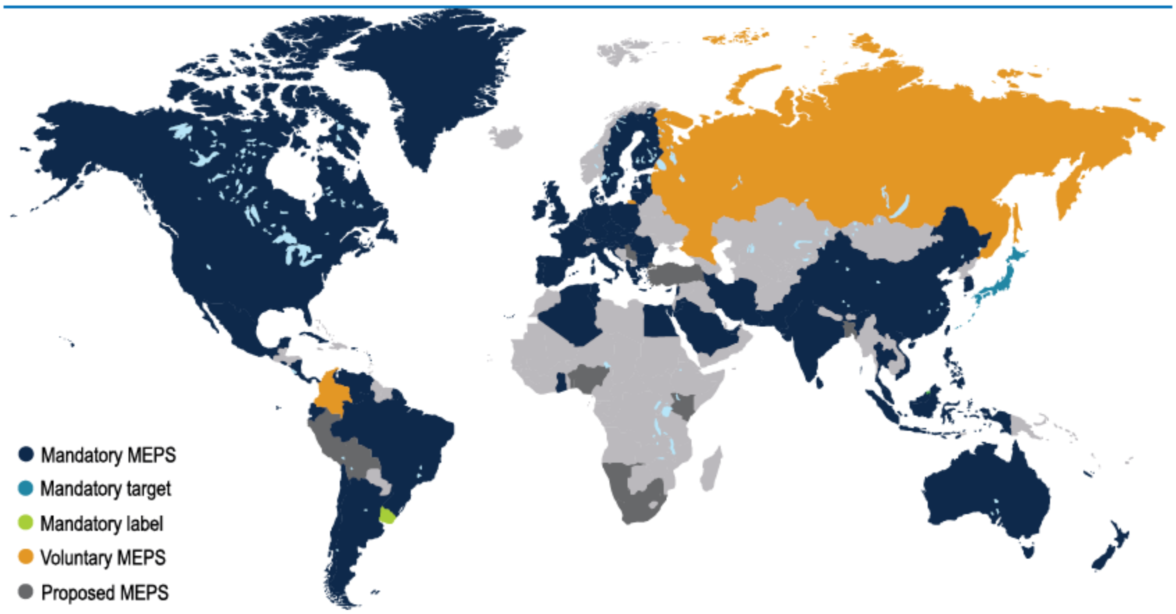
Appendix E. Energy efficiency labels and standards for air conditioning equipment

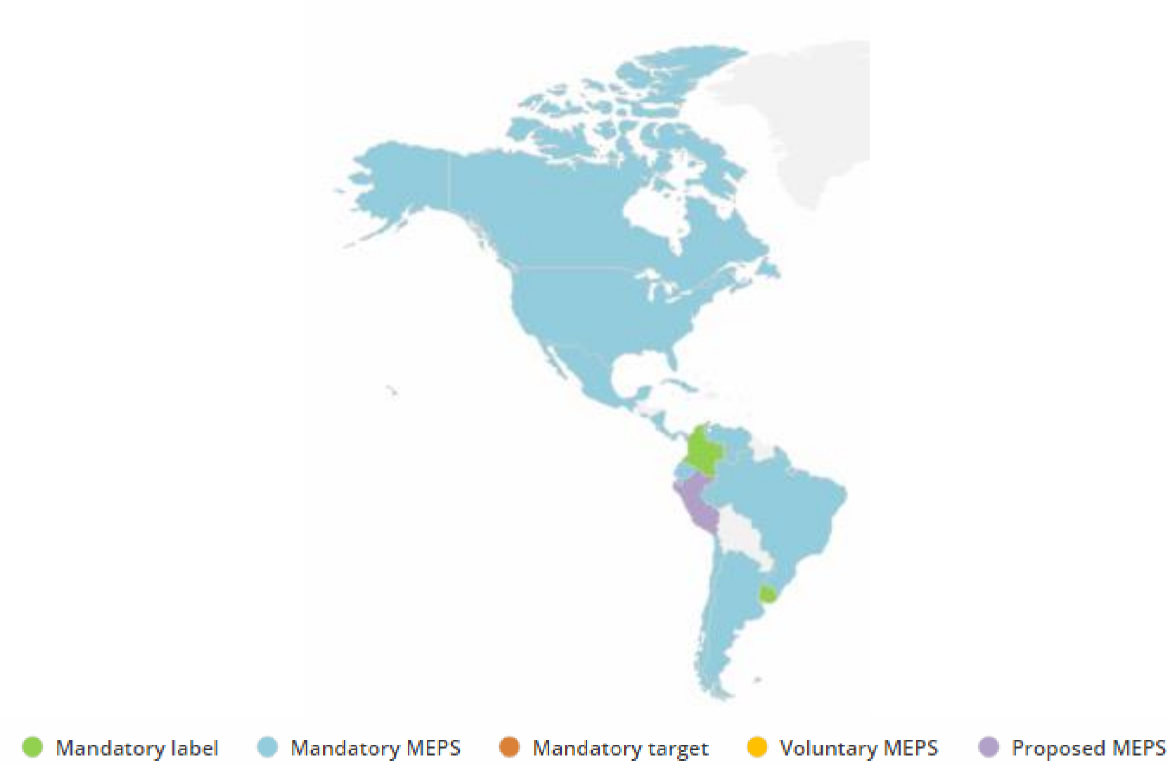
Energy efficiency labels inform consumers on the energy efficiency of products that they purchase, encouraging more informed decisions. Many countries go further, by requiring minimum efficiency performance standards (MEPS), so that products not meeting these standards cannot be commercialized in the country in question. The figure below shows a global compilation of the status of labeling and standards with respect to air conditioning equipment. It is understood that the standards are applicable to unitary equipment, e.g. mini-split A/Cs whose efficiency can be determined as a whole. Standards and labels cannot be applied to systems made up of different components, where system efficiency depends on component efficiency as well overall system design and installation.



Map of minimum efficiency performance standards (MEPS) and labeling

Source: IEA, 2018, Map 2.3.

An additional source of data is: https://www.iea.org/topics/energyefficiency/buildings/cooling/, which includes a map (presumably updated periodically, though the date is not listed) and link to an Excel sheet, which lists the status of countries with respect to labeling and standards.



Labeling and MEPS status in the Americas

Source: selected from map in https://www.iea.org/topics/energyefficiency/buildings/cooling/, accessed 15 August 2019.

Below is a summary of our own review of regulations regarding labeling and standards. For two countries in the table below (Chile and Costa Rica), we have noted that they have MEPS, as indicated in the IEA compilation above, although we have not been able to find details.

Labeling and standards requirements in selected LAC countries

(Source: MGM Innova compilation)

Country	Standard	Name and/or brief description	Comments and relevance for ESCOs
Argentina	IRAM 62406 2019	Labeling standard and efficiency classes, for cooling and heating, upgraded in 2019 to include inverter models as well as efficiency classes up to A+++	Yes, relevant, especially when models more than efficient than A become available. Standard is based on the EU label.
		SE 0228/2014: Establece como eficiencia mínima para equipos de aire acondicionado de hasta 7 kW From 2019, minimum A for cooling, and C for heating[85].	All models sold must be at least A in cooling mode, and at least C in heating mode.

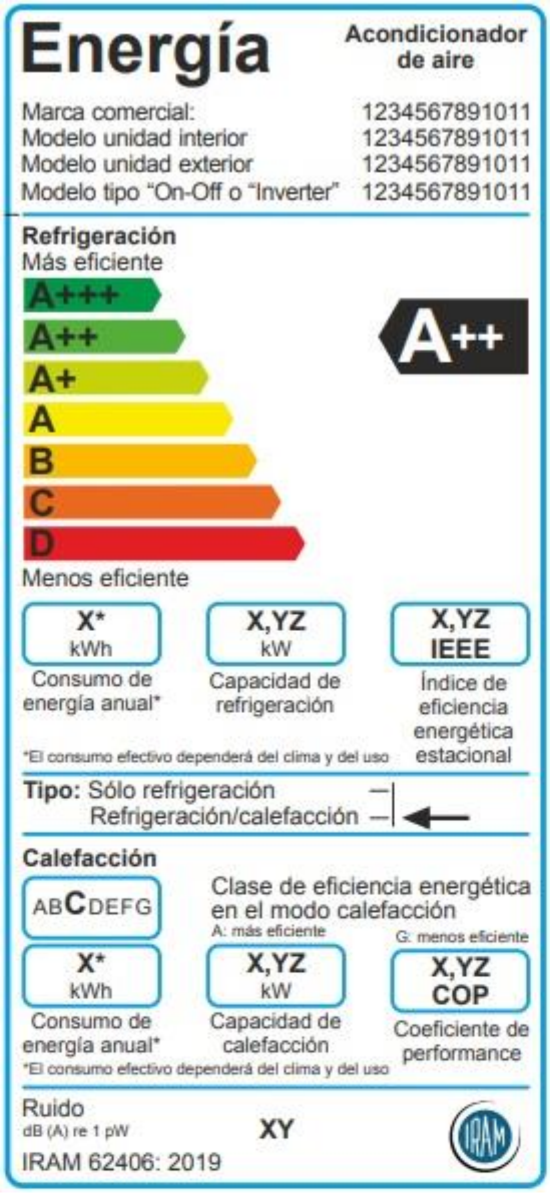
[85] https://www.argentina.gob.ar/energia/uso-responsable/en-el-living/aire-acondicionado

Brazil	INMETRO / MDIC no. 410 of 16/8/2013[86]	Labeling standard and efficiency classes, for both window (wall) type and split air conditioners	ESCOs can choose high efficiency models. Standard is not based on the EU standard.
Colombia	RETIQ	Reglamento Técnico de Etiquetado (RETIQ): Energy efficiency labeling requirement	ESCOs can choose high efficiency models.
Costa Rica	(MEPS)		
Chile	(MEPS)		
Mexico	NOM-021-ENER/SCFI-2017	Eficiencia energética y requisitos de seguridad al usuario en acondicionadores de aire tipo cuarto. Límites, métodos de prueba y etiquetado.	Not applicable to Split systems, not relevant
	NOM-022-ENER/SCFI-2014	Eficiencia energética y requisitos de seguridad al usuario para aparatos de refrigeración comercial autocontenidos. Límites, métodos de prueba y etiquetado.	Self-contained commercial refrigerators. Excludes cold rooms and beverage coolers.
	NOM-023-ENER-2018	Eficiencia energética en acondicionadores de aire tipo dividido, descarga libre y sin conductos de aire. Límites, métodos de prueba y etiquetado.	For split ACs. Yes, relevant
	NOM026-ENER2015	Eficiencia energética en acondicionadores de aire tipo dividido (Inverter) con flujo de refrigerante variable, descarga libre y sin ductos de aire. Límites, métodos de prueba y etiquetado	For invertor type split ACs, with variable refrigerant flow. Very relevant
Uruguay	UNIT 1170:2009	Eficiencia Energética - Acondicionadores de aire y bombas de calor - Especificaciones y etiquetado	This standard is from 2009. It does not appear to have been updated, e.g. to include inverter type equipment.

Argentina

Energy efficiency measurement procedures and energy efficiency labels in Argentina are based on European Union (EU) Regulations. In the case of air conditioners they are based on EU Regulation 626 of May 2011. The most recent version of the label design, as required by Argentina standard IRAM 62406 (2019) is shown below.

[86] http://www.inmetro.gov.br/legislacao/rtac/pdf/RTAC002015.pdf



Top ten Argentina publishes a list of the most efficient models. In the case of air conditioning, the models are divided into two categories:

1. Air conditioning (only cold): currently there are 11 models[87], all with the A rating, currently the minimum required. Cop values are around 3.3.
2. Air conditioning (heat and cold): , currently with 13 models[88], all with A/A rating, meaning A for cold and A for heat. Although an A rating is required for cold, the heat requirement currently in only a C. Generally the efficiency classes for cold and heat tend to be the same. The COP values for the 13 models are around 3.3.

[87] List updated 27 June 2019.
[88] List updated 27 June 2019.

Brazil

The Brazilian labeling system and efficiency classes are shown in the table below, with the A rating corresponding to a minimum of 3.23. http://www.inmetro.gov.br/consumidor/pbe/condicionadores_ar_split_hiwall_indicenovo.pdf, updated 14/08/2018.

Most A class models have a COP between 3.24 and 3.3, while the least efficient models (D class) are around 2.8, though a few models have a slightly lower value, e.g. 2.66. The table below shows that most fixed speed models were in the A,B or C classes, whereas virtually all variable speed models (i.e. inverter) were in the A class.

CONDICIONADORES DE AR SPLIT HI-WALL — **Data atualização: 14/8/2018**

Classes	Coeficiente de eficiência energética (W/W)			Split Hi-Wall			
				Rotação Fixa		Rotação Variável	
A	3,23	<CEE		390	42,5%	336	92,3%
B	3,02	<CEE≤	3,23	182	19,8%	22	6,0%
C	2,81	<CEE≤	3,02	276	30,1%	6	1,6%
D	2,60	≤CEE≤	2,81	70	7,6%	0	0,0%

Mexico

Mexico has had minimum energy performance standards (MEPS) for many years, covering air conditioners as well as many other household appliances and other equipment. The values corresponding to the most recent standards upgrade are shown below.

Range of SEER of Split system A/C equipment in Mexico
Nivel de la REEE, en acondicionadores de aire tipo dividido, descarga libre y sin conductos de aire
Source: SE-NOM-023-ENER, 2018

Capacidad de enfriamiento Watts (Btu/h)	REEE Wt/We (Btu/hW)
Hasta 4 101 (13 993)	3,37 (11,5)
Mayor que 4 101 (13 993) Hasta 5 859 (19 991,493)	
Mayor que 5 859 (19 991,493) Hasta 10 600 (36 168,26)	3,31 (11,3)
Mayor que 10 600 (36 168,26) Hasta 19 050 (65 000,505)	3,28 (11,2)

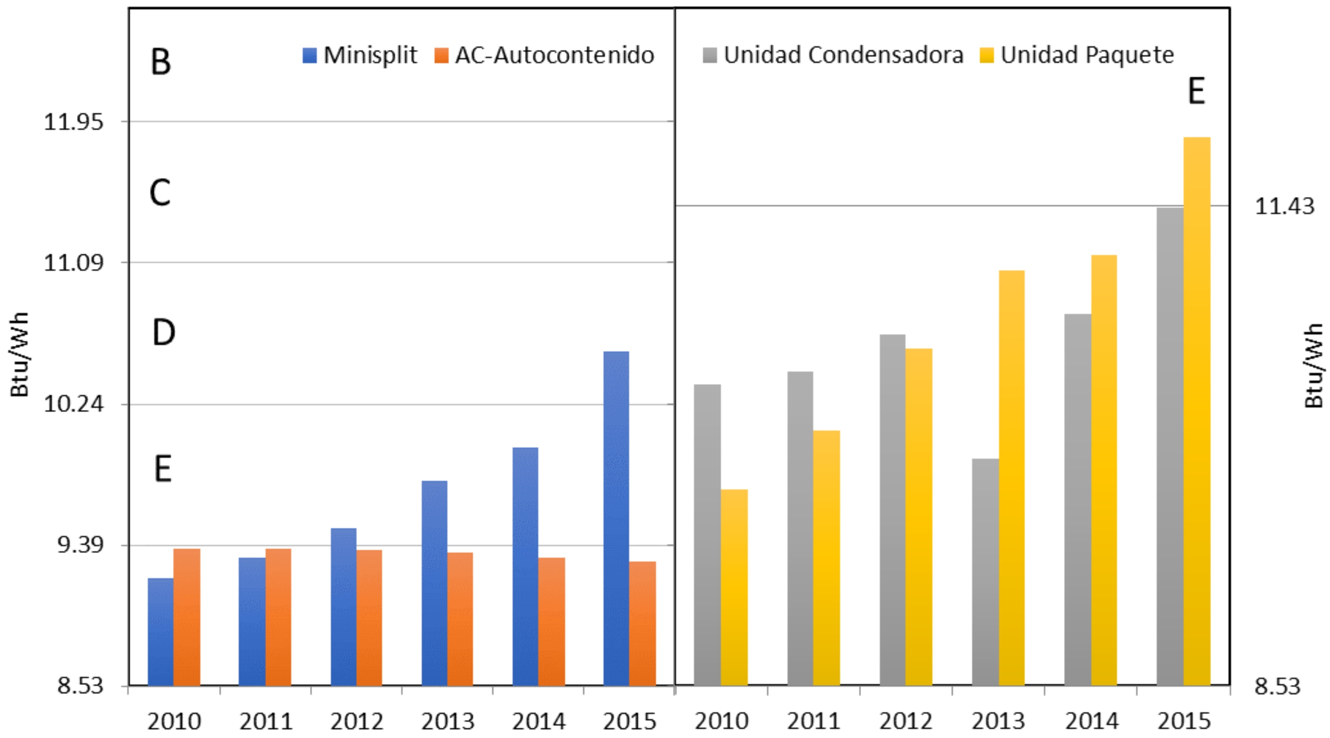
Colombia

Colombia initiated a labeling program in recent years, after Mexico, Brazil and Argentina. It is called RETIQ. However, the *efficiency requirements are higher than in the other countries*, and are shown in the table below. Note that the C class of Colombia is roughly equivalent to the A class of Argentina or Brazil.

Range of energy efficiency (COP) for air conditioners in Colombia, according to RETIQ
Source: Gov. of Colombia, Resolución 41012, 2015**,** as reported in MGM; 2019, Deliverable 1, Table 1.

Class	Equipment with cooling capacity Up to 3 TR (= 10.5 kW)		Equipment with cooling capacity from 3 TR to 5 TR (10.5 to 17.5 kW)	
	Lower limit Wt/We (Btu/Wh)	Upper limit Wt/We (Btu/Wh)	Lower limit Wt/We (Btu/Wh)	Upper limit Wt/We (Btu/Wh)
A	3,75 (12,80)		4,75 (16,21)	
B	3,50 (11,95)	3,75 (12,80)	4,40 (15,02)	4,75 (16,21)
C	3,25 (11,09)	3,50 (11,95)	4,05 (13,82)	4,40 (15,02)
D	3,00 (10,24)	3,25 (11,09)	3,70 (12,63)	4,05 (13,82)
E	2,75 (9,39)	3,00 (10,24)	3,35 (11,43)	3,70 (12,63)

The average efficiency of mini-split ACs improved in recent years, as can be seen below, reaching a value of about 10.4 Btu/Wh (COP = 3.0 W/W), which is within the D class in Colombia, but the B class in Brazil.



Evolution of the average energy performance values in (Btu / Wh) for each of the types of equipment installed in the 2010-2015 period

Source: MGM Innova, 2019, Deliverable 1, Figure 12.

Appendix F. Emissions factors for electricity generation and consumption

From the point of view of an energy efficiency activity, the emission factor of the electricity grid is defined as the "marginal" impact of energy savings on CO_2 emissions, i.e., what is the impact of a electricity savings of 1 kWh on the emissions in electricity generation. This marginal emissions factor is different from the average emissions factor determined by dividing total CO_2 emissions in electricity generation by total electricity generation. The average emissions factor in most Latin American countries is very low, because of the major presence of hydroelectricity. However, electricity savings would not affect the amount of hydroelectric generation. Therefore, hydroelectric power plants and other so called low cost /must run power plants are excluded from the determination of marginal emissions factor for electricity generation. The average emissions factors are used in the determination of GHG inventories for countries, as well as for corporate and other entities, since they reflect the average emissions for the country or entity.

For the determination of the emissions factor for electricity generation, we recommend the use of the CDM methodological tool called: "Tool to calculate the emission factor for an electricity system" (Tool to calculate the emission factor of an electrical system). This methodological tool presents several alternatives for the determination of the "consolidated" emission factor from the operating margin (OM) and the build margin (BM). The selection of the "Simple adjusted OM" option is recommended for the determination of the operating margin. The Excel spreadsheets that accompany the tool are useful in this regard. The combined margin (CM) is generally the arithmetic mean between the OM and the BM.

The emissions factor for electricity *consumption* (or savings) is somewhat higher than the emissions factor for *generation*, because of transmission and distribution losses (TDL). Such losses can be because of technical factors, related to the impedance of transmission and distribution lines, transformer losses, etc. or from electricity theft, meter tampering, etc., called "non-technical" losses. Here we consider only technical losses, in order to relate amount of electricity generate to satisfy a given electricity demand.

$$EF_{cons} = \frac{EF_{gen}}{1 - TDL}$$

where:

EF_{cons}	=	Emissions factor for electricity consumption
EF_{gen}	=	Emissions factor for electricity generation
TDL	=	Transmission and distribution losses (technical)

A number of countries publish official values of the national emissions factor, see table below and left side of figure further below. In most cases, the methodology version is the same as suggested above. However, Brazil and Chile use instantaneous dispatch data to calculate hourly emissions factor, with annual averages, shown below. Costa Rica publishes average emissions factor[89], which does not take the CDM "marginal" approach as recommended above. The *average* emissions factor for Costa Rica is very low (0.0754 tCO_2/MWh), as it is also for other countries with significant hydro generation (Brazil, Colombia, etc.)

Emissions factor for electricity generation, as published by some LAC country governments

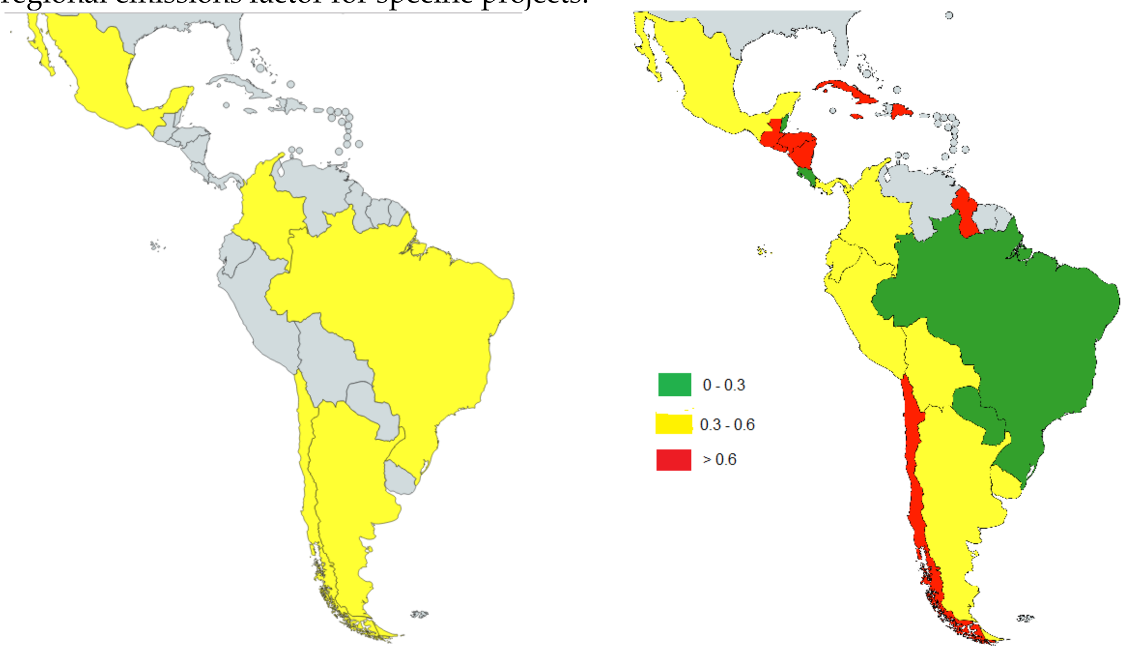
Country	Emissions factor, tCO_2/MWh	Year	Comments
Argentina[90]	0.480	2017	Ex-post Operating Margin
Brazil[91]	0.539	2018	Annual average from published monthly average data
Chile (Central)[92]	0.336	2017	Annual average
Chile (Norte Grande)	0.773	2017	Annual average. Note that the North of Chile (mostly desert) has no hydro and a very high emissions factor
Colombia[93]	0.367	2017	
Mexico[94]	0.527	2018	
Peru	0.432	2016	For intermittent renewables (i.e. wind and solar). Source: namasenergia.minem.gob.pe [95]
Peru	0.412	2016	For all other (than intermittent renewable), Same source.

The Institute of Global Environment Studies (IGES, Japan) compiles and publishes emissions factors from registered CDM projects from each country where data are available[96]. The data are shown graphically in right hand side of the figure below, where we have added Paraguay (which would have zero emissions factor since the country consumes a part of the electricity generated by two binational hydroelectric projects shared with Brazil (Itaipú) and Argentina (Yacyretá). For some Central American and all Caribbean countries, the emissions factor is high because of the extensive use of liquid fossil fuel power plants. The IGES compilation, based on the most recent CDM projects, is often not up-to-date, and sometimes does not coincide with the more recent national values as can be seen in the figure below. Moreover, IGES publishes a

89 http://cglobal.imn.ac.cr/documentos/publicaciones/factoresemision/factoresemision2018/offline/download.pdf
90 http://datos.minem.gob.ar/dataset/calculo-del-factor-de-emision-de-co2-de-la-red-argentina-de-energia-electrica
91 https://www.mctic.gov.br/mctic/opencms/ciencia/SEPED/clima/textogeral/emissao_despacho.html
92 http://energiaabierta.cl/visualizaciones/factor-de-emision-sic-sing/
93 Resolución UPME 804 (26 de diciembre de 2017). Detalles del cálculo en el documento "Doc_calculo_del_FE_del_SIN_2016.docx", disponible en Internet.
94 https://www.gob.mx/cms/uploads/attachment/file/442910/Aviso_Factor_de_Emisiones_2018.pdf
95 http://namasenergia.minem.gob.pe//Content/fileman/Uploads/archivo/Estudios/RER%20Conectado/EF%20SEIN%202016%20vfinal.pdf
96 https://iges.or.jp/en/pub/list-grid-emission-factor

single national emissions factor, which is appropriate for most LAC countries. However, some countries, e.g. Chile has two major grids with very different emissions factors, as can be seen in the table above. Most of Mexico is connected to a central grid. However, large parts of Baja California (peninsula to the west of Mexico) are not connected to the central grid, and has much higher emissions factor. Energy efficiency activities for climate change mitigation are more effective in countries and regions with high grid emissions factor.

Thus, whenever available, the most recent national data should be used, taking care to include a regional emissions factor for specific projects.



Emissions factor for electricity generation, tCO_2/MWh, according to CDM methodology, as published by countries (left, for Chile based on the value for the Central Grid) and Combined Margin emissions factor as compiled by IGES.

Source: Left from table above, right based on data compiled by IGES (2019): IGES_GRID_EF_v10.4_20190207.xlsx

Appendix G. The United States and refrigerant flammability

The USA has much more stringent rules on the use of flammable refrigerants. This is more for legal reasons than for absolute technical factors, since global manufacturers offer their products both in the USA as well as in Europe as elsewhere, where hydrocarbon use is common. As Calm (2008, p. 1130) noted:

> *Hydrocarbon refrigerants, notably R-600a (isobutane) and isobutane blends, have displaced R-12 and later R-134a and now dominate in domestic refrigerators in Europe, but not in North America and especially not in the United States (UNEP, 2007). Although widely perceived as a safety concern, that is not the case for refrigerators that have very small refrigerant charge amounts (typically less than 120 g). The major appliance manufacturers operate globally and could not deem hydrocarbons safe in Europe but unsafe in the USA. Typical refrigerator sizes are larger in the USA than in Europe, but are more comparable to those in Japan and Korea where isobutane use also is increasing in refrigerators and vending machines. The distinction lies in tort laws in the USA, which lead manufacturers to fear having to defend against assertions of cause of or contribution to domestic fires given the availability of nonflammable alternatives. The situation is quite different from use of natural gas and other hydrocarbons in cooking and water-heating appliances, for which there is general acceptance that a flammable substance is unavoidable. Flammability and explosion hazards generally impede hydrocarbon use in large capacities, except in chemical process applications for which the processes themselves present greater hazards and already are protected.*

Because of greater concern for flammability, a lot more research on refrigerant flammability as well as a search for non flammable refrigerants has been undertaken in the USA.

The US National Institute of Standards and Technology (NIST) noted that most single component refrigerant alternatives with low GWP are at least slightly flammable. "*Since the number of components blended may be up to five, the number of permutations is very large*", in 2018, NIST proposed the development of "*analytical tools for predicting the burning velocity of refrigerants blends so that industry can use it to optimize the blends for minimum flammability (as well as the other necessary properties)*"[97].

Already in mid 2019, NIST had conducted an extensive modeling study to find nonflammable refrigerant blends to replace R-134a (Bell et al., 2019). As noted in the paper Abstract:

> *We investigated refrigerant blends as possible low GWP (global warming potential) alternatives for R- 134a in an air-conditioning application. We carried out an extensive screening of the binary, ternary, and four-component blends possible among a list of 13 pure refrigerants comprising four hydrofluoroolefins (HFOs), eight hydrofluorocarbons (HFCs), and carbon dioxide. The screening*

[97] **Flammability Metrics for New Low-GWP Refrigerants.** https://www.nist.gov/programs-projects/flammability-metrics-new-low-gwp-refrigerants

> *was based on a simplified cycle model, but with the inclusion of pressure drops in the evaporator and condenser. The metrics for the evaluation were nonflammability, low GWP, high COP (coefficient of performance), and a volumetric capacity similar to the R-134a baseline system. While no mixture was ideal in all regards, we identified 16 binary and ternary blends that were nonflammable (based on a new estimation method) and with COP and capacity similar to the R-134a baseline; the tradeoff, however, was a reduction in GWP of, at most, 54% compared to R-134a. An additional seven blends that were estimated to be "marginally flammable"(ASHRAE Standard 34 classification of A2L) were identified with GWP reductions of as much as 99%. These 23 "best"blends were then simulated in a more detailed cycle model.*

Since the above study focused on alternatives to R-134A, it is not the most relevant for this report, since other refrigerants are more common for commercial RAC in LAC.

Also from NIST, Domanski et al. (2018) came to the following conclusion:

> *The study showed that the low-GWP refrigerant options are very limited, particularly for fluids with volumetric capacities similar to those of R-410A and R-404A. The identified fluids with good COP and low toxicity are at least mildly flammable. The probability of finding better-performing low-GWP fluids is minimal.*

Appendix H. AHRI Low-Global Warming Potential Alternative Refrigerants Evaluation Program

The American Heating and Refrigeration Institute (AHRI) has been conducting an extensive evaluation of Low-Global Warming Potential Alternative Refrigerants. The list of reports listed below are most relevant for equipment manufacturers. However, some tests comprise drop-in refrigerant replacements, which are also relevant to service personnel. A drop-in replacement is unlikely to be relevant even to a company investing in energy efficient /low GWP retrofits of existing unitary equipment (ice maker, bottle cooler, etc.) since the replacement may lower GWP of the refrigerant in use, but may not improve energy efficiency. Moreover, refrigerant replacement requires the removal and disposal of the high GWP (and possible ozone depleting) refrigerant, and infrastructure may not be available in the smaller LAC countries. Some tests are specific to heating, water heating and other situations not relevant to ESCOs in LAC countries. Calorimeter tests are more relevant for equipment manufacturers and beyond ESCO scope. Test results most likely to be relevant for ESCOs are highlighted in yellow below.

- **001:** *System Drop-in Test of R-410A Alternative Fluids (ARM-32a, ARM-70a, DR-5, HPR1D, L-41a, L-41b, and R-32) in a 5-RT Air-Cooled Water Chiller (Cooling Mode)*
- **002:** *System Drop-In Test of L-40, L-41a and N-40b in Ice Machines*
- **003:** *System Drop-In Test of R-32/R-152a (95/5) in Air Source Heat Pump*
- **004:** *System Drop-in Test of Refrigerant R-32 in Split System Heat Pump (with Addendum)*
- **005:** *Soft-optimized System Test of Refrigerant R-32 in 3-ton Split System Heat Pump*
- **006:** *System Drop-in Tests of R-22 Alternative Fluids (ARM-32a, DR-7, L-20, LTR4X, LTR6A, and D52Y) in a 5-RT Air-Cooled Water Chiller (Cooling Mode)*
- **007:** *System Drop-In Tests of R134a Alternative Refrigerants (ARM-42a, N-13a, N-13b, R-1234ze(E), and OpteonTM XP10) in a 230-RT Water-Cooled Water Chiller*
- **008:** *System Drop-In Tests of R-134a, R-1234yf, OpteonTM XP10, R-1234ze(E), and N13a in a Commercial Bottle Cooler/Freezer*
- **009:** *System Drop-In Tests of Refrigerant Blends L-40, DR-7 and ARM-30a in a Trailer Refrigeration Unit Designed for R-404A*
- **010:** *System Soft-Optimized Test of Refrigerant HFO-1234yf (R-1234yf) in a Split System Heat Pump (with Addendum)*
- **011:** *Compressor Calorimeter Test of R-410A Alternatives R-32, DR-5, and L-41a*
- **012:** *System Drop-In Tests of Refrigerant Blends N-13a and AC5 in Bus Air-Conditioning Unit Designed for R-134a*
- **013:** *System Drop-In Tests of Refrigerant Blends L-20 and D52Y in Bus Air-Conditioning Unit Designed for R-407C*
- **014:** *System Drop-In Test of Refrigerant Blend ARM-42a in an Air-Cooled Screw Chiller*
- **015:** *System Drop-In Test of Refrigerant R-32 in a VRF Multi-split Heat Pump*
- **016:** *System Drop-in Test of Refrigerant Blend R-32/R-134a (95/5), R-32, and DR-5 in Water-To-Water Heat Pump*
- **017:** *Compressor Calorimeter Test of Refrigerants R-22 and R-1270*
- **018:** *Compressor Calorimeter Test of Refrigerants R-134a, N-13a and ARM-42a*
- **019:** *Compressor Calorimeter Test of Refrigerants R-134a and N-13a*

- **020:** *System Drop-In Tests of Refrigerants R-32, D2Y-60, and L-41a in Air Source Heat Pump*
- **021:** *Compressor Calorimeter Test of R-404A Alternatives ARM-31a, D2Y-65, L-40, and R-32/R-134a (50/50)*
- **022:** *System Drop-in Testing of R-410A Replacements in Split System Heat Pump*
- **023:** *System Soft-Optimized Test of Refrigerant L-41a in Air Source Heat Pump*
- **024:** *Compressor Calorimeter Test of Refrigerant DR-5 in a R-410A Scroll Compressor*
- **025:** *System Drop-in Test of R134a Alternative Fluids R-1234ze(E) and D4Y in a 200 RT Air-Cooled Screw Chiller*
- **026:** *Compressor Calorimeter Test of Refrigerant R-32 in a R-410A Rotary Type Compressor*
- **027:** *System Drop-In Test of Refrigerant Blend ARM70a and DR-5 in An Air to Water Heat Pump*
- **028:** *Compressor Calorimeter Test of R-404A Alternative Refrigerant L-40 in Reciprocating Compressors*
- **029:** *Compressor Calorimeter Test of R-404A Alternative Refrigerant DR-7 in Reciprocating Compressors*
- **030:** *Compressor Calorimeter Test of R-134a Alternative Refrigerant R-1234yf in Reciprocating Compressors*
- **031:** *System Drop-in Test of Refrigerant R-32 in Split Air-conditioning System*
- **032:** *System Soft-Optimized Test Of Refrigerant D2Y60 in Air Source Heat Pump*
- **033:** *Compressor Calorimeter Test of R-410A Alternative: R-32/R-134a Mixture Using a Scroll Compressor*
- **034:** *Compressor Calorimeter Test of Refrigerant DR-7 in a R-404A Scroll Compressor*
- **035:** *Compressor Calorimeter Test of Refrigerant DR-7 in a R-404A Reciprocating Compressor*
- **036:** *Compressor Calorimeter Test of Refrigerant L-40 in a R-404A Scroll Compressor*
- **037:** *Compressor Calorimeter Test of Refrigerant L-40 in a R-404A Reciprocating Compressor*
- **038:** *Compressor Calorimeter Test of Refrigerant L-41b in a R-410A Scroll Compressor*
- **039:** *Compressor Calorimeter Test of Refrigerant R-32 in a R-410A Scroll Compressor*
- **040:** *Compressor Calorimeter Test of Refrigerant DR-5 in a R-410A Rotary Type Compressor*
- **041:** *System Drop-in Tests of Refrigerant DR-34 (R-452A) in a Trailer Refrigeration Unit Designed for R-404A*
- **042:** *System Soft-optimization Tests of Refrigerant R-32 in a 3-ton Split System Air-Conditioner*
- **043:** *System Drop-in Tests of Refrigerants L-41-1, L-41-2, and R-32 in Water-to-Water Heat Pump*
- **044:** *System Drop-in Tests of Refrigerant R-32 in Single Packaged Vertical Heat Pump (SPVH)*
- **045:** *System Drop-in Test of Refrigerant Blends ARM-20b and N-40c (R-448A) in Automatic Commercial Ice Maker Designed for R404A*
- **046:** *System Drop-in Test of Refrigerants R32, DR-5A, L-41-1 and L-41-2 in a Water Chiller*
- **047:** *System Drop-in Test of R-32 and Refrigerant Blends ARM-71a, HPR2A, L-41-2 and DR-5A in a Five-Ton R 410A Rooftop Packaged Unit*
- **048:** *System Drop-in Tests of Refrigerants N-40 and L-20 in a R-404A Ice Machine*
- **049:** *Compressor Calorimeter Test of Refrigerant Blend HDR110 in a R-404A Reciprocating Compressor*
- **050:** *Compressor Calorimeter Test of Refrigerant Blend DR-3 in a R-404A Reciprocating Compressor*

- **051:** *Compressor Calorimeter Test of Refrigerant DR-33 (R-449A) in a R-404A Reciprocating Compressor*
- **052:** *System Drop-in Tests of Refrigerant Blends ARM-71a, DR-5A (R-454B), HPR2A, L-41-1 (R-446A), L-41-2 (R-447A) in a R-410A Split System Heat Pump*
- **053:** *System Drop-In Test of Refrigerant Blend DR-55 in a Five-Ton R-410A Rooftop Packaged Unit*
- **054:** *System Drop-In Test of Refrigerants DR-5A, R-32, and L-41-2 in a 2.5-Ton R-410A Heat Pump*
- **055:** *System Soft-optimization Tests of Refrigerant R-32 in a 6-ton Rooftop Packaged Air-Conditioner*
- **056:** *System Soft-optimization Tests of Refrigerant R-32, DR-5A, and DR-55 in a R-410A 4-ton Unitary Rooftop Heat Pump-Cooling Mode*
- **057:** *System Soft-optimization Tests of Refrigerant R-32 in a 2.5 ton Rooftop Heat Pump*
- **058:** *Compressor Calorimeter Test of Refrigerant DR-5A in a R-410A Scroll Compressor*
- **059:** *Compressor Calorimeter Test of Refrigerant L41-1, DR-5A, ARM-71a, D2Y-60 and R-32 in a R-410A Reciprocating Compressor*
- **060:** *System Drop-in Tests of DR-5A, DR-55, L41-2 and R-32 in Water-To-Air Heat Pump*
- **061:** *System Drop-in Tests of DR-3, L-20 (R-444B), and R-290 in Air-to Water Heat Pump-Heating Mode*
- **062:** *Soft-Optimized System Test of Alternative Lower GWP Refrigerants in 1.5-ton Mini-Split Air Conditioning Units*
- **063:** *System Soft-optimization Tests of Refrigerant R-32, DR-5A, and DR-55 in a R-410A 4-ton Unitary Rooftop Heat Pump-Heating Mode Performance*
- **064:** *Compressor Calorimeter Test of Refrigerant DR-7 (R-454A) in a R-404A Reciprocating Compressors*
- **065:** *Compressor Calorimeter Test of Refrigerant L-41-2 (R-447A) in a R-410A Scroll Compressor*
- **066:** *Compressor Calorimeter Test of Refrigerant HPR2A in a R-410A Scroll Compressor*
  067: *Compressor Calorimeter Test of Refrigerant ARM-25 in a R-404A Reciprocating Compressors*