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Influence of commercial refrigeration system design and refrigerant options on life cycle climate performance

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ABSTRACT

Ongoing efforts to reduce direct and indirect emissions of commercial refrigeration systems include using leak reduction measures, refrigerant charge minimization, low global warming potential (GWP) refrigerants and energy efficiency measures. In this paper, Life Cycle Climate Performance (LCCP) analysis is used to estimate the lifetime carbon dioxide equivalent emissions of commercial refrigeration system designs and refrigerant options. Commercial refrigeration systems investigated in this study include the centralized direct expansion (DX) system with hydrofluorocarbon (HFC) and hydrofluoroolefin (HFO) refrigerant blends, the transcritical R-744 booster system, and self-contained systems using R-290. The results of the LCCP analysis are presented for a variety of cities around the world, and recommended systems and refrigerant options are provided based on direct and indirect carbon emissions.
Keywords: Commercial Refrigerator, Global Warming, Life Cycle Climate Performance, Refrigerant.

1. INTRODUCTION

The traditional centralized direct expansion (DX) refrigeration system used in commercial applications is known to suffer from significant refrigerant leakage, especially in older existing systems. EPA (2012) estimates that the U.S. supermarket industry-wide average refrigerant emission rate is on the order of 25%. The use of high Global Warming Potential (GWP) refrigerants in these systems, combined with high refrigerant leakage, can result in considerable direct carbon dioxide equivalent (CO_{2e}) emissions. In addition, commercial refrigeration systems consume a substantial amount of electrical energy, resulting in high indirect CO_{2e} emissions. Thus, there are ongoing efforts to reduce the direct and indirect environmental effects of commercial refrigeration systems through the use of leak reduction measures, refrigerant charge minimization, low GWP refrigerants and energy efficiency measures.

With the phase-out of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, manufacturers turned to hydrofluorocarbons (HFC) as substitutes. These HFC refrigerants are commonly used in air-conditioning, heat pumping and refrigeration applications, and while they have zero ozone-depleting potential (ODP), many HFC refrigerants have relatively high GWPs. The need to be compliant with the Montreal Protocol and related governmental mandates has driven the industry to revisit the use of long-term alternative refrigerants that are favorable for the environment and exhibit better thermodynamic cycle efficiency. Alternative refrigerants with lower or near zero GWP are available, including hydrocarbons such as propane (R-290) and isobutane (R-600a), ammonia (R-717), carbon dioxide (R-744) and hydrofluoroolefin (HFO) refrigerants such as R-1234yf and R-1234ze(E) and their blends (UNEP, 2010a,b).

Hydrofluoroolefin refrigerants are a relatively new class of refrigerant and they have very low GWPs; however, many of them are classified as mildly flammable. Nevertheless, refrigerant blends consisting of the proper concentrations of HFOs and HFCs can be made non-flammable, resulting in alternative refrigerants with GWP values significantly lower than HFCs alone. Such lower GWP

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HFO refrigerant blends have the potential to be direct replacements for commonly used high GWP HFC refrigerants, thereby extending the useful life of HFC-based refrigeration systems.

Hydrocarbon refrigerants have zero ODP and relatively low GWP; however, their flammability poses a significant safety concern. Therefore, application of hydrocarbon refrigerants is limited to smaller equipment with limited charge sizes. In commercial refrigeration applications, small self-contained refrigerated display cabinets which consist of a thermally insulated compartment for the storage of foods and beverages and an integrated compact refrigeration system can utilize hydrocarbon refrigerants.

Another refrigerant which has recently gained the attention of the commercial refrigeration industry is carbon dioxide (R-744). Since R-744 has zero ODP and a GWP value of 1, it is considered an environmentally-friendly refrigerant option. R-744 is non-flammable and nontoxic, and, it has great heat transfer characteristics. However, operating pressures for R-744 are significantly higher compared to commonly used HFC refrigerants. In addition, the critical temperature of R-744 is low, which indicates that at high ambient temperatures, R-744 will operate in a supercritical cycle. Thus, transcritical R-744 booster refrigeration systems are currently sought for commercial refrigeration applications. These systems are currently being designed to maximize performance and safety. In cool and moderate climates, the on-going developments in transcritical R-744 booster refrigeration technology have resulted in systems which are competitive with HFC systems (Ge and Tassou, 2011).

The selection of an appropriate refrigeration system and/or refrigerant should be based on several factors, including the GWP of the refrigerant, the energy consumption of the refrigeration system over its operating lifetime, and leakage of refrigerant over the system lifetime. For example, focusing on energy efficiency alone may overlook the significant environmental impact of refrigerant leakage; while focusing on GWP alone might result in lower efficiency systems that result in higher indirect impact over the equipment lifetime. Therefore, in this paper, Life Cycle Climate Performance (LCCP) is used to estimate the lifetime direct and indirect carbon dioxide equivalent emissions of various commercial refrigeration system designs and refrigerant options for a variety of cities around the world, with the goal of providing guidance on lower GWP refrigerant solutions with improved LCCP compared to baseline systems. Commercial refrigeration systems investigated in this study include the centralized direct expansion (DX) system with hydrofluorocarbon (HFC) and hydrofluoroolefin (HFO) refrigerant blends, the transcritical R-744 booster system, and self-contained systems using R-290.

Systems investigated in this study include the baseline centralized direct expansion (DX) system with R-404A, and alternative systems and refrigerant options such as the centralized DX system with R-448A, the transcritical CO_2 (R-744) booster system and the self-contained R-290 system.

2. REFRIGERATION SYSTEMS

The energy and LCCP impacts of several refrigeration system architectures and refrigerant options were investigated in this study. The baseline refrigeration system consists of a centralized direct expansion (DX) system utilizing R-404A. Other refrigeration system options included a centralized DX system utilizing R-448A, a transcritical R-744 booster system, and the air-cooled, self-contained R-290 system. In general, all of the refrigeration systems had a nominal medium-temperature refrigeration load of 207 kW and nominal low-temperature refrigeration load of 103 kW. The refrigeration systems provided cooling for 184 m of low-temperature (frozen food) display cabinets, including reach-in multi-deck cabinets and coffin cabinets, as well as 138 m of medium-temperature (chilled food) display cabinets, including open single- and multi-deck cabinets and coffin cabinets. In addition, the refrigeration systems cooled 139 m^2 of walk-in freezer storage space and 399 m^2 of walk-in cooler storage space. A list of design parameters and assumptions for each refrigeration system type and refrigerant option are shown in Table 1.

Table 1. Refrigeration system design parameters and assumptions

System Parameter	Centralized DX, baseline	Centralized DX	Transcritical R744 booster	Self-contained
Refrigerant (GWP)	R-404A (3943)	R-448A (1273)	R-744 (1)	R-290 (3)
Refrigerant charge (kg)	1400 kg	1400 kg	750 kg	50 kg
Annual refrigerant leak rate (including service)	18%	18%	18%	5%
Refrigerant loss at end-of-life	10%	10%	10%	15%
MT suction temperature	-6.7°C	-6.7°C	-5.5°C	-6.7°C
LT suction temperature	-28.9°C	-28.9°C	-27.7°C	-28.9°C
MT and LT superheat	5 K	5 K	5 K	5 K
MT return gas temperature	15°C	15°C	15°C	10°C
LT return gas temperature	5°C	5°C	5°C	0°C
Minimum condensing temperature	21°C	21°C	10°C	N/A
LT subcooling or subcooler outlet temperature	4.4°C outlet	4.4°C outlet	0°C	3°C
Condenser or gas cooler approach temperature	4°C	4°C	4°C	4°C

3. ENERGY MODELING

The whole-building energy modelling tool, EnergyPlus, was used to estimate the annual energy consumption of a prototypical supermarket with the various refrigeration systems. The energy analysis was performed for 12 cities across the world, as shown in Table 2. The average, minimum and maximum temperatures shown in Table 2 for each city were obtained from the weather files used as input to the EnergyPlus simulations. The prototypical supermarket used in the EnergyPlus simulations has a floor area of 4181 m^2 and is based on the new construction reference supermarket model developed by the US Department of Energy (Deru et al., 2011).

Table 2. Cities and their annual average temperatures, as used in the energy and LCCP analyses

City, Country	Annual average temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)
Athens, Greece	17.9	2.0	37.2
Atlanta, USA	16.7	-12.8	36.7
Cairo, Egypt	21.7	7.0	43.0
Guangdong, China	22.3	6.0	37.0
Melbourne, Australia	13.8	0.0	39.0
Mexico City, Mexico	16.9	2.5	30.0
Miami, USA	24.5	5.0	35.6
Minneapolis, USA	7.7	-31.1	37.2
New Delhi, India	24.5	4.2	43.6
Phoenix, USA	23.8	2.2	44.4
Riyadh, Saudi Arabia	26.2	4.0	46.0
Sao Paulo, Brazil	19.9	8.0	35.0

4. LIFE CYCLE CLIMATE PERFORMANCE (LCCP)

The Life Cycle Climate Performance (LCCP) of a refrigeration system is defined as the sum of the direct and indirect carbon dioxide equivalent (CO_{2e}) equivalent emissions resulting from system construction, operation and decommissioning. Direct emissions include the environmental effects of leakage of refrigerant which occurs during system operation, servicing, and at the end-of-life as well as during refrigerant production and transportation. Indirect emissions include the environmental effects associated with the production and distribution of the energy required to operate the

refrigeration system as well as energy associated with production, transportation and disposal of the system.
The Life Cycle Climate Performance, *LCCP*, of a refrigeration system may be determined as follows:

$$LCCP = E_{dir} + E_{indir} \quad \text{Eq. (1)}$$

where E_{dir} is the direct emissions and E_{indir} is the indirect emissions. The direct emissions are determined as follows (IIR, 2016):

$$E_{dir} = \mathrm{C}(L \cdot ALR + EOL)(GWP + GWP_{adp}) \quad \text{Eq. (2)}$$

where *C* is the refrigerant charge (kg), *L* is the average lifetime of the refrigeration system (yr), *ALR* is the annual refrigerant leak rate (in percentage of refrigerant charge), *EOL* is the end-of-life refrigerant leakage (in percentage of refrigerant charge), *GWP* is the global warming potential of the refrigerant (kg CO_{2e}·kg^{-1}) and GWP_{adp} is the global warming potential of the atmospheric degradation products of the refrigerant (kg CO_{2e}·kg^{-1}). The indirect emissions are determined as follows (IIR, 2016):

$$E_{indir} = \mathrm{L} \cdot \mathrm{AEC} \cdot \mathrm{EM} + \sum(m \cdot MM) + \sum(mr \cdot RM) + \mathrm{C} \cdot (1 + L \cdot ALR) \cdot \mathrm{RFM} + \mathrm{C} \cdot (1 - \quad \text{Eq. (3)}$$

where *AEC* is the annual energy consumption of the refrigeration system (kWh), *EM* is the carbon dioxide emissions associated with energy production (kg CO_{2e}·kWh^{-1}), *m* is the mass of the refrigeration system (kg), *MM* is the carbon dioxide emissions associated with material production (kg CO_{2e}·kg^{-1}), *mr* is the mass of recycled material (kg), *RM* is the carbon dioxide emissions associated with recycled material production (kg CO_{2e}·kg^{-1}), *RFM* is the refrigerant manufacturing carbon emissions (kg CO_{2e}·kg^{-1}) and *RFD* is the refrigerant disposal emissions (kg CO_{2e}·kg^{-1}). Table 3 provides emissions factors used for the LCCP analysis (Deru and Torcellini, 2007; Brander et al., 2011).

Table 3. Emission factors for electricity production

City, Country	Emission factor for electricity production (kg CO_{2e}·kWh^{-1})
Athens, Greece	2.107
Atlanta, USA	0.788
Cairo, Egypt	0.573
Guangdong, China	1.076
Melbourne, Australia	1.076
Mexico City, Mexico	0.549
Miami, USA	0.788
Minneapolis, USA	0.788
New Delhi, India	1.801
Phoenix, USA	0.594
Riyadh, Saudi Arabia	0.877
Sao Paulo, Brazil	0.110

5. RESULTS AND DISCUSSION

5.1. Energy Consumption

The annual energy consumption for the four refrigeration systems is summarized in Fig. 1. As expected, the annual energy consumption correlated well with the annual average ambient temperature, with the warmer cities exhibiting higher annual refrigeration system energy consumption (see Fig. 2). For all cities modelled, it was found that the centralized R-448A DX system consumed less energy than the baseline centralized R-404A system. On average, the R-448A DX system consumed 7.2% less energy than the baseline R-404A system. Both the transcritical CO_2 booster system and the self-contained R-290 system consumed on average approximately 6% more energy than the baseline R-404A DX system. The transcritical CO_2 booster system showed greater energy efficiency for the colder climate (Minneapolis, USA), while the self-contained R-290 systems performed slightly better than the baseline system for the hottest climate (Riyadh, Saudi Arabia).

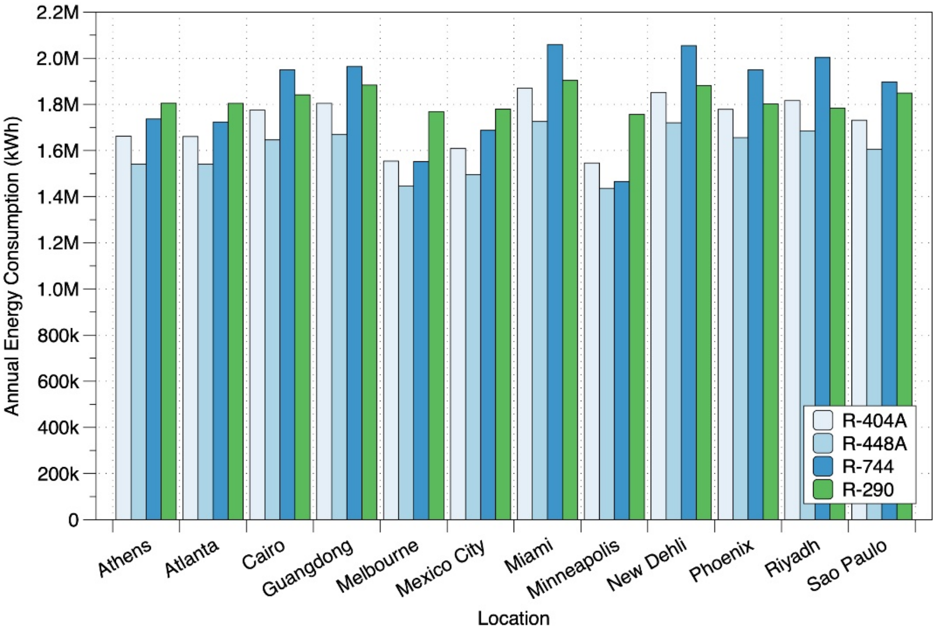

Figure 1: Annual energy consumption of the four refrigeration systems

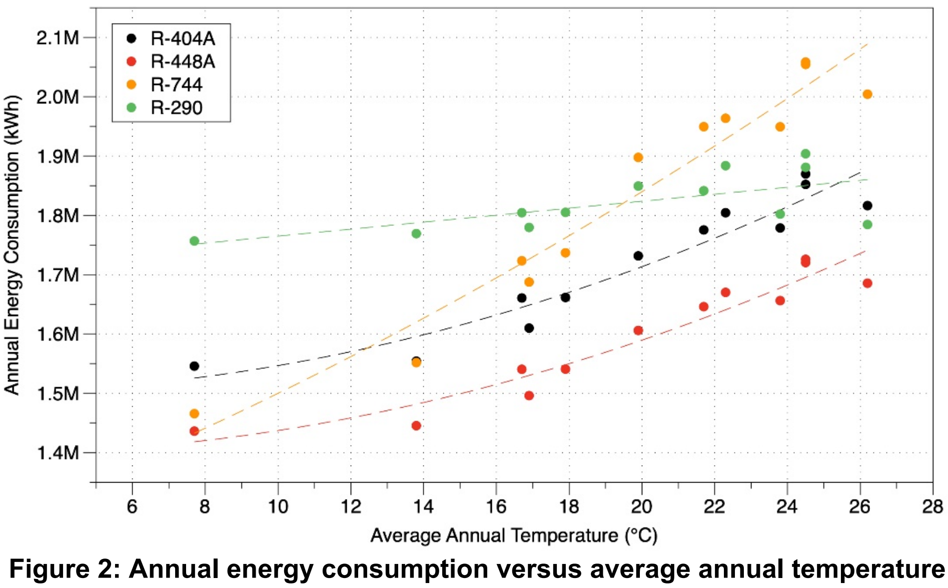

Figure 2: Annual energy consumption versus average annual temperature

5.2. Life Cycle Climate Performance (LCCP)

The total lifetime carbon dioxide equivalent emissions of each of the four refrigeration systems in the various cities is shown in Fig. 3. Note that the total emissions shown in Fig. 3 are divided into the direct and indirect contributions. It can be seen that the R-448A DX system, the transcritical CO_2 booster system and the self-contained R-290 systems all exhibit lower total carbon dioxide equivalent emissions than the baseline R-404A DX system. Direct emissions associated with the baseline R-404A system are significant, and many times represent nearly half of the total carbon emissions. Compared to the baseline R-404A DX system, direct carbon dioxide equivalent emissions are reduced by 67% with the R-448A DX system. Direct emissions from the transcritical CO_2 booster system and the self-contained R-290 systems are negligible. Furthermore, the indirect emissions which are associated with energy consumption generally dominate the total emissions for all the refrigeration systems investigated.

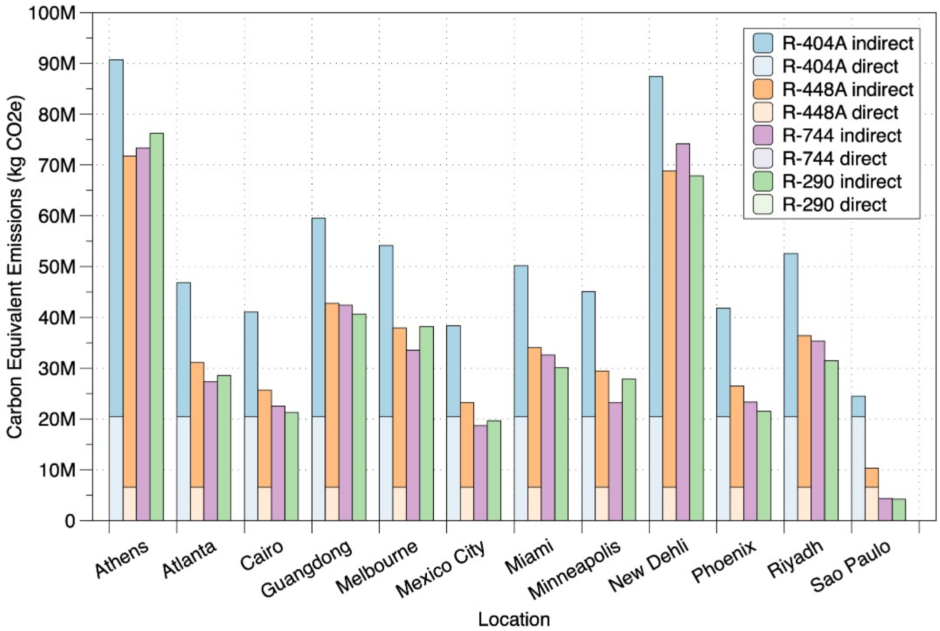

Figure 3: Total lifetime carbon dioxide equivalent emissions of the four refrigeration systems

The influence of sources of electric power generation on indirect emissions is illustrated in Fig. 4. Renewable energy, consisting mainly hydroelectric power with smaller contributions from wind and solar, account for nearly 80% of Brazil's electrical energy generation (EIA, 2017a). Thus, Brazil's carbon emissions associated with electrical power generation are very low compared with the other countries considered in this study. Therefore, the total lifetime carbon dioxide equivalent emissions associated with the four refrigeration systems is by far the lowest for Sao Paulo. Greece and India, on the other hand, rely almost totally on fossil fuel fired plants for electrical energy production (EIA, 2016), resulting in large indirect and total carbon dioxide equivalent emissions.

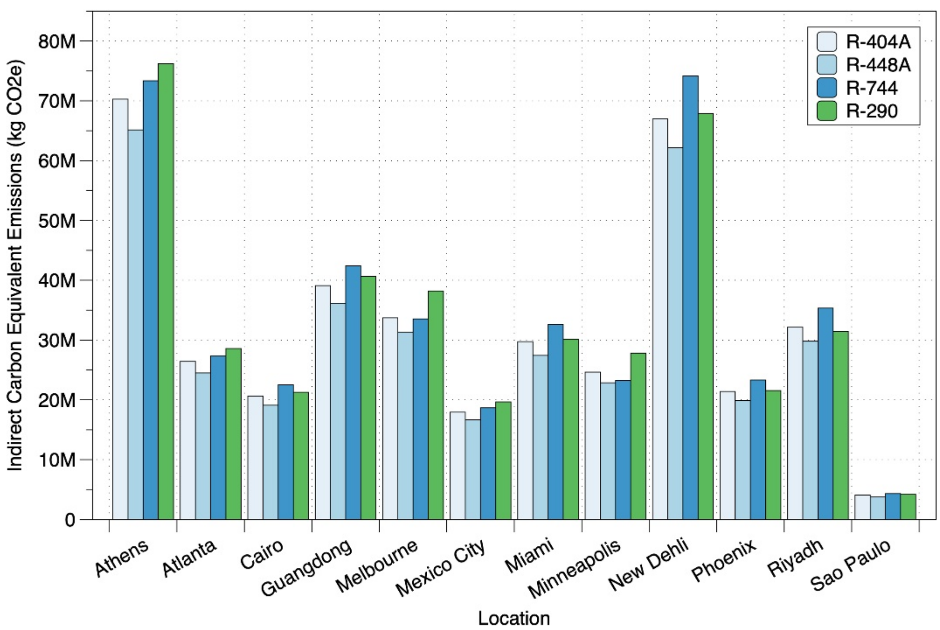

Figure 4: Indirect carbon dioxide equivalent emissions of the four refrigeration systems

The cities of Atlanta, Miami, Minneapolis and Phoenix in the United States produced similar levels of emissions, where on average, 63% of US electricity is produced by fossil fuelled power plants.

Cairo, Egypt and Riyadh, Saudi Arabia rely heavily on natural gas for electrical energy production (EIA, 2017b; EIA, 2018) and showed similar levels of carbon dioxide equivalent emissions, with Riyadh producing higher levels than Egypt due its slightly warmer climate.
On average, the total lifetime carbon dioxide equivalent emissions for the R-448A DX system was 34% lower than that of the baseline R-404A DX system for the cities investigated. In addition, the total lifetime carbon emissions for the transcritical CO_2 booster system and the self-contained R-290 systems were approximately 40% lower than that of the baseline R-404A DX system.

6. CONCLUSIONS

In this paper, energy analyses and life cycle climate performance (LCCP) analyses were performed on four different commercial refrigeration systems for 12 cities across the world. The four commercial refrigeration systems included the R-404A DX system, the R-448A DX system, the transcritical CO_2 booster refrigeration system, and the self-contained R-290 system. The energy and LCCP analyses provided insight into the environmental effects associated with refrigeration system design and refrigerant selection across the world.
Compared to the baseline R-404A DX refrigeration system, the R-448A DX refrigeration system was found to have 7.2% less energy consumption on average over the climate zones investigated. Both the transcritical CO_2 booster system and the self-contained R-290 system consumed on average approximately 6% more energy than the baseline R-404A system. The transcritical CO_2 booster system showed greater energy efficiency for the colder climate, while the self-contained R-290 systems performed slightly better than the baseline system for the hottest climate.
Compared to the baseline R-404A DX refrigeration system, the R-448A DX refrigeration system was found to have 67% less direct emissions, which is attributed to the lower GWP of the refrigerant, and 7.4% less indirect emissions due to increased system efficiency. The direct emissions of the transcritical CO_2 booster system and the self-contained R-290 system were found to be negligible due to the very low GWP of R-744 and R-290. However, the indirect emissions of the transcritical CO_2 booster system and the self-contained R-290 system were found to be approximately 5% to 6% higher on average than the baseline R-404A DX system due to their higher energy consumption. Nevertheless, all three refrigeration system designs/refrigerant options (R-448A DX, transcritical R-744, and self-contained R-290) produced lower total carbon dioxide equivalent emissions than the baseline R-404A DX system.
It was found that the sources of the electric power generation greatly influenced the total carbon dioxide equivalent emissions of the refrigeration systems. In regions where the electricity is generated primarily from fossil fuel fired power plants, the total carbon dioxide emissions are the greatest and the centralized R-448A DX system provided the lowest total carbon dioxide equivalent emissions for these regions. However, for regions with higher renewable energy sources and less fossil fuel fired power plants, the total carbon dioxide emissions are the lowest and the transcritical CO_2 booster system and the self-contained R-290 systems provided the lowest total carbon dioxide equivalent emissions in these regions.

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NOMENCLATURE

AEC	Annual energy consumption (kWh)	L	Refrigeration system lifetime (yr)
ALR	Annual refrigerant leak rate (% total charge)	LCCP	Life cycle climate performance (kg CO_{2e})
C	Refrigerant charge (kg)	m	Mass of refrigeration system (kg)
E_{dir}	Direct emissions (kg CO_{2e})	MM	Emissions for material production (kg $CO_{2e}\cdot kg^{-1}$)
E_{indir}	Indirect emissions (kg CO_{2e})	mr	Mass of recycled material (kg)

EM	Emissions due to energy production (kg CO_{2e})	RFD	Refrigerant disposal emissions (kg $CO_{2e}\cdot kg^{-1}$)
EOL	End-of-life refrigerant leakage (% total charge)	RFM	Refrigerant manufacturing emissions (kg $CO_{2e}\cdot kg^{-1}$)
GWP	Global warming potential (kg $CO_{2e}\cdot kg^{-1}$)	RM	Emissions for recycled material production (kg $CO_{2e}\cdot kg^{-1}$)
GWP_{adp}	GWP of atmospheric degradation products (kg $CO_{2e}\cdot kg^{-1}$)		

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