# CENTRIFUGAL CHILLER EFFICIENCY - BENEFITS BEYOND REDUCED OPERATING COSTS

**CALM, James M.**
Engineering Consultant
Great Falls, VA, USA

## Summary

*This paper examines current refrigerants and candidate alternatives for centrifugal chillers, the type most widely applied for air conditioning and process cooling in capacities of 2-14 MW (500-4000 RT), though available in capacities as small as 300 kW (90 RT) and as large as 35 MW (10,000 RT). The examination addresses efficiency, resulting use of energy both at full (peak) load and on a seasonal basis, and implications for other resources. It also addresses global environmental impacts and specifically those for stratospheric ozone depletion and climate change. Analyses summarized in this paper indicate reductions of 18% in energy-related greenhouse gas emissions and atmospheric pollutants with upgrade of efficiency levels to the best available, for representative conditions in Hong Kong. They also indicate potential for corresponding reductions up to 22% in peak electricity demand and generation requirements. Additionally, the upgrades identified offer potential reductions in refrigerant-related greenhouse gas emissions, water usage and chemical treatment for cooling towers, and fuel import requirements.*

## Keywords

*chillers, refrigerants, efficiency, environmental impacts, ozone depletion, global climate change*

## 1. Introduction

Chillers are machines used to cool water or other heat transfer fluids for central air conditioning systems or process cooling. Centrifugal (referring to the type of compressor used) chillers are the type offering the highest capacities and performance. Ask a building services engineer, manager, or owner about efficiency improvement for centrifugal chillers and the answer will address cost savings. From a societal viewpoint, additional and more important benefits accrue from energy and resource conservation, emissions and wastes reduction, and savings in associated water use. Further savings – especially important in countries with developing economies – result from reduced infrastructure investment costs.

Air conditioning consumes slightly more than one quarter of the electricity used in commercial buildings, as depicted in Figure 1. Efficiency improvement, therefore, offers substantial opportunity to reduce energy use, energy-related greenhouse gases (GHG) emissions, resulting climate change impacts, other atmospheric pollutants, and additional adverse environmental effects. Though less obvious, efficiency improvement also conserves water, and most commonly potable water, otherwise evaporated or used for contaminant control in cooling towers for heat dissipation. Moreover, efficiency improvement in chillers for building cooling also reduces generation, transmission, and distribution needs for electricity, typically at more favorable investment costs than adding capacity. Whereas most countries with high air-conditioning requirements are net energy importers, the efficiency gains also reduce import dependence and thereby improve self-sufficiency.


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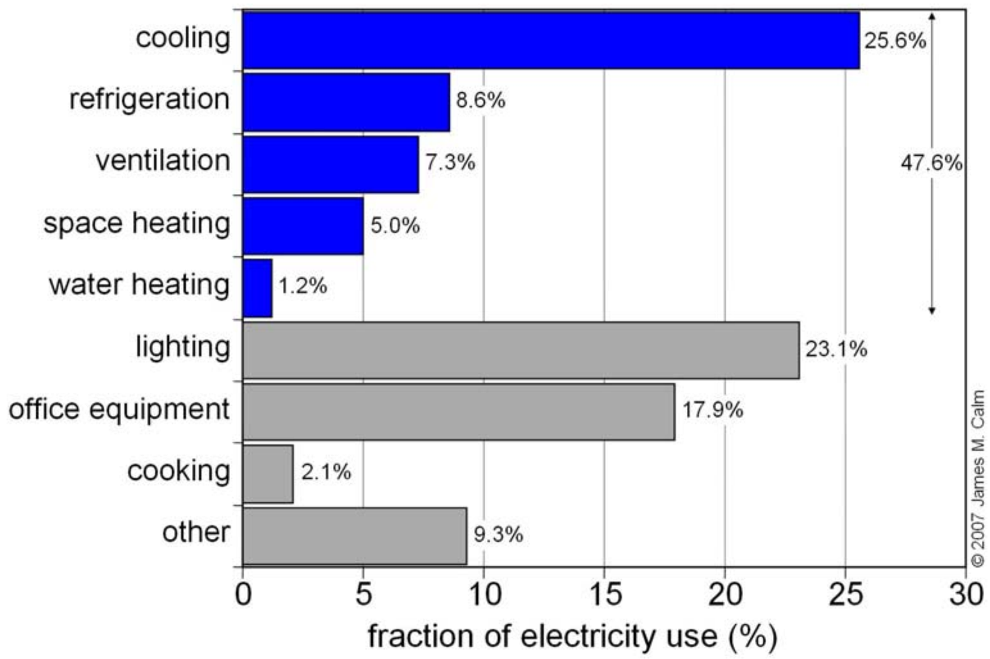


Figure 1. Electricity Use in Commercial Buildings in the USA
(based on data from reference [EIA, 2006])

## 2. Chiller System Basics

Chillers are a type of refrigeration machine, devices that move heat (thermal energy) in the colder (lower potential) to warmer (higher potential) direction – the opposite of natural heat transfer. Simple physics dictates that the equipment efficiency decreases as the temperature lift increases, but many other factors influence chiller energy use. A key first step is reducing cooling loads. Even then, overall system efficiency and consequential greenhouse-gas emissions depend on more than equipment efficiency alone, just like different traffic conditions and drivers change the fuel economy of vehicles.

The way the chiller or more typically chillers are integrated into air conditioning systems is critical. That also is true for process cooling, but with lower sensitivity since industrial cooling loads tend to be less variable. The number of chillers selected and how they are sequenced (how their operation is staggered) to meet cooling loads influence energy use, because efficiency is nonlinear at part-load conditions, compared to at full capacity, and commonly is higher (especially at 60-80% of full load) for centrifugal chillers. Likewise, piping configuration such as use of series-counter-flow arrangements reduces the thermal lift on individual chillers and, therefore, raises efficiency when properly controlled. Modern application approaches employ variable-primary flow distribution schemes for the chiller water to reduce parasitic energy use and pumping heat burdens compared to older, primary-secondary approaches or constant flow designs. Different piping arrangements also improve performance, such as use of two-pipe (separate supply and return pipes) or four-pipe systems (separate supply and return pipes for heating and for cooling) instead of single-pipe, looped circuits. Efficient design even involves optimizing supply temperatures, for example lowering chilled water supply temperatures as a trade-off between chiller, pumping, extent of dehumidification, and terminal heat exchanger efficiencies and costs. Likewise, selection between air-cooled and water-cooled condensers for heat rejection also impacts performance. Air-cooled systems (like scaled-up versions of home air conditioners) are simpler and conserve water where scarce, but require higher condensing temperatures that increase thermal lift at peak ambient temperatures, thus lowering efficiency. In contrast, water-cooled systems employ cooling towers that reject heat by evaporating water. Although more complex, for both design and operation, they offer lower condensing temperatures, thereby reducing thermal lift and increasing overall efficiency. Although much less common, other options include hybrid evaporative condensers, use of ground or surface water, or when feasible productive recovery of condensing heat for process use or service water preheating. These few examples show that the manner of integration and control influences chiller performance, but actual equipment efficiencies as the system core still drive system efficiency for comparably optimized distribution and heat rejection approaches.

The design of chiller equipment begins with selection of an appropriate thermodynamic cycle, most commonly the mechanical vapor-compression (or Perkins) cycle. It is a modified reverse-Rankine cycle, in turn an adaptation of the theoretically ideal Carnot cycle for real fluids and processes. Variants include the absorption cycle, wherein an absorption-process, solution pump, and a thermal desorption process replace the mechanical compressor. Other approaches utilize magnetic, thermoacoustic, adsorption, and other phenomena or combine them into hybrid cycles, but nearly all commercialized chillers are the absorption or mechanical vapor-compression machines.

Absorption chillers are popular to exploit otherwise-wasted or low-cost heat, circumvent inadequate electricity supply, or capitalize on low prices for steam, hot water, or most commonly gas relative to those for electricity. They also are common where subsidized to promote gas use or to avoid peak electricity demand and where economically justified by very high electricity demand costs. Chillers employing mechanical compressors driven by electric motors, or less commonly engines or turbines, are more widely used on a global basis due to their generally lower equipment and installation costs, smaller sizes, and – except as stated for absorption chillers – typically lower operating costs.

All mechanical vapor-compression chillers include one or more evaporators (heat exchangers that remove heat at low temperature and thereby evaporate, or boil, a refrigerant), compressors to boost the pressure of refrigerant vapor (and in doing so also the temperature), condensers (heat exchangers to reject the heat at a higher temperature and thereby condense the refrigerant into a liquid), and a throttling device to regulate flow and separate the high-and low-pressure portion of the cycle before returning the refrigerant to the evaporators. There are many variations on each of these components, how they are combined, how they are controlled, and in some cases enhancements such as use of multistage compressors with economizers to boost efficiency. The compressor types vary by capacity, with overlapping ranges. Common types include reciprocating piston and scroll compressors in small sizes, screw compressors in intermediate capacities, and turbo-compressors in large sizes. The most widely used turbo-compressors are radial designs, more typically referred to as centrifugal, but axial designs can be found in very limited use for refrigerants requiring extreme mass-flow rates. The focus of the following discussion is on chillers employing centrifugal compressors, customarily referred to as “centrifugal chillers.” Such chillers are prevalent in large systems such as central and district systems serving airports, commercial centers and offices, hospitals, hotels, malls, military complexes, universities, and urban complexes.

The essential component with which each of the above-named components works to move heat to provide cooling is the refrigerant

## 3. Refrigerants

The majority of new centrifugal chillers use either R-123 or R-134a. R-123 is a low-pressure refrigerant first commercialized in 1989 to replace R-11. R-134a is an intermediate- or high-pressure refrigerant, depending on the context of comparisons, commercialized in the same year to replace R-12 and R-500. Older centrifugal chillers still in operation (and low quantities being phased out in developing countries) also use R-113, R-114, and (though essentially only in submarine retrofits) R-236fa. A small but declining number of new centrifugal chillers still use R-22. One manufacturer has extended an R-123 design to use R-245fa to increase capacities, but commercial use remains limited thus far for this new product. Concerns regarding depletion of stratospheric ozone and with global climate change (as well as control measures in international treaties as well as implementing laws and regulations addressing these issues) are driving these changes. The international treaties addressing stratospheric ozone depletion are the *Vienna Convention for the Protection of the Ozone Layer* and the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The treaties addressing climate change are the *United Nations Framework Convention on Climate Change* (UNFCCC) and the *Kyoto Protocol*.

### *3.1 Ozone Depletion and Global Warming*

R-11, R-12, R-113, and R-114 are chlorofluorocarbon (CFC) refrigerants no longer produced in developed countries and approaching phaseout deadlines in Article 5 countries (as defined in the Montreal Protocol); R-500 is a blend similarly treated based on inclusion of a CFC component, R-12. R-22 and R-123 are hydrochlorofluorocarbon (HCFC) refrigerants, allowed as transition refrigerants with later phaseout dates. R-134a, R-236fa, and R-245fa are hydrofluorocarbon (HFC) refrigerants, with emission restrictions under the Kyoto Protocol.

Figure 2 summarizes the ozone depletion potentials (ODPs) and global warming potentials (GWPs) of these and selected additional refrigerants. The ODP and GWP data are taken from [CALM and HOURAHAN, 2007] based on or calculated from international consensus values from [IPCC, 2001; IPCC and TEAP, 2005; and WMO, 2007]. No inference should be drawn from this figure that a unit of ODP equals a unit of GWP in negative impact. They are dissimilar metrics and there is no direct way to equate them, but showing them together illustrates which substances are offensive for each or both of these indices as well as comparative potencies for the two effects.

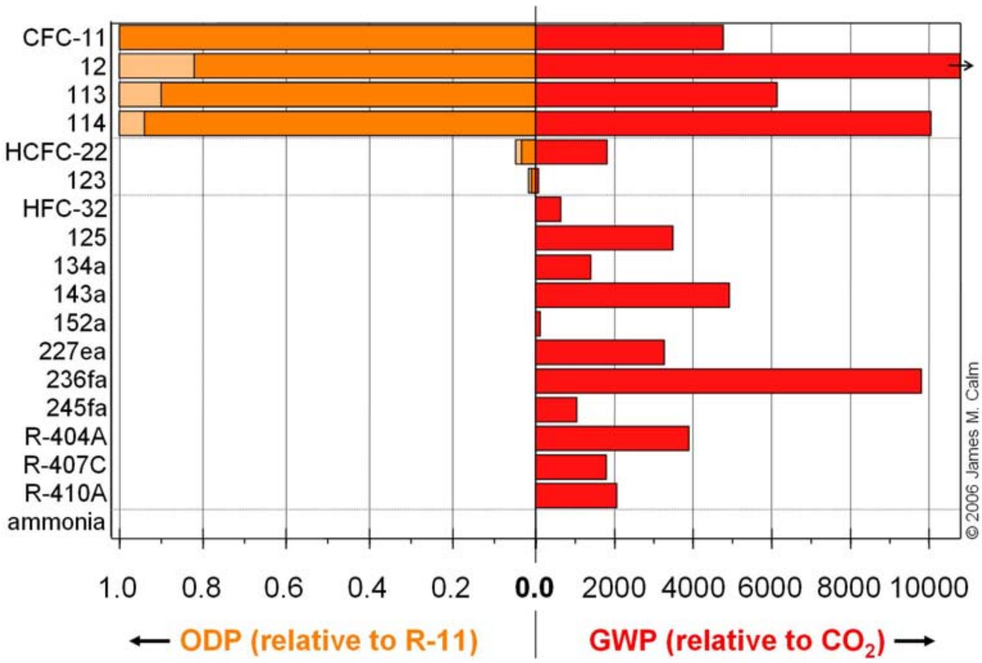


Figure 2. Ozone Depletion Potential (ODP) Contrasted to Global Warming Potential (GWP) for Key Refrigerants (light and dark orange shading indicate semi-empirical and modeled ODPs, respectively). CFCs generally have high ODP and GWP. HCFCs generally have much lower ODP and GWP. HFCs offer near-zero ODP, but some have very high GWPs.

The Montreal Protocol provides for phaseout of ozone depleting substances. It was adopted in 1987 and subsequently amended, notably in 1990 and 1992 with voluntary and binding measures, respectively, for HCFCs. The Montreal Protocol treats these substances by chemical class without regard to severity of individual substance impacts or to offsetting environmental benefits. The later Kyoto Protocol, adopted in 1997, controls emissions of greenhouse gases not already covered by the Montreal Protocol.

While it is not possible to equate ODP and GWP numerically, stratospheric ozone depletion and global warming each affect the other. More importantly, both affect the single environment we live in. We have to address both issues, and that implies concern that we not take actions for one that exacerbate the other.

Accordingly, a very different picture might have emerged had measures addressing global warming been implemented before those for ozone depletion. The left (ODP) side of the plot shows why the framers of the Montreal Protocol focused first on CFCs, allowed HCFCs as transition fluids, and deemed HFCs long-term solutions. The right (GWP) side suggests a different outcome had global warming been addressed first. The parties involved probably would have considered compounds individually rather than by coarse composition groups. It is highly likely that R-123 then would have survived the second cut, for ODPs, with fewer remaining options and recognition of its environmental benefits as addressed in referenced papers [WUEBBLES and CALM, 1997; and CALM, 2005].

### *3.2 Absorption Alternative*

Absorption chillers offer a number of benefits cited above. They commonly use ammonia (R-717) and water as the refrigerant and absorbent, respectively, for capacities less than 250 kW (70 RT). Most large machines use water (R-718), under vacuum conditions, as the refrigerant and lithium bromide (or much less commonly lithium chloride) as the absorbent. Other working fluids have been and are being considered, especially in hybrid cycles, but have not demonstrated sufficient merit for adoption.

The environmental contrasts between absorption and mechanical chillers are interesting. Ammonia and water are both considered “natural” refrigerants and attract environmental constituencies, but attainable efficiencies with single-, double-, and even triple-effect (three-stage) cycles are comparatively low. They reach coefficients of performance (COPs) of only 0.75, 1.2, and 1.4, respectively, and seasonal COPs of 0.65 to 0.70, 0.95 to 1.05, and 1.25 to 1.35, again respectively, with increasing complexity and costs for increasing number of effects. Triple-effect machines have been under development for decades, but were commercialized only recently and then on a limited scale. Even with a COP target of 1.5 and a theoretical limit of 2, these efficiencies are lower on a primary energy basis than mechanical vapor-compression alternatives based on typical, combined efficiencies for electricity generation, transmission, and distribution of 30 to 45% for various fossil-fuel-fired systems.

### *3.3 Refrigerant Impacts on Chiller Efficiencies*

Thermodynamic cycle analyses offer insight into the comparative efficiencies of refrigerants in vapor-compression cycles. All refrigerants can reach essentially similar efficiencies, at least theoretically, with sufficient cycle modification and optimization to exploit or compensate for refrigerant differences [DOMANSKI et al., 1994; DOMANSKI, 1995]. However, each element of added complexity increases costs, refrigerant charge (amount), the potential for leaks, and thermodynamic irreversibilities [CALM and DIDION, 1997]. Each addition also reduces the system’s reliability. Hence, refrigerants with high efficiencies in simple cycles have an inherent advantage to improve efficiencies at lower costs and with lower system risk of environmental harm. Attainable performance differs – often significantly – among individual fluids in practical equipment [CALM and DIDION, 1997; CALM, 2000].

Table 1, extracted from [CALM, 2005], summarizes efficiency comparisons for candidate refrigerants for chillers. [CALM and DOMANSKI, 2004] and [CALM, 2005] provide more extensive comparisons. Of refrigerants used in new centrifugal chillers, R-123 offers a 3 to 5% advantage in theoretical efficiency over the most promising alternatives and even greater benefit compared to additional candidates. That does not imply that all R-123 chillers outperform others, since the ranges of available efficiencies in commercial products overlap, but that R-123 chillers hold a clear advantage to reach the highest efficiencies.

A survey by the Air-Conditioning and Refrigeration Institute (ARI) in November 1996 found that R-123 held a 9 to 20% efficiency advantage for the best available equipment. A special report by the Intergovernmental Panel on Climate Change (IPCC) and the Technology and Economic Assessment Panel (TEAP) addressing hydrofluorocarbons and perfluorocarbons found 10% and 4% advantages for R-123 compared to R-134a for available centrifugal chillers for standardized full-load and integrated part-load value (IPLV) ratings, respectively, the latter with adjustable-speed drives [IPCC and TEAP, 2005]. The R-123 advantage has increased, with further technical advances, to 15.6% at full load based on new product comparisons using certified ratings.

Table 1. Comparative refrigerant efficiencies at standard chiller rating conditions

| | ideal cycle [a,b] | | | typical conditions [b,c] | | |
|---|---|---|---|---|---|---|
| conditions | (°C) | (%) | (°F) | (°C) | (%) | (°F) |
| average evaporating temperature | 6.7 | | 44.0 | 5.0 | | 41.0 |
| superheat | 0.0 | | 0.0 | 1.0 | | 1.8 |
| average condensing temperature | 29.4 | | 85.0 | 35.0 | | 95.0 |
| subcooling [d] | 0.0 | | 0.0 | 5.0 | | 9.0 |
| isentropic compressor efficiency | | 100 | | | 80 | |
| motor efficiency | | 100 | | | 95 | |
| control and other power use | | 0 | | | 0 | |

| refrigerant | ideal cycle COP (kW/kW) | ideal cycle specific power (kW/ton) | typical COP (kW/kW) | typical specific power (kW/ton) |
|---|---|---|---|---|
| R-11 | 11.56 | 0.30 | 6.58 | 0.53 |
| R-12 | 11.03 | 0.32 | 6.29 | 0.56 |
| R-22 | 10.92 | 0.32 | 6.18 | 0.57 |
| R-113 | 11.41 | 0.31 | 6.52 | 0.54 |
| R-114 | 11.08 | 0.32 | 6.34 | 0.56 |
| R-123 | 11.42 | 0.31 | 6.52 | 0.54 |
| R-134a | 10.93 | 0.32 | 6.24 | 0.56 |
| R-236fa | 10.94 | 0.32 | 6.26 | 0.56 |
| R-245fa | 11.24 | 0.31 | 6.43 | 0.55 |
| R-500 [g] | 10.97 | 0.32 | 6.25 | 0.56 |
| R-601a/601 (37.0/63.0) | 11.34 | 0.31 | 6.49 | 0.54 |
| R-717 (ammonia) | 11.21 | 0.31 | 6.24 | 0.56 |

[a] Conditions are those for standard chiller ratings for water-cooled chillers [ARI, 2003].
[b] Calculations were made with CYCLE_D 3.0 [DOMANSKI et al., 2003] and property data updates and additions (R-601 and R-601A) based on REFPROP fluid models from [DOMANSKI, 2005; HUBER, 2005; LEMMON et al., 2003; LEMMON, 2005]
[c] Conditions approximate those typically encountered on the refrigerant side of water-cooled chillers. The "typical" efficiencies shown can be exceeded by optimizing subcooling and superheat, employing multiple stages, or using similar cycle modifications. Likewise, poor designs do not meet them.
[d] Typical subcooling varies by refrigerant; the level shown is a representative selection for comparisons.

### *3.4 Comparative Warming Impacts*

This performance benefit translates into important distinctions in total equivalent warming impact (TEWI), life-cycle-warming impact (LCWI), or life-cycle climate performance (LCCP), which express the combined effects of refrigerant releases and larger effects from system energy use in terms of equivalent carbon dioxide emissions. Such analyses combine the GHG emissions from both refrigerant releases and energy use for system operation. These two categories often are identified as “direct effect” and “indirect effect,” respectively, but the term “indirect effect” in this context should not be confused with “indirect GWP,” which represents the GHG impacts of other atmospheric chemicals created or destroyed by released chemicals including refrigerants through chemical reactions including decomposition in the atmosphere.

Figure 3 compares the warming impacts for typical and the best available centrifugal chillers using R-123 and R-134a. The figure also shows the comparative warming impacts of double- and triple-effect, direct-fired, water/lithium bromide absorption chillers. The refrigerant-related components shown reflect life cycle (*cradle-to-grave*) refrigerant releases. They include on-site emissions from leakage, charging, service, removal, and amortized catastrophic losses. They also include upstream emissions in refrigerant manufacturing, packaging, storage, and transport as well as downstream emissions through ultimate refrigerant disposal. The energy-related components include on- and off-site GHG emissions from energy use to operate the chillers, including adjustments reflecting representative generation, transmission, and distribution losses for electricity. The generation mix shown reflects that in the USA and differs by specific location. The gas components include similar transmission and distribution losses to bring the gas to the site. The GHGs associated with resource extraction, such as from coal mining or well drilling, are not included. The energy-related components shown are for typical use in building air-conditioning applications; the ratios of energy-to refrigerant-related effects would increase for industrial process cooling or for applications with high load factors such as to cool data processing or communications centers, for which the importance of high efficiency would be even

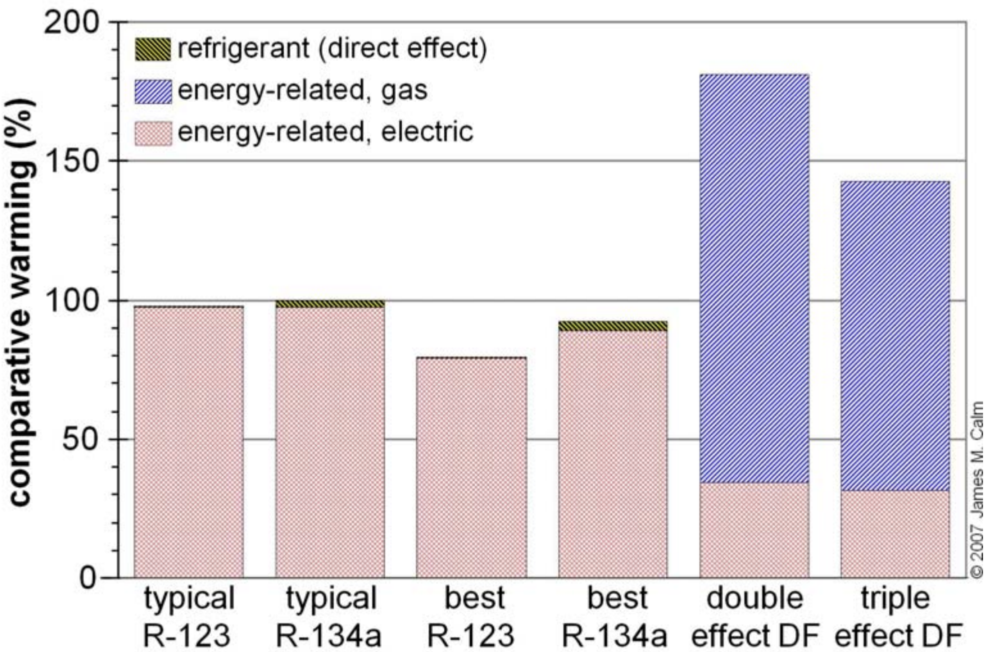


Figure 3. Comparative Global Warming Impacts for Typical and Best Available R-123, R-134a, and Direct-Fired, Water/Lithium Bromide Absorption Chillers (including condensing water pump and cooling tower energy use all normalized to typical R-134a chiller impacts)

greater. The energy-related components include those for the chillers (including solution pumps for the absorption chillers), condensing water pumps, and cooling towers which differ with efficiency, but exclude those for chilled-water and air distribution (though later included in the discussion of impacts). The analysis methods are detailed in [CALM, 1993] as well as prior studies identified therein, but with data that are more recent.

The figure illustrates several points:

1. For typical efficiencies for the centrifugal chillers, in this case taken as the minimum efficiencies meeting ASHRAE Standard 90.1 [ASHRAE, 2004] at full-load and IPLV conditions, the lower R-123 impact is attributable to refrigerant differences. They include reduced charge amount, lower leakage due to low-pressure operation, and most notably a lower GWP of 77 for R-123 and 1430 for R-134a, both for 100 yr integration periods.

2. The best available efficiencies reflect similar differences with adjustment for refrigerant charge sizes to reduce evaporator and condenser approach temperatures. However, the changes in energy-related impacts are much greater, reflecting the best commercially available COPs of 7.85 (0.448 kW/RT) for R-123 and 6.80 (0.517 kW/RT) for R-134a and corresponding IPLVs. While both of these chillers might be deemed “trophy models,” they reflect the current limits in product availability. Similar conclusions would result for the more practical but still high levels of approximately 7.5 (0.47 kW/RT) for R-123 and 6.5 (0.54 kW/RT) for R-134a.

3. While direct-fired absorption chillers offer advantages as discussed above, they increase net warming impacts 80% or more compared to typical centrifugal chillers and by as much as 130% compared to the best available centrifugal chillers. Even triple-effect chillers, despite concerns with costs and durability, increase global warming impacts by more than 40-80% depending on the centrifugal chiller used for comparison.

## 4. Additional Benefits from Improved Efficiency

Chiller efficiency improvement offers a number of additional environmental (and cost) benefits beyond significant potential to reduce GHG emissions.

While COPs at full load and IPLVs at standardized rating conditions indicate relative performance among different chillers, neither measure accurately predicts performance for specific applications with varying operating and weather conditions. Annual simulations, therefore, more accurately indicate performance for specific applications. They consider climate and load profiles, the number and sizing of the chillers, distribution burdens, and operating control sequences. Simulations for a representative building in Hong Kong for the “typical” and “best” equipment showed system efficiencies (including pumps and other accessories) of 8.3 (0.42 kW/RT) and 10.1 (0.35 kW/RT), respectively. The actual chiller modeled had COPs of 6.10 (0.577 kW/RT) and 7.85 (0.448 kW/RT) with corresponding IPLVs (for actual equipment selections) of 7.24 (0.486 kW/RT) and 9.13 (0.385 kW/RT), respectively. The simulations modeled a typical arrangement of three equally sized chillers with optimized operation in each case. The reason the annual efficiencies exceeded the ratings despite addition of system burdens is improved performance at part-load operation, which the IPLVs under-predict for the chosen systems with Hong Kong weather data. Table 2 summarizes the implications of the simulation results.

Table 2. Benefits from Chiller Efficiency Upgrade from Standard 90.1 Minimum Allowed Efficiency to Best Available Centrifugal Chiller Based on Representative Building Simulation for Hong Kong Climate

| reduction (%) | item |
|---|---|
| 3.4 | • cooling tower water usage, chemical treatment, and blow-down disposal |
| 18 | • overall cooling system energy use<br>• energy-related greenhouse gas emissions<br>• atmospheric pollutants from electricity generation<br>• generating fuel imports |
| 22 | • peak electricity demand<br>• required electricity generating, transmission, and distribution system capacities<br>• heat dissipation requirements and noise emanation for transformers (especially noteworthy for those located indoors)<br>• in-building or central plant wiring and switchgear capacities |
| 96 | • refrigerant-related greenhouse gas emissions compared to centrifugal chillers using R-134a |

Although not addressed herein, the higher costs of efficiency improvement are cost effective on a life-cycle basis with reductions in energy costs. The specific payback period depends on the extent of efficiency improvement, but payback periods of less than two years commonly result with efficiency upgrades of 10% or more depending on local utility rates.

## 5. **Conclusions**

Cities could expand by 22% without requirement for additional electricity generation, and even more with replacement of lower efficiency chillers with the best available. Hong Kong, as an example, similarly could reduce atmospheric pollutants and greenhouse-gas emissions associated with chiller energy use by 18% or more. Corresponding opportunities can be determined for other locations.

With recognition that air conditioning represents the single largest use – more than a quarter – of electricity in commercial buildings, the identified demand reduction of 18% by upgrading all chillers from minimum efficiency levels to the best commercially-available efficiencies translates to more than a 4.5% reduction in peak electricity generation, transmission, and distribution capacity requirements for these buildings. The reductions are greater with replacement of both existing and new chillers having even lower efficiencies. Alternatively, urban growth in commercial buildings could increase by more than 5% with the same measures without adding new electricity capacity.

Most importantly, chiller efficiency improvement offers a substantial and cost-effective means to reduce greenhouse gas emissions for the largest use of electricity in commercial buildings. Refrigerant selection influences both the attainable efficiency and the direct action of releases as greenhouse gases. Among current refrigerant options, R-123 offers the highest such potential.

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