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Building Technologies Office 03.02.02.38 Milestone Report—Technology Options for Low Environmental Impact Air-Conditioning and Refrigeration Systems

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August 2023

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Buildings and Transportation Science Division

BUILDING TECHNOLOGIES OFFICE 03.02.02.38 MILESTONE REPORT—TECHNOLOGY OPTIONS FOR LOW ENVIRONMENTAL IMPACT AIR-CONDITIONING AND REFRIGERATION SYSTEMS

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1. INTRODUCTION

Because of increasing concerns about global warming, various environmental regulations will eventually phase out refrigerants used in air-conditioning (R-410A) and refrigeration (R-404A) applications. Several refrigerants and technologies have been proposed as replacements, offering a variety of global warming potentials (GWPs), levels of energy efficiency, and flammability. Some of these options are synthetic hydrofluorocarbon (HFC)/hydrofluoroolefin (HFO) mixtures such as R-454C and R-455A, and others are commonly called *naturals* such as R-290 (propane) and CO_2. This study evaluates and discusses the merits of the leading options for air-conditioning and refrigeration systems. The fundamental requirements such as environmental, safety, and performance (United Nations Environment Programme [UNEP] Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Committee, 2022) are employed to fairly evaluate these technologies. Performance data and life cycle analysis results for these options are presented for the United States, Europe, and other global locations. Overall, this study aims to provide information needed to judge the prospects of getting adequate replacement for R-410A and R-404A on a long-term, sustainable basis.

2. ENVIRONMENTAL MATTERS

Ozone depletion potential (ODP) and GWP have been the main metrics to evaluate refrigerants' acceptability from an environmental point of view. Metrics and regulations based on ODP and GWP have been mandated by the Montreal Protocol of 1987 (*UNEP Handbook*, 2019) and the Kigali Amendment (United Nations, 2016).

A third issue has appeared recently: the formation of pollutants during the breakdown of refrigerants that could affect the environment. Of particular interest is the formation of trifluoroacetic acid (TFA). Quantitative metrics to evaluate the effect of this third issue are not yet well-defined because investigations are still ongoing.

The *ODP* level is well-defined and is evaluated on a relative basis to R-11. A refrigerant ODP is considered acceptable when its environmental effect is small enough to be considered negligible. The actual values and acceptability are given by the Montreal Protocol's list of regulated ozone-depleting substances.

GWP is evaluated on a relative basis compared with CO_2. The direct effect of a system on global warming is evaluated by quantifying the leaks during the lifetime operation and the end-of-life of the equipment. The GWP of refrigerants is typically controlled by regional and national regulations, which are influenced by global regulations such as the Kigali Amendment. Notably, considerable debate still occurs about possible future limits in each region and how they may impact the environment and the cost of the equipment (Domanski and Yana Motta, 2022). The GWP values used for most regulations can be found in IPCC (2007) while the latest values reported by the scientific community are in IPCC (2021). All evaluations in this report will use the IPCC (2007).

The *formation of byproducts* occurs during the atmospheric oxidation of some refrigerants, which happens after they are released outside the equipment either by leaks during operation or end-of-life disposal. Some of the current HFC and new low-GWP HFO refrigerants can produce TFA (trifluoroacetic acid) and other byproducts. TFA could affect aquatic life if it reaches those locations and concentrates in excessive quantities. Thus, the present work observed that some of the studies have been focused on three characteristics: (1) TFA formation, (2) potential distribution (propagation) in the environment, and (3) concentration and effects.

The *TFA formation*, quantified as yield in some publications, has been the subject of many studies. Most of the initial studies (Figure 1; European FluoroCarbons Technical Committee [EFCTC], 2023) are still based on chemical simulations, which may not reflect the actual yield. In some cases, chemical reactions do not necessarily follow theoretical behavior due to unaccounted reactions (i.e., dimerization) and interferences.

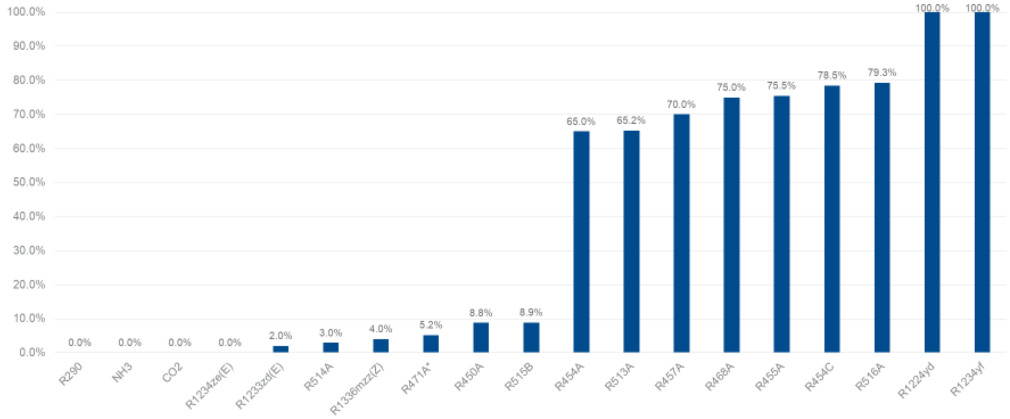


Figure 1. TFA yield estimates by the EFCTC (EFCTC, 2023).

Later estimates published in the UNEP Environmental Effects Assessment Panel (EEAP) (2022) report are also mostly based on theoretical estimates (Figure 2). These latest results show large uncertainties, which indicates the need for further evaluations to determine the real TFA yields.

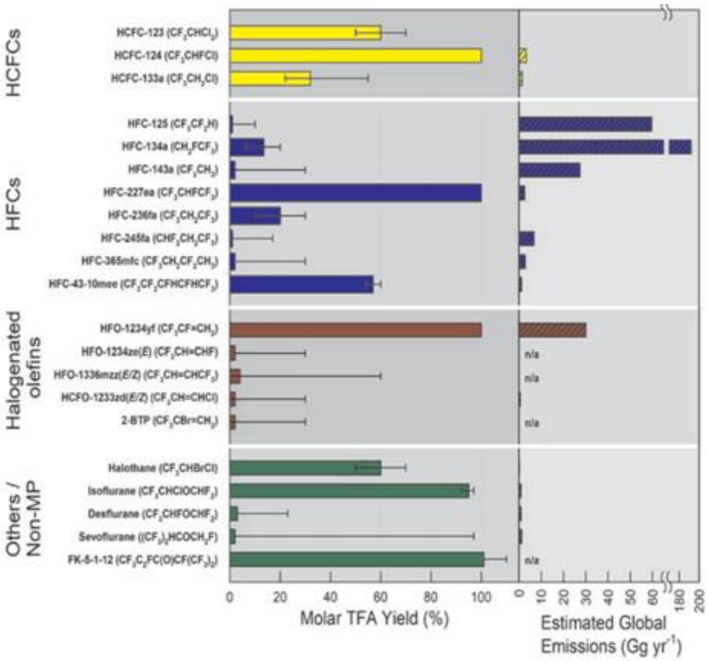


Figure 2. Estimated TFA yields and global emissions of fluorinated refrigerants (UNEP EEAP, 2022).

The UNEP EEAP (2022) data reflect the learning of a wide group of scientists convocated by the UNEP. Thus, the data indicate a gap of experimental studies to measure the actual formation of TFA during refrigerant breakdown in the environment. Additional scientifically acceptable experimental studies that directly tackle the atmospheric transformation and dispersions of TFA are advisable.

The learnings in this work from the scientifically verified literature (e.g., UNEP EEAP 2022, World Meteorological Organization [WMO] 2022) indicate that the distribution in the environment depends on the following aspects: (1) geographic location of the release, (2) meteorological conditions, and (3) chemical reactivity of the molecule. All these factors could affect the breakdown process (i.e., yield). Still, this dependence is a very complex phenomena, so other not yet known aspects can affect the distribution and reach of TFA to the aquatic systems.

The effects on living creatures, such as the aquatic life mentioned previously, depend on the concentrations and the effect that those concentrations can have on the living creatures. Understanding toxicity effects acceptably usually requires complex experimental studies and solid, statistically proven results.

The WMO (2022) and the UNEP EEAP (2022) reports show an increased confidence that TFA produced from the breakdown of new low-GWP refrigerants will not harm the environment over the next few decades. Nevertheless, the uncertainties associated with the sources (i.e., yield) and sinks (i.e., distribution) of TFA and its persistence warrants continued and uniform monitoring in the environment.

3. SAFETY

Most of the new low-GWP alternatives are flammable and classified as 2L (lower flammability), 2 (flammable), and 3 (higher flammability) by refrigerants safety standards American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 34 (2019) and International Organization for Standardization (ISO) Standard 817 (2014). The emergent use of mildly flammable class 2L refrigerants has driven intense research on flammability. Investigations have been performed on fundamental flammability characteristics (International Institute of Refrigeration [IIR] 36th Informatory note, 2017), full-scale experiments (Air-Conditioning, Heating, and Refrigeration Institute [AHRI] report 8828, 2021), and risk assessments. The results have informed the updates of safety standards used by the stationary air-conditioning (AC) and refrigeration industries. These updates included standards for refrigerants designation and classification (ASHRAE Standard 34 and ISO 817), installation standards (ASHRAE Standard 15, 2019; ISO 5149, 2014) and equipment standards (International Electrotechnical Commission [IEC] 60335-2-40, 2018; IEC 60335-2-89, 2019; UL Standards [UL] 60335-2-40, 2019; UL 60335-2-89, 2021). The research efforts have been focused on four main areas: electric devices, hot surfaces, allowable charge, and severity of possible events.

- The electric components (e.g., motors, switches) used in 2L systems must comply with the concept of the minimum safety gap (IEC 60335-2-40, 2018). This concept essentially ensures that the enclosure of a sparking device does not allow the flame to propagate outside.

- The concept of hot surfaces ignition temperature (HSIT) was introduced to evaluate the use of devices such as electric heaters used in AC and refrigeration systems. The standard IEC 60335-2-40 (2018) adopted a general hot surface temperature limit of 700°C for 2L fluids. It also includes a table listing the HSIT for each specific 2L refrigerant.

- Experimental studies using computational fluid dynamic modeling of refrigerant concentration have allowed manufacturers to define the amount of refrigerant that can be charged in systems. As a result, some small-charge systems will be fully exempted from any mitigation.

- Large-scale experiments where the ignition and deflagration were simulated allowed researchers to verify the severity of such events. The results were useful when defining guidelines for firefighters and other trades that could be exposed to fumes in the event of fires (AHRI report 8828, 2021).

These developments have been heavily focused on 2L refrigerants, which now have clear guidance about the use of sparking electric devices (e.g., switches) and hot surfaces (e.g., defrost heaters, supplementary heaters). Additionally, systems charge allowance and mitigation (e.g., leak detection, shut-off valves) have been defined for most applications. As an example, the building codes in the United States are adopting the following standards for the main applications:

- Air-conditioning systems use ASHRAE Standard 15.2 and UL 60335-2-40
- Refrigeration applications refer to ASHRAE Standard 15 and UL 60335-2-89
- Appliances use UL 60335-2-24

In the case of highly flammable (class 3 by ASHRAE Standard 34) refrigerants such as R-290, some specific developments have occurred. For instance, the charge allowances have been increased significantly in some of the international standards such as IEC 60335-2-89, which applies for most refrigeration systems.

- Charges for some self-contained refrigeration systems have increased from 150 g/circuit to 500 g/circuit. The United States is also in the process of updating the equivalent equipment standards (UL 60335-2-89) with some deviations. In general, the United States is still going through the process of evaluating these changes by performing risk assessment studies.

- For small domestic refrigeration appliances, the international standard IEC 60335-2-24 allows 150 g/system. The United States had a limit of 57 g in the UL 250 standard but has recently replaced this standard by UL 60335-2-24. This new standard has adopted the 150 g/system guideline similar to the international standards.

- As for air conditioning applications, the allowance in UL 60335-2-40 is very limited (e.g., 114 g for small AC equipment). The massive nature of air-conditioning applications seems to require a more exhaustive risk assessment before adopting class 3 refrigerants. For instance, the use of secondary systems for residential AC can allow enough refrigeration charge because the refrigeration system will be located outdoors. Still, the current standards (ASHRAE Standard 15.2 and UL 60335-2-40) need to be updated to cover such a configuration.

Overall, safety standards are only guidelines until they are adopted and enforced by countries, states, or cities. In the United States, these safety standards are incorporated in building codes, which ultimately are adopted by states and cities. Other countries have their own process to implement such changes. They very often adopt modified versions of the international standards (ISO and IEC standards) without using building codes.

4. PERFORMANCE

The performance of systems is usually related to energy consumption, which typically depend on two fundamental factors: thermal load and efficiency.

The thermal load greatly depends on the ambient conditions (e.g., location), usage of the application, and the design of the building (e.g., house, commercial building, insulated box, display case, refrigerator box). Although significant attention goes to the improvement of the equipment’s energy efficiency, the thermal load deserves more attention because it defines the need for cooling or heating energy and, consequently, the size of the equipment. Thus, further development of technologies or better practices should be implemented. Some of these practices are described in the following list.

- Improvements of insulation for residential and commercial buildings (e.g., walls, windows) and refrigerated boxes (e.g., domestic refrigerators, vending machines, display cases, storage coolers/freezers)

- Improved lighting of display cases, vending machines, and refrigerators to adopt new light-emitting diode technologies

- Changes in design of supermarket display cases to avoid the use of open configurations (cooled air losses) in favor of tighter cases, such as glass-door ones.

- Better handling of moisture in buildings to produce comfort without using low-temperature thermostat settings—recent developments in desiccant technologies can also be useful because they can reduce the latent heat load for the equipment.

- Localized cooling/heating instead of whole-building, which is well-described by the concept of zone-systems used in commercial buildings and which could potentially be incorporated in the residential house designs.

- Personal cooling already used for military applications—the development of cost-effective and reliable commercial systems could significantly reduce the building thermal load because the cooling will be supplied only for each individual.

- Some new cooling technologies proposed for data centers that provide cooling to only the equipment instead of the whole building, greatly reducing the thermal load and, consequently, the size of the equipment, which at the same time affect the energy consumption.

- Efficient operation and increased capacity of heat pump equipment at low ambient temperatures (cold climate heat pump), which enables less use of electric resistance heat.

Energy efficiency has been the main drivers of regulations on minimum efficiency levels and has required significant efforts by equipment manufacturers. Still, the progress in AC and refrigeration have been dissimilar.

For AC equipment, significant developments have occurred in mass applications (e.g., residential AC). Still, the deployment of highly efficient systems is challenging because of the relatively high initial cost. In general, the solutions will vary depending on the county geographic and cultural characteristics. Even in the same country, these challenges may affect the acceptability of highly efficient technologies (e.g., multifamily/low-income buildings).

For refrigeration, some improvements have occurred lately. Still, these systems may have opportunities for improvements with respect to current systems based on the high-GWP refrigerant R-404A (GWP of 3922 according to IPCC 2007). For instance, supermarket refrigeration systems are large, offering the opportunity to optimize the configuration and design.

4.1 PERFORMANCE AND LIFE CYCLE CLIMATE PERFORMANCE ANALYSIS FOR AC APPLICATIONS

This analysis includes residential AC systems for the US and European markets. Most US residential houses employ ducted-split systems, where a duct system distributes the air through the house. Thus, this study will consider options that fit the current housing architecture: ducted systems.

Houses outside the United States (Europe, Asia, and other regions) are not designed to use ducts for distribution. Very often, AC is incorporated into existing buildings. Thus, splits systems with multiple evaporators are more suitable options. Such systems are commonly called *multiple split* systems and have up to four evaporators. This study will use such systems as the benchmark for the European and global market.

To make an initial selection of the technology options, this study compares options the based on the three main requirements (environmental, performance, safety), with additional comments on the feasibility of manufacturing.

- Environmental (ODP, GWP, environmental degradation products)
- Performance (capacity, efficiency, life cycle climate performance [LCCP])
- Safety (flammability, toxicity)
- Feasibility of manufacturing (material compatibility, reliability, relative cost)

4.1.1 Performance and LCCP analysis for the US AC market

The efficiency of these technology options is compared with a standard US R-410A system in Table 1.

Table 1. Technology options for US residential AC

	HFC/HFO mixtures **Split systems using R-454C or R-455A**	**Propane** **Secondary loop system (Mini chiller)**
Performance	• Lower volumetric capacity than R-410A introduces system loses (pressure drop related) and requires larger compressor displacement. • Will require improved compressor and enhanced heat exchangers	• Significant penalties owing to the use of additional intermediate heat exchanger and larger indoor coils (water) • Will require significant higher-efficiency compressor to offset the penalties
Environmental	• A GWP <150 seems to be the most restrictive value in proposed regulations. They will comply with such regulations. • Generation of TFA and its environmental impact is still under considerable study. Still, recent assessments (UNEP EEAP, 2022) report no significant impact.	• Propane has a very low GWP, which would comply with any possible regulation. • No issues with degradation products
Safety	• Most of these alternatives are flammable class 2L by ASHRAE Standard 34. • Recent updates to installation (ASHRAE Standard 15) and equipment (UL 60335-2-40) standards allow the safe use of these refrigerants. • Owing to the relatively high lower flammable limit, class 2L refrigerants have significantly larger allowable charges compared with class 3 ones.	• Propane is a highly flammable refrigerant class 3 by ASHRAE Standard 34. • The allowable charge in direct systems is very limited and requires significant safety mitigation. • A secondary loop system would allow adequate refrigerant charge. Still, the safety standards need to be updated to include such equipment/ installation in residential applications.

Feasibility of manufacturing	• The resize/redesign of the compressor will likely increase the cost of this component. • Heat exchangers will need to be either enhanced (internal/external fins for tube-in-tube type, more rows of tubes, smaller tube diameters to pack more tubes in a volume) or changed to new ones (microchannel type). • Overall, a cost increase is expected.	• A newly optimized compressor will likely increase the cost. • Additional (intermediate) and bigger heat exchangers (indoor water fan-coil) will significantly increase the cost. • Compliance with safety standards, even when installed outdoors, will likely increase the first cost and the ownership cost (maintenance, servicing).

4.1.1.1 Performance Assumptions and Results

Using the qualitative information of Table 1, this study made the following assumptions for the US system evaluations.

- Use the most common US residential system as a benchmark: A 3-ton, 14 seasonal energy efficiency ratio (SEER), split ducted AC system equipped with a single-speed compressor and using R-410A as the refrigerant.

- Synthetic options R-454C and R-455A will be evaluated using the same size of heat exchangers, optimizing the number of circuits only so they will have pressure drop penalties such as the benchmark (R-410A). The compressor displacement will be modified so all systems will have the same capacity.

- For R-290 (propane), use an indirect system (mini chiller), which will use water as a secondary fluid. Thus, the indoor fan-coil becomes an air-to-water heat exchanger. The R-410A condensing unit will be converted to a mini chiller by adding a plate heat exchanger as evaporator. Also, add a liquid pump to circulate the water inside the house. The intermediate heat exchanger (plate), the indoor coil, and the compressor are sized for a 3-ton system.

- In all cases, the compressor displacements are sized to obtain the same cooling capacity. The efficiency represents the performance of the best compressor available for R-410A: 75%. This efficiency is also the efficiency assumed for R-454C, R-455A (Emerson product selection, 2022). Notably, current R-290 scroll compressors for AC have efficiencies lower than 70%. Thus, we assumed a 70% efficiency for R-290, which will need significant development. All volumetric efficiencies are assumed to be 95%.

- All connecting lines are sized to obtain pressure drop penalties such as R-410A, resulting similar saturation temperature drops in connecting lines. Thus, refrigerants such as R-454C and R-455A will have larger-diameter suction lines. In the case of R-290, the connecting lines are very short because of the mini chiller configuration.

- The scope/definitions listed in this section will allow the comparison of systems with a similar cost for R-410A, R-454C, and R-455A. In the case of R-290, a higher cost is unavoidable because of the use of an intermediate heat exchanger, a liquid pump, and an air-to-water exchanger, which is, in principle, larger than the typical air-to-refrigerant one. This last issue is mainly because of the use of single-phase inner heat transfer instead of flow boiling.

- All thermodynamic and transport properties were calculated using the latest version of the refrigerant properties (REFPROP 10) developed by the National Institute of standards (Lemmon et al. 2018)

Prior to performing any simulations, Oak Ridge National Laboratory's system model (DOE/ORNL Heat Pump Design Model, i.e., HPDM) was calibrated using experimental data for two refrigerants, R-410A and R-32, at AHRI 210 conditions A, B, C, and H1 (Kaimi et al, 2021). The calibrated model was able to predict all main parameters within experimental uncertainty (±5%). The HPDM model is well described by Shen and Rice (2016).

Using the calibrated model and based on the system assumptions, the performance was simulated for AHRI 210 conditions A, B, and all temperature bins necessary for the LCCP calculations (67°F to 102°F).

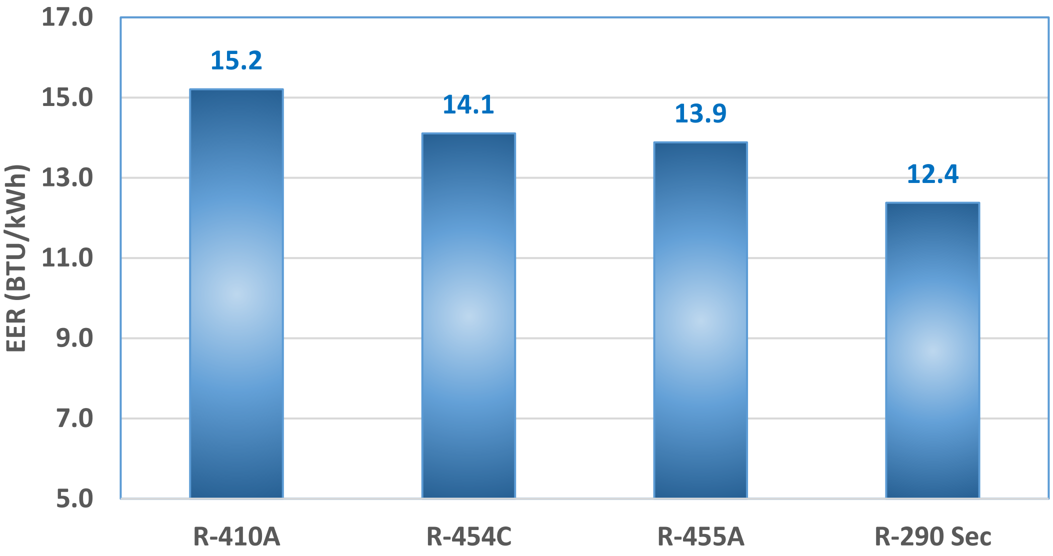


Figure 3 shows the relative efficiency of all these refrigerants when evaluated at AHRI condition B, which is typically used to evaluate the efficiency of residential AC systems in the United States. The full performance

for a wide range of ambient temperatures is shown in

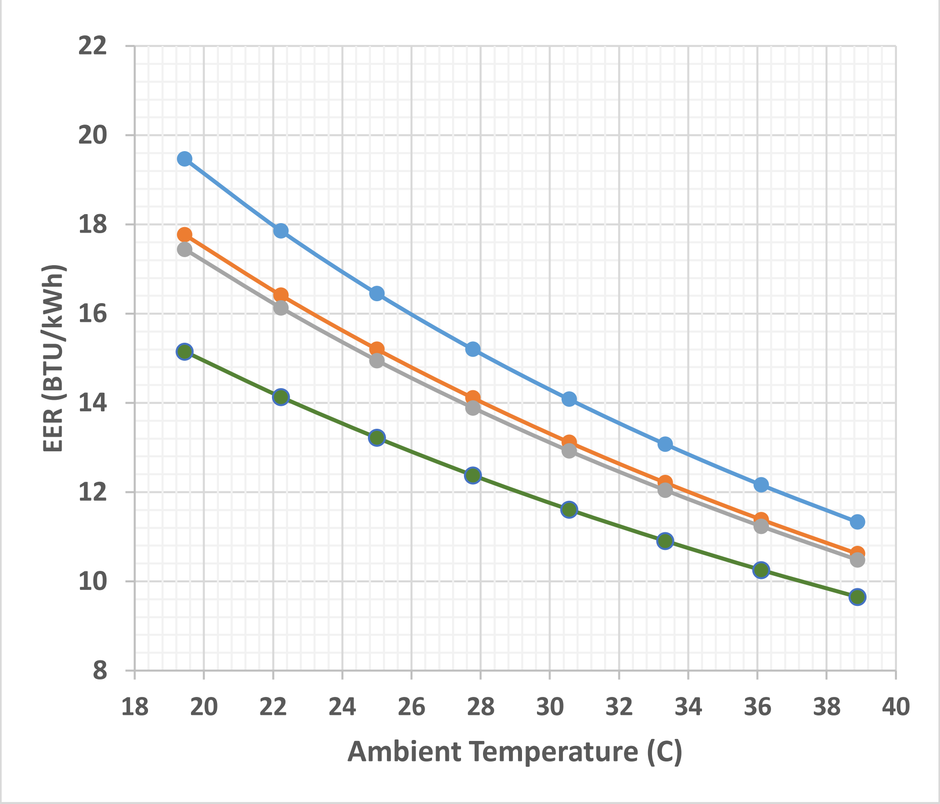


Figure 4.

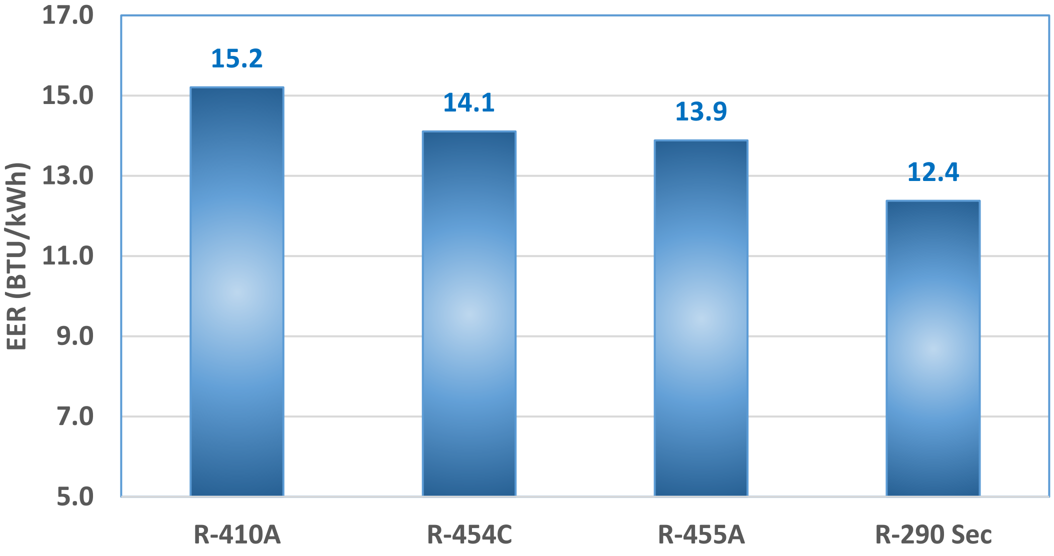


Figure 3. Efficiency evaluated at AHRI condition B.

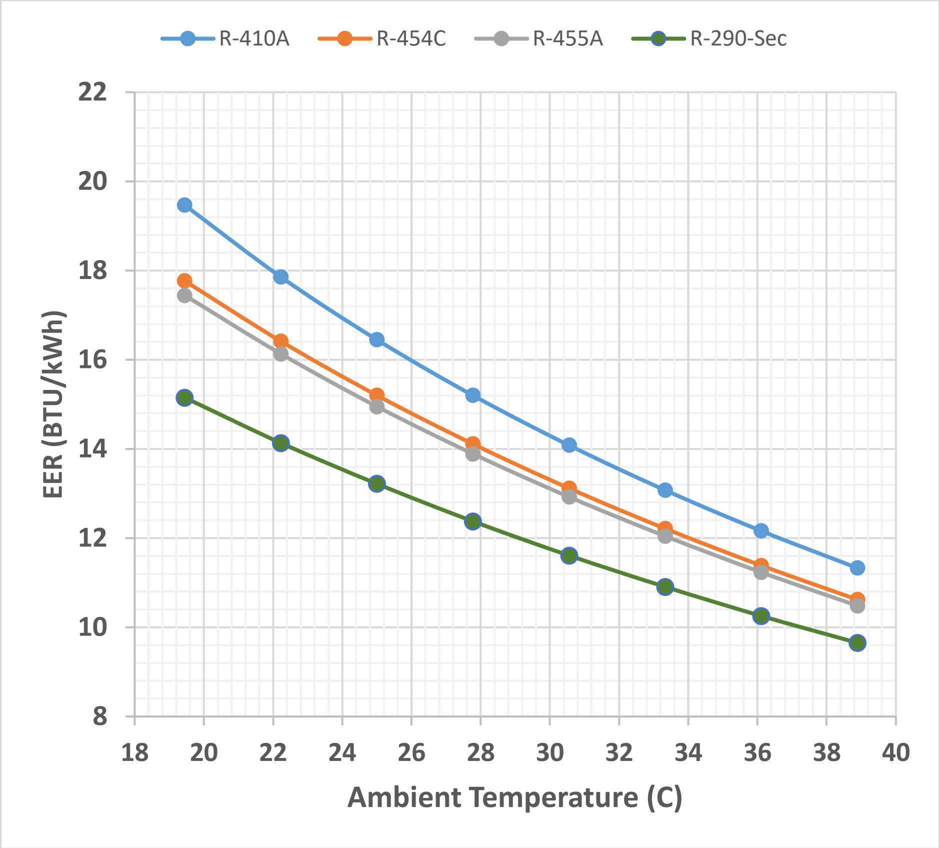


Figure 4. Energy Efficiency Ratio vs. ambient temperature.

The efficiency of the 14 SEER R-410A system is as expected for a typical US residential AC system. On the other hand, two HFC/HFO mixtures show 7% to 9% lower efficiency compared with R-410A. This lower efficiency is expected because they are being evaluated using the same heat exchangers (i.e., similar cost systems). To overcome these gaps, both heat exchangers and the compressor will need optimization.

In the case of heat exchangers, the number of circuits are already optimized; therefore, further improvements are needed. These improvements will probably require an increase of the heat transfer area, which can be done in two ways:

- Use smaller diameter tubes (e.g., 5 mm), which are now readily available. This smaller size will allow the number of tubes to increase while maintaining the same volume of the heat exchanger. The number of circuits will need to be optimized, as the current evaluation did.
- Increase the number of rows, where possible, without changing the volume. As an example, outdoor coils that currently have one row can be increased to two rows without any major change of the condensing unit volume.

An example of such effort can be found in the study performed by Zhenning et al. (2023). In that study, heat exchangers were redesigned and fully optimized for each refrigerant.

As for the compressor, the use of refrigerants with lower volumetric capacity and thermal properties compared with R-410A point to changes in the design in these areas:

- Penalties associated to the suction passages (pressure drop and compression heat) can be minimized by proper sizing and optimization.
- The volumetric displacement needs to be increased without affecting the volumetric efficiency.
- Any improvements of the electric motor can also contribute increased compressor efficiency.
- Both material compatibility and refrigerant interaction with the lubricant should be evaluated and modified as needed.

In the case of R-290 secondary fluid configuration, the efficiency is 18.6% lower than R-410A. This lower value is expected because this system has significant cycle loses, which are described in the following list.

- The vapor compression cycle operates at lower evaporating temperature compared with a standard R-410A direct expansion (DX) system (7 °C). This lower temperature results in lower compressor efficiency because of the larger compression ratio. It also increases losses in the expansion process.
- The indoor coil is an air-to-liquid heat exchanger, which does not have the benefit of the high-flow boiling heat transfer coefficients regularly found in DX systems. Thus, this heat exchanger will be significantly larger than the standard R-410A one. Additionally, it will require the liquid temperature to be well below the level found in a standard R-410A system (7°C to 10°C). This requirement adds another penalty to this configuration.

Because of these reasons, a secondary system using R-290 will require significant improvements in cycle and components to match R-410A. Some of the suggested improvements are described in the following list.

- During the simulations, this study assumed compressor with 70% efficiency. Current R-290 compressors have efficiencies ranging from 67% to 70% at the best (Emerson selection software PSS, 2021). Offsetting the low system efficiency in the compressor is a quite substantial a challenge.
- Cycle modifications such as the use of liquid-line/suction-line heat exchangers and a vapor-injection/economizer can also be explored.
- The use of a secondary fluid that will experience flow boiling can minimize some of the penalties associated with the intermediate heat exchanger and the indoor fan coil.

4.1.1.2 LCCP Assumptions and Analysis

LCCP analysis has been extensively used by the HVAC industry and clearly explained in publications such as IIR (2016), Hanlong (2021) and Troch et al, (2016). Thus, this study performed an LCCP analysis for the US technologies using the following assumptions:

- Used the bin methodology for these cities: Phoenix (warm), Atlanta (average) and Chicago (cold)
- 15-year lifetime, 4%/year leak rate, 15% end-of-life (EOL) leak
- Use a typical load profile for a US house.
- The average energy factor of 0.497 kg CO_2/KWh is used for all US cities.

As a representative sample of the wide range of ambient temperatures found in the USA, we present below (Figure 5, Figure 6 and Figure 7) the results for three cities: 1) Chicago representing a cold weather location, 2) Atlanta represents a moderate weather and is often used as an average for the US, and 3) Phoenix representing the warmest temperatures.

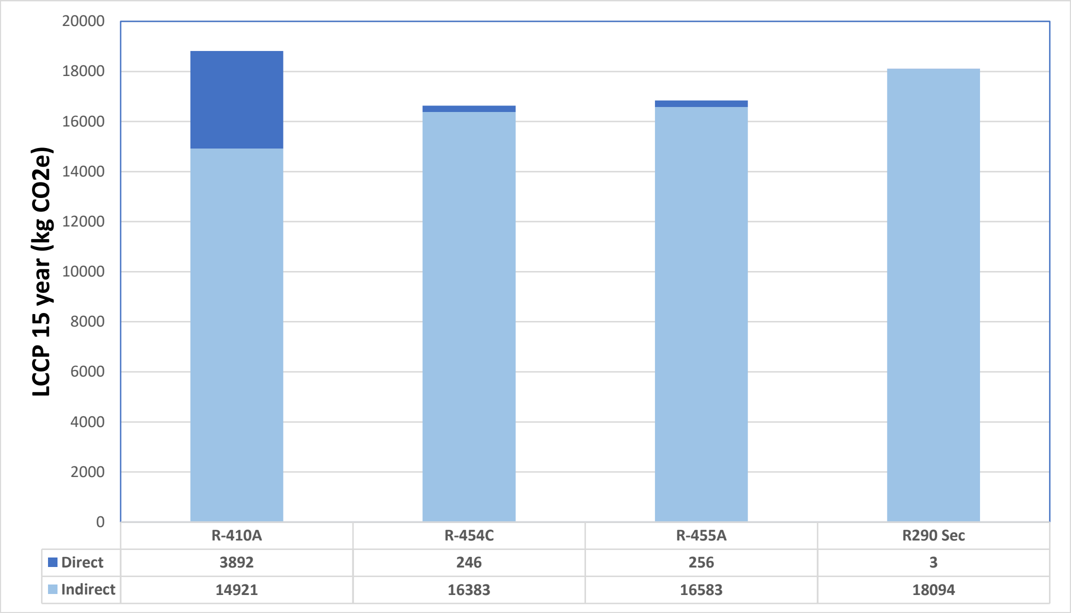


Figure 5. LCCP analysis for Chicago.

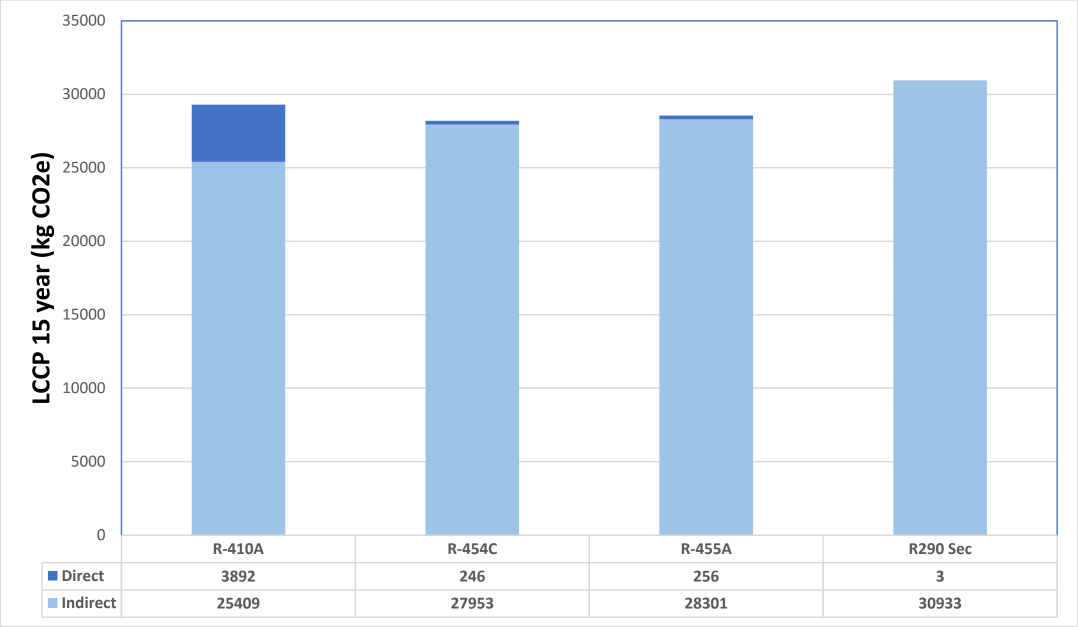


Figure 6. LCCP analysis for Atlanta.

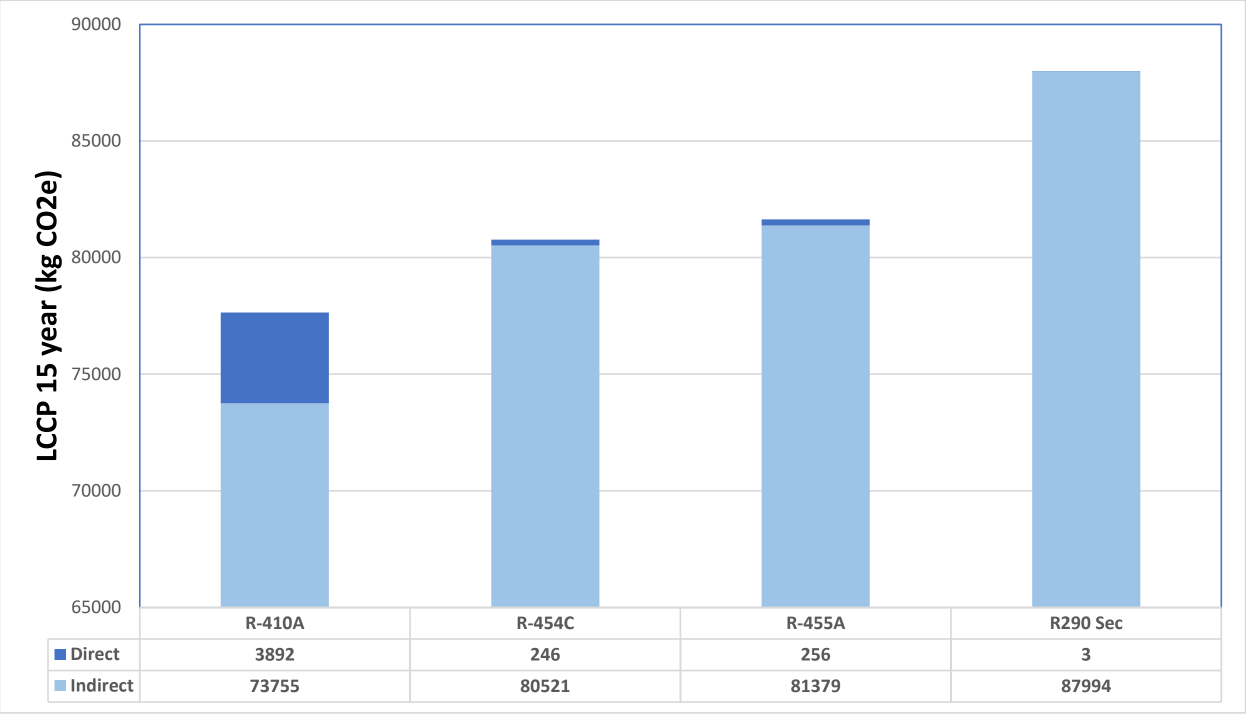


Figure 7. LCCP analysis for Phoenix.

Figures 5-7 show the effect of warmer weather on emissions. Energy consumption for Phoenix is the highest, followed by Atlanta and Chicago, which essentially validates the veracity of these results. Another relevant observation for the United States is that energy consumption is the largest source of emissions. Thus, the performance of the system (i.e., energy consumption) deserves a great deal of attention. Therefore, the design and optimization of the system together with proper installation and controls should be two of the most relevant technology priorities for the United States. To better use the results obtained, this study looked at two potential scenarios (tables 2 and 3) for an average city such as Atlanta.

4.1.1.3 Scenario 1: HFC/HFO Mixtures 100% Adopted to Replace R-410A

Under the original assumptions of this study (same size heat exchangers, equivalent pressure drop as R-410A, and modified compressor displacement to achieve equivalent capacity), from table 2, HFC/HFO mixtures can reduce the total lifetime emission from 2.5% to 3.8%. Still, the emissions related to energy consumption indicate an increase in energy consumption of 10% to 11.4%.

Table 2. Relative emissions and energy consumption of HFC/HFO mixtures

GHG Emissions	HFC/HFO Mixtures					
	Same size heat exchangers (similar cost) and same compressor efficiency of R410A			Optimized and larger heat transfer area heat exchangers (higher cost)		
	R-410A	R-454C	R-455A	R-410A	R-454C	R-455A
Total Lifetime Emission	100.0%	96.2%	97.5%	100.0%	87.6%	87.6%
Total Direct Emission	13.3%	0.8%	0.9%	13.3%	0.8%	0.9%
Total Indirect Emissions	86.7%	95.4%	96.6%	86.7%	86.7%	86.7%
Energy vs R-410A (%)	100.0%	110.0%	111.4%	100.0%	100.0%	100.0%

The use of improved heat exchangers with larger heat transfer areas can allow these options to match R-410A's efficiency. Additionally, the use of simple cycle variations such as suction-line/liquid-line heat exchangers can potentially improve efficiency. Thus, indirect effects can be realistically assumed as similar to R-410A. This best-case scenario can reduce total lifetime greenhouse gas (GHG) emissions by 12.4% and maintain the current energy consumption. Any additional optimization of the system can further reduce the total lifetime GHG emissions. Still, the cost of such systems should be considered.

Scenario 2: R-290 Secondary Fluid 100% Adopted to Replace R-410A

Table 3. Relative emissions and energy consumption of R-290 secondary system

GHG Emissions	Properly sized heat exchangers and same compressor efficiency of R410A (higher cost)		Assumed 5% increase in efficiency due to cycle improvements (higher cost)	
	R-410A	R-290 Secondary	R-410A	R-290 Secondary
Total Lifetime Emission	100.0%	105.6%	100.0%	100.6%
Total Direct Emission	13.3%	0.0%	13.3%	0.0%
Total Indirect Emissions	86.7%	105.6%	86.7%	100.5%
Energy vs R-410A (%)	100.0%	121.7%	100.0%	115.9%

Although an ultralow-GWP such as R-290 is used, a secondary fluid system designed for a typical US house does not reduce emissions. This lack of reduction is mostly because of the low efficiency of this system, which is mainly a result of the addition of an intermediate heat exchanger and a secondary fluid that does not benefit from boiling. In fact, this system increases the energy consumption by 21.7%. Because a high-efficiency compressor (75%) is already being used in this work, the only option is to improve cycle efficiency. This improvement can be done by using a higher efficiency compressor and a multiple-stage, vapor-injected cycle. The efficiency is assumed to be improved by 5%; the energy consumption is still significantly higher (15.9%), as shown in Table 3). Significant work is needed to overcome this gap.

4.1.2 Performance and LCCP Analysis for the European Union and Global AC Market

The effectiveness of these technology options is compared with a multiple-split R-410A system in Table 4.

Table 4. Technology Options for the European Union and Global Residential A/C.

	HFC/HFO mixtures Multi-split systems using R-454C or R-455A	**Propane (R-290) Direct and secondary loop systems (mini chiller)**
Performance	• Lower volumetric capacity than R-410A introduces system losses (pressure drop–related) • Will require improved compressor and enhanced heat exchangers	• Significant penalties owing to the use of additional intermediate heat exchanger and larger indoor coils (water) • Will require significantly higher efficiency compressor to offset the penalties. • For direct R-290 systems, the performance will be similar to current R-410A
Environmental	• A GWP <150 seems to be the most restrictive value in proposed regulations. They can comply with future regulations. • Generation of TFA and its environmental impact is still under considerable study. Still, recent assessments (UNEP EEAP 2022) report no significant impact.	• Propane has a very low GWP, which would comply with any possible regulation. • No issues with degradation products
Safety	• Most of these alternatives are flammable class 2L by ASHRAE Standard 34 and ISO 817. • Recent updates to IEC 60335-2-40, ISO 5149, and EN378 standards allow the safe use of these refrigerants. • Owing to the relatively high lower flammable limit, class 2L refrigerants have significantly larger allowable charges compared to class 3 ones.	• Propane is a highly flammable refrigerant listed as class 3 by ASHRAE Standard 34 and ISO 817. • The allowable charge in direct systems is still limited to small, low-charge systems. To be used in larger systems requires significant safety mitigation or the use of multiple systems. • A secondary loop system would allow adequate refrigerant charge. Thus, it will be a more feasible technology from a safety point of view. Still, the safety standards need to be updated to include detailed installation for residential applications.

Feasibility of manufacturing	• The resize/redesign of the compressor will likely increase the cost of this component. • Heat exchangers will need to be either enhanced (internal/external fins for tube-in-tube type) or changed to new ones (microchannel type). • Overall, a cost increase is expected.	• A newly optimized compressor will likely increase the cost. • Additional (intermediate) and bigger heat exchangers (indoor water fan-coil) will significantly increase the cost. • Compliance with safety standards, even when installed outdoors, will likely increase the first cost and the ownership cost (e.g., maintenance, servicing). • If used in direct systems, it will need to use mitigation or be split in multiple systems. This will increase the cost.

4.1.2.1 Performance Assumptions and Results

Using the qualitative information in Table 4, the following assumptions for the European Union (EU) system evaluations were made. The choice of systems can be also applicable to other markets (e.g., Asia, Latin America) because their house buildings usually cannot accommodate ducted systems. Thus, mini-split and multiple-split systems fit their needs better.

- Use the most common multiple-split system as a benchmark: a 3-ton, 14 SEER split system equipped with multiple rotary compressors and using R-410A as the refrigerant.

- Synthetic options R-454C and R-455A will be evaluated using the same size heat exchangers, optimizing the number of circuits only so they will have pressure drop penalties similar to the benchmark (R-410A). The compressor displacement will be modified so that all systems will have the same capacity.

- R-290 (propane) has two options:
    - The first option is a DX system using the same size heat exchangers of R-410A. Only the number of heat exchanger circuits will be optimized to obtain pressure drop penalties similar to the benchmark (R-410A). The compressor displacement will be modified to match R-410A’s capacity. Although the refrigerant charge may exceed the allowable limits, this system will be used to get the representative performance of a DX system using R-290. Safe designs will probably require splitting this in multiple systems and the use of multiple compressors, which tend to have lower efficiencies because of losses in energy through the can.
    - An indirect system (mini chiller) will use water as a secondary fluid. Thus, the indoor fan-coil becomes an air-to-water heat exchanger. The R-410A condensing unit will be converted to a mini chiller by adding a plate heat exchanger as the evaporator. A liquid pump will also be added to circulate the water inside the house. The intermediate heat exchanger (plate), the indoor coil, and the compressor are sized for a 3-ton system.

- In all cases, the compressor displacements are sized to obtain the same cooling capacity. The efficiency represents the performance of a typical rotary compressor for R-410A: 70%. This value is also the efficiency assumed for R-454C, R-455A, and R-290. All volumetric efficiencies are assumed to be 95%.

- All connecting lines are sized to obtain pressure drop penalties similar to R-410A, resulting in the same saturation temperature drop. Thus, refrigerants such as R-454C, R-455A, and R-290 will have larger-diameter suction lines. In the case of the R-290 secondary system, the connecting lines are very short owing to the mini chiller configuration.

- These scopes/definitions will allow the comparison of systems with similar cost for R-410A, R-454C, and R-455A. In the case of the R-290 secondary, a higher cost is unavoidable because of the use of an intermediate heat exchanger, a liquid pump, and an air-to-water exchanger, which is, in principle, larger than the typical air-to-refrigerant one. The R-290 direct multiple-split sizing is done to maintain similar equipment cost, too. Still, additional cost will probably happen because of the use of safety mitigation: leak detection and the use of multiple systems to reduce charge per circuit.

Using The Heat Pump Design Model HPDM (Shen and Rice, 2016), the performance was simulated for AHRI 210 conditions A, B, and all temperature bins necessary for the LCCP calculations (67°F to 102°F). Figure 8 shows the relative efficiency of all these refrigerants when evaluated at AHRI condition B. The full performance for a wide range of ambient temperatures is shown in Figure 9.

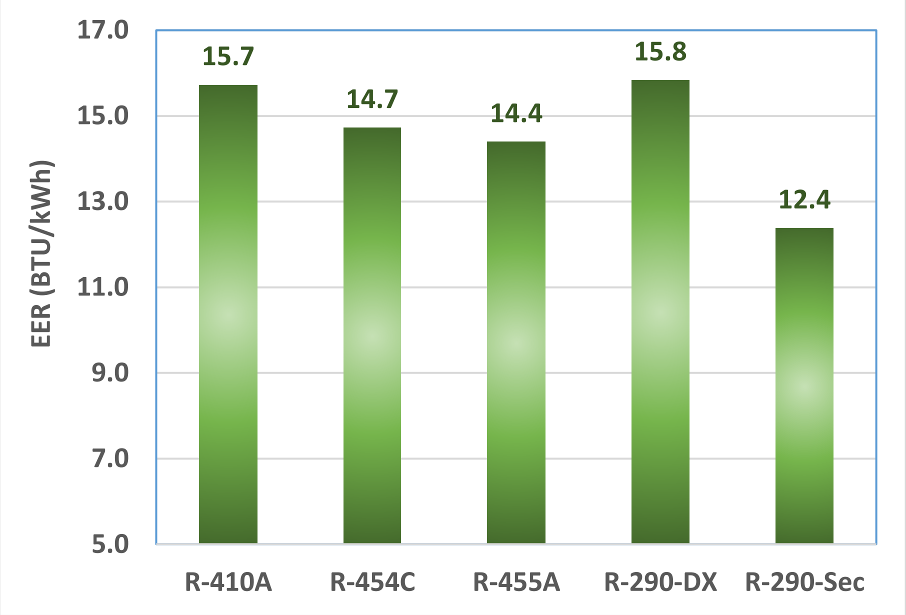


Figure 8. Efficiency evaluated at AHRI condition B.

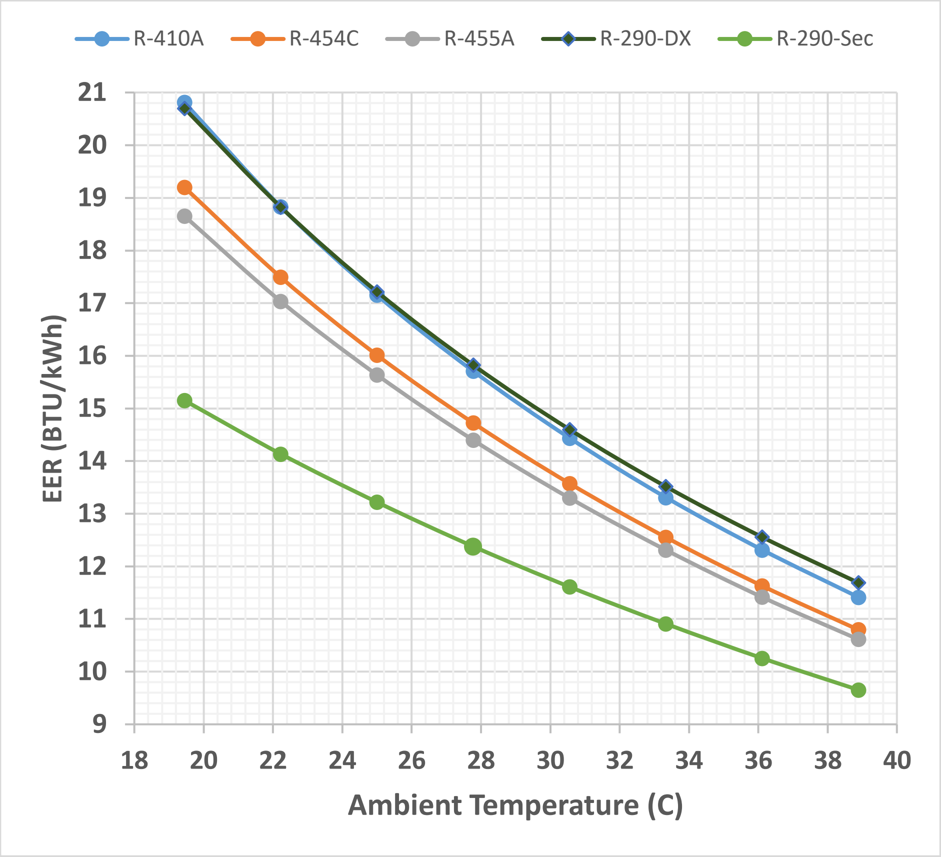


Figure 9. Energy Efficiency Ratio vs. ambient temperature.

The two HFC/HFO mixtures show 7% to 9% lower efficiency compared with R-410A. This result is expected because they are evaluated using the same heat exchangers (i.e., similar cost systems). To overcome these gaps, both heat exchangers and the compressor will need optimization.

In the case of heat exchangers, the number of circuits was already optimized; thus, further improvements are needed. These improvements will probably require an increase of the heat transfer area, which can be done in two ways:

- Use smaller diameter tubes (e.g., 5 mm), which are now readily available. This smaller size will allow the number of tubes to be increased while maintaining the similar volume of the heat exchanger. The number of circuits will need to be optimized as this study did in the current evaluation.
- Increase the number of rows, where possible, without major volume changes. This option is probably more applicable to the outdoor coil, where space is more available. The indoor coil typically has three rows, so an increase will not be that useful. A length increase will probably be more effective in this case.

As for the compressor, the use of refrigerants with lower volumetric capacity and thermal properties compared with R-410A point to changes in the design focused on these areas:

- Penalties associated with the suction passages (pressure drop and compression heat) can be minimized by proper sizing and optimization.

- The volumetric displacement needs to be increased without affecting the volumetric efficiency.
- Any improvements of the electric motor can also contribute to an increase in compressor efficiency.
- Material compatibility and refrigerant interaction with the lubricant should be evaluated and modified as needed.

As for the R-290 DX system, the efficiency matches well with that of R-410A. Thus, this technology has no performance limitations. The use of multiple systems because of charge limitations (i.e., safety) will probably weigh more on the decision by manufacturers.

In the case of the R-290 secondary fluid configuration, the efficiency was 21% lower than R-410A. This result is expected because this system has significant cycle losses, which were described in the US refrigerant and AC section of this work.

4.1.2.2 LCCP Assumptions and Analysis

LCCP analysis was performed for the EU technologies using the following assumptions:

- Used the bin methodology for these cities: Frankfurt, Rome, and Oslo
- 15-year lifetime, 4%/year leak rate, 15% EOL leak
- Use a typical load profile for a house
- A representative average energy factor is used for all European and other regions' cities

LCCP calculations were performed for several cities in the world. Because a wide range of energy factors exists, for this study, cities covering a range were selected, going from very low (Sao Paulo in Brazil, with an energy factor (EF) of 0.13 kg CO_2/kWh) to very high (Delhi in India, with and EF of 1.333 kg CO_2/kWh). Figure 10–Figure 14 show the following cities with the 15-year LCCP in kilograms of CO_2 effective (CO_2e): (1) Delhi (EF = 1.333), (2)Shanghai (EF = 0.831), (3) Frankfurt (EF = 0.6722), (4) Rome (EF = 0.4108), and (5) Sao Paulo (EF = 0.13).

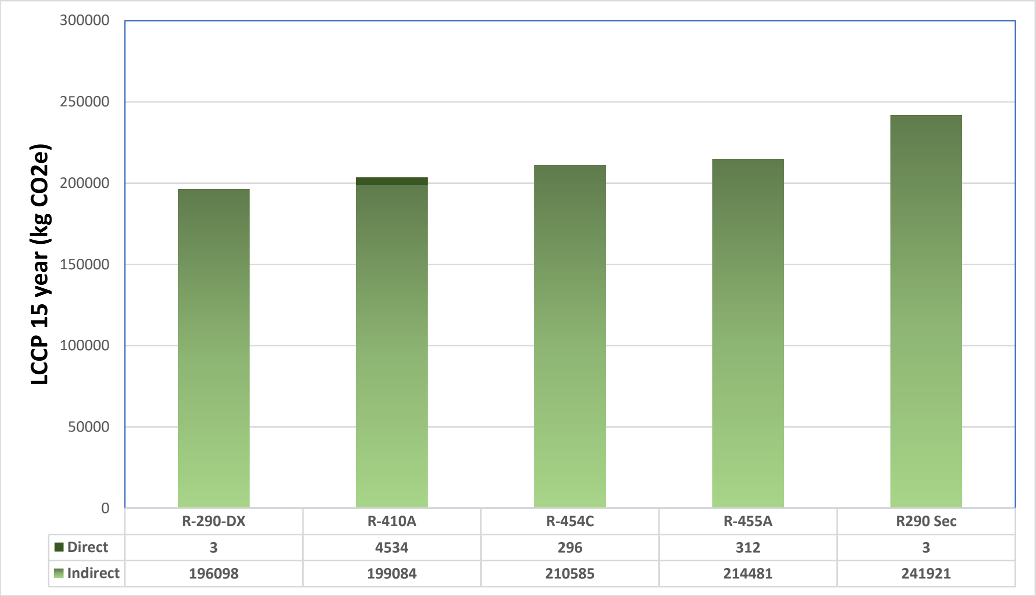
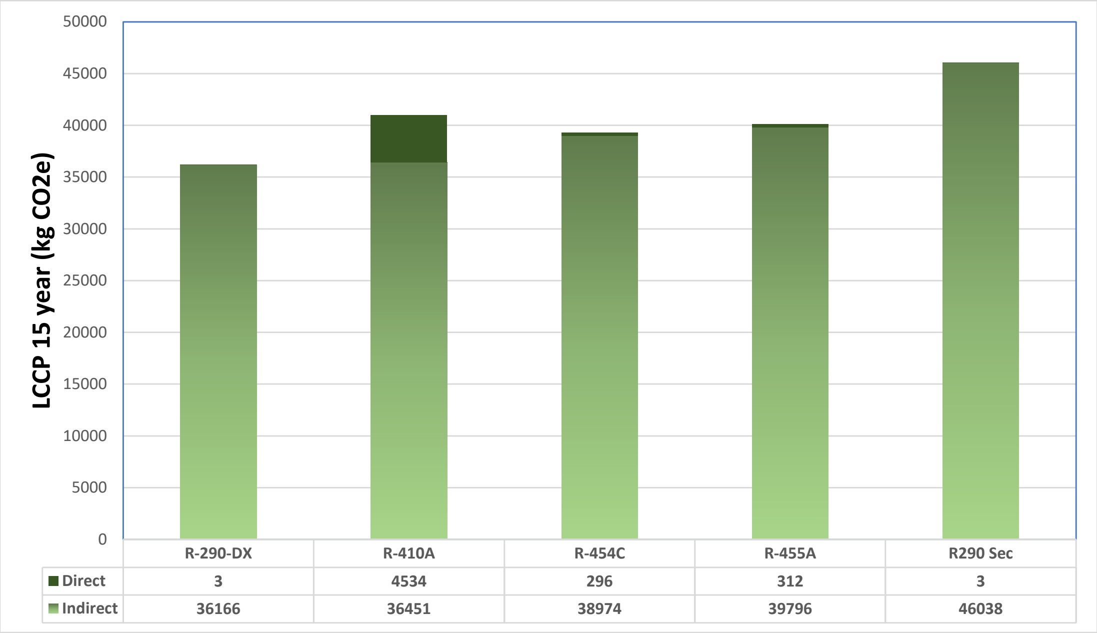
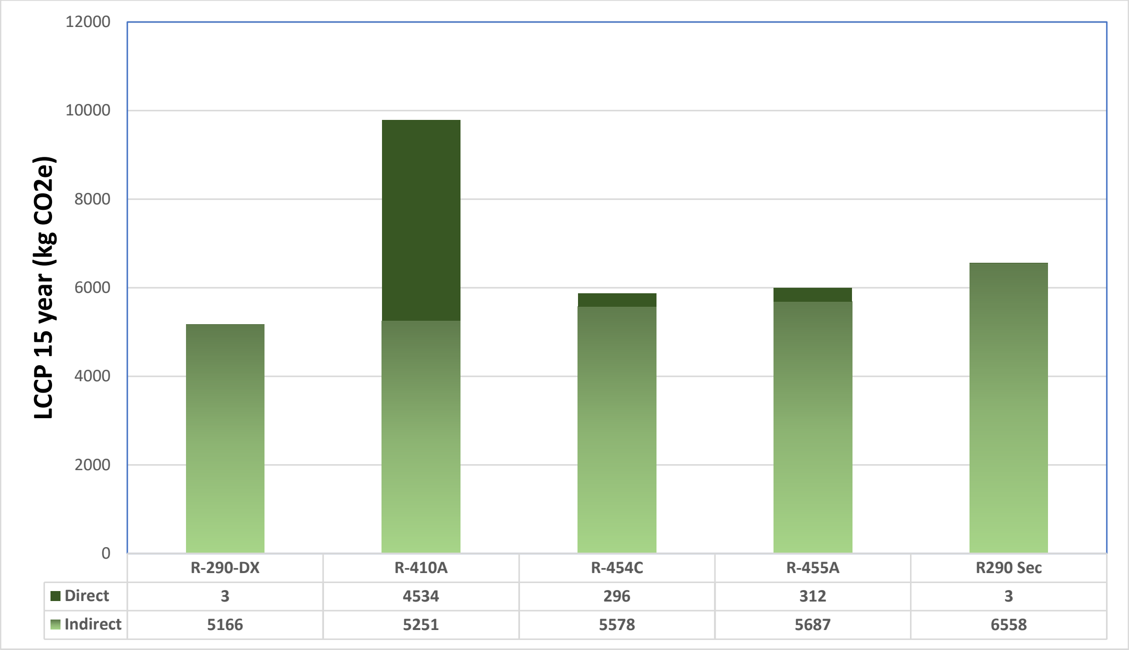


Figure 10. LCCP analysis for Delhi (EF = 1.333).



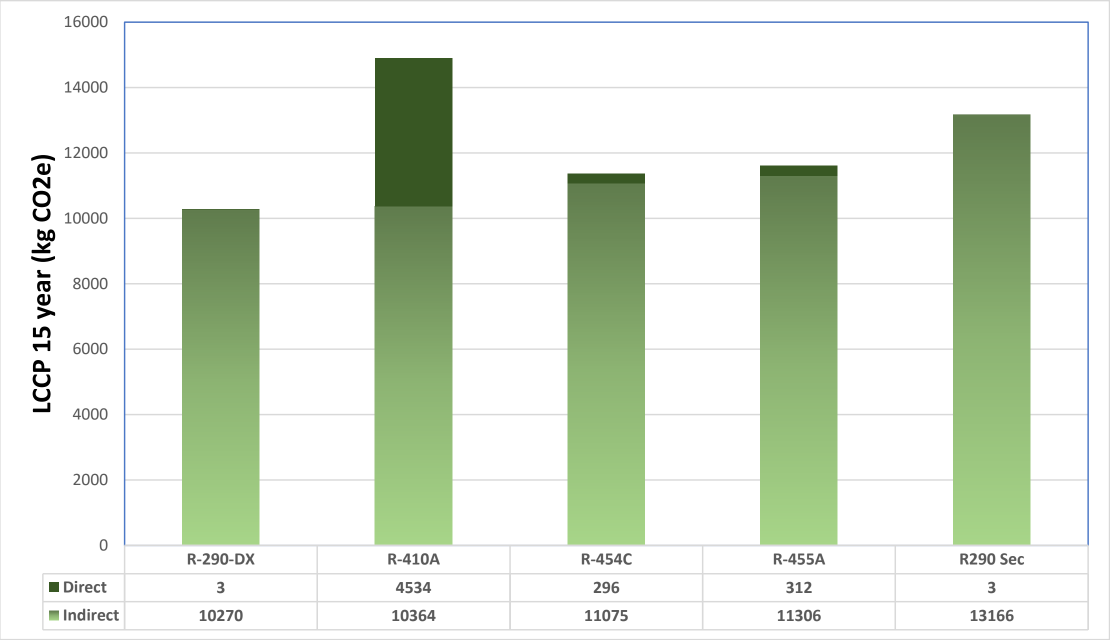
	R-290-DX	R-410A	R-454C	R-455A	R290 Sec
■ Direct	3	4534	296	312	3
■ Indirect	36166	36451	38974	39796	46038

Figure 11. LCCP analysis for Shanghai (EF = 0.831).



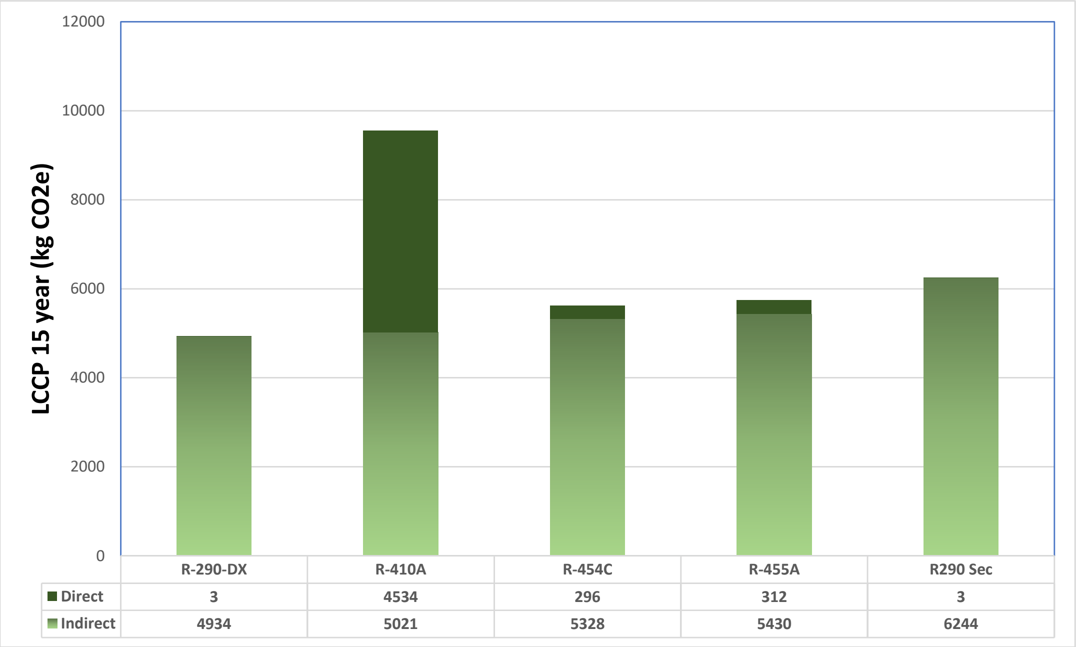
	R-290-DX	R-410A	R-454C	R-455A	R290 Sec
■ Direct	3	4534	296	312	3
■ Indirect	5166	5251	5578	5687	6558

Figure 12. LCCP analysis for Frankfurt (EF = 0.6722).



	R-290-DX	R-410A	R-454C	R-455A	R290 Sec
Direct	3	4534	296	312	3
Indirect	10270	10364	11075	11306	13166

Figure 13. LCCP analysis for Rome (EF = 0.4108).



	R-290-DX	R-410A	R-454C	R-455A	R290 Sec
Direct	3	4534	296	312	3
Indirect	4934	5021	5328	5430	6244

Figure 14. LCCP analysis for Sao Paulo (EF = 0.13).

The overall CO_2 emissions have a noticeable dependency on the EF and ambient temperatures. Therefore, Delhi, with a high EF of 1.333 and relatively warm temperatures, has the highest level of emissions. With AC being an energy-intense application, the EF seems to have a larger influence. This conclusion is validated by the fact that the indirect emissions tend to go down for lower emission factor locations, such as Sao Paulo in Brazil.

Another relevant observation is that energy consumption is the largest source of emissions. Thus, the performance of the system (i.e., energy consumption) deserves a great deal of attention. The design and optimization of the system, together with proper installation and controls, should be two of the most relevant technology priorities. To better use the results obtained, two potential scenarios for Rome were investigated in this work, as it has average weather and a midlevel EF (0.4108).

4.1.2.3 Scenario 1: HFC/HFO Mixtures 100% Adopted to Replace R-410A

Under the original assumptions of this study, both HFC/HFO mixtures (R-454C and R-455A) can reduce overall emissions by up to 13% (Table 5). Still, the emissions related to energy consumption indicate an increase in energy consumption of 10%.

Table 5. Relative emissions and energy consumption of original and optimum systems

	All Calculations									
GHG Emissions	Systems as defined in our assumpions					Optimized Systems				
	R-290-DX	R-410A	R-454C	R-455A	R-290-Sec	R-290-DX	R-410A	R-454C	R-455A	R-290-Sec
Total Lifetime Emission	69%	100%	76%	78%	88%	69%	100%	72%	72%	84%
Total Direct Emission	0%	30%	2%	2%	0%	0.0%	30.4%	2.0%	2.1%	0.0%
Total Indirect Emissions	69%	70%	70%	70%	84%	69%	70%	70%	70%	84%
Energy vs R-410A (%)	100%	100%	108%	110%	129%	100%	100%	100%	100%	123%

The use of improved heat exchangers with a larger heat transfer area can allow these options to match R-410A's efficiency. Thus, the indirect effects can be realistically assumed to be similar to R-410A. This best-case scenario can reduce overall GHG emissions by 27% and maintain the current energy consumption (shown in the right side of Table 5). Any additional optimization of the system can further reduce the overall GHG emissions. Still, one should consider the cost of such systems.

4.1.2.4 Scenario 2: R-290 Secondary Fluid or R-290 DX 100% Adopted to Replace R-410A

Although an ultralow GWP such as R-290 is used, a secondary fluid system designed for a fan-coil configuration can reduce emissions similarly to the other synthetic options (15%, as shown in Table 5. This result is mostly because of the low efficiency of this system, which is mainly owing to the addition of an intermediate heat exchanger and a secondary fluid that does not benefit from boiling. In fact, this system increases the energy consumption by 29%. Even a 5% more efficient system does not reduce enough energy consumption (right side of Table 5).

The R-290 direct expansion system matches R-410A's energy consumption. The total emissions are reduced by 30% compared with R-410A. These values are very similar to the reduction obtained for optimized HFC/HFO mixtures in Scenario 1. Overall, R-290 is a good option from an emissions point of view. The main challenge is to mitigate the risks associated with its high flammability. Measures such as the use of multiple circuits to limit charges, leak detection, and avoidance of ignition sources will likely increase the cost of this technology.

4.2 PERFORMANCE AND LCCP ANALYSIS FOR REFRIGERATION APPLICATIONS

This analysis includes commercial supermarket refrigeration systems for the US and European markets. Most of the regions employ central DX or distributed systems as their main options. The layout of a typical store is depicted by Goetzer et al. (2009) in Figure 15. Display cases are located along the perimeter close to their associated walk-in coolers/freezers used for storage and replenishment.

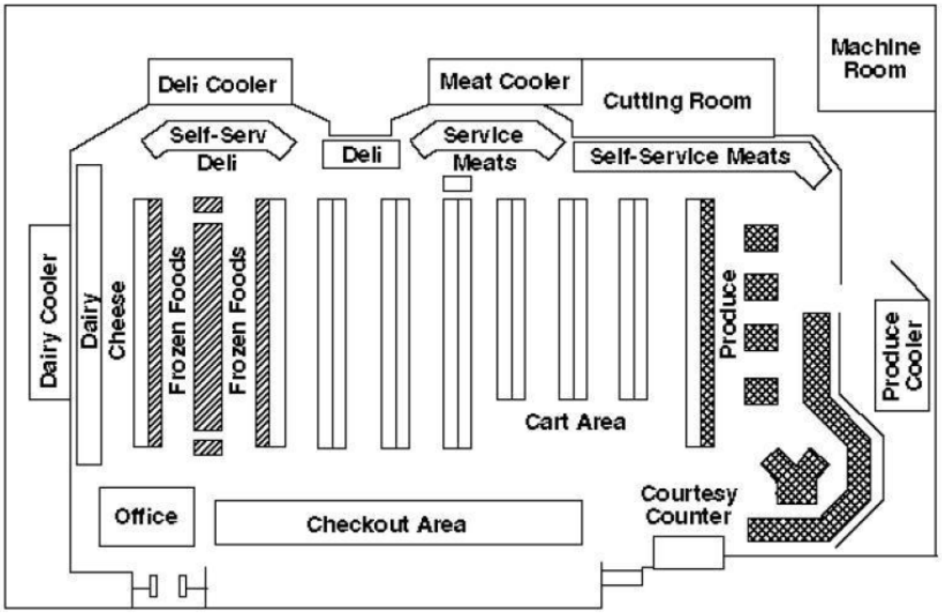


Figure 15. Typical supermarket layout (Goetzer et al., 2009).

A central DX system will have the compressor racks and condensers located in a mechanical room, typically located on the roof of the store. Thus, the refrigerant must be delivered using long connecting lines running from the roof to the display cases and back to the compressor racks. Because of the long connecting lines and large liquid receivers, these systems have large charges of refrigerants. A typical 47,000 ft^2 store (Figure 15; Food Marketing Institute 2008) could have charges ranging from 1,300 to 2,500 lb (International Energy Agency 2003). Because of the long lines and many connections, these systems have leak rates of up to 25% per year.

An additional characteristic is that display cases working at different temperatures (e.g., dairy, vegetables) will usually be in the same compressor group. This arrangement makes sense from the perspective of saving materials (e.g., piping, refrigerant) but it obligates the compressor to work at the lowest evaporating pressure. This low pressure increases the compression ratio (discharge pressure/suction pressure), lowering the compressor efficiencies (e.g., isentropic, volumetric). This lower efficiency will ultimately affect the efficiency of the system (or increase the energy consumption).

From this discussion, this work infers that distributed systems will tend to perform better from the point of direct and indirect emissions. The refrigerant charges and leak rates of distributed systems are lower than central DX systems. Consequently, the direct emissions will be lower. Additionally, the better grouping of compressors and short connecting lines will tend to reduce energy consumption (because of an increase of the compressor efficiency), which translates in a reduction of indirect emissions. Therefore, this comparative analysis will focus on distributed systems. The systems selected for side-by-side comparisons will be distributed for R-404A, R-454C, R455A, and R-290 (propane). To this group, the CO_2 transcritical booster system will be added in the only configuration available: central DX.

To perform the comparative analysis, the four main requirements for refrigeration systems will be used:

- Environmental (ODP, GWP, environmental degradation products)
- Performance (capacity, efficiency, LCCP)
- Safety (flammability, toxicity)

- Feasibility of manufacturing (material compatibility, reliability, relative cost)

4.2.1 Performance Assumptions and Results

Using the qualitative information in Table 6, the following assumptions were made for the four distributed systems (R-404A as the benchmark and R-454C, R-455A, and R-290 as options) and the CO_2 central DX configuration. In the case of supermarket refrigeration, the choice of systems can be applicable globally (e.g., United States, EU, Asia, Latin America) because their stores can technically accommodate all these technologies.

- A standard R-404A distributed system will be used as a benchmark. This system will be sized for a 45,000 ft^2 store. The refrigeration system will employ multiple scroll compressors and air-cooled condensers.

- Synthetic options R-454C and R-455A will be evaluated using the same size of heat exchangers, optimizing the number of circuits only so they will have pressure drop penalties similar to the benchmark (R-404A). The compressor displacement will be modified so that all systems will have the same capacity.

- For R-290 (propane), a water-cooled system will be used. Maintaining the size of the R-404A evaporators, the circuits will be optimized to accommodate R-290. The water-cooled condenser and chiller are sized to fulfill the total heat rejection. The chiller is assumed to use R-290 as the refrigerant to minimize direct emissions.

Table 6. Technology options for the US, EU, and global commercial supermarket refrigeration

	HFC/HFO mixtures R-454C or R-455A Distributed	**Propane (R-290) Water-cooled microcascade Distributed**	**CO_2 (R-744) Transcritical booster Central DX**
Performance	• Because of their lower volumetric capacity than R-404A, they tend to have higher pressure drop–related loses. Still, their relatively higher thermodynamic efficiency compared with R-404A will offset the penalties. • Improved compressors and enhanced heat exchangers can further enhance the performance of these refrigerants.	• Significant penalties owing to the use of a water-cooled condenser, which requires a chiller to provide cooling to the water or glycol-water liquid • To match R-404A's performance, R-290 will require a significantly higher efficiency compressor to offset the penalties.	• Owing to its lower critical temperature, CO_2 has an inherently lower thermodynamic efficiency. • The lower efficiency is being mitigated by using a two-stage system commonly known as a *booster*. • Still, the performance at moderate and high ambient temperatures will be lower than other options.
Environmental	• A GWP <150 seems to be the most restrictive value in proposed regulations. They can comply with future regulations. • Generation of TFA and its environmental impact is still under considerable study. However, recent assessments (UNEP EEAP 2022) report no significant impact.	• Propane has a very low GWP, which would comply with any possible regulation. • No issues with degradation products	• CO_2 has a GWP of 1; thus, they would not be affected by any regulations. • No issues with degradation products
Safety	• Most of these alternatives are flammable class 2L by ASHRAE Standard 34 and ISO 817. • Recent updates to IEC 60335-2-40, ISO 5149, and EN378 standards allow the safe use of these refrigerants.	• Propane is a highly flammable refrigerant and class 3 by ASHRAE Standard 34 and ISO 817. • The allowable charge in direct systems is still limited, so they are used in a water-cooled configuration. This configuration allows the use of multiple circuits (systems) to maintain the charge below the allowable value.	• CO_2 systems must ensure that the oxygen deprivation limit is not exceeded in any of the areas of the store. • Owing to a low cardiac sensitization limit, CO_2 has a very low Refrigerant Concentration Limit RCL. Mitigation may be required depending on the installation. • Additionally, the handling of very high-pressure CO_2 will require highly skilled technicians and operators.

Table 6. Technology options for the US, EU, and global commercial supermarket refrigeration (continued)

	HFC/HFO mixtures R-454C or R-455A Distributed	**Propane (R-290) Water-cooled microcascade Distributed**	**CO_2 (R-744) Transcritical booster Central DX**
Feasibility of Manufacturing	• The resize/redesign of the compressor will likely increase the cost of this component. • Heat exchangers will need to be either enhanced (internal/external fins for tube-in-tube type) or changed to new ones (microchannel type). • Overall, a cost increase is expected.	• A newly optimized compressor is needed and will likely increase the cost. • An additional chiller to provide cooled water for the condenser will increase the cost. • Compliance with safety standards, even when installed at low-charge levels, will likely increase the first cost and the ownership cost (e.g., maintenance, servicing). • The use of multiple circuits (systems) will increase the cost.	• The inherent sophistication of a transcritical/high-pressure system will significantly increase the first cost. • The ownership cost will increase owing to the use of highly skilled engineers and technicians to service these systems. • The reliability of CO_2 systems has historically been an issue. They are typically prone to leaks and very sensitive to charge levels.

- In all cases, the compressor displacements are sized to obtain the same cooling capacity. The efficiency represents the performance of a typical scroll compressor for R-404A: 60% for low temperatures and 65% for medium temperatures. These values are also the efficiencies assumed for R-454C, R-455A, and R-290. In the case of R-290, this efficiency is a very forward-looking assumption because multiple small compressors may be required. These smaller-capacity compressors will introduce energy losses through the compressor can, so the efficiency will be lower. Notably, for the CO_2 system, a highly efficient compressor is assumed to be available in the future (70% efficiency). All volumetric efficiencies are assumed to be 95%.

- All connecting lines are sized to obtain pressure drop penalties similar to R-404A (i.e., similar drop of saturation temperature). Thus, refrigerants such as R-454C, R-455A, and R-290 will have larger-diameter suction lines. In the case of R-290 systems, the connecting lines are very short owing to the multiple circuit configuration.

- These scopes/definitions will allow the comparison of systems with similar cost for R-404A, R-454C, and R-455A. In the case of the R-290 water-cooled system, a higher cost is unavoidable because of the use of an external chiller. Other safety mitigation mandated by risk assessment (e.g., leak detection, use of multiple systems to reduce charge per circuit) will likely increase the cost, too.

Using HPDM’s calibrated model, the performance was simulated at design conditions (95°F or 35°C) and at all temperature bins necessary for the LCCP calculations. Figure 16 shows the relative efficiency of distributed systems at design condition. To compare all options in a single plot, the CO_2 central DX system was also added. Notably, CO_2 is only designed for central DX configurations.

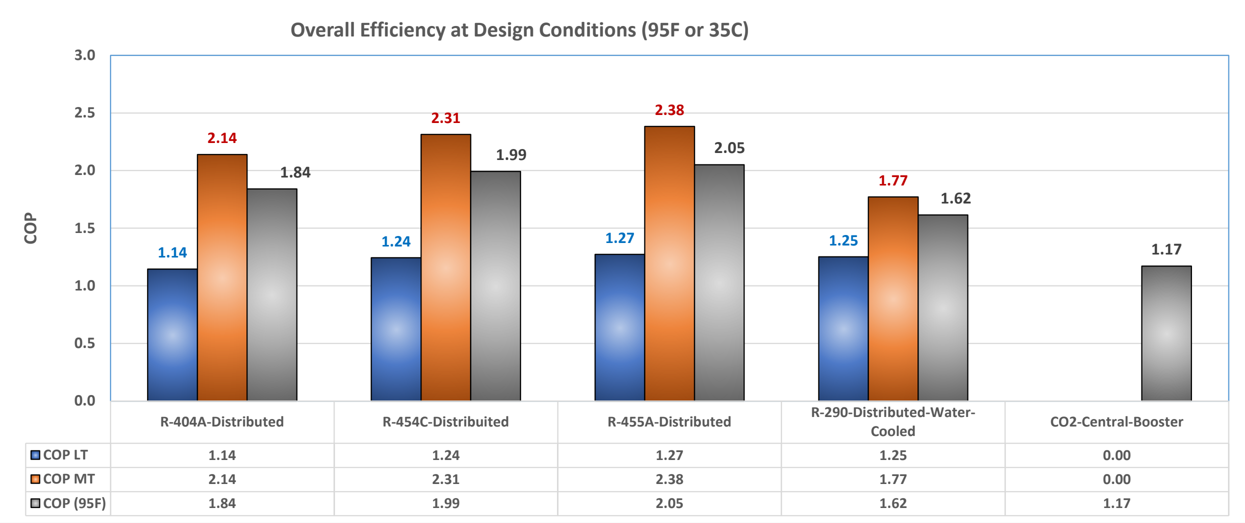


Figure 16. Efficiency evaluated at typical design condition (35°C or 95°F). COP is coefficient of performance.

The two HFC/HFO mixtures show better efficiency compared with R-404A. This result is expected because they are being evaluated using the same heat exchangers (i.e., similar cost systems). Still, potential improvements exist in heat exchangers and compressor technologies.

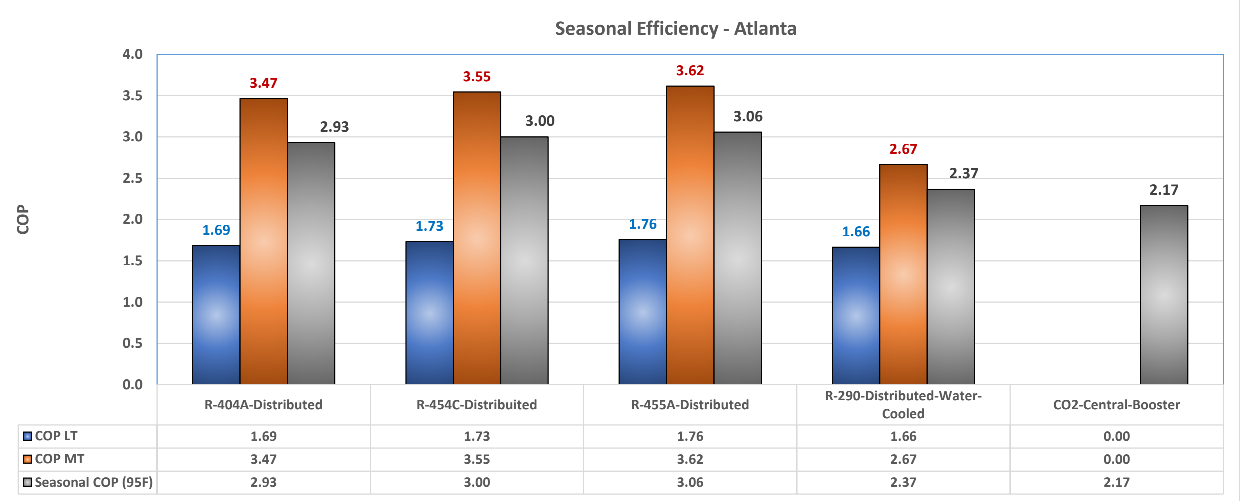
In the case of heat exchangers, the number of circuits was already optimized. Still, further improvements can be done by using smaller-diameter tubes (e.g., 5 mm), which are now readily available. This smaller size will allow the number of tubes to be increased while maintaining the similar volume of the heat exchanger. The number of circuits will need to be optimized as was done in the current evaluation.

As for the compressor, the use of refrigerants with lower volumetric capacity and thermal properties compared with R-404A point to changes in the design focused on these areas:

- Penalties associated to the suction passages (i.e., pressure drop and compression heat) can be minimized by proper sizing and optimization.
- The volumetric displacement needs to be increased without affecting the volumetric efficiency.
- Any improvements of the electric motor can also contribute to an increase in compressor efficiency.
- Material compatibility and refrigerant interaction with the lubricant should be evaluated and modified as needed.

As for the R-290 water-cooled system, the efficiency is lower than that of R-404A. This lower efficiency is mainly because of the penalties associated with the use of an intermediate heat exchanger and an external chiller.

The transcritical booster CO_2 system shows a lower efficiency, too. This lower efficiency is expected because the CO_2 will be working at transcritical operation at the design temperature. The lower thermodynamic efficiency of CO_2 affects the system performance at this condition. To further analyze the performance at more average conditions, the seasonal efficiency was calculated in this work. This seasonal efficiency will allow CO_2 to take advantage of ambient conditions in which subcritical operations happen. Figure 17 shows such performance. Although a slight improvement is noticeable, the CO_2 seasonal coefficient of performance is still lower than the benchmark (i.e., distributed R-404A).



	R-404A-Distributed	R-454C-Distribuited	R-455A-Distributed	R-290-Distributed-Water-Cooled	CO2-Central-Booster
🟦 COP LT	1.69	1.73	1.76	1.66	0.00
🟧 COP MT	3.47	3.55	3.62	2.67	0.00
⬜ Seasonal COP (95F)	2.93	3.00	3.06	2.37	2.17

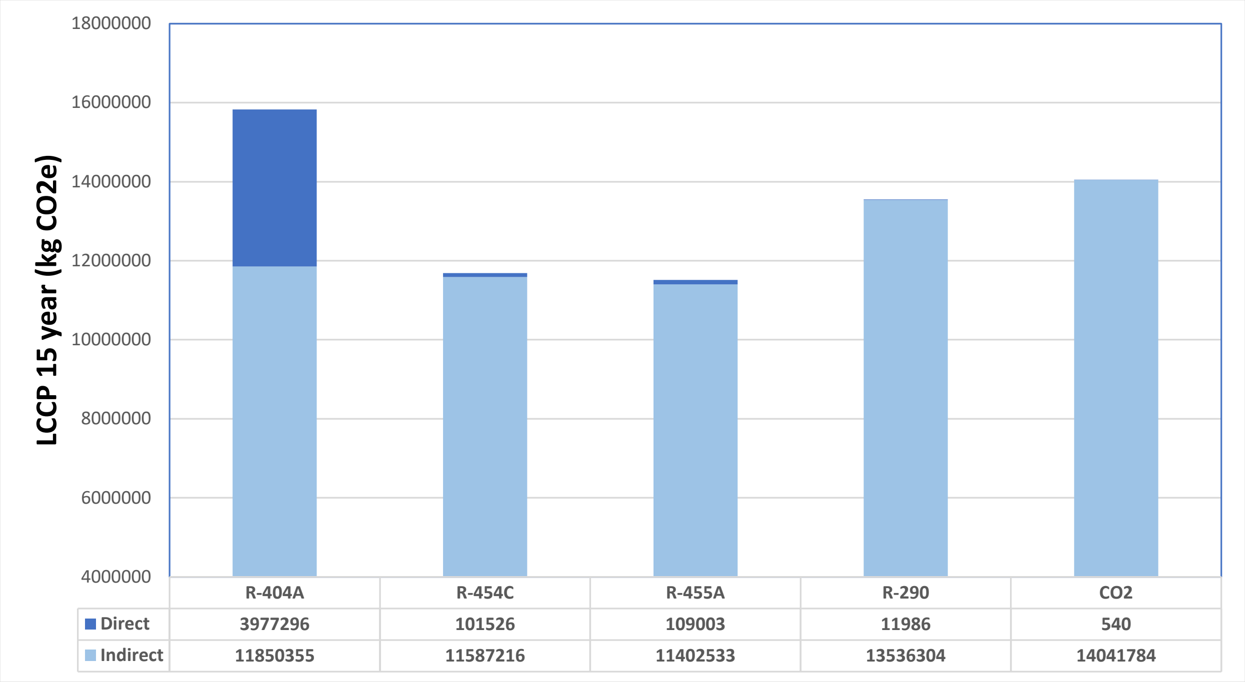
Figure 17. Seasonal efficiency evaluated for Atlanta weather.

4.2.2 LCCP Assumptions and Analysis

LCCP analysis of these technologies was performed using the following assumptions:

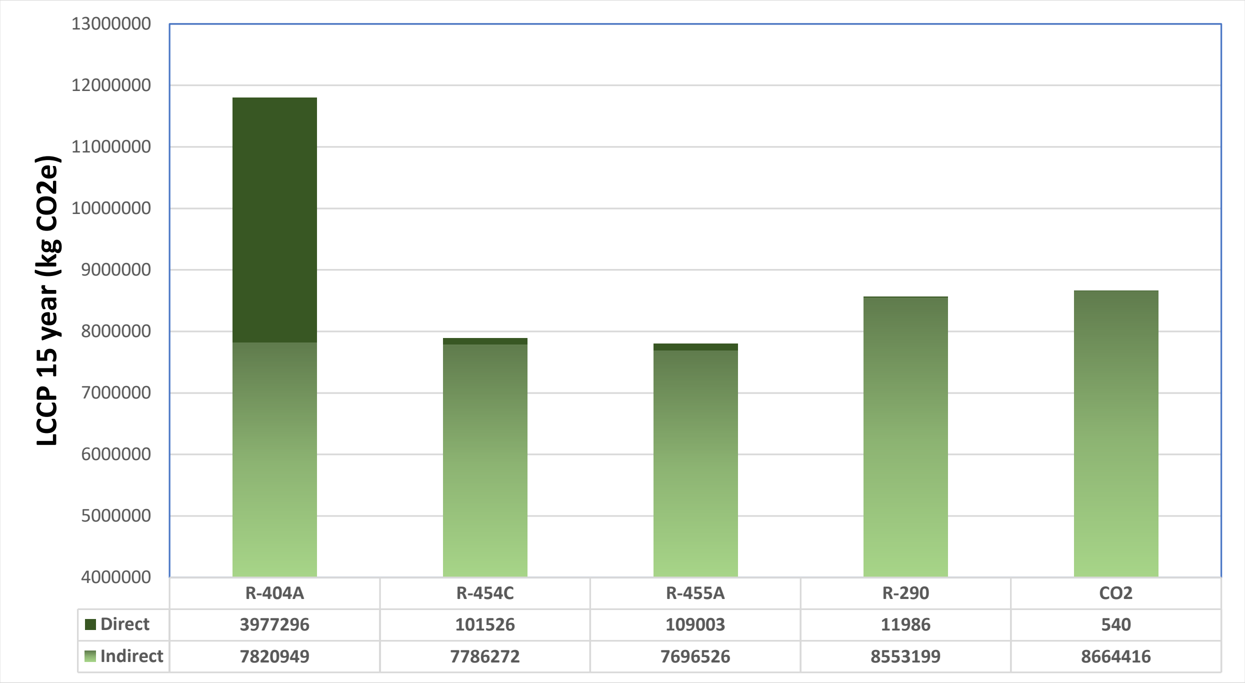
- Used the bin methodology for these regions/cities: United States (Phoenix, Atlanta, and Chicago), EU (Rome, Frankfurt, and Oslo), and Asia (Shanghai)
- 15-year lifetime and 15% EOL leak—the yearly leak rates were assumed to be the following:
  - 10% for a distributed R-404A system (benchmark)
  - 5% for the distributed systems because they use improved mitigation (leak detection, multiple circuits)
- Use a typical load profile for a supermarket
- A representative average EF is used for every country/city

LCCP calculations were performed for several cities around the world. Because a wide range of EFs exist, a range of cities were selected, from very low EFs (Oslo in Norway, with an EF of 0.1 kg CO_2/kWh) to very high (Shanghai in China, with an EF of 0.831 kg CO_2/kWh). Figure 18–Figure 24 show the following cities: (1) Shanghai (EF = 0.831), (2) Frankfurt (EF = 0.6722), (3) Atlanta (EF = 0.497), (4) Rome (EF = 0.4108), and (5) Oslo (EF = 0.1).



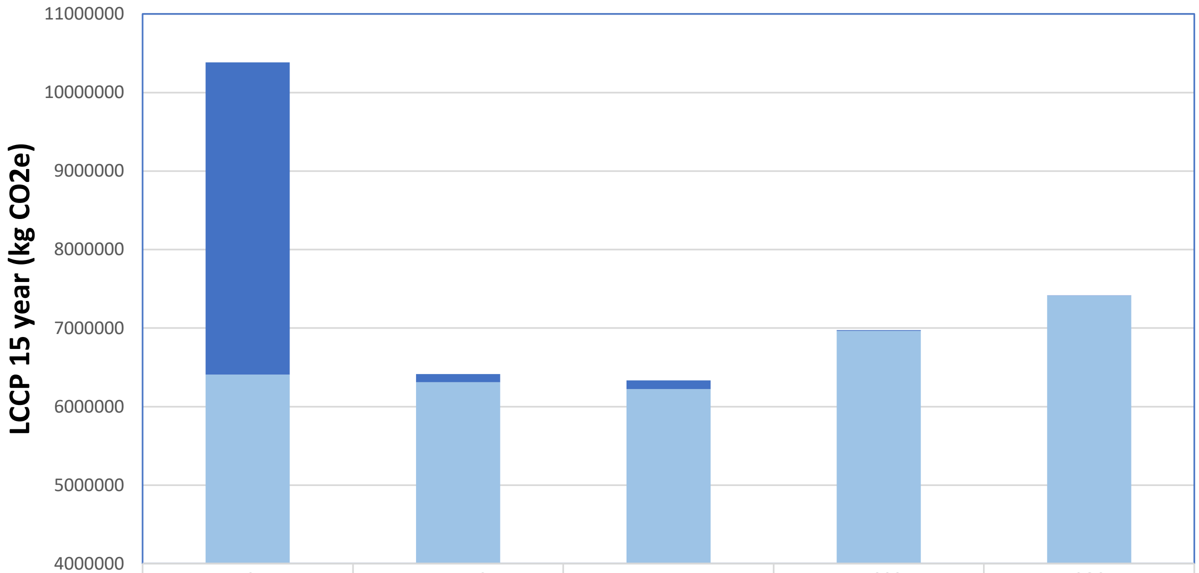
	R-404A	R-454C	R-455A	R-290	CO2
■ Direct	3977296	101526	109003	11986	540
■ Indirect	11850355	11587216	11402533	13536304	14041784

Figure 18. LCCP analysis for Shanghai (EF = 0.831).



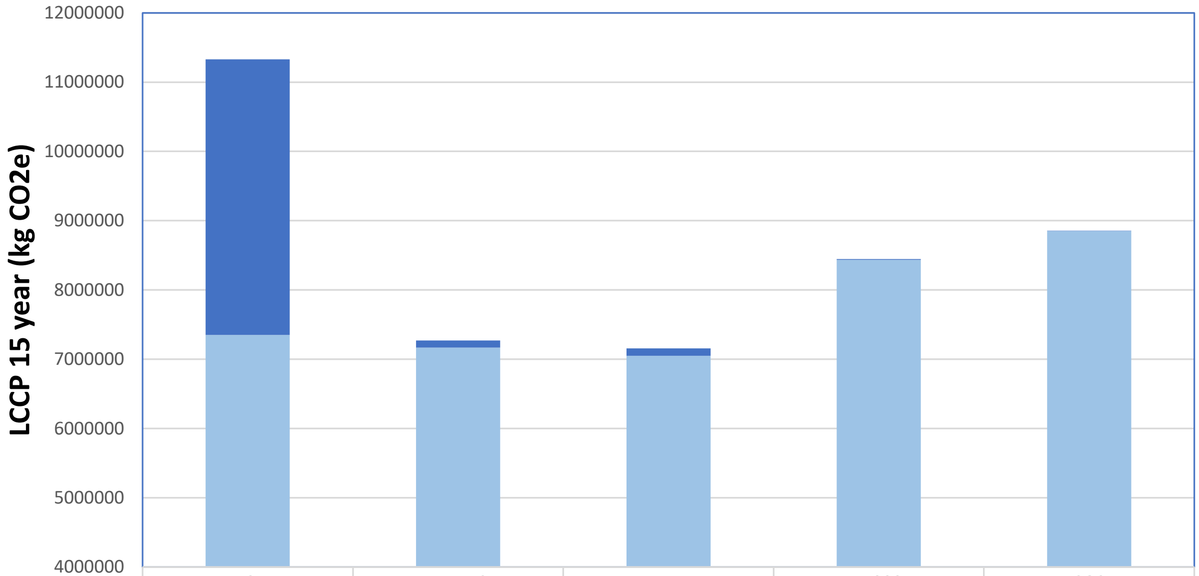
	R-404A	R-454C	R-455A	R-290	CO2
■ Direct	3977296	101526	109003	11986	540
■ Indirect	7820949	7786272	7696526	8553199	8664416

Figure 19. LCCP analysis for Frankfurt (EF = 0.6722).



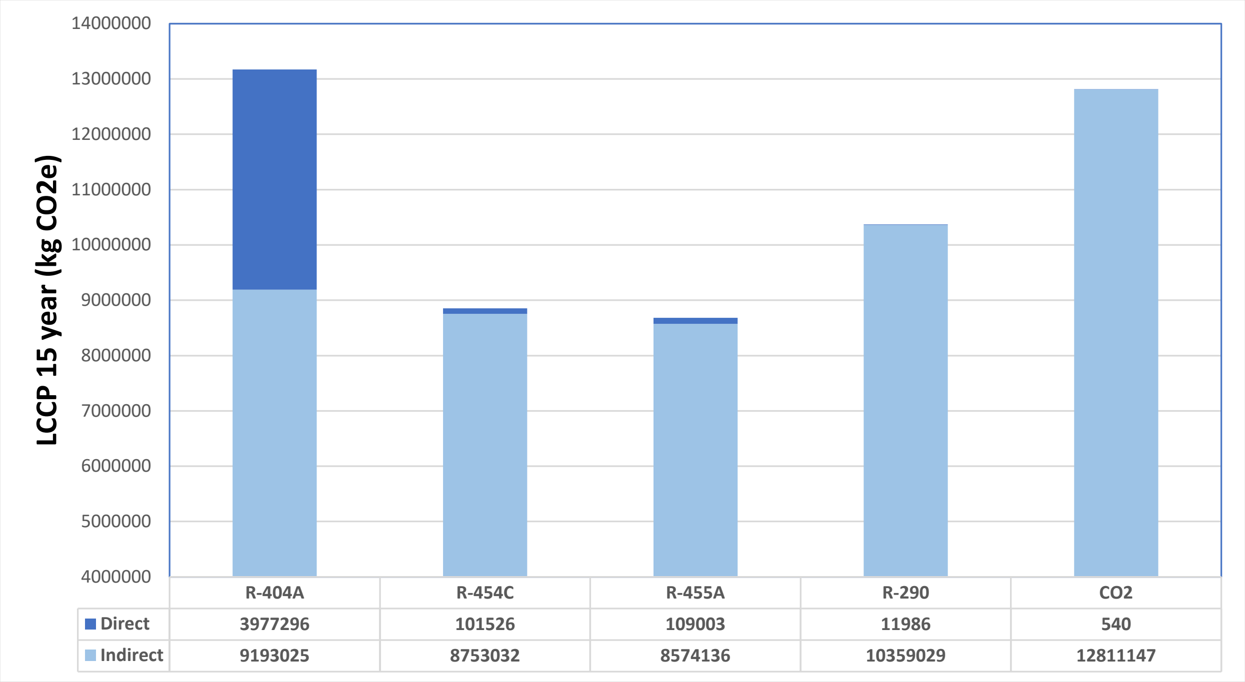
	R-404A	R-454C	R-455A	R-290	CO2
■ Direct	3977296	101526	109003	11986	540
■ Indirect	6406538	6312309	6224533	6964115	7414989

Figure 20. LCCP analysis for Chicago (EF = 0.497).



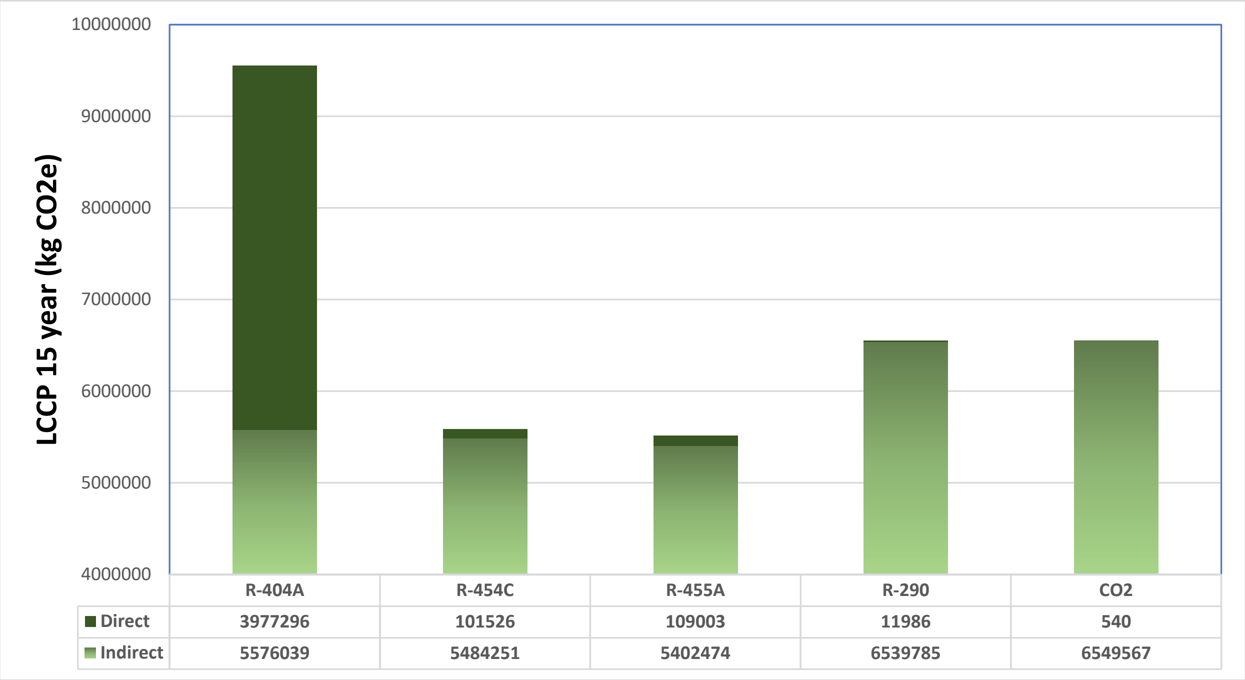
	R-404A	R-454C	R-455A	R-290	CO2
■ Direct	3977296	101526	109003	11986	540
■ Indirect	7350723	7168375	7049016	8432778	8852761

Figure 21. LCCP analysis for Atlanta (EF = 0.497).



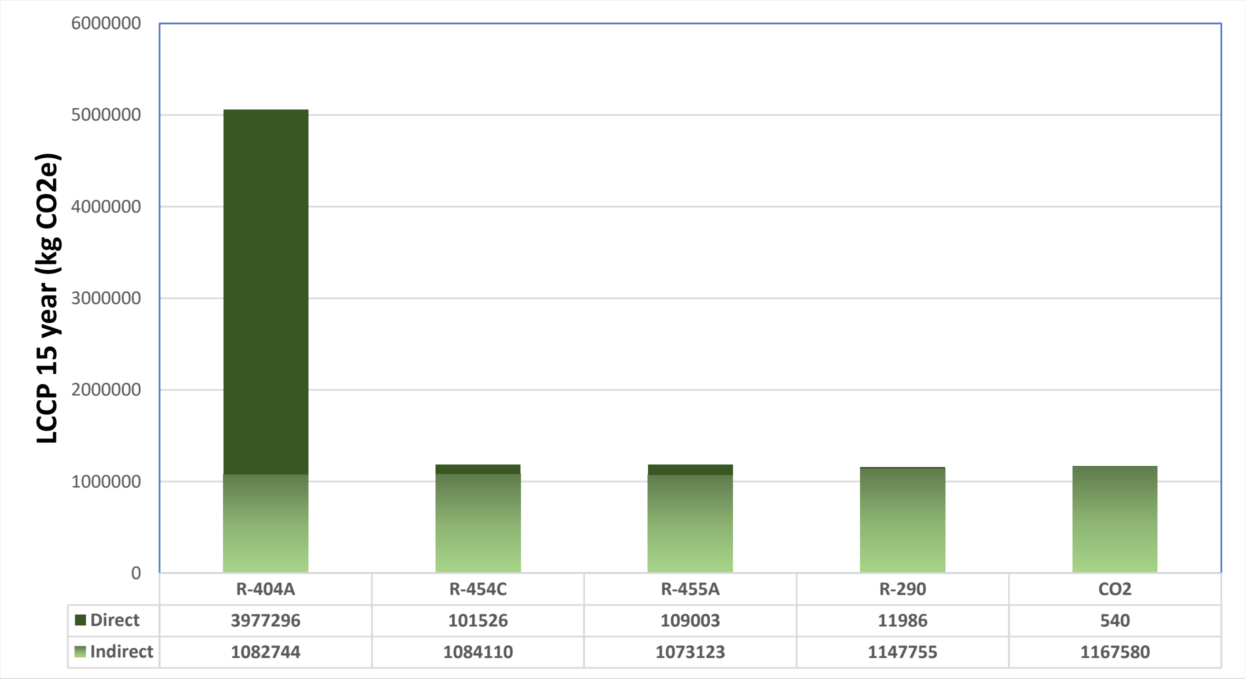
	R-404A	R-454C	R-455A	R-290	CO2
■ Direct	3977296	101526	109003	11986	540
■ Indirect	9193025	8753032	8574136	10359029	12811147

Figure 22. LCCP analysis for Phoenix (EF = 0.497).



	R-404A	R-454C	R-455A	R-290	CO2
■ Direct	3977296	101526	109003	11986	540
■ Indirect	5576039	5484251	5402474	6539785	6549567

Figure 23. LCCP analysis for Rome (EF = 0.4108).



	R-404A	R-454C	R-455A	R-290	CO2
🟩 Direct	3977296	101526	109003	11986	540
▨ Indirect	1082744	1084110	1073123	1147755	1167580

Figure 24. LCCP analysis for Oslo (EF = 0.1).

Overall CO_2 emissions have a noticeable dependency on the EF and ambient temperatures. Therefore, Shanghai, with a high EF of 0.831 and average ambient temperatures, has the highest level of emissions. The EF seems to have a larger influence than temperature. This observation is validated because indirect emissions tend to go down for lower-EF locations, such as Oslo in Norway.

Additionally, the three US cities (Chicago, Atlanta, and Phoenix) using the same EF clearly show a dependence on ambient temperatures. This work showed that CO_2 tends to perform better at lower ambient temperatures, as shown in the LCCP for Chicago. At high ambient temperatures such as Phoenix, CO_2 tends to have higher energy consumption.

Another relevant observation is that direct emissions are quite significant in current R-404A systems. This significance is because of the relatively high GWP of R-404A (GWP = 3,922) and the inherent high leak rates even for distributed systems (10%). With the use of lower-GWP refrigerants and the reduction of leak rates owing to the use of leak detection and other techniques, the energy consumption is becoming more relevant.

Because of these ideas discussed in this section, the performance of the system (i.e., energy consumption) deserves a great deal of attention. The design and optimization of the system, together with proper installation and controls, should be the most relevant of technology priorities.

5. CONCLUDING COMMENTS

This study evaluated technology options for two main applications: residential AC and commercial supermarket refrigeration. Equipment and refrigerant technologies suited for both the United States and global markets were evaluated in terms of energy efficiency and life cycle emissions. Life cycle emissions include the direct effect (related to the GWP of the refrigerant) and indirect emissions (related to energy consumption). System simulations considered optimizing current heat exchangers for each refrigerant and available compressor efficiencies. Thus, the results are believed to represent the relative performance merits of the studied fluids.

The refrigerants included are judged to be leading options because they have GWP lower than 150 and would comply with current proposed regulations. They should also help countries to comply with national and regional regulations and the phase-down schedule mandated by the Kigali Amendment. The most representative low GWP replacements for R-410A and R-404A were included. These replacements included not only synthetic alternatives such as HFC/HFO mixtures (R-454C and R-455A) but also the so-called *natural refrigerants* R-290 (propane) and R-744 (CO_2).

Overall, the existing trade-off between GWP, flammability, and system cost implies that both synthetic and natural refrigerants have significant challenges to match the incumbent refrigerants. Hence this study provides not only an assessment of performance and LCCP but the possible improvement needed to truly reduce environmental impact.

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