5

Residential and Commercial Air Conditioning and Heating

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Contents

EXECUTIVE SUMMARY

The various applications, equipment and products included in residential and commercial air-conditioning and heating sector can be classified in three groups: stationary air conditioners (including both equipment that cools air and heat pumps that directly heat air), chillers and water-heating heat pumps.

Stationary Air Conditioners (Heat Pumps for Cooling and Heating)
Air conditioners and air-heating heat pumps generally fall into four distinct categories:
- window-mounted, portable, and through-the-wall;
- non-ducted split residential and commercial;
- ducted residential split and single packaged;
- ducted commercial split and packaged.

The vast majority of stationary air conditioners (and air-heating heat pumps) use vapour-compression cycle technology with HCFC-22 refrigerant. This refrigerant is already being phased out in some countries ahead of the schedule dictated by the Montreal Protocol. In Europe HCFC-22 had been phased out of new equipment by 31 December 2003. In the USA, production of HCFC-22 for use in new equipment will end on 1 January 2010. In Japan, HCFC-22 is to be phased out of new equipment on 1 January 2010; however, almost all new equipment has already been converted to HFCs.

The refrigerant options being considered as replacements for HCFC-22 are the same for all of the stationary air conditioner categories: HFC-134a, HFC blends, hydrocarbons, and CO_2. At present, two of these are being used: HFC blends in the vast majority of systems and hydrocarbons in a very small number of smaller systems.

It is estimated that more than 90% of the installed base of stationary air conditioners currently use HCFC-22, and an estimated 368 million air-cooled air conditioners and heat pumps are installed worldwide. This represents an installed bank of approximately 548,000 tonnes of HCFC-22 (UNEP, 2003).

Water Chillers
Water chillers combined with air handling and distribution systems frequently provide comfort air conditioning in large commercial buildings (e.g., hotels, offices, hospitals and universities) and to a lesser extent in large multi-family residential buildings. Water chillers using the vapour-compression cycle are manufactured in capacities ranging from approximately 7 kW to over 30,000 kW. Two generic types of compressors are used: positive displacement and centrifugal. Heat-activated absorption chillers are available as alternatives to electrical vapour-compression chillers. However, in general these are only used where waste heat is available or the price of electricity, including demand charges, is high.

HFCs (particularly HFC-134a) and HFC blends (particularly R-407C and R-410A) are beginning to replace HCFC-22 in new positive-displacement chillers. Ammonia is used in some positive-displacement chillers in Europe. The high discharge temperatures associated with ammonia permit a greater use of heat recovery than is the case for other refrigerants. Some chillers which use hydrocarbon refrigerants (as substitute for HCFC-22), are also produced in Europe each year.

Centrifugal compressors are generally the most efficient technology in units exceeding 1700 kW capacity. HCFC-123 and HFC-134a have replaced CFC-11 and CFC-12, respectively, in new centrifugal chillers produced since 1993.

Water-Heating Heat Pumps
Water-heating heat pumps using vapour-compression technology are manufactured in sizes ranging from 1 kW heating capacity for single room units, to 50–1000 kW for commercial/institutional applications, and tens of MW for district heating plants.

Various heat sources exist: air, water from ponds and rivers, and the ground. Integrated heat pumps that simultaneously heat water and cool air are also available.

In developed countries, HCFC-22 is still the most commonly used refrigerant but HFC alternatives are being introduced. In developing countries, CFC-12 is also used to a limited extent. HFC refrigerants are used in Europe in equipment produced after 2003 (EU, 2000).

In the area of non-HFC refrigerants, carbon dioxide is being introduced in domestic, hot-water heat pumps in Japan and Norway, ammonia is being used in medium-size and large-capacity heat pumps in some European countries, and several northern-European manufacturers are using propane (HC-290) or propylene (HC-1270) as refrigerants in small residential and commercial water-to-water and air-to-water heat pumps.

Reduction in HFC emissions
Options for reducing HFC emissions in residential and commercial air-conditioning and heating equipment involve containment in HFC vapour-compression systems (applicable worldwide and for all equipment) and the use of non-HFC systems (applicable in certain cases but not all due to economic, safety and energy efficiency considerations). Non-HFC systems include vapour-compression cycles with refrigerants other than HFCs, and alternative cycles and methods to produce cooling and heating.

Containment can be achieved through:
- the improved design, installation and maintenance of systems to reduce leakage;
- designs that minimize refrigerant charge quantities in systems
- the recovery, recycling and reclaiming of refrigerant during servicing, and at equipment disposal.

A trained labour force using special equipment is needed to minimize installation, service and disposal emissions. However, implementing best practices for the responsible use of HFCs requires an infrastructure of education, institutions and equipment that is not widely available in much of the developing world. There is also a role for standards, guidelines, and regulations on HFC emission reduction that are appropriate for regional or local conditions.

A number of other non-traditional technologies have been examined for their potential to reduce the consumption and emission of HFCs. With only a few exceptions, these all suffer such large efficiency penalties that the resultant indirect effects would overwhelm any direct emission reduction benefit.

Global warming effects

Several factors influence the direct and indirect emission of greenhouse gases associated with residential and commercial air-conditioning and heating equipment. In those warm climate regions where electricity is predominantly generated using fossil fuels, the generation of energy to power air conditioners can cause greenhouse-gas emissions that are greater than the direct refrigerant emissions by an order of magnitude or more. Therefore, improving the integrity of the building envelope (reduced heat gain or loss) and other actions to reduce building energy consumption can have a very significant impact on indirect emissions. In cooler climates where air conditioning is used less often, or in locations where power generation emits little or no carbon dioxide, the direct emissions can exceed the indirect greenhouse-gas emissions.

Residential and commercial air-conditioning and heating units are designed to use a given charge of a refrigerant, and not to emit that refrigerant to the atmosphere; however, emissions can occur due to numerous causes. The effects of refrigerant gas emissions are quantified by multiplying the emissions of a refrigerant in kg by its global warming potential (GWP). The emissions calculated are on a kgCO_2-equivalent basis. If more than a few specific systems are analyzed then it is appropriate to use average annual emission rates for each type of system to calculate the comparative direct greenhouse-gas emissions.

5.1 Stationary air conditioners (heat pumps for cooling and heating)

The several applications, equipment and products that are included in the sector of residential and commercial air conditioning and heating can be classified in three groups: stationary air conditioners (this section), chillers (section 5.2), and water heating heat pumps (section 5.3).

Air-cooled air conditioners and heat pumps, ranging in size from 2.0−700 kW, account for the vast majority of the residential and light-commercial air-conditioning market. In fact, over 90% of the air-conditioning units produced in the world are smaller than 15 kW. In the rest of this chapter the term *air conditioners* will be used for air conditioners and heat pumps that directly cool or heat air.

5.1.1 Technologies and applications

The vast majority of air conditioners use the vapour-compression cycle technology, and generally fall into four distinct categories:

- window-mounted, portable and through-the-wall air conditioners;
- non-ducted or duct-free split residential and commercial air conditioners;
- ducted residential split and single package air conditioners;
- ducted commercial split and packaged air conditioners.

5.1.1.1 Window-mounted, through-the-wall, and portable air conditioners

Due to their small size and relatively low cost, window-mounted, through-the-wall, and portable air conditioners[1] are used in small shops and offices as well as private residences. They range in capacity from less than 2.0 kW to 10.5 kW. These types of air conditioners have factory-sealed refrigerant cycles that do not require field-installed connections between the indoor and outdoor sections. Therefore refrigerant leaks resulting from imperfect installation practices do not occur in these systems unless the unit is damaged during installation and service and a leak results. Representative refrigerant leakage rates are in the order of 2−2.5% of the factory charge per year (UNEP, 2003).

5.1.1.2 Non-ducted (or duct-free) split air conditioners

In many parts of the world, non-ducted split air conditioners are used for residential and light-commercial air-conditioning. Non-ducted split air conditioners include a compressor/heat exchanger unit installed outside the space to be cooled or heated. The outdoor unit is connected via refrigerant piping to one ('single-split') or more ('multi-split') indoor units (fan coils) located inside the conditioned space. Capacities range from 2.2−28 kW for a single split, and from 4.5−135 kW for a multi-split. Representative leakage rates for single split are in the order of 4−5% of the nominal charge per year (UNEP, 2003). As multi-split air conditioners have more connections the probability of leaks is higher.

5.1.1.3 Ducted split residential air conditioners

Ducted split residential air conditioners have a duct system that supplies cooled or heated air to each room of a residence or individual zones within commercial or institutional buildings. A compressor/heat exchanger unit outside the conditioned space supplies refrigerant to a single indoor coil (heat exchanger) installed within the duct system or air handler. Capacities range from 5−17.5 kW. Representative leakage rates are in the order of 4−5% of the nominal charge per year (UNEP, 2003).

5.1.1.4 Ducted, commercial, split and packaged air conditioners

Ducted, commercial, split-system units must be matched with an indoor air handler and heat exchanger. Packaged units contain an integral blower and heat exchanger section that is connected to the air distribution system. The majority of ducted, commercial split and single package air conditioners are mounted on the roof of office, retail or restaurant buildings or on the ground adjacent to the building. The typical range of capacities for these products is 10-700 kW.
Representative leakage rates are in the order of 4−5% of the factory charge per year (UNEP, 2003).

5.1.2 Refrigerant use and equipment population

There are no global statistics on the percentage of air-cooled air conditioners that have been manufactured with non ozone depleting refrigerants. However, it is estimated that more than 90% of the installed base of stationary air conditioners currently uses HCFC-22 (UNEP, 2003).

Estimates of the installed base (number of units) and refrigerant inventory were made using a computer model which predicts the number of units and refrigerant in the installed population on the basis of production data and product longevity models (UNEP, 2003).

An estimated 358 million air-cooled air conditioners (cooling and heating) are installed worldwide with a total capacity of 2.2 x 10^9 kW cooling. Refrigerant charge quantities vary in relation to the capacity. Assuming an average charge of 0.25 kg per kW of capacity, those 358 million units represent an installed bank of approximately 550,000 tonnes of HCFC-22 (Table 5.1).

HCFC-22 is already being phased out in some countries, which elected to phase out ahead of the schedule dictated by the Montreal Protocol. In Europe HCFC-22 had been phased out of new equipment by 31 December 2003. In the USA HCFC-22

[1] Portable air conditioners are a special class of room air conditioners designed to be rolled from room to room. They draw condenser air from the conditioned space or from outdoors and exhaust it outdoors. The air flows from and to outdoors through small flexible ducts which typically go through a window. In some models condenser cooling is further augmented by the evaporation of condensate and water from a reservoir in the unit.

Table 5.1. Units manufactured in 1998 and 2001, unit population and refrigerant inventory.

Product Category	Units Manufactured 2001 (millions)	Units Manufactured 1998 (millions)	Estimated Unit Population (2001) (millions)	Estimated HCFC-22 Inventory (ktonnes)	Estimated Refrigerant Bank HFC (ktonnes)[1]
Window-mounted and Through-the-Wall (Packaged Terminal) Air Conditioners	13.6	12.1	131	84	4
Non-ducted or duct-free Split Residential and Commercial Air Conditioners	24.2	16.3	158	199	10
Ducted Split and single Packaged Residential Air conditioner	5.9	5.7	60	164	9
Ducted commercial split and packaged air conditioners	1.7	1.7	19	101	5
TOTAL	**45.4**	**35.8**	**368**	**548**	**28**

(1) These values were calculated assuming that HCFC-22 bank is 95% of the total, for each category
Source: ARI, 2002; JARN, 2002b; DRI, 2001

will be phased out of new equipment on 1 January 2010. In Japan HCFC-22 is due to be phased out of new equipment on 1 January 2010, but almost all new equipment has already been converted to HFCs.

The refrigerant options being considered as replacements for HCFC-22 are the same for all of the stationary air conditioner categories: HFC-134a, HFC blends, hydrocarbons, and CO_2. At present, two of these are being used: HFC blends, and hydrocarbons (propane, a propane/ethane blend, and propylene).

5.1.2.1 HFC blends

To date, the vast majority of air conditioners using non ozone depleting refrigerants have used HFC blends. Two HFC blends currently dominate the replacement of HCFC-22 in new air-cooled air conditioners. These are R-407C and R-410A. A few other HFC blends have been investigated and/or commercialized as refrigerants; however, none have been widely used in new or existing (retrofit) air conditioners. There is a limited use of R-419A and R-417A as 'drop-in' refrigerants in some CEIT countries.

R-407C

Systems that use R-407C can be designed to match the performance of HCFC-22 systems if appropriate adjustments are made, such as changing the size of the heat exchangers. This is demonstrated by the availability of R-407C systems in Europe and Japan at capacities and efficiencies equal to the HCFC-22 units which they replace. In Europe, R-407C has been predominantly used as the replacement for HCFC-22 in air-to-air air-conditioning applications. In Japan, R-407C has primarily been used in the larger capacity duct-free and multi-split products.

R-410A

R-410A is being used to replace HCFC-22 in new products in some markets. R-410A air conditioners (up to 140 kW) are currently available on a commercial basis in the USA, Asia and Europe. A significant proportion of the duct-free products sold in Japan use R-410A. In 2002, approximately 5% of the equipment sold into the US ducted residential market used R-410A. It is likely that the US ducted residential market will mainly use R-410A as the HCFC-22 replacement.

5.1.2.2 Hydrocarbons and CO_2

The use of hydrocarbons in air-conditioning applications has been limited due to the safety concerns inherent in the application of flammable refrigerants.

Propane (HC-290) has mainly been used in portable (factory sealed) air conditioners. Approximately 90,000 HC-290 portable air conditioners are reported to have been sold in Europe in 2003. The typical charge quantity used in these units is approximately 0.10 kg kW^{-1}.

To date, CO_2 units have been essentially limited to custom built applications or demonstration units. A component supply base from which to manufacture CO_2 systems does not currently exist.

5.1.3 *Options for reducing HFC emissions*

Options for reducing HFC emissions include refrigerant conservation in HFC vapour-compression systems and the use of non-HFC systems. These options are discussed below.

5.1.3.1 HFC vapour-compression systems

Residential and commercial air-conditioning and heating units are designed to use a specified charge of a refrigerant, and not to emit that refrigerant to the atmosphere during normal operation. However, refrigerant emissions due to losses can occur as a result of several factors:

- Refrigerant leaks associated with poor design or manufac-

turing quality, such as leaks from valves, joints, piping and heat exchangers represent on average 2–5% of the factory refrigerant charge per year;
- Leaks in poorly installed field-interconnecting tubing, which can emit 5–100% of factory charge within the first year of installation;
- Accidental releases due to mechanical failure or damage of equipment components can result in up to 100% loss of the system charge;
- Intentional venting of refrigerant during servicing (e.g., air purging) or disposing of equipment (in many countries this practice is still legal). This type of emission can represent anywhere from a small percentage to the total system charge;
- Losses of refrigerant during equipment disposal (up to 100% of the system charge).

For air conditioners working on the vapour-compression cycle and using any refrigerant, there are several practical ways to promote refrigerant conservation, and to reduce refrigerant emissions. The most significant are:
- Improved design and installation of systems to reduce leakage and consequently increase refrigerant containment;
- Design to minimize refrigerant charge quantities in systems;
- Adoption of best practices for installation, maintenance and repairing of equipment, including leak detection and repair;
- Refrigerant recovery during servicing;
- Recycling and reclaiming of recovered refrigerant;
- Refrigerant recovery at equipment decommissioning;
- Appropriate government policies to motivate the use of good practices and to promote refrigerant conservation.

Standards and good practice guidelines, like ANSI/ASHRAE[2] Standard 147-2002, outline practices and procedures to reduce the inadvertent release of halogenated refrigerants from stationary refrigeration, air conditioning, and heat pump equipment during manufacture, installation, testing, operation, maintenance, repair, and disposal.

5.1.3.1.1 Developing country aspects

Developing countries face specific issues with respect to the containment and conservation of refrigerants. Since the manufacturing process is approaching a global standard, and most of the developing countries are importers and not manufacturers of air-conditioning equipment, the specific issues faced by these countries are mostly related to servicing, training of technicians, legislation and regulations. Important points, in addition to those mentioned above, are:

- Technician training and awareness are essential to the success of refrigerant conservation, especially where preventive maintenance procedures have not been routine in the past;
- Developing countries could devote resources to developing a reclamation infrastructure, with the necessary refrigerant recovery and reclaiming network, or emphasize on-site refrigerant recycling. The Multi-Lateral Fund of the Montreal Protocol supports this practice;
- In many developing countries, preventive maintenance of air-conditioning and refrigeration equipment has been rare. Conservation approaches, which rely heavily on regular maintenance, could be successfully implemented if countries were to provide incentives to encourage routine scheduled maintenance (UNEP, 2003).

5.1.3.2 Non-HFC systems

Non-HFC systems include vapour-compression cycles with refrigerants other than HFCs, and alternative cycles and methods to produce refrigeration and heating. The four stationary air conditioner categories described in Section 5.1.1 have the non-HFC system options described below.

5.1.3.2.1 Vapour-compression cycle with non-HFC refrigerants

Many factors need to be taken into consideration when designing an air-conditioning product with a new refrigerant, for example, environmental impact, safety, performance, reliability, and market acceptance. Non-HFC refrigerants that are currently being investigated and used are now detailed.

Hydrocarbon refrigerants

An extensive literature review on the performance of hydrocarbon refrigerants was performed in 2001 (ARTI, 2001). Many articles reported that refrigerants such as propane offer similar or slightly superior efficiency to HCFC-22 in air-conditioning systems. Few rigorous comparisons of fluorocarbon and hydrocarbon systems have been reported. However, the available data suggest that efficiency increases of about 2–5% were common in drop-in 'soft-optimized' system tests. In a system specifically optimized for hydrocarbons, it might be possible to achieve efficiency increases somewhat greater than 5% by using propane rather than HCFC-22, assuming no other fire safety measures need to be taken which would reduce efficiency. In certain countries safety regulations require the use of a secondary loop and this significantly reduces the efficiency of the hydrocarbon system and increases its cost compared to the HCFC-22 system. In order to offer equipment which meets the market requirements for the lowest cost, manufacturers will need to determine how the costs of safety improvements required for hydrocarbon systems compare with the costs required to raise the efficiency of competing systems. Safety standards are likely to vary around the world and this may lead to different choices. Vigorous debates among advocates of hydrocarbon and competing refrigerants are likely to continue, due to the differences in perceived

[2] ANSI is the American National Standards Institute, Inc. ASHRAE is the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

and acceptable risk in different countries. However under the appropriate conditions, for example limited charge and sealed circuits hydrocarbons can be used safely (ARTI, 2001).

Carbon dioxide
Carbon dioxide (CO_2) offers a number of desirable characteristics as a refrigerant: availability, low-toxicity, low direct GWP and low cost. CO_2 systems are also likely to be smaller than systems using other common refrigerants but will not necessarily be cheaper (Nekså, 2001). There is a significant amount of conflicting data concerning the efficiency of CO_2 in air- conditioning applications. Some of the data indicate very low efficiencies compared to HCFC-22 systems while other references indicate parity to better performance. Additional research and development will be needed to arrive at a definitive determination of the efficiency of CO_2 in comfort air-conditioning applications.

5.1.3.2.2 Alternative technologies to vapour-compression cycle
The absorption cycle offers a commercially-available alternative to the vapour-compression cycle. At least two Japanese manufacturers have had commercially-available, split-type absorption air conditioners available for about 5 years. One Italian manufacturer has also been selling small-scale absorption units for some commercial installations. It is reported that over 360,000 gas-fired absorption units with capacities below 7.5 kW have been produced in Europe and North America using the ammonia-water cycle (Robur, 2004). The performance of a direct-fired absorption system will generally result in a higher total-equivalent-warming-impact (TEWI) value than for a vapour-compression system, unless the regional electrical power generation has a high CO_2 emission factor.

A number of other non-traditional technologies have been examined for their potential to reduce consumption and emission of HFCs. These include desiccant cooling systems, Stirling cycle systems, thermoelectrics, thermoacoustics and magnetic refrigeration. With the exception of the Stirling cycle and desiccants, all of these alternatives suffer such large efficiency penalties that the consequent indirect effects would overwhelm any direct benefit in emission reduction. In the USA, the Stirling cycle has remained limited to niche applications, despite the research interest and very substantial funding by the US Department of Energy, and has never been commercialized for air conditioning. In high latent-load applications, desiccant systems have been used to supplement the performance of conventional mechanical air conditioning.

5.1.4 Global warming effects

Several factors influence the emission of greenhouse gases associated with residential and commercial air-conditioning and heating equipment. These include direct emissions during equipment life and at the end of life, refrigerant properties, system capacity (size), system efficiency, carbon intensity of the electrical energy source, and climate. Some of the sensitivities are illustrated by the examples in Figures 5.1 to 5.9. In regions with cooler climates, where air conditioning is used less often or where the electricity generation energy source is not carbon-intensive, direct emissions can outweigh the indirect effects.

Including the life-cycle climate performance (LCCP) as a design criterion is one aspect that can minimize the GWP of residential and commercial air-conditioning and heating equipment. Factoring LCCP into the design methodology will result in an optimum design that is different from one just optimized for lowest cost. By optimizing for the best LCCP, the designer will also improve on a number of other parameters, for example, the design for energy efficiency, the type and amount of refrigerant used in the unit (determined by refrigerant cycle design), reduced leakage (service valve design, joining technologies, manufacturing screening methods, sensor technologies for the early detection of refrigerant leaks), and reduced installation and service losses (factory sealed refrigerant circuits, robust field connection technologies, service valves that reduce losses during routine service). The investment required to achieve a given reduction in LCCP will differ per factor.

5.1.4.1 LCCP examples for air conditioners
Several examples of LCCP calculation are now given for technologies typical of those described above (i.e. vapour compression cycle with HCFC and HFC refrigerants), as well as technologies that have been studied for their potential to reduce greenhouse-gas emissions from air-conditioning applications. As stated previously, the results obtained by these studies are dependent on the assumptions made (leakage rate, recovery rate, use of secondary loop, etc.). Changing these assumptions can lead to different results.

Figure 5.1 compares LCCP values for 3 tonne (10.5 kW) air-conditioning and heat pump units operating in Atlanta, Georgia, USA. LCCP values are calculated for three efficiency levels – seasonal energy efficiency ratio (SEER) levels of 10, 12, and 14 Btu Wh^{-1}. By 2010 when HCFC-22 has been phased out for new equipment and higher energy efficiency standards (13 SEER in the US) are in place, an HFC blend refrigerant is likely to represent a large part of the market for new equipment. The results generally show that direct warming impacts due to life-cycle refrigerant emissions are less than 5% of the LCCP. The difference in the indirect warming component of LCCP at different efficiency levels is much greater. Propane and CO_2 emissions have a negligible warming impact. However, the possible additional cost for using propane safely or for achieving a given efficiency level with CO_2, exceeds the difference in cost between the 12 and 14 SEER performance levels, which have a greater impact on LCCP than the direct warming from refrigerant emissions. (Figure 5.1 is based upon annual make-up losses of 2% of charge and an end-of-life loss of 15% of charge, electrical generation with emissions of 0.65 kg CO_2 kWh^{-1}, annual cooling load of 33.8 million Btu and heating load of 34.8 million Btu, and a 15-year equipment lifetime) (ADL, 2002).

Figure 5.2 provides a comparison of LCCP values for a small, commercial, rooftop air conditioner in Atlanta, Georgia

Figure 5.1. LCCP values for 3 tonne (10.5 kW) air conditioner units operating in Atlanta, Georgia, USA (ADL, 2002).

Figure 5.2. LCCP values for a 7.5 tonne (26.3 kW) commercial rooftop air conditioner in Atlanta, Georgia and Pittsburgh, Pennsylvania, USA (ADL, 2002; Sand *et al*., 1997).

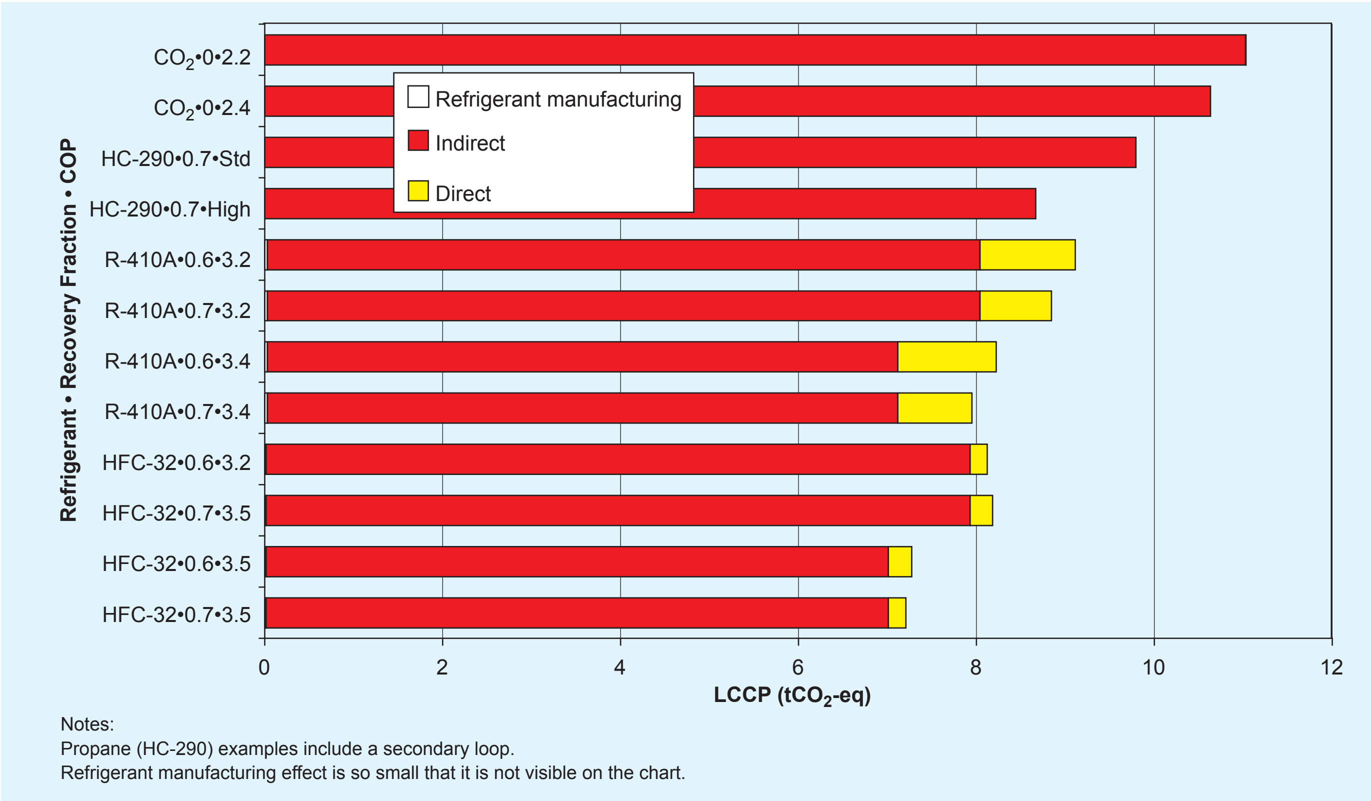

Figure 5.3. LCCP values for 4 kW mini-split air conditioner units in Japan with COPs varying from 2.2–3.5 and with end-of-life refrigerant recovery rates of 60% or 70% (Onishi *et al*., 2004).

and Pittsburgh, Pennsylvania, USA. The results are similar to those shown in Figure 5.1. Differences in efficiency have a much greater effect on LCCP than the direct effect of refrigerant emissions. (Figure 5.2 is based upon annual make-up losses of 1% of charge and an end-of-life loss of 15% of charge, electrical generation with emissions of 0.65 kg CO_2 kWh^{-1}, and equivalent full load cooling hours of 1400 in Atlanta and 600 in Pittsburgh, and a 15-year equipment lifetime) (ADL, 2002).

Figure 5.3 presents LCCP values for 4 kW mini-split heat pump units in Japan. The chart compares units with 4 different refrigerants: CO_2, propane (HC-290), R-410A, and HFC-32. Other parameters varied in this chart are the assumptions about the amount of refrigerant recovered at the end of the equipment life (recovery is assumed to be consistent with normal practice in Japan; 60% and 70% are analyzed) and the coefficient of performance (COP) level of the equipment (standard models compared with high COP models – values shown on the chart). Equipment life is taken to be 12 years with no refrigerant charge added during life, and power generation emissions of 0.378 kg CO_2 kWh^{-1} are assumed. The units are assumed to run for 3.6 months for cooling and 5.5 months for heating according to Japanese Standard JRA4046-1999 (JRAIA, 1999). The figure shows that the LCCP for these mini-splits is dominated by the COP, which is why CO_2 has such a high LCCP. The source for the data assumed that a secondary heat transfer loop would be required for propane, reducing COP and adding a 10–20% cost penalty. The two end-of-life refrigerant recovery rates examined have only a secondary effect on LCCP. This is only apparent for R-410A, which has the highest GWP of those compared. In Japan and many other countries, it is unclear whether HFC-32 (a flammable refrigerant) in mini-splits would be permitted for use in direct expansion or whether it would require a secondary loop (work to determine this is still underway including an IEC[3] standard). The LCCP penalty for a secondary loop in the HFC-32 system is not shown here. This penalty would make HFC-32 systems less attractive than R-410A.

Figure 5.4 shows LCCP values for 56 kW multi-split air conditioners for commercial applications in Japan. The refrigerants compared are propane, R-407C, and R-410A with two rates of refrigerant recovery at the end of the equipment life, 50% and 70%. Each system has a COP level shown on the chart, which has been obtained by using the variable compressor speed (inverter drive). For comparative purposes, a propane system without inverter has been added. The source for the data assumed that the propane system would have a secondary heat transfer loop. Multi-split air conditioners for commercial application units are assumed to operate 1941 h yr^{-1} for cooling

[3] IEC is the International Eletrotechnical Commission

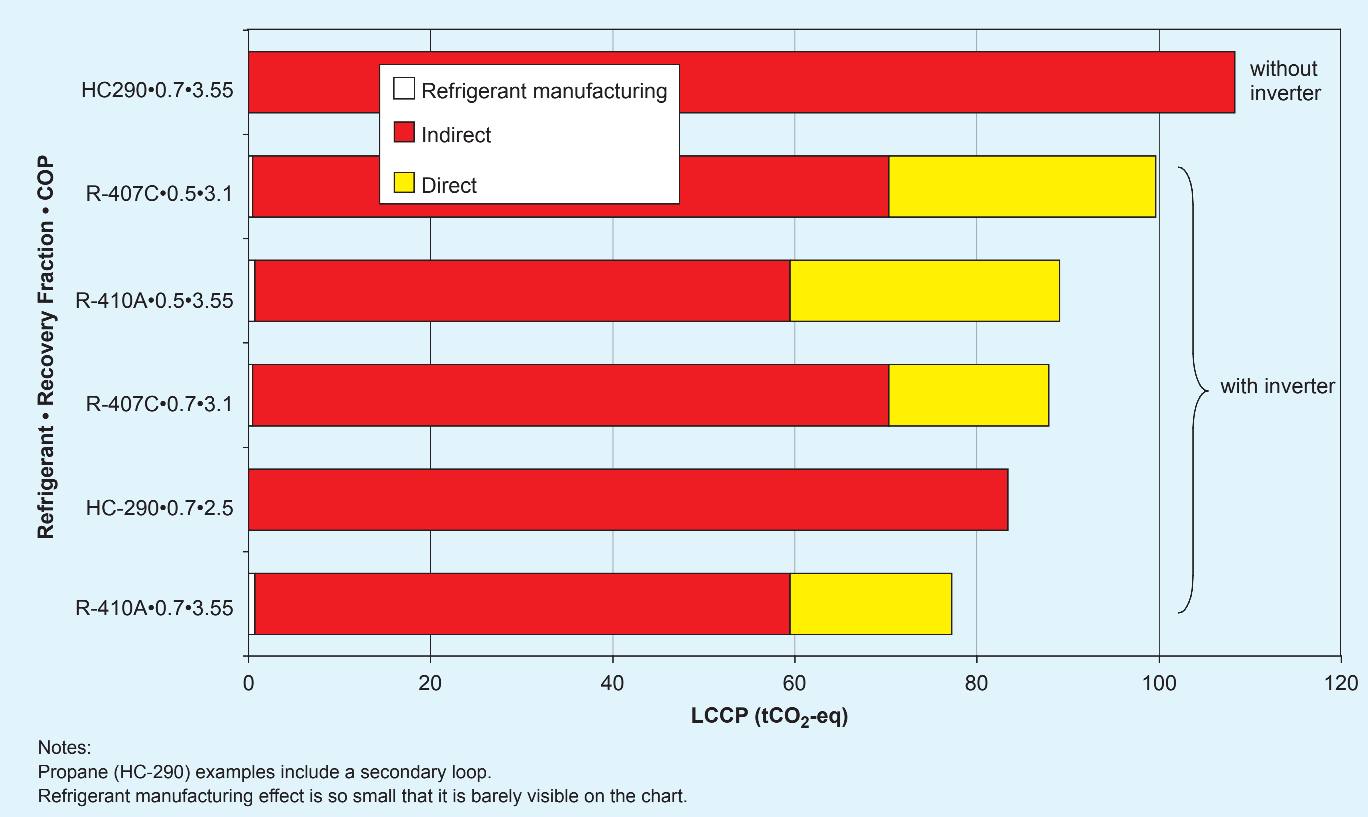

Figure 5.4. LCCP values for 56 kW multi-split air conditioners in Japan with COPs varying from 2.5−3.55 and end-of-life refrigerant recovery rates of 50% or 70% (Onishi *et al*., 2004).

and 888 h yr^{-1} for heating (JRAIA, 2003). Equipment life is assumed to be 15 years with no additional charge required during the operating life. Power generation emissions are assumed to be 0.378 kg CO_2 kWh^{-1} (Onishi *et al*., 2004). The figure shows that the combination of COP improvements obtained with inverter drive plus the lower emissions rate for power generation in Japan, mean that the indirect component of LCCP is less important than in the previous US cases. Also the higher the COP, the less important differences in COP are to the overall LCCP. This figure clearly shows the value of achieving a high recovery rate of refrigerant at the end of service life.

5.1.4.2 Global refrigerant bank

Table 5.1 estimates the refrigerant banks in 2001 as 548,000 tonnes of HCFC-22 and 28,000 tonnes of HFCs. Another source (Palandre *et al*., 2004) estimates that in 2002, the stationary AC bank consisted of over 1,000,000 tonnes of HCFCs and nearly 81,000 tonnes of HFCs. Although stationary AC includes more than just air-cooled air conditioners and heat pumps, it is clear that this type of equipment constitutes a large part of the HCFC bank. Emission estimates for stationary air conditioners are given in Section 5.4.

5.2 Chillers

Comfort air conditioning in large commercial buildings (including hotels, offices, hospitals, universities) is often provided by water chillers connected to an air handling and distribution system. Chillers cool water or a water/antifreeze mixture which is then pumped through a heat exchanger in an air handler or fan-coil unit to cool and dehumidify the air.

5.2.1 Technologies and applications

Two types of water chillers are available, vapour-compression chillers and absorption chillers.

The principal components of a vapour-compression chiller are a compressor driven by an electric motor, a liquid cooler (evaporator), a condenser, a refrigerant, a refrigerant expansion device, and a control unit. The refrigerating circuit in water chillers is usually factory sealed and tested; the installer does not need to connect refrigerant-containing parts on site. Therefore leaks during installation and use are minimal.

The energy source for absorption chillers is the heat provided by steam, hot water, or a fuel burner. In absorption chillers, two heat exchangers (a generator and an absorber) and a solution pump replace the compressor and motor of the vapour-

Table 5.2. Chiller capacity ranges.

Chiller Type	Capacity Range (kW)
Scroll and reciprocating water-cooled	7–1600
Screw water-cooled	140–2275
Positive displacement air-cooled	35–1500
Centrifugal water-cooled	350–30,000
Centrifugal air-cooled	630–1150
Absorption	Less than 90, and 140–17,500

Source: UNEP, 2003

compression cycle. Water is frequently the refrigerant used in these systems and the absorbent is lithium bromide. Small absorption chillers may use an alternative fluid pair: ammonia as the refrigerant and water as the absorbent.

Vapour-compression chillers are identified by the type of compressor they employ. These are classified as centrifugal compressors or positive displacement compressors. The latter category includes reciprocating, screw, and scroll compressors. Absorption chillers are identified by the number of heat input levels they employ (i.e., single-stage or two-stage), and whether they are direct-fired with a burning fuel, or use steam or hot water as the heat energy source. Table 5.2 lists the cooling capacity range offered by each type of chiller.

For many years, centrifugal chillers were the most common type of chillers above 700 kW capacity. Reciprocating compressors were used in smaller chillers. From the mid-1980s onwards, screw compressors became available as alternatives to reciprocating compressors in the 140–700 kW range and as alternatives to centrifugal compressors in the range up to about 2275 kW. Scroll compressors were introduced at about the same time and have been used as alternatives to reciprocating compressors in the 7 to over 90 kW range.

The Japan Air-Conditioning, Heating, and Refrigeration News (JARN, 2001) estimates that:

- The market for centrifugal and large screw chillers is divided between 40% in the USA and Canada, 25–30% in Asia, and smaller percentages in other regions in the world;
- The market for large absorption chillers is highly concentrated in Japan, China, and Korea with the USA and Europe as the remaining significant markets;
- The world market for smaller, positive displacement chillers (with hermetic reciprocating, scroll, and screw compressors) is much larger in absolute terms than for the other chiller types.

The coefficient of performance (COP) is one of the key criteria used to describe chillers. Other efficiency parameters are kW $tonne^{-1}$ (electrical power consumption in relation to cooling capacity) and energy efficiency ratio (EER) or Btu Wh^{-1} (cooling capacity related to power consumption).

Each type of chiller and refrigerant combination has a best-in-class COP level that can be purchased. This COP level tends to increase over the years as designs are improved. However, the chillers with the best COPs tend to be more expensive as they employ larger heat exchangers and other special features. In the absence of minimum efficiency standards, many purchasers choose to buy lower-cost, lower-COP chillers.

Full-load COP is commonly used as a simple measure of chiller efficiency. With the increasing recognition of the dominant contribution of the power consumption of chillers to their GWP, more attention has been paid to the energy efficiency of chillers at their more common operating conditions. In a single-chiller installation, chillers generally operate at their full-load or design point conditions less than 1% of the time. Manufacturers developed techniques such as variable-speed compressor drives, advanced controls, and efficient compressor unloading methods to optimize chiller efficiency under a wide range of conditions. In the US, ARI developed an additional performance measure for chillers called the Integrated Part Load Value (IPLV) which is described in ARI Standard 550/590 (ARI, 2003). The IPLV metric is based on weighting the COP at four operating conditions by the percentage of time assumed to be spent at each of four load fractions (25%, 50%, 75%, and 100%) by an individual chiller. The IPLV metric takes into account chiller energy-reducing features which are increasingly becoming common practice, but are not reflected in the full-load COP.

For a single chiller it is appropriate to use IPLV as the performance parameter, multiplied by actual operating hours when calculating the LCCP. For multiple chiller installations, which constitute about 80% of all installations, the calculation of LCCP includes full load COP and the IPLV based on the actual operating hours estimated for each load condition.

The ARI IPLV calculation details are based on single chiller installations and an average of 29 distinct US climate patterns. A modified version is being considered for Europe (Adnot, 2002).

Most installations have two or more chillers, so ARI recommends use of a comprehensive analysis that reflects the actual weather data, building load characteristics, number of chillers, operating hours, economizing capabilities, and energy for auxiliaries such as pumps and cooling towers to determine the overall chiller-plant system performance (ARI, 1998).

5.2.2 *Refrigerant use and equipment population*

Estimates and data about refrigerant use and equipment population, for the different types of chillers are presented below.

5.2.2.1 Centrifugal chillers

Centrifugal chillers are manufactured in the United States, Asia, and Europe. Prior to 1993, these chillers were offered with CFC-11, CFC-12, R-500, and HCFC-22 refrigerants. Of these, CFC-11 was the most common. With the implementation of the Montreal Protocol, production of chillers using CFCs or refrigerants containing CFCs (such as R-500) essentially ended in 1993. Centrifugal chillers using HCFC-22 rarely were produced after the late 1990s.

Table 5.3. Centrifugal chiller refrigerants.

Refrigerant	Capacity Range (kW)
CFC-11	350–3500
CFC-12	700–4700
R-500	3500–5000
HCFC-22	2500–30,000
HCFC-123	600–13,000
HFC-134a	350–14,000

The refrigerant alternatives for CFC-11 and CFC-12 or R-500 are HCFC-123 and HFC-134a, respectively. These refrigerants began to be used in centrifugal chillers in 1993 and continue to be used in 2004 in new production chillers.

Chillers employing HCFC-123 are available with maximum COPs of 7.45 (0.472 kW $tonne^{-1}$). With additional features such as variable-speed drives, HCFC-123 chillers can attain IPLV values of up to 11.7. Chillers employing HFC-134a are available with COPs of 6.79 (0.518 kW $tonne^{-1}$). With additional features such as variable-speed drives, HFC-134a chillers can attain IPLV values of up to 11.2.

Table 5.3 shows the range of cooling capacities offered for centrifugal chillers with several refrigerants. Table 5.4 shows the equipment population in a number of countries. This table provides estimates of the refrigerant bank in these chillers, assuming an average cooling capacity of 1400 kW in most cases and approximate values for the refrigerant charge for each refrigerant. The refrigerant charge for a given cooling capacity may vary with the efficiency level of the chiller. For any given refrigerant, higher efficiency levels often are associated with larger heat exchangers and, therefore, larger amounts of charge.

Production of a new refrigerant, HFC-245fa, as a foam-blowing agent commenced in 2003, and it has been considered as a candidate for use in new chiller designs. It has operating pressures higher than those for HCFC-123 but lower than for HFC-134a. Its use requires compressors to be redesigned to match its properties, a common requirement for this type of compressor. Unlike those for HCFC-123, heat exchangers for HFC-245fa must be designed to meet pressure vessel codes. Chillers employing HFC-245fa are not available yet. No chiller manufacturer has announced plans to use it at this time.

Centrifugal chillers are used in naval submarines and surface vessels. These chillers originally employed CFC-114 as the refrigerant in units with a capacity of 440–2800 kW. A number of CFC-114 chillers were converted to use HFC-236fa as a transitional refrigerant. New naval chillers use HFC-134a.

5.2.2.2 *Positive displacement chillers*

Chillers employing screw, scroll, and reciprocating compressors are manufactured in many countries around the world. Water-cooled chillers are generally associated with cooling towers for heat rejection from the system. Air-cooled chillers are equipped with refrigerant-to-air finned-tube condenser coils and fans to reject heat from the system. The selection of water-cooled as opposed to air-cooled chillers for a particular application varies

Table 5.4 Centrifugal chiller population and refrigerant inventory.

Country or Region	Refrigerant	Avg. Capacity (kW)	Avg. Charge Level (kg kW^{-1})	No. Units	Refrigerant Bank (tonnes)	Source of Unit Nos.
USA	CFC-11	1400	0.28	36,755	14,400	Dooley, 2001
USA	HCFC-123	1400	0.23	21,622	7000	Dooley, 2001
	HFC-134a	1400	0.36	21,622	10,900	with 50% split
Canada	CFC-11	1400	0.28	4212	1650	HRAI, 2003
Canada	HCFC-123	1400	0.23	637	205	HRAI, 2003
	HFC-134a	1400	0.36	637	320	with 50% split
Japan	CFC-11	1100	0.40	7000	3080	JARN, 2002c
	HCFC-123 and HFC-134a	1600	0.40	4500	2880	JRAIA, 2004
India	CFC-11	1450	0.28	1100	447	UNEP, 2004
China	CFC-11	65% of total are	0.28	3700	2540	UNEP, 2004
	CFC-12	1400–2450, rest	0.36	338	300	Digmanese, 2004
	HCFC-22	are 2800–3500:	0.36	550	485	
	HCFC-123	2450 avg.	0.23	3200	1800	
	HFC-134a		0.36	3250	2870	
Brazil	CFC-11	1350	0.28	420	160	UNEP, 2004
	CFC-12	1450	0.36	280	145	
17 Developing Countries	CFC-11 CFC-12		*Avg. unit charge of 364 kg*	11,700	4000	UNEP, 2004

Source for charge levels: Sand *et al*., 1997; for HFC-134a, ADL, 2002.

Table 5.5. Positive displacement chiller refrigerants and average charge levels.

Refrigerant and Chiller Type	Evaporator Type	kg kW^{-1}
HCFC-22 and HFC-134a screw and scroll chillers	DX	0.27
R-410A and R-407C scroll chillers	DX	0.27
HCFC-22 and HFC-134a screw chillers	flooded	0.35
HCFC-22 reciprocating chillers	DX	0.26
Ammonia (R-717) screw or reciprocating chillers(1)	DX	0.04–0.20
Ammonia (R-717) screw or reciprocating chillers(1)	flooded	0.20–0.25
Hydrocarbons	DX	0.14

Source: UNEP, 2003
(1) Charge levels for R-717 chillers tend to decrease with capacity and are lowest for plate-type heat exchangers rather than with tube-in-shell (UNEP, 1998)

with regional conditions and owner preferences.

When they were first produced in the mid-1980s, **screw chillers** generally employed HCFC-22 as the refrigerant. HFC-134a chillers have recently been introduced by a number of manufacturers and in some cases these have replaced their HCFC-22 products.

Screw chillers using a higher pressure refrigerant, R-410A, have recently been introduced. Screw chillers using ammonia as the refrigerant are available from some manufacturers and these are mainly found in northern-European countries. The numbers produced are small compared to chillers employing HCFC-22 or HFCs.

Air-cooled and water-cooled screw chillers below 700 kW often employ evaporators with refrigerant flowing inside the tubes and chilled water on the shell side. These are called direct-expansion (DX) evaporators. Chillers with capacities above 700 kW generally employ flooded evaporators with the refrigerant on the shell side. Flooded evaporators require higher charges than DX evaporators (see Table 5.5), but permit closer approach temperatures and higher efficiencies.

Scroll chillers are produced in both water-cooled and air-cooled versions using DX evaporators. Refrigerants offered include HCFC-22, HFC-134a, R-410A, and R-407C. For capacities below 150 kW, brazed-plate heat exchangers are often used for evaporators instead of the shell-and-tube heat exchangers employed in larger chillers. Brazed-plate heat exchangers reduce system volume and refrigerant charge.

Air-cooled chiller systems are generally less expensive than the equivalent-capacity water-cooled chiller systems that include a cooling tower and water pump. However, under many conditions water-cooled systems can be more efficient due to the lower condensing temperatures.

Reciprocating chillers are produced in both water-cooled and air-cooled versions using DX evaporators. Air-cooled versions have increased their market share in recent years. Prior to the advent of the Montreal Protocol, some of the smaller reciprocating chillers (under 100 kW) were offered with CFC-12 as the refrigerant. Most of the smaller chillers, and nearly all the larger chillers, employed HCFC-22 as the refrigerant. Since the Montreal Protocol, new reciprocating chillers have employed HCFC-22, R-407C, and to a small extent, HFC-134a and propane or propylene. Some water-cooled reciprocating chillers were manufactured with ammonia as the refrigerant but the number of these units is very small compared to the number of chillers employing fluorocarbon refrigerants. As with scroll chillers, the use of brazed-plate heat exchangers reduces the system volume and system charge.

Table 5.5 shows approximate charge levels for each type of positive displacement chiller with several refrigerants.

The refrigerant blend R-407C is being used as a transitional replacement for HCFC-22 in direct expansion (DX) systems because it has a similar cooling capacity and pressure levels. However, R-407C necessitates larger and more expensive heat exchangers to maintain its performance. For R-407C DX evaporators, some of this difficulty is offset in new equipment by taking advantage of the refrigerant's 'glide' characteristic ('glide' of about 5^{o}C temperature variation during constant-pressure evaporation) in counter-flow heat exchange. The glide also can be accommodated in the conventional condensers of air-cooled chillers. In time, the higher-pressure blend, R-410A, is expected to replace the use of R-407C, particularly in smaller chillers (UNEP, 2003).

5.2.2.3 *Absorption chillers*

Absorption chillers are mainly manufactured in Japan, China, and South Korea. A few absorption chillers are manufactured in North America. Absorption chiller energy use can be compared to electrical chiller energy by using calculations based on primary energy. Absorption systems have higher primary energy requirements and higher initial costs than vapour-compression chillers. They can be cost-effective in applications where waste heat is available in the form of steam or hot water, where electricity is not readily available for summer cooling loads, or where high electricity cost structures (including demand charges) make gas-fired absorption a lower-cost alternative. In Japan, government policy encourages absorption systems so as to facilitative a more balanced gas import throughout the year and to reduce summer electrical loads.

Single-stage absorption applications are typically limited to sites that can use waste heat in the form of hot water or steam as the energy source. Such sites include cogeneration systems where waste engine heat or steam is available. Two-stage absorption chillers, driven by steam or hot water or directly fired by fossil fuels, were first produced in large numbers in Asia (primarily in Japan) for the regional market during the 1980s. Two-stage chillers were produced in North America shortly afterwards, often through licensing from the Asian manufacturers. Small single-stage gas-fired absorption chillers with capacities below 90 kW are produced in Europe and North America using ammonia as the refrigerant and water as the absorbent.

5.2.2.4 World market characteristics

Table 5.6 summarizes the market for chillers in 2001. It shows that air-cooled positive displacement chillers represented nearly 75% of the number of units in the positive displacement category. Chillers larger than 100 kW are dominant in the Americas, the Middle East, and southern Asia while smaller air-cooled chillers and chiller heat pumps for residential and light commercial use are more common in East Asia and Europe.

In a number of countries the commercial air-conditioning market appears to be moving away from small chillers toward ductless single-package air conditioners or ducted unitary systems, due to the lower installation cost (JARN, 2002a).

Market conditions in China are particularly interesting due to the recent rapid development of its internal market, chiller manufacturing capabilities, and export potential. The centrifugal chiller population in China is included in Table 5.4. Significant growth began in the 1990s. Before 1995, most centrifugals were imported. After 1995, increasing numbers of chillers were produced in China by factories using US designs (primarily HCFC-123 (30%) and HFC-134a (70%)) (ICF, 2003). For chillers of all types, China is now the largest market in the world with sales of 34,000 units in 2001 and a growth of over 8.5% yr^{-1}. The main market is East China where there is a growing replacement market. Over half of all chiller sales are now reversible heat pumps that can provide cooling and heating. Screw and scroll chiller sales, mostly using HCFC-22, are rising as their technology becomes more familiar to the major design institutes. Demand for absorption chillers has been slowing since 1999 when national energy policy changed to relax controls on electricity for commercial businesses. China has a major residential market for chillers with fan coil units (BSRIA, 2001).

5.2.3 Options for HFC emissions reduction

As with stationary air conditioners, options for reducing HFC emissions in chillers include refrigerant conservation as described in Section 5.1.3.1 and the use of non-HFC systems. These options are now detailed.

5.2.3.1 HFC vapour-compression systems

Over the past 30 years, the life-cycle refrigerant needs of chillers have been reduced more than tenfold (Calm, 1999) due to design improvements and, in particular, the improved care of equipment in the field. The approaches that have been used to reduce CFC emissions over the last 30 years can also be applied to HCFCs and HFCs.

The starting points for reducing HFC emissions from chillers were designing the chiller and its components to use a reduced amount of refrigerant charge, employing a minimum number of fittings that are potential leakage sources, avoiding the use of flare fittings on tubing, and including features that minimize emissions while servicing components such as shut-off valves for oil filters and sensors. Many manufacturers have already implemented such changes.

Service technicians can be trained and certified to perform their tasks while minimizing refrigerant emissions during installation and refrigerant charging, servicing, and ultimately taking equipment out of service. Charging and storing the refrigerant in the chiller at the factory prior to delivery can reduce emissions at installation. Refrigerant should be recovered at the end of equipment life. Appropriate government policies can be effective in accomplishing these objectives. Some countries require annual inspections of equipment or monitoring of refrigerant use to determine whether emissions are becoming excessive and require action if this is the case.

Remote monitoring is becoming an established method for monitoring the performance of chillers. It is also being used to detect leakage either directly through leak detectors or indirectly through changes in system characteristics (e.g., pressures). Remote monitoring can provide alerts to maintenance engineers and system managers so as to ensure that early action is taken to repair leaks and maintain performance.

Table 5.6. The world chiller sales in 2001 (number of units).

Chiller Type	North and South America	Middle East, S. Asia, Africa	East Asia and Oceania	Europe	World Total
Positive Displacement	16,728	11,707	66,166	77,599	172,200
Air cooled	12,700	7749	43,714	61,933	126,096
Water cooled	4028	3958	22,542	15,666	46,104
<100 kW	2721	1678	48,444	58,624	111,467
>100 kW	14,007	10,029	17,722	18,975	60,733
Centrifugal	5153	413	2679	664	8908
Absorption >350 kW	261	289	5461	528	6539
Total chillers	**22,142**	**12,409**	**74,306**	**78,791**	**187,648**

Source: JARN, 2002b

5.2.3.2 Non-HFC systems

5.2.3.2.1 Vapour-compression cycle with non-HFC refrigerants

5.2.3.2.1.1 Positive displacement chillers
The non-HFC refrigerants that have been used in positive displacement compressor chillers are presented below.

Ammonia
Chillers using ammonia as the refrigerant are available in the capacity range 100–2000 kW and a few are larger than this. The use of ammonia is more complex than that of many other refrigerants because ammonia is a strong irritant gas that is slightly toxic, corrosive to skin and other membranes, and flammable. Recommended practice (ASHRAE, 2001a; ISO, 1993; CEN, 2000/2001) limits the use of large ammonia systems in public buildings to those systems, which use a secondary heat transfer fluid (which is intrinsic in chillers), so that the ammonia is confined to the machine room where alarms, venting devices, and perhaps scrubber systems can enhance safety. Guidelines are available for the safe design and application of ammonia systems (IEA, 1998, Chapter 4; ASHRAE, 2001a). Modern, compact factory-built units contain the ammonia far more effectively than old ammonia plants.

The high discharge temperatures associated with ammonia permit a far greater degree of heat recovery than with other refrigerants.

The wider acceptance of ammonia requires public officials being satisfied that ammonia systems are safe under emergency conditions such as building fires or earthquakes, either of which might rupture refrigerant piping and pressure vessels. The most important factor is the establishment of building codes that are acceptable to safety officials (e.g., fire officers).

Hydrocarbons
Hydrocarbon refrigerants have a long history of application in industrial chillers in petrochemical plants. Before 1997 they were not used in comfort air-conditioning chiller applications due to reservations about the system safety. European manufacturers now offer a range of hydrocarbon chillers. About 100 to 150 hydrocarbon chiller units are sold each year, mainly in northern Europe (UNEP, 2003). This is a small number compared to the market for more than 78,000 HCFC and HFC chillers in Europe (Table 5.6). The major markets have been office buildings, process cooling, and supermarkets.

In a system optimized for hydrocarbons, one might be able to achieve efficiency increases of more than 5% by using propane instead of HCFC-22. In the literature, efficiency comparisons for HCFC, HFC, and HC systems sometimes show substantial differences but do not represent rigorous comparisons. This issue was discussed in Section 5.1.3.2.1. The cost of HC chillers is higher than that of HCFC or HFC equivalents, partly due to the fact that hydrocarbon chillers still are a niche market.

A major disadvantage of hydrocarbons is their flammability, which deters their consideration for use in many applications. Refrigeration safety standards have been developed for hydrocarbon systems, for example, IEC 60355-2-40, AMD. 2 ED. 4, 'Safety of Household and Similar Electrical Appliances, Part 2'. Typical safety measures include proper placement and/or gas tight enclosure of the chiller, application of low-charge system design, fail-safe ventilation systems, and gas detector alarm activating systems. An alternative is outdoor installation (ARTI, 2001). Comprehensive guidelines for safe design, installation, and handling of hydrocarbon refrigerants have been produced (ACRIB, 2001). These guidelines limit the charge for domestic/public applications to <1.5 kg for a sealed system or <5 kg in a special machinery room or outdoors. For commercial and private applications the limits are <2.5 kg and <10 kg respectively.

Carbon dioxide
Carbon dioxide is being investigated for a wide range of potential applications. However, CO_2 does not match the cycle energy efficiencies of fluorocarbon refrigerants for typical water chilling applications (ASHRAE, 2001b). Therefore, there is usually no environmental incentive to use CO_2 in chillers instead of HFCs. In Japan, CO_2 has not been used in a chiller on a commercial basis, but one demonstration unit has been built.

5.2.3.2.1.2 Centrifugal chillers
The non-HFC refrigerants that have been used in centrifugal compressor chillers are discussed below.

Hydrocarbons
Hydrocarbon refrigerants are used in centrifugal chillers in petrochemical plants where a variety of hazardous materials are routinely used and where the staff are highly trained in safety measures and emergency responses. Hydrocarbon refrigerants have not been used elsewhere due to concerns about system safety due to the large charges of flammable refrigerants.

Ammonia
Ammonia is not a suitable refrigerant for centrifugal chillers due to the large number of compressor stages required to produce the necessary pressure rise ('head') for the ammonia chiller cycle.

Water
Water is a very low-pressure refrigerant, with a condensing pressure of 4.2 kPa (0.042 bar) at 30°C and a suction pressure of 1.6 kPa (0.016 bar) at 9°C. Traditionally, water has been used in specialized applications with steam aspirators, and rarely with vapour compressors. The low pressures and very high volumetric flow rates required in water vapour-compression systems necessitate compressor designs that are uncommon in the air-conditioning field.

The few applications that use water as a refrigerant, use it to chill water or produce an ice slurry by direct evaporation from a pool of water. These systems carry a cost premium of more than

50% above conventional systems. The higher costs are inherent and are associated with the large physical size of water vapour chillers and the complexity of their compressor technology.

Recent studies indicate that there are no known compressor dsigns or cycle configurations of any cost that will enable water vapour-compression cycles to reach efficiencies comparable to existing technology (ARTI, 2000; ARTI, 2004).

5.2.3.2.2 Alternative technologies to vapour-compression cycle

Absorption Chillers

Absorption chillers are inherently larger and more expensive than vapour-compression chillers. They have been successful in specific markets as described in Section 5.2.2.3.

Some countries have implemented the use of water-LiBr absorption chillers in trigeneration systems. Trigeneration is the concept of deriving three different forms of energy from the primary energy source, namely, heating, cooling and power generation. This is also referred to as CHCP (combined heating, cooling, and power generation). This option is particularly relevant in tropical countries where buildings need to be air-conditioned and many industries require process cooling and heating. Although cooling can be provided by conventional vapour-compression chillers driven by electricity, heat exhausted from the cogeneration plant can drive the absorption chillers so that the overall primary energy consumption is reduced.

5.2.4 Global warming effects

5.2.4.1 LCCP examples for chillers

Figure 5.5 presents LCCP values for chiller technology alternatives at 350 tonnes rated capacity (1230 kW) applied to a typical office building in Atlanta, Georgia, USA. LCCP values for centrifugal and screw chillers fall within a ±8% range and refrigerant emissions account for less than 3% of the LCCP of any of these technology options. Ammonia has been included as a technical option, but local codes may affect its use. The data source did not calculate LCCP for a hydrocarbon system. However, hydrocarbon refrigerants have not been used in centrifugal chillers in office buildings due to concerns about safety with large charges of flammable refrigerants (UNEP, 2003).

The major portion of LCCP is the indirect warming associated with energy consumption. Direct warming due to refrigerant emissions only amounts to between 0.2 and 3.0% of the total LCCP. The LCCP values of the vapour-compression alternatives fall within a reasonably narrow range and show the clear superiority of vapour compression over absorption in terms of LCCP.

The LCCP of a typical direct-fired, two-stage water-LiBr absorption chiller is about 65% higher than the average LCCP for vapour-compression cycle chillers.

The basic assumptions used to create Figure 5.5 include 2125 annual operating hours, 30-year equipment life, 0.65 kg CO_2 kWh^{-1} power plant emissions, and inclusion of cooling

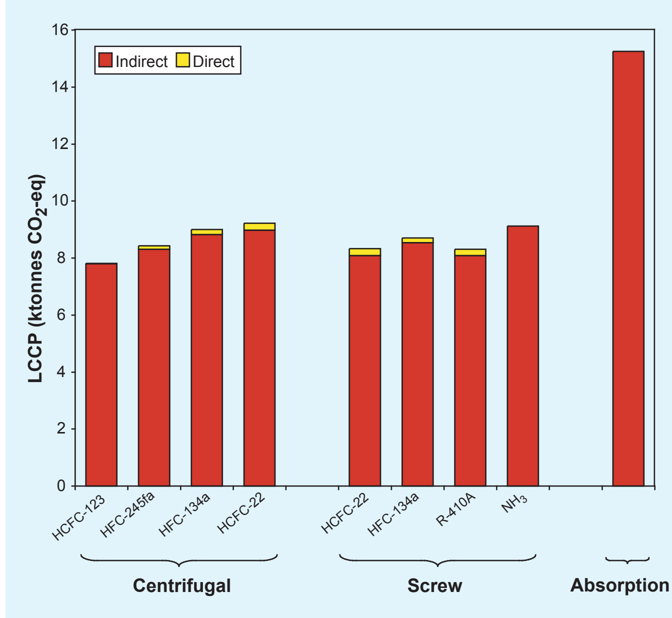

Figure 5.5. LCCP values for 1230 kW chiller-technology alternatives in an office building in Atlanta, Georgia, USA with a 1% refrigerant annual make-up rate (ADL, 2002).

tower fan and pump power. The annual charge loss rates are assumed to be 1% yr^{-1} for the vapour-compression chillers to account for some end-of-life losses and accidental losses in the field (ADL, 2002).

Figure 5.6 compares TEWI values for 1000 tonne (3500 kW chillers) with a 1% refrigerant annual make-up rate. CFC-11 and CFC-12 chiller data for equipment with 1993 vintage efficien-

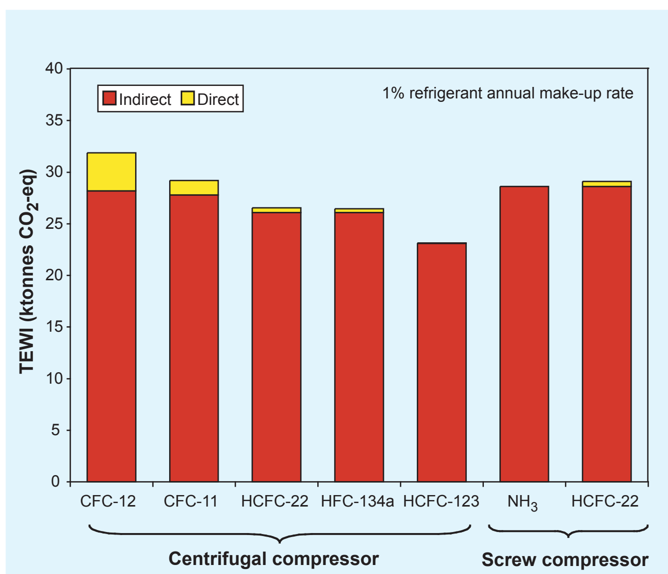

Figure 5.6. LCCP TEWI values for 1000 tonne (3500 kW) chillers with a 1% refrigerant annual make-up rate in an Atlanta office application (Sand *et al.*, 1997).

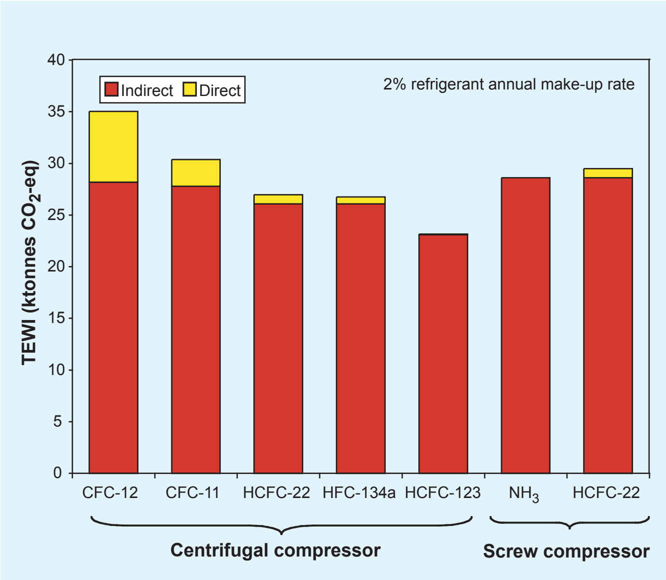

Figure 5.7. LCCP TEWI values for 1000 tonne (3500 kW) chillers with a 2% refrigerant annual make-up rate in an Atlanta office application (Sand *et al*., 1997).

cies are shown because many chillers are still operating with these refrigerants. The figure shows the environmental benefits obtained by replacing CFC chillers with chillers employing non-CFC refrigerants that have higher COPs and a lower direct warming impact. In practice, the environmental benefits from replacement are greater because older CFC chillers are likely to have refrigerant leak rates of 4% or more, which is higher than the 1% rate assumed in this figure.

Figure 5.7 shows the effect on TEWI for chillers in Figure 5.6, if the annual refrigerant make-up rate is doubled to 2% for the chillers and the end-of-life refrigerant loss is 5%. The impact of the increased loss rate on TEWI is small, especially for the non-CFC chillers.

The leakage rates of 1% and 2% used in Figures 5.6 and 5.7 are lower than the historical average for chillers, but 2 to 4 times the best-practice value of 0.5% per year available today in the leading centrifugal and screw chillers.

The basic assumptions for Figures 5.6 and 5.7 are the same as for Figure 5.5 with the exception of the increased cooling capacity, the CFC chiller characteristics mentioned above, and the additional assumption of a 5% loss of charge when the chiller is scrapped.

Figure 5.8 compares LCCP values for air-cooled 25 kW scroll chiller/heat pumps in Japan. Two refrigerants, propane and R-407C, are compared for these chiller/heat pumps with two levels of end-of-life refrigerant recovery, 50% and 70%. The units are assumed to operate 700 h yr^{-1} for cooling and 400 h yr^{-1} for heating No additional charge has been added during the 15-year life of the chiller, and the emissions from power generation are taken to be 0.378 kg CO_2 kWh^{-1} for Japan (Onishi *et al*., 2004). The figure shows that the indirect component of LCCP is dominant for this application but the effect of only 50% end-of-life recovery is not negligible. In this comparison, the propane system is not equipped with a secondary heat transfer loop with its added COP penalties. This is because chillers and chiller/heat pumps inherently contain secondary loops in their water-to-water or air-to-water systems. However, propane chiller/heat pumps will have a 10–20% cost increase for safety features compared to a system with a non-flammable refrigerant and the same COP. For the same 10–20% cost increase, an increase in COP from 2.65–3.05 should be achievable for the R-407C system. This makes the LCCP with R-407C lower than that of an equivalent-cost propane system (Onishi *et al*., 2004).

Figure 5.9 shows LCCP values for 355 kW air-cooled screw chillers in Japan using propane, HFC-134a, or R-407C as refrigerants in systems with several levels of COP. The chiller life is assumed to be 25 years with end-of-life refrigerant recovery assumed to be either 70% or 80%. Also, during the life of the equipment it is assumed that a 10% additional charge is needed to compensate for emissions. The units are assumed to operate 700 h yr^{-1} for cooling and 400 hours yr^{-1} for heating. Emissions from power generation are assumed to be 0.378 kg CO_2 kWh^{-1} for Japan (Onishi *et al*., 2004). The figure shows that the indirect component of LCCP is dominant for this application and end-of-life refrigerant recovery rate. A comparison of the LCCP values for the propane and HFC-134a air-cooled screw chiller/heat pumps reveals that only a modest increase in COP is required for the HFC-134a system to have a better LCCP than propane. This COP increase with HFC-134a could be achieved by investing the cost of safety features for flammable refrigerant systems in performance improvements to the HFC systems instead (Onishi *et al*., 2004).

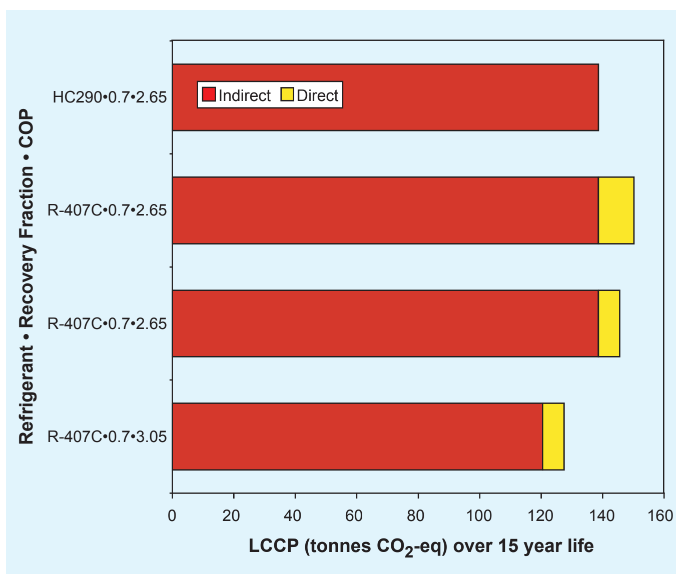

Figure 5.8. LCCP values for air-cooled 25 kW scroll chiller/heat pumps in Japan for R-290 and R-407C, with end-of-life recovery of 70% or 50% of the refrigerant charge, and with a system COP of 2.65 or 3.05 (Onishi *et al*., 2004).

Table 5.7. HFC consumption and emission estimates for chillers.

	Year	
	2000	**2010**
HFC consumption, kt yr^{-1}	2.5	3.5–4.5
HFC consumption, MtC-eq yr^{-1}	1	2.3–3.0
HFC emissions, kt yr^{-1}	0.2	0.5–0.7
HFC emissions, MtC-eq yr^{-1}	0.1	0.3–0.5

Source: IPCC, 2001

5.2.4.2 Global refrigerant bank and emissions

Table 5.4 provides a sample of the large and varying refrigerant bank in chillers. One source (Palandre *et al*., 2004) estimates the Stationary AC banks in 2002 to be nearly 84,000 tonnes CFCs and nearly 81,000 tonnes of HFCs. Although Stationary AC includes more than just chillers, it is clear that the CFC-11 and CFC-12 banks in chillers make up nearly the entire CFC bank estimated. The growing use of HFC-134a in chillers contributes substantially to the HFC bank as well.

Table 5.7 shows estimates of global HFC consumption and emission for chillers in 2000 and 2010. These estimates are based on information from IPCC (IPCC, 2001). Additional information on emission estimates is provided in Section 5.4.

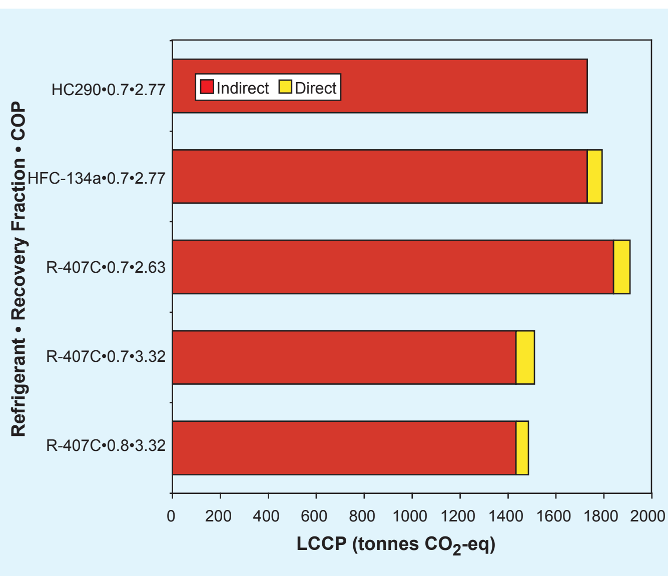

Figure 5.9. LCCP values for 355 kW air-cooled screw chillers in Japan for HFC-134a, R-290, and R-407C, with end-of-life refrigerant recovery of 70% or 80%, and COPs of 2.63, 2.77, or 3.32 (Onishi *et al*., 2004).

5.3 Water-heating heat pumps

This section describes equipment and refrigerants for heating water with heat pumps[4].

5.3.1 Technologies and applications

5.3.1.1 Vapour-compression cycle, heat-pump water heaters

Almost all heat pumps work on the principle of the vapour-compression cycle. Heating-only, space-heating heat pumps are manufactured in a variety of sizes ranging from 1 kW heating capacity for single room units, to 50–1000 kW for commercial/institutional applications, and tens of MW for district heating plants. Most small to medium-sized capacity heat pumps in buildings are standardized factory-made units. Large heat pump installations usually are custom-made and are assembled at the site.

In several countries water heating for swimming pools is provided by heat pumps. This is a growing market for heat pumps.

Heat sources include outdoor, exhaust and ventilation air, sea and lake water, sewage water, ground water, earth, industrial wastewater and process waste heat. Air-source and ground-coupled heat pumps dominate the market. For environmental reasons, many countries discourage the use of ground water from wells as a heat pump source (ground subsidence, higher-value uses for well water). In countries with cold climates such as in northern Europe, some heat pumps are used for heating only. In countries with warmer climates, heat pumps serve hydronic systems with fan coils provide heat in the winter and cooling in the summer. Heat pumps with dual functions, such as heating water and cooling air simultaneously, are also available.

In mature markets, such as Sweden, heat pumps have a significant market share as heating systems for new buildings and are entering into retrofit markets as well. In Europe, comfort heating dominates heat pump markets – mostly with hydronic systems using outside air or the ground. There is increasing use of heat pumps that recover a portion of exhaust heat in ventilation air to heat incoming air in balanced systems. This reduces the thermal load compared to having to heat the incoming air with primary fuel or electricity. Heat pumps in Germany and Sweden provide up to 85% of the annual heating in some buildings. For these buildings, supplementary heat is required only on the coldest days.

Heat pumps have up to a 95% share of heating systems in new buildings in Sweden. This is due to the initial development support and subsidies from the government that made the units reliable and popular, high electricity and gas prices, widespread use of hydronic heating systems, and rating as a 'green' heating system by consumers (IEA, 2003a).

Heat pumps for combined comfort heating and domestic

[4] Heat pumps that heat air are included in section 5.2 on Stationary Air Conditioners.

hot-water heating are used in some European countries. Most of the combined systems on the market alternate between space and water heating, but units simultaneously serving both uses are being introduced (IEA, 2004).

The heat pumps for comfort heating have capacities up to 25 kW. Supply temperatures are 35–45°C for comfort heat in new constructions and 55°–65°C for retrofits. Regulations in a number of European countries require domestic water heaters to produce supply temperatures of 60–65°C.

Small capacity (10–30 kW) air-to-water heat pump chillers for residential and light commercial use in combination with fan-coil units are popular in China as well as Italy, Spain, and other southern-European countries. Hot water delivery temperatures are in the 45–55°C range. In the future, the market growth of small air-to-water heat pumps may be slowed in some markets by the growing popularity of variable-refrigerant-flow systems combined with multiple, indoor fan coil units connected to a refrigerant loop for direct refrigerant-to-air heat transfer.

In Japan, heat pump chillers are mainly for commercial applications above 70 kW. Commercial size heat pump chillers of up to 700 or 1000 kW capacity are used for retrofit, replacing old chillers and boilers to vacate machine room space and eliminate cooling towers (JARN, 2002b).

Night-time electricity rates in Japan are only 25% of daytime rates. As a consequence, domestic hot-water heat pumps are a rapidly-growing market. They are operated only at night and the hot water is stored for daytime use. Germany and Austria have been installing dedicated domestic hot water (DHW) heat pumps for a number of years (IEA, 2004).

5.3.1.2 *Absorption heat pumps*

Absorption heat pumps for space heating are mostly gas-fired and commonly provide cooling simultaneously with heating. Most of the systems use water and lithium bromide as the working pair, and can achieve about 100°C output temperature. Absorption heat pumps for the heating of residential buildings are rare. In industry, absorption heat pumps are only employed on a minor scale.

5.3.2 *Refrigerant use and equipment population*

In the past, the most common refrigerants for vapour-compression heat pumps were CFC-12, R-502, HCFC-22, and R-500. In developed countries, HCFC-22 still is used as one of the main refrigerants in heat pumps, but manufacturers have begun to introduce models using HFC alternatives (HFC-134a, R-407C, R-404A) or hydrocarbons to replace their HCFC-22 models.

Data on the installed base of water-heating heat pumps are not readily available for most countries. In particular, the data needed to estimate the bank of various refrigerants in use in these heat pumps do not seem to exist. Global sales of these heat pumps were small until 1995, but have increased steadily since. The installed base of ground-source heat pumps was estimated to be about 110,000 units in 1998 (IEA, 1999).

Total sales of water-heating heat pumps in Sweden were close to 40,000 units in 2002. Of these, 60% used water or brine as a source, and the rest used air or exhaust air. Fifty percent of these heat pump sales are for retrofits. The Swedish Energy Agency estimates that over 300,000 heat pumps are in operation there, a small portion of which are 'air-to-air' (IEA, 2003b).

In the rest of Europe, heat pumps are primarily used in new construction and provide combined operation – comfort heating and DHW heating.

Switzerland had heat pump sales of 7500 units in 2002, of which 50% were air-to-water and 43% were brine-to-water. Heat pump sales in Germany were 12,500 units in 2002, of which 43% were ground-source combined heat pumps and 33% were for DHW heating only (JARN, 2004a).

In China, the use of heat pumps is rapidly increasing and had reached 35,000 units in 2002. Sales have increased as a result of nationwide housing development projects where the preference is for hydronic systems. More than half of the sales volume is for units with a capacity of less than 30 kW (JARN, 2003).

5.3.3 *Options for reducing HFC emissions*

5.3.3.1 *HFC vapour-compression systems*

The actions described in Section 5.1.3.1 can also be used to reduce emissions in heat pumps.

5.3.3.2 *Vapour-compression cycle with non-HFC refrigerants*

Hydrocarbons

In most applications HC-290 will yield an energy efficiency comparable to or slightly higher (e.g., 5–10% higher) than that of HCFC-22. The performance difference increases in heat pumps at lower ambient temperatures. When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions must be taken to ensure safe operation and maintenance. Several standards that regulate the use of hydrocarbons in heat pumps exist or are being developed in Europe, Australia, and New Zealand. An example is European Standard EN 378 (CEN, 2000/2001).

In some countries hydrocarbons are considered to be a viable option in small, low-charge residential heat pumps. Several northern-European manufacturers are using propane (HC-290) or propylene (HC-1270) as refrigerants in small residential and commercial water-to-water and air-to-water heat pumps. The hydrocarbon circuit is located outdoors using ambient air, earth, or ground water sources, and is connected to hydronic floor heating systems (IEA, 2002).

Carbon Dioxide

The transcritical CO_2 cycle exhibits a significant temperature glide on the high temperature side. Such a glide can be advantageous in a counter-flow heat exchanger. Heat pumps generating water temperatures of 90°C have been developed in Japan for home use. Typical heating capacities are 4.5 kW. The COP achieved by CO_2 water-heating heat pumps is 4.0 and is slightly higher for 'mild climates'. This COP also is attained by R-410A heat pumps, but the highest water temperature available is about 80°C (JARN, 2004b).

Carbon dioxide is being introduced as a refrigerant for heat pumps, particularly those with a DHW function. Japan and Norway have been leaders in the development of CO_2 water-heating heat pumps. Because there is government support in Japan for the introduction of high-efficiency water heaters, 37,000 heat pump water heaters were sold in Japan in 2002 that used CO_2 or R-410A as refrigerants. The sales are estimated to have increased to 75,000–78,000 units in FY 2003 (JARN, 2004b).

Ammonia

Ammonia has been used in medium-sized and large capacity heat pumps, mainly in Scandinavia, Germany, Switzerland, and the Netherlands (IEA, 1993, 1994, 1998 (Chapter 4); Kruse, 1993). System safety requirements for ammonia heat pumps are similar to those for ammonia chillers, which were discussed in Section 5.2.

5.3.4 Global warming effects

There are no known published data on the global warming effects of water heating heat pumps.

5.4 Estimates for refrigerant emissions and costs for emission reductions

There are many data sources that can be used to estimate discrete equipment inventories and refrigerant banks (e.g., ICF, 2003; JARN, 2002b, and JARN, 2002c). Several studies have used these data along with 'bottom-up' methodologies to estimate refrigerant banks and/or refrigerant emissions, for past, current and/or future years, and for various countries, regions or the world.

These studies point to the dynamic and competitive nature of the air-conditioning market, especially as the transitions from CFCs and HCFCs to HFCs and other refrigerants, as described earlier in this chapter, occur. Therefore due consideration must be given to the data used, the assumptions made, and the methodologies employed in estimating refrigerant banks and emissions. The differences that arise for current estimates of banks and emissions are large, and are often further exacerbated when projecting future banks and emissions. Some of the aspects that may vary from study to study are:

- Equipment Inventories. What type of equipment is included? How is it disaggregated?
- Refrigerant Charge. What is the average refrigerant charge? Are different charges used for different types or different vintages of equipment?
- Emission Sources. Are various emissions sources (e.g., installation, operating, servicing, end-of-life disposal) evaluated separately, or is an average emission rate used?
- Equipment Lifetimes. How long is equipment assumed to exist? Are emission rates assumed to be constant over the lifetime?
- Emissions Scope. Are all refrigerants included, or just those reported in national inventories under the UNFCCC (i.e., HFCs and PFCs)? Does the source also estimate indirect emissions from power generation?
- Geographical Extrapolation. If data are only available for a particular region, how are the data extrapolated to other countries or regions or disaggregated into individual countries within the region?
- Temporal Extrapolation. How are data extrapolated into the future? Do emission rates or refrigerant charges change in the future? If so, by how much and on what basis?
- Global Warming Potentials. What source is used for GWPs? If CFCs and HCFCs are included in estimates, do GWPs represent the direct effect or include the indirect effect as well?

Table 5.8 compiles several estimates for recent (1996–2005) emission rates. The data shown are direct emissions only. Estimates for residential and commercial air conditioning and heating (also called 'stationary air conditioning and heating') are sometimes divided into subcategories. For instance, some studies report separate estimates for air conditioners (for cooling and/or heating) and chillers, as described in Sections 5.1 and 5.2, respectively. No studies were found that contained separate emissions of water-heating heat pumps as described in Section 5.3.

Table 5.8 mostly shows estimates for the entire world, with two examples for industrialized Europe to further highlight the differences in the literature. Estimates for the entire air conditioning and refrigeration sector are included to provide a perspective; see Chapter 4 and Chapter 6 for more information on Refrigeration and Mobile Air Conditioning.

It is clear that different sources provide vastly different emission estimates. Similar differences are seen for refrigerant banks. Some of the differences shown above can be explained by the transition from ODS to non-ODS refrigerants (e.g., in 1996 relatively few HFC units existed, whereas by 2005 substantially more HFC units had been installed). However, the major difference in the estimates is due to the data and methodologies used.

Table 5.9 provides some example estimates of future emissions under 'baseline' or 'business-as-usual' conditions, in 2010 and 2015. Again, the data is for direct emissions only. The data for 2010 are mainly included to show that any given source is not always consistently higher or lower than another source (e.g., compare estimates from sources Harnisch *et al.*, 2001, and US EPA, 2004).

Some authors also examine various options for reducing the predicted emissions and the costs associated with this. As with the emission estimates, there is a lot of variation between the sources and the results are heavily influenced by the assumptions made. The economic factors used, such as the monetary

Table 5.8. Refrigeration and air conditioning emission estimates ($MtCO_2$-eq yr^{-1}) for past and current years.

Region	Substance	Year	Application(s) Refrigeration and Air Conditioning: Stationary AC and Heating – Chillers	Stationary AC and Heating – AC – Commercial AC&H	Stationary AC and Heating – AC – Residential AC&H	Refrigeration	MAC	Source/Notes
EU-15	HFCs	1995	4.3					March Consulting Group, 1998
West. Europe		1996	16.1					Harnisch *et al.*, 2001
World	HFCs	1996	0.2			X	X	Harnisch *et al.*, 2001
		2001	>19.9	2.0–2.4				See note[1]
		2002	8.4			X	X	Palandre *et al.*, 2004
			222.7					
		2005	7.6	1.7	1.4	X	X	US EPA, 2004
			10.7			X	X	
			219.7					
	HFCs, HCFCs, CFCs	1996	20.0			X	X	Harnisch *et al.*, 2001
			638.0					
		2002	222.8			X	X	Palandre *et al.*, 2004
			1676.8					

X = applications not included in emission estimate(s) shown

[1] Air-conditioner emissions calculated using Table 5.1 for bank, and averages from Section 5.1.1 for annual emission rates. Range assumes 0% to 100% R-407C with the remainder R-410A. GWPs of blends calculated using GWPs from Table 2.6. Minimum chiller emissions calculated as total centrifugal chiller HFC-134a bank for USA, Canada and China as shown in Table 5.4 (note Table 5.4 does not represent the complete world inventory) multiplied by emission rate of 1% yr^{-1} as used in Figures 5.5 and 5.6, and the same GWP source as above.

Table 5.9. Unmitigated refrigeration and air conditioning emission estimates (MtCO2-eq yr-1) for future years.

Region	Substance	Year	Scenario	Application(s) Refrigeration and Air Conditioning: Stationary AC and Heating – Chillers	Stationary AC and Heating – AC – Commercial AC&H	Stationary AC and Heating – AC – Residential AC&H	Refrigeration	MAC	Source
EU-15	HFCs	2010	BAU	28.2					March Consulting Group, 1998
			Base	36.6					US EPA, 2004
West. Europe			Base	68.8					Harnisch *et al.*, 2001
World	HFCs	2015	Base	9.2	31.7	49.4	X	X	US EPA, 2004
				90.3			X	X	
				472.0					
			Sc1	100.1			X	X	Palandre *et al.*, 2004
				667.0					
			Base	14.8			X	X	Harnisch *et al.*, 2001
	HFCs, HCFCs, CFCs	2015	Sc1	322.8			X	X	Palandre *et al.*, 2004
				1527.2					
			Base	23.5			X	X	Harnisch *et al.*, 2001
				293.5					

X = applications not included in emission estimate(s) shown
Base = Baseline scenario
BAU = Business-as-usual scenario
Sc1 = Scenario 1 (business-as-usual) in Palandre *et al.*, 2004.

Table 5.10. Abatement options applicable for residential and commercial air conditioning and heating.

Application	Option	Region	Cost per tCO_2–eq	Monetary Unit	Discount Rate	Source
AC	Alternative Fluids and Leak Reduction	EU-15	23 to 26	ECU (year not stated)	8%	March Consulting Group, 1998
AC	Energy Efficiency Improvements	EU-15	−79 to −70[(1)]	ECU (year not stated)	8%	March Consulting Group, 1998
AC	HC Refrigerant	EU-15	114[(1)]	1999 Euro	4%	Harnisch, 2000
AC	Leak Reduction	EU-15	44	1999 Euro	4%	Harnisch, 2000
Chillers	HC and Ammonia Refrigerant	EU-15	49	1999 Euro	4%	Harnisch, 2000
Chillers	Leak Reduction	EU-15	173	1999 Euro	4%	Harnisch, 2000
Stationary AC	Leak Reduction and Recovery	World	38	1999 USD	5%	Harnisch et al., 2001
Stationary AC and others	STEK-like Programme	EU-15	18.3	Euro (year not stated)	Not stated	Enviros, 2003
AC and others	Recovery	World	0.13	2000 USD	4%	US EPA, 2004
AC and others	Recovery	World	0.13	2000 USD	20%	US EPA, 2004
Chillers and others	Leak Repair	World	−3.20	2000 USD	4%	US EPA, 2004
Chillers and others	Leak Repair	World	−1.03	2000 USD	20%	US EPA, 2004
AC and others	Recovery	World	1.47	2000 USD	4%	Schaefer *et al*., 2005
Chillers and others	Leak Repair	World	1.20	2000 USD	4%	Schaefer *et al*., 2005

[(1)] These costs incorporate savings or additional costs due to assumed changes in energy efficiency; see the referenced source for more details.

Table 5.11 Mitigated refrigeration and air-conditioning emission estimates ($MtCO_2$-eq yr^{-1}) for future years and mitigation costs (USD per tCO_2-eq abated).

<table>
<tr><th rowspan="5">Region</th><th rowspan="5">Substance</th><th rowspan="5">Year</th><th rowspan="5">Scenario</th><th colspan="5">Application(s)</th><th rowspan="5">Source</th></tr>
<tr><th colspan="5">Refrigeration and Air Conditioning</th></tr>
<tr><th colspan="3">Stationary AC and Heating</th><th rowspan="3">Refrigeration</th><th rowspan="3">MAC</th></tr>
<tr><th rowspan="2">Chillers</th><th colspan="2">AC</th></tr>
<tr><th>Commercial AC&H</th><th>Residential AC&H</th></tr>
<tr><td rowspan="13">World</td><td rowspan="7">HFCs</td><td rowspan="7">2015</td><td rowspan="3">Mit</td><td>8.9 @ -3.20 to -1.03</td><td>29.2 @ 0.13</td><td>45.5 @ 0.13</td><td>X</td><td>X</td><td rowspan="3">US EPA, 2004</td></tr>
<tr><td colspan="3">83.6 @ −3.20 to 0.13</td><td>X</td><td>X</td></tr>
<tr><td colspan="5">364.9 @ −75 to 49</td></tr>
<tr><td rowspan="2">Sc2</td><td colspan="3">67.9</td><td>X</td><td>X</td><td rowspan="4">Palandre et al., 2004</td></tr>
<tr><td colspan="5">452.8</td></tr>
<tr><td rowspan="2">Sc3</td><td colspan="3">43.0</td><td>X</td><td>X</td></tr>
<tr><td colspan="5">286.8</td></tr>
<tr><td>Mit</td><td colspan="3">7.6 @ 38.26</td><td>X</td><td>X</td><td>Harnisch et al., 2001</td></tr>
<tr><td rowspan="6">HFCs, HCFCs, CFCs</td><td rowspan="6">2015</td><td rowspan="2">Mit</td><td colspan="3">9.4 @ 8.37–41.14</td><td>X</td><td>X</td><td rowspan="2">Harnisch et al., 2001</td></tr>
<tr><td colspan="5">109.6 @ 1.05–85.14</td></tr>
<tr><td rowspan="2">Sc2</td><td colspan="3">225.2</td><td>X</td><td>X</td><td rowspan="4">Palandre et al., 2004</td></tr>
<tr><td colspan="5">1114.2</td></tr>
<tr><td rowspan="2">Sc3</td><td colspan="3">149.6</td><td>X</td><td>X</td></tr>
<tr><td colspan="5">783.5</td></tr>
</table>

X = applications not included in emission estimate(s) shown
Sc2 = Scenario 2 (some mitigation of emissions) in Palandre et al., 2004.
Sc3 = Scenario 3 (partial HFC phase-out) in Palandre et al., 2004.

unit (USD, EUR, etc.) and discount rates, also vary. Table 5.10 tabulates several examples of abatement options. Only one source was found to estimate the effectiveness of energy efficiency improvements. This indicates the confidential nature of any such data. When these savings were included in the calculations this option proved to be by far the most cost-effective. The remaining options concentrate on other items highlighted earlier in this chapter (e.g., recovery, alternative refrigerants). Many of these options are assumed to partially exist in the baseline (e.g., recovery occurs to some extent) and are assumed to increase if the option is applied. Note that some costs are negative, indicating that energy-efficiency improvements or lower refrigerant costs render the option cost effective under the assumptions applied.

A few of the studies assume certain market penetration, beyond that assumed in the baseline, of the aforementioned abatement options and predict mitigated emissions under various scenarios. These estimates (again, only direct refrigerant emissions) along with the cost-effectiveness of the mitigation option are shown in Table 5.11. Note that the cost-effectiveness of the mitigation option is shown as '@ ###' per tonne CO_2-eq, where ### is the cost using the monetary unit and discount rate shown in Table 5.10.

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