6
Results

An analysis of energy consumption and both direct and indirect global warming impacts was conducted in terms of the life cycle climate performance (LCCP).

6.1
Life cycle climate performance

The LCCP is a measure of the global warming impact of equipment based on the total related emissions of greenhouse gases during the manufacturing and operation of the equipment, as well as the manufacturing and disposal of the operating fluids at the end-of-life [186]. As reported by Arthur D. Little (ADL) [3], the LCCP accounts for the warming impact of a process or a product over its entire lifetime – from production and manufacturing of the raw materials to the end of life disposal.

Life cycle climate performance comprises the indirect warming impacts, due to energy consumption, and the direct warming, associated with the refrigerant emissions plus the embodied energy and fugitive emissions associated with manufacturing. For that matter, LCCP consists of a rigorous method of calculating the so called "cradle-to-grave" warming impact of any product [3].

Figure 6.1, adapted from Papasavva and Andersen [187] and Hwang [114], illustrates the processes considered in the determination of LCCP. It can be calculated, as expressed in Eq. (6.1), as the sum of two parts.

$$LCCP = \text{direct emissions} + \text{indirect emissions} \tag{6.1}$$

Table 3.84, adapted from Hwang [114], presents the parameters of a product or equipment that must be evaluated in order to determine each component of the LCCP.

With that in mind, the LCCP calculation method can be expressed as in Eq.(6.2), based on the standardised methodology to calculate the LCCP of stationary refrigeration and air conditioning equipment developed by The Air Conditioning, Heating and Refrigeration Technology Institute (AHRTI) [3, 186].

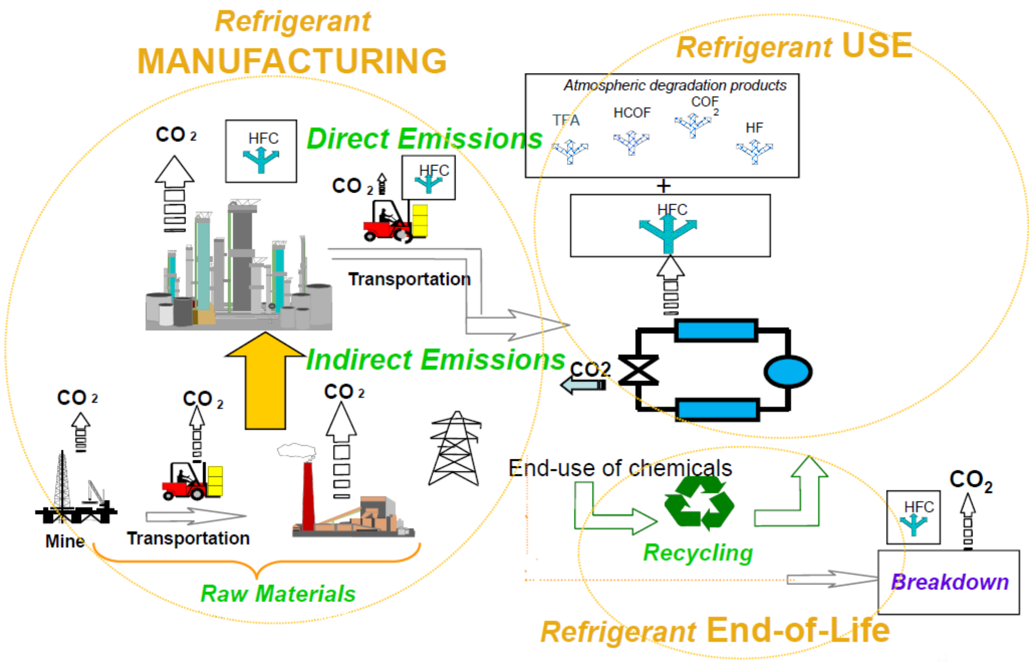


Figure 6.1: Scheme for the calculation of LCCP, adapted from Papasavva and Andersen [187] and Hwang [114].

Table 6.1: Components that take part in the determination of the LCCP, adapted from Hwang [114].

Direct emissions	**Indirect emissions**
Regular emissions	Energy consumption of the system
Fugitive emissions	Energy to make systems/components
Service emissions	Energy to produce refrigerant
End-of-life emission	Energy to transport
Leakage during production and transport	Energy for end-of-life, recycling/recovery of system and refrigerant

$$LCCP = GWP_{tot}\left(L_{annual} \cdot n + EOL\right) + \left(E_{annual} \cdot \beta \cdot n\right) \tag{6.2}$$

The total global warming potential, GWP_{tot}, includes the GWP of the refrigerant as well as the warming impact associated with manufacturing [21]. Two basic categories of manufacturing related impacts are, according to ADL [3], identified. One is consequence of the energy consumed to manufacture both the fluid and the raw materials required to its development, called the “embodied energy”. The other is related to the warming impact of by-product greenhouse gases emitted during the manufacturing process itself, referred to as “fugitive emissions”.

The annual leak rate, L_{annual}, is composed by gradual leakage during normal operation, catastrophic losses amortized over the life of the equipment and losses during service and maintanance, with losses at the end of plant life not included in the parameter value [186]. EOL comprises the refrigerant leaks at end of life.

The system operating life, n, represents the expected useful life of the equipment measured in years, whilst the total annual energy consumption of the system, E_{annual}, is the sum of the power consumption of refrigeration compressors and additional components, like the heat exchanger fans, given in kWh per year [186].

The indirect electricity emission factor, β, is the mass of carbon dioxide emitted by the generator per kWh of electrical power supplied to the system, taking in efficiency losses in generation and distribution [186]. Also referred to as CO_2 emission factor, it is based on average emissions intensity of total electric sector generation for the country, state or region [186]. It is significantly dependent on the energy matrix of that region.

Determination of the total global warming potential, GWP_{tot}, the refrigerant leakage rate per year, L_{annual}, and the refrigerant loss at end-of-life, EOL, are considered, respectively, by Eqs.(6.3), (6.4) and (6.5) [3, 186].

$$GWP_{tot} = GWP_{rf} + GWP_{fug} + GWP_{emb} \tag{6.3}$$

$$L_{annual} = m_{rf} \cdot \gamma \tag{6.4}$$

$$EOL = m_{rf} \cdot (1 - \alpha_{rec}) \tag{6.5}$$

The global warming potential of a refrigerant, GWP_{rf}, expressed in kg of CO_2 per kg of refrigerant, is defined as the ratio between the integrated radiative forcing over a time spam following an assumed release of 1 kg of the refrigerant, and the integrated radiative forcing over the same period from release of 1 kg of CO_2 [186].

Fugitive emissions are associated with the release of emissions that take place during manufacture, processing and delivery of equipment and fluids, with their impact expressed by GWP_{fug}. For the greenhouse gas emissions related to the embodied energy in materials and processes used to produce equipment and fluids, GWP_{emb} is considered [186].

Finally, the original refrigerant charge of the system is designated by m_{rf} [kg rf], with γ [% rf/year] representing the percentage of refrigerant leak per year. The recovery/recycling factor, α_{rec} [% rf], corresponds to the percentage of refrigerant removed from a system and stored in an external container [186].

6.2
Experimental facility analysis

Considering the simulation model developed for the multi-compressor multi-evaporator direct expansion (DX) refrigeration system, R404A and refrigerant blends with potential to replace the former have been compared in terms of life cycle climate performance (LCCP). In this first analysis, parameters from the experimental setup, such as heat exchangers physical description, compressor performance maps and operational data are utilized as reference. In that sense, the main goal is to predict which refrigerant, if applied as operating fluid of the DX cycle present in the experimental facility , Figure 5.14, would provide the best environmental performance, measured by means of the LCCP.

Regarding the location choice, Atlanta (GA) was considered, since plenty of information regarding specific LCCP calculation parameters, such as indirect emission factors, can be found in the literature. Another reason for selecting Atlanta is the proximity to the stores considered by Kazachki [34] as reference for supermarket data, a key condition in the analysis that follows in Section 6.3.

Outdoor air ambient temperature is obtained in terms of the weather bin data for the geographic location. Results are calculated fow two different minimum condensing temperature: 10°C, as reported by Ge and Tassou [77], and 21°C, stated by Emerson [32] as the value assumed in typical supermarket stores. Calculations, once again, were performed accross the range of ambient temperatures for Atlanta during the year, as power input and number of operating hours vary with the ambient temperature. Table C.1, in Appendix C, details the bin hours for the city selected [133].

Refrigerants selected for comparison were, as previously discussed, R404A, R407F, HDR21 and HDR81. Refrigerant HDR21 is another mixture that, together with R407F and HDR81, represents a retrofit solution for existing R404A systems, given the environmental gains and low energy costs. To determine an average refrigerant charge of the system, an approximation was carried out by calculating refrigerant charge for each operational bin, with a weighted average based on the number of hours associated with each temperature interval.

It is assumed, as reported by Kazachki [34], that net refrigerating loads do not vary with outdoor air ambient conditions, with the indoor air temperature for medium temperature application considered as 1.7°C (35°F), whilst the indoor ambient temperature for low temperature level is set at -26.1°C (-15°F). These temperature values closely match those present in Kazachki's reference supermarket store.

The calibration factors considered for the DX system were the same as those determined after the validation process in Section 5.5. Their values are specified in Table 5.3 for medium and low temperature levels. Likewise, the compressor selection follows that of the validation procedure: for medium temperature level, Copeland's KAKA-020A-TAC was chosen, whilst in low temperature applications, Copeland's 2DF3-0300-TFC was considered [185].

Following the experimental analysis, performed by Sotomayor [184] and Honeywell [185], of the DX technology with different working fluids, operational features of the experimental facility exposed in Table 5.1 were selected as reference for the set of input parameters mantained constant in both temperature levels. Thus, the key conditions assumed for the LCCP analysis are described in Table 5.1. Additionally, the evaporator superheating degree, which is not described in Table 5.1, is also fixed at 5.00°C.

The direct GWP of refrigerant is a significant part of the LCCP calculation [3]. The Intergorvernmental Panel of Climate Change (IPCC), recognized as the most authoritarive scientific and technical reference on GWP values, has refined values over the past two decades, publishing four assessments on the subject [186]. The fourth assessment values (AR4) are selected for being a more accurate technical appraisal. A 35% margin of uncertainty for early assessments of GWP values is, however, reported by the IPCC. For fluorocarbons, comparative uncertainties are around 10% [186].

In principle, as expressed in Eq.(6.2), fugitive emissions and embodied energy in the materials and processes used to produce the refrigerant and the DX refrigeration system components should be included in the LCCP calculations. They can be neglected, though, due to the small magnitude of their warming impact contribution, according to ADL [3]. Aditionally, Pearson [188] verified that combined fugitive emissions and embodied energy for the production of R404A and a number of hydrofluorocarbon blends accounts for around 1% of their GWP value, considerably less than the uncertainty in an LCCP calculation for stationary equipment. Nevertheless, as suggested by ADL [3], the total manufacturing related warming impact is accounted for by summing $9 + 0.3\% GWP_{ref}$ to the global warming potential of the refrigerant. Table 6.2 provides the global warming potential values assumed for the four refrigerants considered.

Values for annual leak rate vary significantly with the class of equipment, refrigerant type, equipment design, workmanship of installation, refrigerant leak detection, maintenance and operating conditions [186]. The United Nations Environment Programme (UNEP), the Technology and Economic As-

Table 6.2: GWP values for different refrigerants based on IPCC's AR5 and ADL [3].

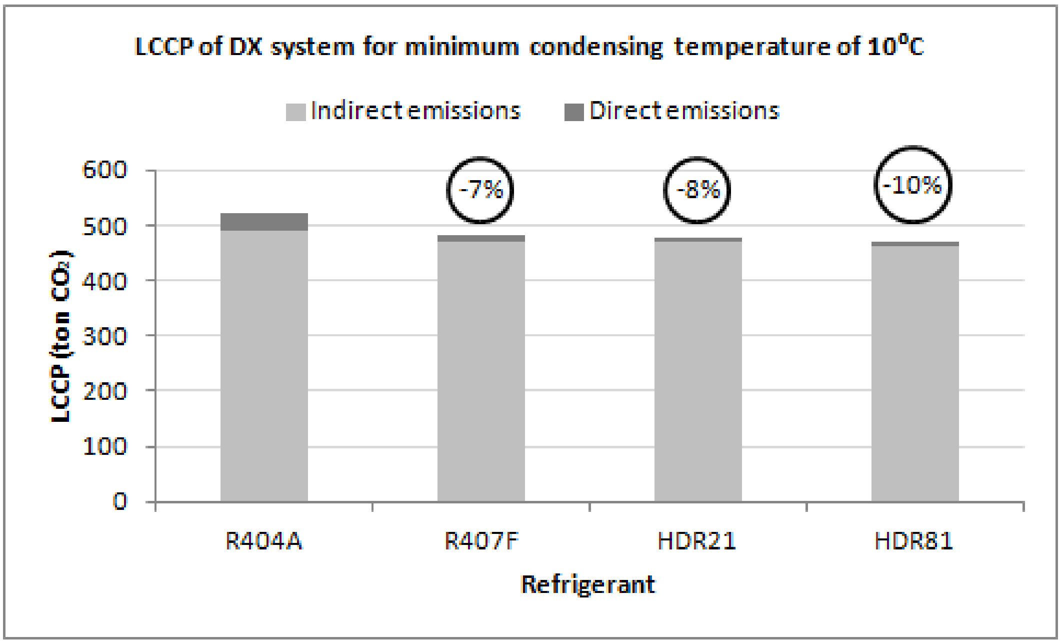
Refrigerant	GWP_{rf} (kg CO_2/kg rf)	GWP_{tot} (kg CO_2/kg rf)
R404A	3943	3964
R407F	1674	1688
HDR21	1222	1235
HDR81	1273	1286

sessment Panel (TEAP), and the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, in a recent study, reported that annual refrigerant leaks have been reduced from 25% to about 12%. The typical emission rate of small stores is suggested to vary between 15 and 25%, whilst for large supermarkets the value falls between 20 and 35% [186]. According to the IPCC [117], recent annualized emission rates in the range of 13 to 22% were reported for several supermarket systems in the USA. The Department of Climate Change National Greenhouse and Energy Reporting (NGERS) Technical Guidelines and the NGERS Act 2007 prescribe a leak rate of 23% for commercial refrigeration, whilst the IPCC good practice guidelines suggest values from 1 to 15% for stand-alone commercial refrigeration, and 10 to 35% for medium and large commercial refrigeration [186]. In that sense, an annual refrigerant leak rate of 15% is assumed for the DX system considered for the present analysis.

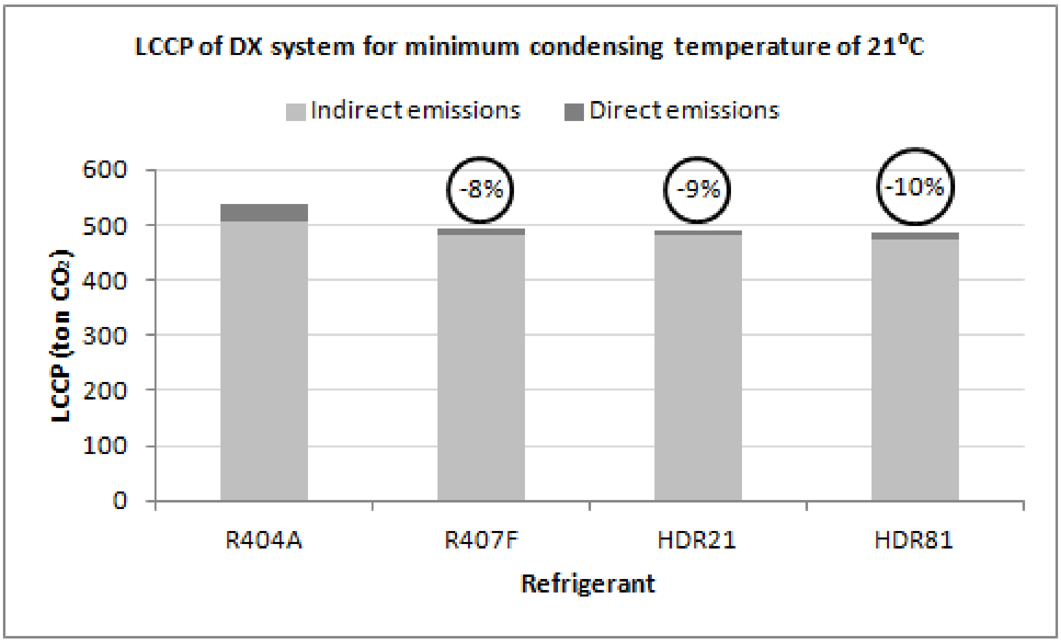
For the refrigerant recovery rate, the IPCC suggests practical values spanning from 90 to 95% of the remaining charge when a system with a refrigerant charge greater than 100 kg is considered. A recovery efficiency of about 70% is, in contrast, prescribed for equipments with a smaller charge [186]. As the refrigerant mass of the system under study is considerably lower than 100 kg, the recovery factor is taken as 0.70.

Regarding indirect emission factors, the IPCC [117] and Portilla [52] consider electrical generation with emissions of 0.65 kg CO_2/kWh when operating in Atlanta, as proposed by ADL [3]. System lifespan for conventional DX systems is reported to be around 15 years in Atlanta, according to ADL [3], with the IPCC [117] and Portilla [52] also considering such value in their reports. With that in mind, equipment life is, then, taken to be 15 years, and power generation emissions of 0.65 kg CO_2/kWh are assumed.

Figure 6.2 shows predictions for life cycle climate performance of the DX system operating with distinct refrigerants in Atlanta, for the two different minimum condensing temperatures considered. Tables E.1 to E.3, in Appendix E, provide a more detailed set of results for annual consumption, refrigerant charge and LCCP, organized by minimum condensing temperature condition, operating refrigerant and temperature level.



6.2(a): LCCP of DX in Atlanta with minimum condensing temperature of 10°C



6.2(b): LCCP of DX in Atlanta with minimum condensing temperature of 21°C

Figure 6.2: LCCP analysis of the experimental facility direct expansion system operating in medium and low temperature levels with different refrigerants in Atlanta. Percentual values refer to the relative difference in LCCP when R404A is replaced with the blend indicated below each bar.

Comparing the four fluids in terms of LCCP, one observes that, when operating with the retrofit substitutes of R404A considered, the environmental performance of the DX system can be improved by up to 10% for both minimum condensing temperature conditions. For the two cases, R407F was the blend with the lowest reduction in LCCP, about 7 and 8% for minimum condensing temperatures of 10 and 21°C, respectively. HDR21 provided results slightly superior, with percentual differences of 8 and 9%, respectively, when its LCCP is compared to that of R404A. HDR81 is the fluid which produces the smallest impact when operating in the medium and low temperature DX refrigeration cycle in Atlanta: for the two minimum condensing temperature conditions, LCCP values were 10% lower than those of R404A.

Figure 6.2 also shows that, for all fluids, the indirect emissions are those which contribute the most for the warming impact. It is worth mentioning that, comparatively, Atlanta presents a high value of indirect emission factor, 0.65 kg CO_2/kWh [3], which contributes to the significant participation of indirect emissions in the composition of the LCCP. This may not be the case for other geographic location, as, for example, South Australia, where power generation emissions are reported [189] to be less than half of those of Atlanta (0.30 kg CO_2/kWh), due to the distinct characteristics of the energy matrix of that region.

In that sense, replacing R404A with any of the blends analyzed impacts positively the LCCP, though HDR81 is the refrigerant for which the reduction is the most significant. In any case, it is important to notice that, according to the IPCC, if different fluids applied in a refrigeration system are compared in terms of their LCCP values, if calculated impacts are within 10% of each other, then essentially their environmental warming impacts are the same [186]. Taking the IPCC recomendation in consideration when interpreting the simulation results, one concludes that all four refrigerants can be considered to perform equally for the conditions analyzed.

6.3
Extension to supermarket case study LCCP analysis

A second analysis in terms of LCCP is performed, considering the model developed for the multi-compressor multi-evaporator DX cycle, with R404A and potential substitues as operating fluids. The goal is, in this case, to predict the fluid that would perform best when considered in a supermarket store DX system, with cooling loads and power consumption varying accordingly.

To predict the LCCP values related to a supermarket DX system, Kazachki's approach [34] is, once again, considered for application. In that sense, specifications for cooling load of the store layout which was studied by the author, reflecting currently-designed supermarket refrigeration systems, were selected as reference.

An important assumption is, thus, considered in the present analysis: an installation of the size of Kazachki's case study [34] shall present the same COP variation as the experimental facility previously studied in Section 6.2. With that in mind, the idea was to calculate COP values accross the range of ambient temperatures in Atlanta during the year, based on all the input data considered in the experimental facility analysis. Then, considering cooling loads that match those present in the supermarket store selected by Kazachki (250.89 kW for medium and 87.921 kW for low temperature levels [34]), total power consumption can be obtained for each temperature bin.

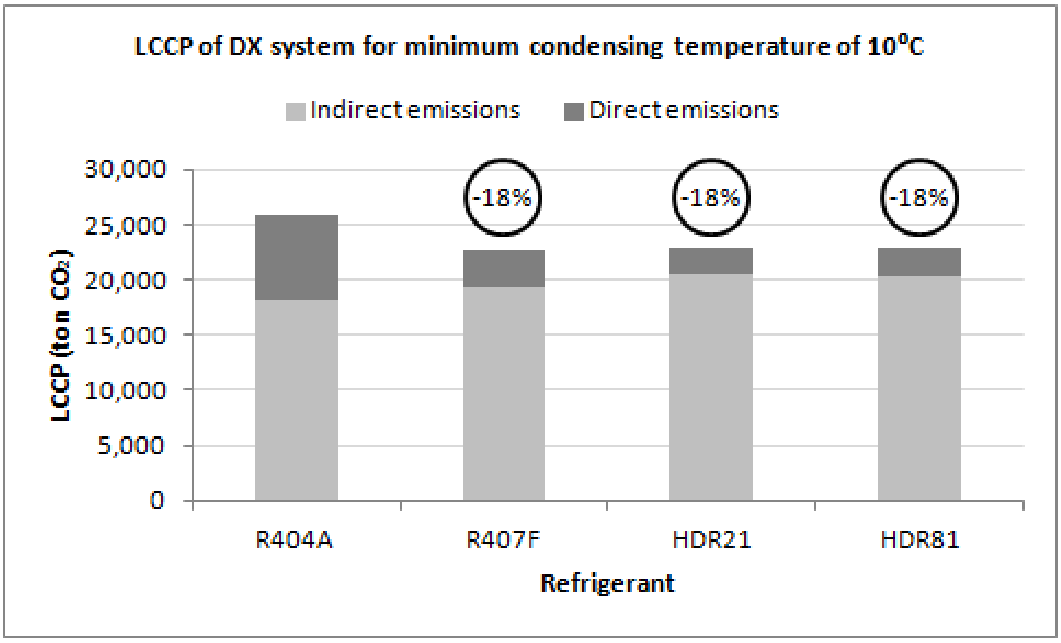
To estimate the refrigerant charge of an actual supermarket DX refrigeration system, values predicted by ADL [3] were considered. The authors suggest that typical refrigerant charge of a DX system, expressed in kg, is 29.29% of the floor area in m^2. Based on the supermarket of 4,180.6 m^2 (45,000 ft^2) from Kazachki's case study [34], a refrigerant mass of 1224 kg was estimated for the DX refrigeration system.

Regarding the LCCP calculation, the same values presented and discussed in Section 6.2 were applied, except for the refrigerant recovery rate. Since a refrigerant charge greater than 100 kg is now present, a recovery efficiency of about 90% was considered [186].

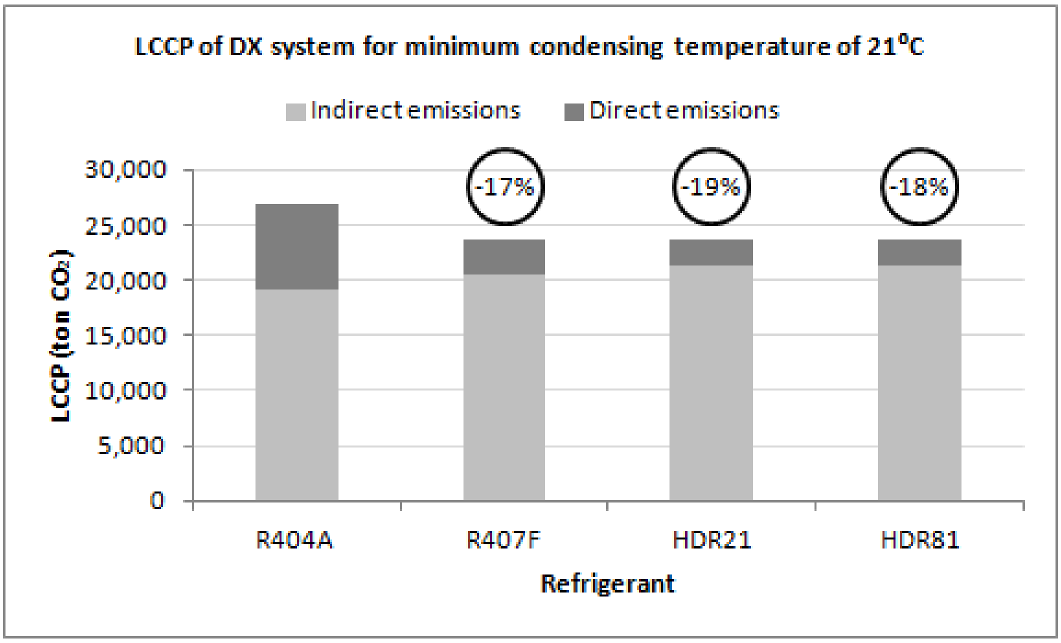
Analogously as in the experimental facility case, the analysis was performed for minimum condensing temperatures of 10 and 21°C. Life cycle climate performance values for R404A, R407F, HDR21 and HDR81 operating in a DX refrigeration system in Atlanta are depicted in Figure 6.3, for the two distinct conditions. A more detailed description of the calculated results for annual consumption and LCCP is shown in Tables E.4 and E.5 of Appendix E.

As it can be observed in Figure 6.3, substituting refrigerant R404A in the DX systems for medium and low temperature applications with a replacement blend may result in a reduction of 17 to 19% of the LCCP value. The largest improvement in performance is verified for HDR21 when operating in the DX cycles with minimum condensing temperature of 21°C, Figure 6.3(b). It also becomes clear, comparing Figures 6.2 and 6.3, that the reduction in LCCP when replacing R404A is more proeminent for the supermarket store (17–19%), with smaller values obtained in the experimental facility analysis (7–10%).

Direct emissions are, once again, less significant in the composition of the life cycle climate performance, with R404A representing the fluid for which the discrepancy between the different emissions contribution is the smallest. Additionally, for the supermarket DX systems, Figure 6.3, the direct emission contribution to the LCCP is more significant, if compared to that of the



6.3(a): LCCP of DX in Atlanta with minimum condensing temperature of 10°C



6.3(b): LCCP of DX in Atlanta with minimum condensing temperature of 21°C

Figure 6.3: LCCP analysis of the supermarket store direct expansion system operating in medium and low temperature levels with different refrigerants in Atlanta. Percentual values refer to the relative difference in LCCP when R404A is replaced with the blend indicated below each bar.

experimental setup DX cycles, Figure 6.2. Evidently, in supermarkets system, notably of the DX technology, the refrigerant charge per refrigerant capacity is much greater than that of a compact experimental apparatus.