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Exploring Low-Global Warming Potential Refrigerants for Medium-Charge Systems

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The rising global warming potential (GWP) of refrigerants, particularly R-410A and R-134a, has driven the urgent need for environmentally friendly alternatives in cooling and heating systems. While low-GWP refrigerants are increasingly available for large and small refrigerant charge systems, a significant gap remains in identifying viable replacements for medium-charge applications, particularly in high and moderate climate conditions. This study addresses this critical gap by evaluating 15 lower GWP refrigerant options, including hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs), hydrochlorofluoroolefins (HCFOs), and hydrocarbons (HCs). The analysis focuses on their direct and indirect environmental impacts, ease of design integration, operational parameters such as capacity and efficiency, and economic feasibility. A novel aspect of this work is including internal heat exchanger performance as a function of refrigerant properties, offering unique insights into how system design can influence cycle efficiency. Key findings reveal that while several refrigerants can effectively replace R-410A in chiller applications, variable refrigerant flow systems present greater challenges due to performance and safety considerations. R-447A exhibits superior performance in standard ambient conditions among the studied refrigerants, whereas R-454B is better suited for high ambient environments. Additionally, refrigerants such as R-1233zde, R-1234yf, R-1234zee, R-1234zez, R-1243zf, and R-1336mzz(Z) demonstrate significantly lower total environmental weighted impact compared to R-410A, emphasizing their potential for reducing environmental harm. This study advances the current understanding of medium-charge refrigerant applications, providing actionable insights for researchers, policymakers, and manufacturers navigating the transition away from high-GWP HFCs.

1. Introduction

Since the introduction of the modern air conditioner, the vapor compression cycle (VCC) has been widely adopted for building heating and cooling. According to recent predictions, the global market size of heating, ventilation, and air conditioning (HVAC) is expected to hit USD 176 billion in 2029.[1,2] The growing demand for HVAC equipment creates enormous pressure on the industry to deal with the rising concerns about the equipment's environmental effects. Evidently, no better technology can replace the VCC in the foreseeable future. In the VCC, the refrigerant is used as a heat carrier, using the property of pressure-related evaporation and condensing temperatures of fluids. So, the refrigerant properties significantly affect the cycle performance. In the 19th century, chlorofluorocarbons and hydrochlorofluorocarbons were extensively used in refrigeration and air conditioning vapor compression. That continued until Molina and Rowland identified CFCs as the significant source of ozone-destroying stratospheric chlorine in 1974.[3] As a result, the Montreal Protocol suggested phasing out both CFCs and HCFCs. Hydrofluorocarbons (HFCs) were developed as strategic alternatives to CFCs and HCFCs. These refrigerants have many advantages, including zero ozone depletion potential (ODP), good performance, and material compatibility. However, they have a relatively high global warming potential (GWP).

According to industry-related statistics, the most used refrigerants for building HVAC systems are R-134a and R-410A. R-410A belongs to the HFCs refrigerants family with zero ODP but a relatively high GWP of 2088.[4] R-410A is used in many residential and commercial building cooling applications in different equipment types, such as room air conditioners, commercial air conditioners, variable refrigerant flow (VRF) equipment, and stationary equipment, such as chillers (CHLRs).[5] Driven by the recent rising concern about global warming, there is an international direction to phase down refrigerants with high GWP in the coming years. Many refrigerants were proposed to replace R-134a. However, finding a replacement for R-410A is more challenging due to its unique properties, which are represented by its high efficiency and cycle pressure. R-32 replaced R-410A in small refrigerant charge applications, but it is not a viable replacement for medium and large refrigerant charge applications due to its flammability. McLinden et al. carried out a comprehensive study to identify chemical compounds that could fit the air conditioning application as a

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working fluid. Their study concluded that limited options can satisfy the environmental aspects of low GWP. This study examined the fluids' performance, safety, chemical stability, and environmental impact and identified some fluids to replace the HFC refrigerants. However, the study did not predict these fluids' lifetime performance and suitability for specific applications.[6] Uddin et al. studied the performance of binary and ternary R-32 blends using several promising refrigerants as an alternative for the R-410A. The authors of this study concluded that the most critical issue for using blends is their suitability for drop-in use in the existing equipment, as the refrigerant properties differ from the R-410A. In this study, only blended refrigerants were studied.[7] Tsvetkov et al. studied the potential replacements of the current refrigerants in high-temperature heat pump applications. The study concluded that with the limited options available to replace the current refrigerants in different applications, the hydrofluoroolefins (HFOs), the hydrochlorofluoroolefins, and their blends could be suitable replacements.[8] In a recent study, Franco et al. investigated the performance and lifespan analysis of some newly proposed refrigerants as a replacement for R-410A, and the study concluded that the best drop-in fluids are R-452B and R-454B. The study also recommended further investigation to find a strategic alternative for refrigerants to meet environmental and technical requirements.[9]

Several studies have highlighted the promising performance of alternative refrigerants in terms of thermodynamic efficiency and environmental sustainability. For instance, the study by Saran et al. evaluated low-GWP refrigerants in ground source heat pump systems, identifying R-152a as a leading candidate due to its superior coefficient of performance (COP), which was 8.5% higher than R-410A.[10] Similarly, Xu et al. investigated refrigerant blends for domestic air conditioning and found that R-454A achieved a 2% improvement in COP, demonstrating its potential as a sustainable replacement for R-410A.[11] The integration of advanced cycle enhancements has also been a focus area. For example, Zhao et al. analyzed the exergetic performance of low-GWP refrigerants in split air conditioners, reporting a 9.2% higher COP for R-447A compared to R-410A.[12] These findings underscore the importance of cycle optimization in maximizing the efficiency of alternative refrigerants. Alternative refrigerants must also perform well under varying climatic conditions. A study by Lin et al. assessed the energy performance of low-GWP refrigerants in air source heat pumps, concluding that R-32, R-454B, and DR-5 exhibited robust performance even in high ambient temperatures, making them viable for regions with extreme climates.[13] Retrofitting existing R-410A systems to use low-GWP refrigerants presents a practical transition pathway. According to Smith et al. retrofitting with refrigerants like R-454B not only reduces environmental impact but also ensures compatibility with existing infrastructure.[14] Furthermore, life cycle assessments in several studies have emphasized the trade-offs between flammability, efficiency, and operational safety, highlighting the complexities of selecting suitable alternatives.[15] Together, these studies emphasize the potential of low-GWP refrigerants as replacements for R-410A. However, they also highlight the need for further research into long-term performance, system suitability, and strategic implications to ensure a smooth transition toward sustainable HVAC systems.

This study addresses this gap by identifying the most suitable refrigerant options, both pure and blended, to replace R-410A in medium-charge air conditioning applications, including VRF and CHL systems. Additionally, the research explores incorporating the internal heat exchanger (IHX) to assess its impact on cycle performance. By examining the environmental impacts of these refrigerants, particularly in terms of GWP and total equivalent warming impact (TEWI), this study provides valuable insights into the feasibility of these low-GWP alternatives in real-world HVAC applications.

This study is structured as follows: Section 1 introduces the challenges faced by medium and large air conditioning systems, particularly focusing on the need to replace high-GWP refrigerants like R-410A and R134a. Section 2 outlines the refrigerant selection criteria, discussing the environmental impact, performance, and safety aspects of the alternative refrigerants considered. Section 3 details the methodology, including the approach used to simulate VRF and CHL systems, with and without the IHX, under moderate (T1) and high ambient (T3) temperature conditions. Section 4 presents the results and discussion, highlighting the performance and environmental impact of the refrigerants. Finally, Section 5 concludes the study by summarizing the findings, identifying the most suitable refrigerants for replacing R-410A, and offering recommendations for future research and practical applications in medium and large air conditioning systems.

2. Refrigerant Selection Criteria

The refrigerant properties dictate the application and the cycle operating conditions for any refrigerant, including the cycle pressure, compressor type, and operating temperatures. R-410A is a zeotropic blend of R32 and R-125, which works on a relatively high cycle pressure of 790 kPa on the low-pressure side and around 2750 kPa on the high-pressure side. For any refrigerant to replace R-410A as a drop-in substitute or in a new system without major changes in the system's design, the refrigerant has to have a similar cycle pressure, close volumetric capacity, and close or better COP. However, for new system designs, the refrigerant has to achieve the system's goals without operating in the same cycle conditions. Potential replacement refrigerants should be investigated across various performance and environmental metrics. That includes, but is not limited to, the thermodynamic and thermophysical properties, such as thermal conductivity, thermal capacity, viscosity, normal boiling temperature, critical temperature, and volumetric capacity. Also, the environmental impact of its life cycle includes GWP, ODP, and any damage it may cause to the ecosystem. Moreover, it should achieve certain criteria for chemical stability, material compatibility, flammability, and toxicity. Technically, it is nearly impossible to identify a single refrigerant that meets all operational, safety, and environmental requirements. However, current efforts are primarily focused on minimizing the environmental impact of refrigerants, particularly addressing those with unacceptable levels of GWP and ozone depletion.[16]

Table 1. Refrigerant safety classification chart.[41]

BV ≥ 10 cm s^{-1}	A3	B3	Highly flammable
	A2	B2	Flammable
BV < 10 cm s^{-1}	A2L	B2L	Mildly flammable
Zero BV	A1	B1	Not flammable
Low toxicity			High toxicity

2.1. Refrigerant Thermophysical Properties

Refrigerants transfer energy through a phase change. Accordingly, one of the main criteria to look at is the latent heat of vaporization, which indicates the ability of the refrigerant to absorb heat from the conditioned space and release it to the surrounding environment. Also, it has to have a good thermal heat capacity, indicating the refrigerant's ability to absorb and release heat in the subcooling and superheating processes. At the same time, the thermal conductivity and the normal boiling temperature must match the system requirements. The normal boiling point can be identified as the temperature at which the refrigerant starts to evaporate under normal conditions. The normal boiling temperature dictates the system's operating pressure for a specific refrigerant. It may indicate the refrigerant's volumetric capacity, as a high boiling temperature is usually associated with low volumetric capacity. However, more research is needed to determine the relationship between the normal boiling temperature and the volumetric efficiency. The volumetric capacity of a refrigerant can be identified as the amount of heat that the refrigerant can carry per unit volume in its vapor state and can be measured in Joules m^{-3}. The importance of the volumetric capacity of refrigerant comes from its relationship with the compressor size and capacity, as the refrigerant with lower volumetric capacity will necessarily require a larger compressor to drive it through the cycle. Other thermophysical properties directly influence refrigerant performance, including surface tension, which affects the evaporation rate as the fluid with lower surface tension has a higher evaporation rate. Similarly, the refrigerant with higher viscosity has a lower evaporation rate. The refrigerant viscosity also dramatically impacts the pressure drop around the cycle.

2.2. Refrigerant Safety

Refrigerant flammability is an important aspect related to human and property safety. It can be evaluated using three primary properties: 1) the ability to ignite or the flammability; 2) the amount of heat required for ignition; and 3) the burning velocity (BV). ISO classifies refrigerants by considering their flammability and BV (1, 2L, 2, and 3), and the classification codes are shown in **Table 1**. Another safety-related property of refrigerants is toxicity. Refrigerants can be classified as (A) nontoxic or (B) toxic. Refrigerant toxicity can be identified by the concentration of the refrigerant that may cause harm to humans. In summary, refrigerant safety concerns include flammability, toxicity, and asphyxiation. System design, control, and selecting the suitable application for the refrigerant can mitigate the risks associated with using refrigerants.

2.3. Refrigerant Environmental Performance

The refrigerant's environmental impact could be divided into two primary sources: the direct impact caused by the refrigerant leaking into the atmosphere and the indirect impact generated by the emissions emitted to produce power to operate the equipment. Other than the direct terms such as the GWP and the ODP, there are two primary ways to assess the refrigerant environmental impact—the TEWI and the life cycle climate performance (LCCP). The TEWI is a simpler term to use than the LCCP and can be calculated by considering the direct and indirect GWP.[17] On the other hand, the LCCP is a more accurate calculation to weigh the environmental impact of the system's refrigerant throughout its life, not only during its operation but also during production and till the end of its life. The direct impact of the system depends on the refrigerant used in the systems, the refrigerant charge, the leakage rate that varies between applications, as shown in **Table 2**, and the refrigerant lost during maintenance or when the system is scrapped.

3. Methodology

This study employs a quantitative, numerical approach to evaluate the thermodynamic performance and environmental impact of low-GWP refrigerants as substitutes for R-410A in medium-charge applications. Fifteen pure and blended refrigerants are investigated to find the best-performing fluid, starting with R-410A as a reference baseline. The analytical approach is grounded in thermodynamic theory and environmental impact assessment. The primary analytical techniques include seasonal energy efficiency ratio (SEER) calculations and TEWI analysis. Data were collected from the simulation tool, as explained in

Table 2. Estimated leakage percentage for different cooling systems.[42]

System type	Cooling capacity [kW]	Refrigerant charge [kg]	Estimated annual leak [%]	Estimated annual leak amount [kg System^{-1}]
Small split unit	2–12	0.5–3	4	0.02–0.12
Ducted split and multisplit	5–50	3–10	4	0.12–0.4
VRF system	8–240	5–100	5	0.25–5
Large ducted and rooftop	12–750	5–200	6	0.3–12
Small and medium CHLs	50–750	40–500	4	1.6–20
Large CHLs	750–22 000	500–36 000	4	20–1440

Section 3.1, where various low-GWP refrigerants were tested in a standardized refrigeration system. Performance metrics such as cooling capacity, power consumption, and refrigerant charge were obtained from the simulation results. Environmental data and refrigerant leakage rate data were sourced from existing literature and trusted databases.

3.1. Numerical Simulation Model

To test and compare refrigerant performance, we established a 100 kW R-410A cycle using the CYCLE_D simulation tool with operating parameters to suit four main temperature ranges: VRF at T1, VRF at T3, air-cooled CHL at T1, and air-cooled CHL at T3. T1 refers to the standard cooling condition with an outdoor ambient temperature of 35 °C, while T3 represents a high ambient temperature of 46 °C, often seen in hotter climates. Also, we studied the effect of adding an IHX on refrigerant performance. Both the condenser and evaporator were chosen to be of the cross-flow type. The CYCLE_D model is a specialized software that simulates vapor compression refrigeration cycles through calculations based on refrigerant properties to generate results that include the COP, volumetric capacity, thermodynamic parameters, and thermodynamic charts. The user can specify the cycle inputs, including the refrigerant, heat transfer fluid inlet and exit conditions, and the cycle structure. The evaporator and condenser are represented by specifying each heat exchanger's refrigerant temperature or pressure. Similarly, the refrigerant superheats at the evaporator exit can also be specified. **Table 3** shows the cycle conditions we considered in this study for the four study cases. Furthermore, the simulation provided insights into system efficiency under varying ambient conditions, which helped us evaluate the impact of environmental factors on performance. The effect of subcooling and its enhancement on the cycle's energy consumption was also analyzed using the CYCLE_D outputs. A sensitivity analysis was conducted to explore how refrigerant mass flow rates and heat transfer coefficients influenced system behavior. These results were crucial for understanding the overall efficiency of the cycle and potential improvements when switching to lower GWP refrigerants in similar setups.

Table 3. Boundary conditions (VRF, variable refrigerant flow; CHL, chiller; HTF, heat transfer fluid).

	T1		T3	
	VRF	CHL	VRF	CHL
Evaporation [°C]	12	2	12	2
Condensing [°C]	49	49	58	58
Subcooling [°C]	2	2	2	2
Superheating [°C]	2	2	2	2
Evaporator HTF inlet temperature [°C]	25	12	25	12
Evaporator HTF outlet temperature [°C]	14	6	14	6
Condenser HTF inlet temperature [°C]	35	35	46	46
Condenser HTF outlet temperature [°C]	45	45	52	52
Temperature difference [°C]	9	9	8	8
Saturated temperature difference [°C]	0.5	0.5	0.5	0.5

In the condenser, the refrigerant temperature or pressure can be represented as the bubble point, dew point, or average value. This study specifically examines the average temperature or pressure, which is calculated as the arithmetic mean of the dew point and bubble point values. Additionally, it is possible to specify the refrigerant subcooling at the condenser outlet. The refrigerant pressure loss across the heat exchangers can be tailored according to the specific application. The simulation results for the thermodynamic cycle are derived per unit mass of refrigerant circulated through the compressor and the overall system. These results are based on the system's cooling capacity or capacity multiplier. To determine the line sizing information, CYCLE_D utilizes the thermodynamic parameters established throughout the cycle, along with the refrigerant mass flow rate required to meet the target system capacity. The detailed mathematical calculations employed by this tool are described in Section 3.2. This approach ensures precise modeling of the refrigerant behavior and system performance, aiding in the accurate design and analysis of refrigeration and air conditioning systems.

Figure 1 presents the study workflow starting from the refrigerant selection, through the simulation steps, and ending with postprocessing and validation.

3.2. Mathematical Model

The rate of heat absorbed by the evaporator can be calculated using Equation (1):

$$q_{\text{eva}} = \dot{m} \cdot h_{\text{fg}} + \dot{m} C_{\text{p}\cdot\text{v}} \Delta T_{\text{superheating}} \tag{1}$$

where mass flow rate h_{fg} is the latent heat of vaporization for the refrigerant at the lower cycle pressure, $C_{\text{p}\cdot\text{v}}$ is the specific heat capacity of the refrigerant at vapor state, and $\Delta T_{\text{superheating}}$ is the refrigerant superheating. This heat is equivalent to the heat transferred to the fluid when using a heat transfer medium fluid, as represented in Equation (2):

$$q_{\text{fluid}} = \dot{m}_{\text{fluid}} C_{\text{p}} \Delta T_{\text{fluid}} \tag{2}$$

where $\dot{m}_{\text{fluid}}$ is the heat transfer fluid mass flow rate, C_{p} is the heat transfer fluid specific heat, and ΔT_{fluid} is the temperature difference of the heat transfer fluid across the heat exchanger. Similarly, the rate of heat dissipated to the surroundings or the heat transfer fluid through the condenser can be represented by Equation (3):

$$q_{\text{con}} = -\left(\dot{m} \cdot h_{\text{fg}} + \dot{m} C_{\text{p}\cdot\text{l}} \Delta T_{\text{subcooling}}\right) \tag{3}$$

Here, h_{fg} is the latent heat of vaporization for the refrigerant at the higher cycle pressure, $C_{\text{p}\cdot\text{l}}$ is the refrigerant specific heat capacity at the liquid state, and $\Delta T_{\text{subcooling}}$ is the refrigerant subcooling measured in Kelvin. As for the evaporator, this heat is equivalent to the rate of heat transfer to the heat transfer fluid:

$$q_{\text{fluid}} = -\left(\dot{m}_{\text{fluid}} C_{\text{p}} \Delta T_{\text{fluid}}\right) \tag{4}$$

The compressor power can be expressed by the enthalpy difference across the compressor with consideration of the mechanical efficiency as in Equation (5) and (6):

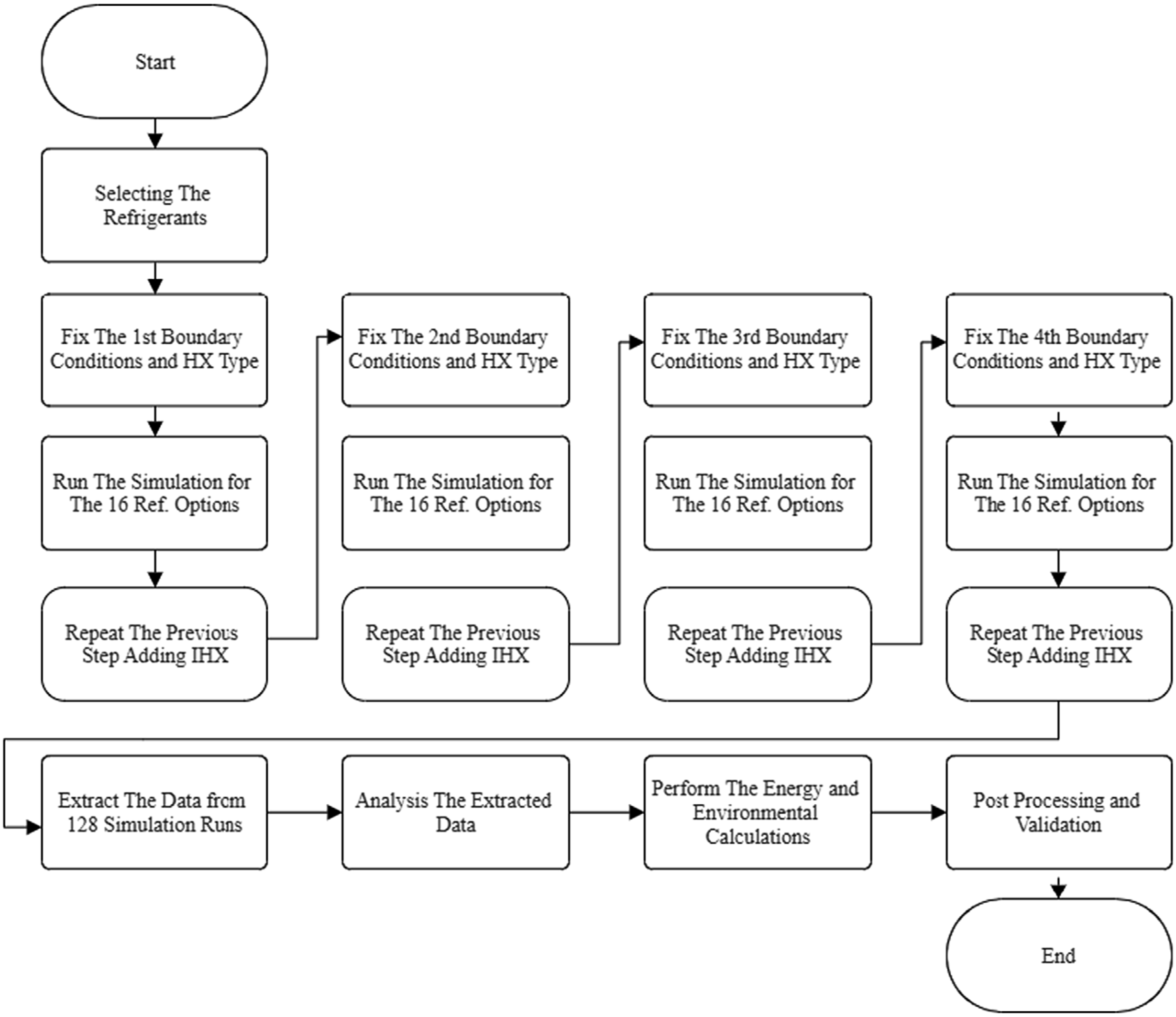

Figure 1. The study workflow.

$$W_{\text{comp}} = \dot{m}_{\text{ref}} \cdot (h_{\text{con}} - h_{\text{eva}}) \cdot \frac{1}{\eta_{\text{mec}}} \quad (5)$$

$$q_{\text{comp}} = (1 - \eta_{\text{comp}})\Delta h \quad (6)$$

where W_{comp} is the compressor power in Watts, $\dot{m}_{\text{ref}}$ is the refrigerant mass flow rate, h_{con} and h_{eva} are the condenser and evaporator enthalpies, and η_{mec} is the mechanical efficiency; the opposite process of the compression is the expansion process which is essential for the VCC to operate, as it is required to reduce the refrigerant pressure to allow the refrigerant to evaporate at a lower cycle pressure; the net rate of energy wasted through the expansion device can be estimated by Equation (7):

$$E_{\text{exp}} = (W_{\text{comp}} + q_{\text{eva}}) - q_{\text{con}} \quad (7)$$

The VCC energy performance is measured by the COP, which is a unitless number; the COP can be calculated by Equation (8) and (9) in the cooling and heating cases:

$$\text{COP}_{\text{C}} = \frac{q_{\text{eva}}}{W_{\text{comp}}/\eta_{\text{elec}}} \quad \text{and} \quad (8)$$

$$\text{COP}_{\text{h}} = \frac{q_{\text{con}}}{W_{\text{comp}}/\eta_{\text{elec}}} \quad (9)$$

η_{elec} is the electrical efficiency of the compressor motor.

One of the common ways to evaluate the cycle performance is to compare it to the ideal cycle, which is the Carnot cycle; the Carnot cycle COP can be calculated by Equation (10) and (11) for cooling and heating:

$$\text{COP}_{\text{C (cooling)}} = \frac{T_{\text{Evap}}}{T_{\text{Cond}} - T_{\text{Evap}}} \quad \text{and} \quad (10)$$

$$\text{COP}_{\text{C (Heating)}} = \frac{T_{\text{Cond}}}{T_{\text{Cond}} - T_{\text{Evap}}} \quad (11)$$

where T_{Evap} and T_{Cond} are the evaporator and condenser temperatures in Kelvin.

The length of the refrigerant tube is calculated using the following equation:

$$L = \frac{2\Delta P D \rho}{f G^2} \tag{12}$$

where D is the tube inner diameter in meters, f is Darcy friction factor, G is the refrigerant mass flux in kilograms per unit area, L is the tube length in meters, ΔP is the pressure drop pascals, and ρ is the refrigerant density.

The friction factor is directly related to the Reynolds number (Re); when Re is less than 2000, the friction factor can be calculated as

$$f = 64/\mathrm{Re} \qquad \mathrm{Re} < 2000 \tag{13}$$

$$f = \frac{1}{(1.58 * \ln(\mathrm{Re} - 3.28))^2} \qquad \mathrm{Re} \geq 2000 \tag{14}$$

The calculations are based on the assumption that the refrigerant is free of lubricants and flows through adiabatic tubes. They employ refrigerant parameters that are averaged from the inlet and outlet pressures. These parameters typically encompass properties such as viscosity, density, and surface tension.

3.3. Environmental Impact Calculations

To evaluate the refrigerant environmental impact, a lifecycle assessment has to be performed, as looking at the GWP and COP data of the refrigerant could be misleading as they do not provide the total impact of the refrigerant throughout the equipment's life. Accordingly, in this study, we investigated the seasonal efficiency ratio, the TEWI, system lifetime energy consumption (LTEC), and the carbon dioxide emissions caused by the system throughout its life, which is mainly affected by the system energy consumption and GWP. The main criteria for selecting the refrigerants for this study are lower GWP than R-410A, low flammability, and nontoxic. Also, the selected refrigerants have a critical pressure and temperature that is suitable for the application, as listed in **Table 4**. In order to account for the direct and indirect environmental impact of refrigerants, we considered the direct and indirect impact of refrigerant global warming throughout its lifetime by accounting for refrigerant leaks and energy consumption, as in Equation (18):[18]

$$\mathrm{TEWI} = N[(\mathrm{GWP} x L) + (E_c x \beta)] \tag{15}$$

where N is the system's expected lifetime as the number of years, L is the annual refrigerant leakage, E_c is the system energy consumption, and β is the carbon dioxide emission factor calculated by CO_2 emitted kWh^{-1}. $\beta = 0.73$ in NSW.[19]

While the TEWI method is considered to provide an accurate estimation of a system's cumulative environmental impact, the LCCP method offers a more precise evaluation of the system's GWP by accounting for the total global warming impact (GWI) from manufacturing to end-of-life (EOL). Direct emissions result from refrigerant leakage, which includes regular and irregular leaks, refrigerant loss at EOL, and other minor direct emissions, such as leakage during manufacturing. Indirect emissions due to energy consumption encompass the system's operating energy consumption over its lifetime, the energy required to manufacture the components and refrigerant, the energy needed to scrap the system, and the GWI of the refrigerant released at system EOL, as outlined in Equation (2)–(4). The distinction between TEWI and LCCP lies in their scope. While LCCP considers the GWI of system operation along with emissions from manufacturing and EOL disposal, TEWI focuses solely on operational emissions. In this study, we chose TEWI as the more effective metric for comparing the performance of different refrigerants, given that manufacturing and disposal emissions are consistent across all refrigerants.[20]

Table 4. The selected refrigerants and their critical temperature and pressure limits.[16]

Fluid name	Critical temperature [°C]	Critical pressure [kPa]	GWP
R-1233zde	166.5	3623.7	5
R-1234yf	94.7	3382.2	4
R-1234zee	109.4	3634.9	7
R-1234zez	150.1	3530.6	2
R-1243zf	103.8	3517.9	1
R-1336mzz(Z)	171.4	2903.0	2
R-452B	77.1	5220.1	470
R-454B	78.1	5266.9	468
R-447A	58.3	5711.1	572
R-450A	104.5	3822.4	547
R-451A	94.4	3443.0	133
R-451B	94.3	3448.4	146
R-513A	94.9	3647.8	573
R-32	78.1	5782.0	675

To comprehensively evaluate the environmental impact of HVAC systems, we employ the LCCP metric, which integrates both direct and indirect GWI. The LCCP is calculated using the equation (Equation (16)). Direct GWI, defined by Equation (17), accounts for the GWP of the refrigerant, factoring in annual leakage rates, the system's operational lifespan, the refrigerant charge, and total refrigerant loss at the EOL. Indirect GWI encompasses the entire LTEC and material usage of the system, incorporating the equivalent carbon dioxide emissions per kWh of energy consumed and per kilogram of materials used and recycled (Equation (18)). This holistic approach provides a comprehensive measure of an HVAC system's total environmental footprint, enabling more informed decisions toward sustainable practices:

$$\mathrm{LCCP} = \mathrm{Direct\,(GWI)} + \mathrm{Indirect\,(GWI)} \tag{16}$$

$$\begin{aligned}\mathrm{Direct\,(GWI)} = {} & \mathrm{GWP} \times \mathrm{Annual\,Leakage\,\%} \\ & \times \mathrm{System\,Life\,(years)} \times \mathrm{Refrigerant\,Charge} \\ & + \mathrm{Total\,Refrigerant\,loss\,(EOL)}\end{aligned} \tag{17}$$

$$\begin{aligned}\text{Indirect (GWI)} = &\ \text{Lifetime (years)} \times \Sigma\,(\text{Equivalent CO}_2\ \text{kg/kWh}^{-1} \\ &\times \text{Annual energy consumption}) \\ &+ \Sigma\ \text{Equivalent CO}_2\ \text{kg/kg}^{-1}\ \text{material} \\ &\times \text{Mass of materials kg}) \\ &+ \Sigma\,(\text{Equivalent CO}_2\ \text{kg/kg}^{-1}\ \text{material} \\ &\times \text{Mass of recycled materials kg})\end{aligned} \tag{18}$$

The indirect GWI of the refrigerant is highly dependent on the system's SEER. SEER is a more accurate term than COP and EER since it reflects the system's energy efficiency on a seasonal basis closer to the actual operating conditions. The other terms, such as the COP and the EER, indicate the system efficiency at standard temperature conditions. The SEER rating is calculated in British Thermal Units (BTU)/Wh by dividing the total number of BTUs of heat transferred from the conditioned space by the total amount of energy required by the system in Watt-hours. The SEER relates the cooling capacity of the system to its energy consumption in one term. The higher the SEER, the less energy consumption it consumes; thus, it is a more efficient system. To convert SEER to the Seasonal Coefficient of Performance (SCOP), we multiply by 0.293, which is the basic conversion of BTUs to Watts.[21] The SEER is highly dependent on the climate conditions of the air conditioning system location, and no accurate formula can be used to obtain the SEER other than the actual test. However, the following equation can be used to do an approximate conversion between the COP and the SEER:[22]

$$\text{EER} = 3.41214 \times \text{COP} \tag{19}$$

$$\text{SEER} = \text{EER} \times (1 + (T_c - T_o)/100) \tag{20}$$

where SEER is the seasonal energy efficiency ratio, EER is the energy efficiency ratio, T_c is the average temperature during the cooling season in °F, and T_o is the outdoor design temperature in °F.[23]

To estimate the TEWI of the system, some assumptions have to be made about the system's operating conditions. Accordingly, the system is assumed to be 100 kW and used for 2496 h year^{-1} in a commercial building in Sydney, Australia, where the current carbon dioxide index is 0.73. For that system size, the system holds a refrigerant charge of 50 kg and a leakage rate suitable for each system type, as listed in Table 3. Also, the system's expected life is 15 years, according to the industry standard for commercial HVAC systems.

4. Results and Discussion

This section presents the study's findings on low-GWP refrigerants' environmental and thermodynamic performance as substitutes for R-410A. The results are organized according to the research questions outlined in the introduction. **Figure 2** and 3 show the refrigerant performance compared to the R-410A; these performance parameters include the COP, the volumetric capacity, and the compression ratio at the standard temperature range (T1) as in Figure 1 and high ambient temperature range (T3) as in Figure 3.

One of the key properties of refrigerants is their volumetric capacity, which measures the amount of cooling effect produced per unit volume of the refrigerant. High volumetric capacity is often desirable for systems that require compact and efficient designs. However, medium volumetric capacity refrigerants strike a balance between performance and practical considerations, making them suitable for a range of applications; low volumetric capacity refrigerants could achieve a high COP, however, with a payoff on their size and cost. In this section, the refrigerants are classified into three subsections based on their volumetric capacity.

4.1. Low Volumetric Capacity Refrigerants

Some refrigerants were found to have a low volumetric capacity compared to R-410A, which indicates their requirement for high-flow compressors. For instance, R-1233zde offers better COP than R-410A at both T1 and T3 conditions, as shown in Figure 2 and 3. Nevertheless, its low volumetric capacity requires a higher cycle flow rate on the vapor side of the cycle. Also, the cycle pressure, as shown in **Table 5**, is 7% of the R410a cycle pressure on the lower pressure side and 10% on the higher side, indicating its requirement for a higher compression ratio of 142–173% compared to the R-410A. On the other hand, it has a lower compressor discharge temperature (CDT) of 57.8–68.6 °C compared to 72.1–90.2 °C for R-410A. R-1233zde is a nonflammable fluid, classified as A1, with a GWP of 1.

Accordingly, R-1233zde could be suitable for some compressor types capable of delivering a high flow rate, such as the centrifugal CHL application; however, it is not suitable for direct expansion, including VRF in its current form. On the other hand, this refrigerant showed a lower CDT than the R-410A, which indicates its suitability for high ambient temperature applications as it has a critical temperature of about 167 °C. Also, it has to be mentioned that R-1234zde has a negligible ODP, which might limit its use on a large scale. Similarly, R-1234zez has a higher COP than R-1234zde but requires a higher compression ratio to achieve the same capacity.

Also, it has a relatively low volumetric capacity, which makes it more suitable for centrifugal CHLs due to the capabilities of this type of compressor to deliver high flow rates. Compared to R-410A, it can offer 13–19% higher COP; however, with a low volumetric capacity of 13–15% compared to the R-410A, it requires a larger compressor and a higher compression ratio. R-1234zez showed less improvement for using IHX, with 5–9% for different applications and temperature ranges, as shown in Figure 3. This could result from the low fluid's thermal capacity or density in its liquid and vapor states. Another refrigerant with low volumetric capacity is R-1336mzz, which can achieve a higher COP than R-410A, ranging from 9% to 14% depending on the temperature lift; as the temperature lift goes higher, the gap between the COP of the R-1336mzz and R-410A goes higher. However, the volumetric capacity of R-1336mzz is very low, with only around 5% of R-410A, and requires double the compression ratio. On the other hand, the CDT at the wide temperature lift was found to be 57.7 °C with a pressure ratio of 8.78, which is relatively high and may require multistage compression. R-1336mzz is a refrigerant that belongs to the HFO

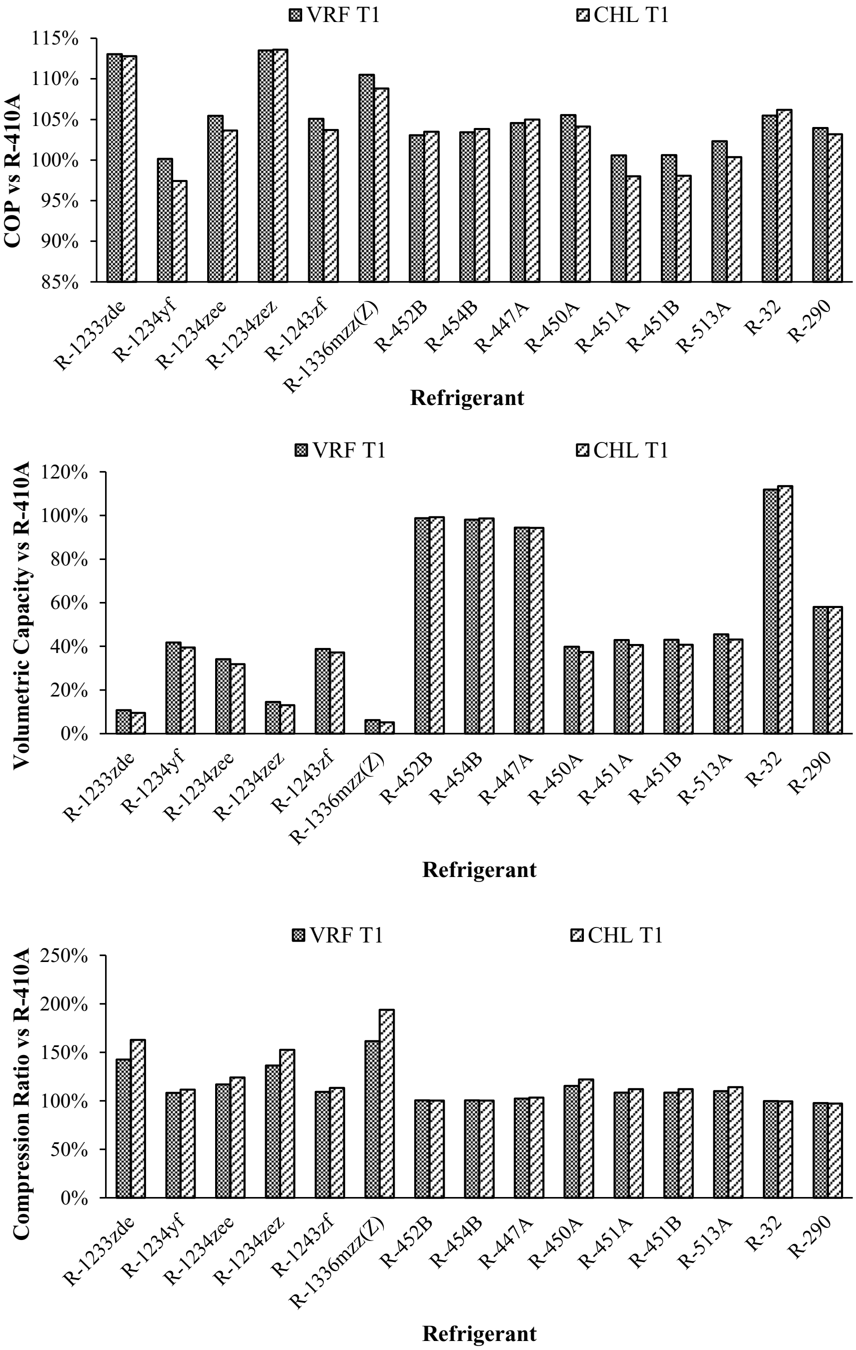

Figure 2. Simulation results. Refrigerant performance at T1 conditions compared to R-410A (top—COP, center—volumetric capacity, bottom—compression ratio).

refrigerants group. It is nonflammable and nontoxic. Though R-1336mzz has an attractive COP, it has a low cycle pressure driven by its relatively high boiling temperature of 33 °C, high compression ratio, and low volumetric capacity. This refrigerant could suit high-temperature heat pumps or high ambient centrifugal CHLs. However, the compressor size will be enormous and might need a higher compression ratio of more than 190% compared to R-410A.

4.2. Medium Volumetric Capacity Refrigerants

This subsection explores the characteristics and applications of medium volumetric capacity refrigerants. Specific refrigerants are examined, and their thermodynamic properties and suitability for various applications are analyzed. Additionally, the trade-offs and considerations involved in selecting these refrigerants for different systems are discussed. One of these refrigerants

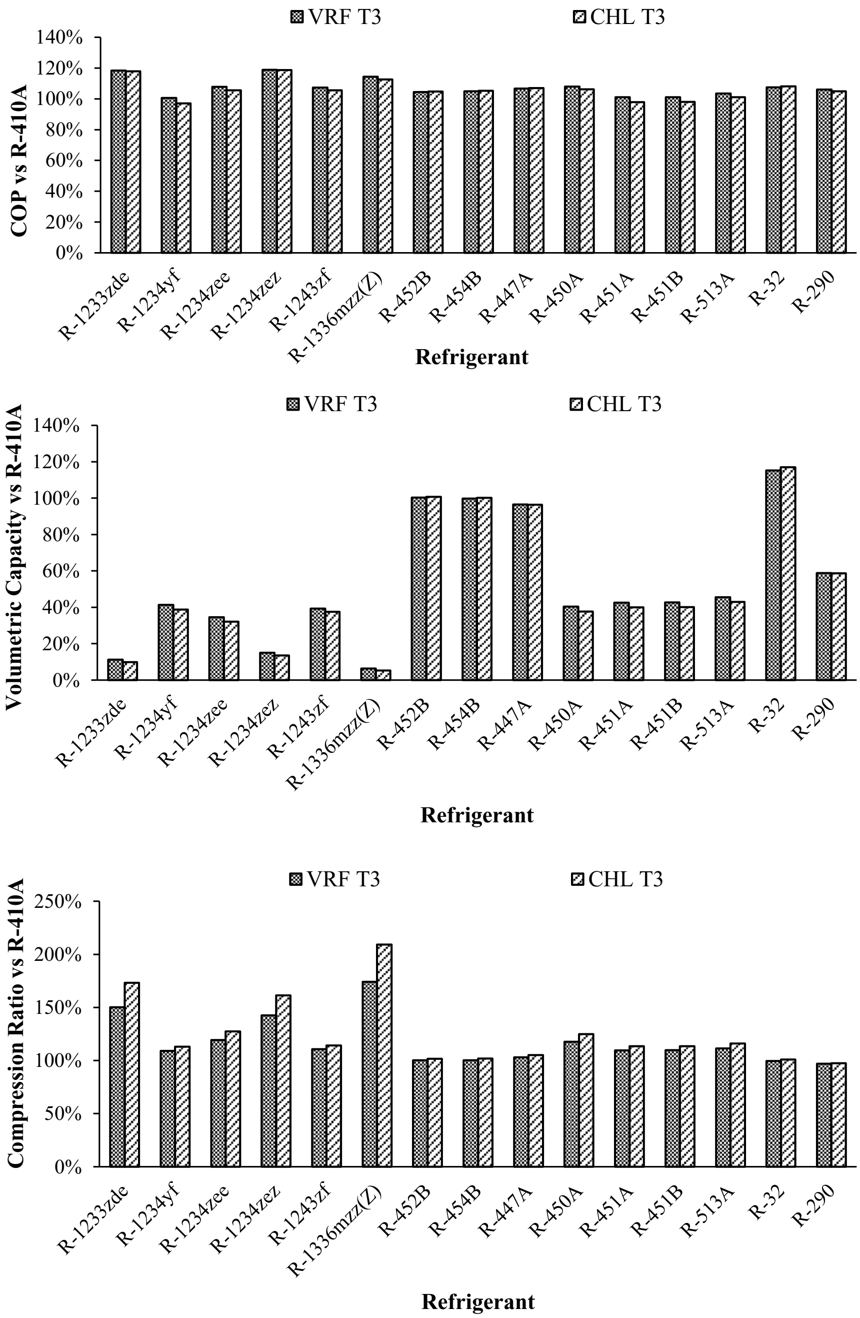

Figure 3. Simulation results. Refrigerant performance at T3 conditions compared to R-410A (top—COP, center—volumetric capacity, bottom—compression ratio).

is R-1234yf, which could achieve 9% higher COP than R-410A and showed high sensitivity to using the IHX, as its COP improved by 12–23%, which is higher than any refrigerant in this study, as shown in Figure 3. The COP and the compression ratio for R-1234yf are higher than for R-410A. However, as shown in Figure 1, the volumetric efficiency is around 40% of that for R-410A, which means it requires more than double the compressor size to achieve the same capacity. Also, the low and high side cycle pressure is 40–44% of the R-410A cycle pressure. Also, the CDT was around 54.4–63.1, which is around 30% less than R-410A. R-1234yf is classified as A2L or mildly flammable. However, with a low GWP of (1–4), its thermophysical properties are close to R-134a. Nevertheless, R-1234yf has desirable properties as a refrigerant; the main unsolved issue affecting the broader adoption of this refrigerant is related to the degradation of this fluid in case of fire as it releases hydrogen fluoride, which is toxic and highly corrosive, and carbonyl fluoride. Also, HFO-1234yf degrades in the atmosphere to trifluoroacetic acid (TFA), which is a strong organic acid and may cause damage to the ecosystem in the form of acidic rain.[24] R-1234zee was found to have

Table 5. Refrigerants cycle pressure and compression ratio versus R-410A for VRF at T1 conditions.

Fluid name	Low cycle pressure versus R-410A [%]	High cycle pressure versus R-410A [%]	Compression ratio	Compression ratio versus R-410A [%]
R-1233zde	7	10	4.58	153
R-1234yf	40	44	3.33	111
R-1234zee	29	34	3.64	121
R-1234zez	10	14	4.35	145
R-1243zf	35	38	3.38	113
R-1336mzz(Z)	4	7	5.31	177
R-452B	94	95	3.06	102
R-454B	93	93	3.06	102
R-447A	86	89	3.14	105
R-450A	34	40	3.59	120
R-451A	41	45	3.34	111
R-451B	41	45	3.35	112
R-513A	42	47	3.40	113
R-32	102	102	3.04	101
R-290	58	57	2.96	99

a relatively medium cycle pressure of around 29–34% of R-410A, as in Table 4, making it unsuitable as a direct replacement in the VRF application where the refrigerant must run through long piping to deliver the refrigerant to the conditioned space. R-1234zee can achieve a comparable COP with a 20% higher compression ratio than the R-410A, as shown in Figure 1. The CDT of R-1234zee was in the same range as R-1233zde and R-1234yf, with around 30% less than R-410A. R-1234zee could be a suitable replacement for traditional refrigerants in different applications. It has a low GWP of under 1 and an ODP of 0. It is classified as A2L, which means it is a nontoxic, low-flammability refrigerant. On the other hand, there is a concern about forming R-23 due to the atmospheric breakdown of this refrigerant as a secondary product. This could be risky as R-23 is an HFC with a significant GWP of 18 400. Therefore, more research is needed to identify the breakdown pathways before the wide adoption of this refrigerant on a large scale.

Like other HFOs, there are concerns about the formation of TFA due to the presence of this fluid in the atmosphere, which could potentially impact water quality over time. However, R-1234zee is considered safe for its intended refrigeration and air conditioning applications. A notable feature of this refrigerant is its nonflammability under normal handling and storage conditions at temperatures below 30 °C, making it safe for such applications. Despite this, R-1234zee could become flammable if it leaks and mixes with air, but it would require ten times more concentration and 250 000 times more energy compared to hydrocarbons (HCs) to ignite. R-1234zf demonstrates a COP that is 5–7% higher than R-410A and offers slightly better performance under high ambient temperatures or high-temperature lifts. It also has a reasonable volumetric capacity of 37–39% compared to R-410A, with a compression ratio of ≈15% higher. Adding an IHX improves the COP by 9–19%, depending on the temperature lift, as depicted in Figure 3, indicating moderate performance relative to other refrigerants.

This refrigerant performs well, especially in high ambient conditions, as shown in Figure 2, making it a viable alternative to current refrigerants due to its ultralow GWP of less than 1, short atmospheric lifespan of 6 days, and its nonflammability—a feature that distinguishes it from most other HFOs. Similarly, R-450A, a zeotropic blend of R-134a and R-1234ze classified as A1, has a low GWP of 547. It operates efficiently within a medium pressure range of 1200–1600 Pa and performs well across various applications and temperature ranges. Simulation results suggest that R-450A is suitable for medium-pressure cooling applications, including air- or water-cooled CHLs, direct expansion medium-temperature cooling systems, and higher-stage cascade cooling cycles. It also shows a higher COP compared to R-410A under high-temperature lift conditions, as illustrated in Figure 3.

In the same way, R-513A is a low-GWP HFO-based blend with zero ODP. It can provide a COP similar to R-410A but has a 50% lower volumetric capacity and a 10% higher compression ratio. That could make it more suitable for direct expansion, positive displacement CHLs, and centrifugal CHLs. Nevertheless, due to the lower volumetric capacity than R-410A, the compressor will be larger than it is for R-410A. Moreover, R-513A could perfectly match R-134a in capacity and efficiency with a lower GWP of 573 and safe operation as it is classified as A1, meaning nontoxic and not flammable. Accordingly, we can conclude that R-513a is an excellent and safe refrigerant, but major system improvements are required to replace R-410A. Similarly, R-451A and R-451B have relatively low GWPs of 140 and 150, respectively. They are classified as A2L, nontoxic with low flammability, and work on medium cycle pressure. They can achieve a COP similar to R-410A with a slightly higher compression ratio driven by their lower volumetric efficiency. On the other hand, they could achieve a COP advantage over R-410A using IHX as they showed better improvement of 12–22% compared to R-410A with 3–6%. These refrigerants may not be suitable for multisplit and VRF systems due to their negative impact on the system capital cost resulting from their requirement for a larger compressor to achieve a similar capacity, and their lower cycle pressure may affect the system's long refrigerant piping ability. However, they might replace R-410A in other applications. Similarly, R-513A is a nonflammable, nontoxic A1-classified azeotropic blended refrigerant that offers better efficiency than HFC refrigerants, with a COP slightly higher than R-410A and balanced properties. This refrigerant works on a medium cycle pressure of around 45% of R-410A, as shown in Table 5. It might suit many applications, including medium-temperature direct expansion systems such as rooftop packages, large ducted units, and DX-air handling units. Similarly, it could be used in water- and air-cooled CHLs.

The implications of these results are considered in the context of the current literature and potential applications. Based on the results of this study, we can conclude that many fluids can replace R-410A in CHL applications due to the CHL application's flexibility in terms of cycle pressure and compressor type. Most of these refrigerants overperform R-410A in terms of COP. However, a trade-off has to be made in regards to the compression ratio and the volumetric efficiency; it is also noted that there is a direct relation between the compression ratio and the volumetric efficiency as it can be noticed that the refrigerant with low volumetric efficiency usually requires a higher compression ratio. Hence, a larger compressor size is required to achieve the same capacity.

4.3. High Volumetric Capacity Refrigerants

This subsection aims to provide an overview of relatively high volumetric capacity refrigerants, highlighting their potential as sustainable alternatives to traditional high-GWP refrigerants. It aims to provide a clearer understanding of the advantages and limitations of these refrigerants, as well as their practical applications in modern refrigeration and air conditioning systems. Compared to other refrigerants in this study, R-452B, R-454B, and R-447A showed high volumetric capacity with a slightly higher COP than R-410A, with properties very close to R-410A regarding the volumetric capacity and the compression ratio. Also, R-447a showed slightly better performance at high-temperature lift than R-410A and the other refrigerants. R-452B is a nonozone depleting, zeotropic blend that consists of 67% R-32/7% R-125/26% R-1234yf; it could work as a low-GWP replacement to R-410A in different comfort air cooling and reversible heating applications. It has a 67% lower GWP valued at 470 compared to 2088 for R-410A, and it can achieve matching efficiency and similar capacity to R-410A, offering to minimize redesign costs and initial expenditures further. The volumetric capacity of R-452B is very close to that of R-410A, as can be seen in Figure 1, which could make it a suitable replacement in many applications. However, R-452B is classified by ASHRAE as A2L, which is mildly flammable and could limit its application, especially when a sizeable refrigerant charge is required. Similarly, R-454B is a zero ODP, a zeotropic binary blend consisting of HFO and HFC with 31.1% R-1234yf and 69.9% R32 that could replace R-410A in CHLs and heat pump applications as a lower GWP alternative. It could be even more attractive than R-452B, with a 78% lower GWP than R-410A. R-454B has a relatively higher critical temperature of 77 °C, and its CDT is lower than R-410A, making it suitable for broader applications, especially low-heat heating applications. These two refrigerants showed the closest performance to the R-410A and could be the best and easiest replacement for the R-410A. However, the flammability of these refrigerants needs to be better understood for a broader expansion. On the other hand, R-447A works on a relatively high cycle pressure compared to other refrigerants and is slightly lower than R-410A. So, R-447A properties could make it a good fit for VRF and CHL applications as it can work with different compressor types, including rotary, screw, and scroll considering its good thermophysical properties. The CDT of the R-452B, R-454B, and R-447A was found to be 98.1, 97.4, and 101.9 °C respectively, which is higher than R-410A with 90.2 °C. Also, these temperatures are higher than the refrigerant's critical temperature, as in Table 4, which means that all of these refrigerants are unsuitable for high ambient applications, especially the R-447a, which has a critical temperature of 58.3 °C. In contrast, one of the best-performing refrigerants that can replace R-410A in new equipment is R-32. R-32 is a zero ODP HFC with a lower GWP than R-410A; the GWP of R-32 is 677 in a 100-year time frame. R-32 is currently used in small-charge air conditioning systems in many countries worldwide as a replacement for R-410A. R-32 performs well compared to other HFC refrigerants in many applications; it has a high volumetric capacity and high COP and requires a lower compression ratio. Also, the cycle pressure of this refrigerant is the closest to R-410A, which makes it a very attractive replacement. However, it is slightly flammable and classified as A2L; hence, it cannot be used in large-charge applications, including VRF and CHLs, due to the industry volumetric concentration limitations of A2L refrigerants in the conditioned space. Moreover, R-32 showed the most negligible improvement in this study's refrigerants for using IHX. It can perform better than R-410A in terms of COP, volumetric capacity, and compression ratio. Also, the refrigerant concentration in the space has to be observed following the standards and regulations of the A2L refrigerants. The A2L-classified refrigerants are all different, as they vary in their BV and minimum ignition energy (MIE) required for the refrigerant to start the flame. The A2L refrigerants could be identified as any refrigerant with a blazing rate of more than zero and up to 10.0 $cm\,s^{-1}$. The refrigerant flammability dictates the allowable refrigerant charge for any refrigerant. Hence, it limits the applications where these refrigerants can be used. For example, the R-32 has a BV of 6.7 $cm\,s^{-1}$, which could be considered more flammable than other refrigerants such as R454B with a BV of 5.2 $cm\,s^{-1}$ and MIE of (calculate). Also, it is more flammable than R-452B, with 3.0 $cm\,s^{-1}$, and R-1234yf, with 1.5 $cm\,s^{-1}$. It is also noted that A2L refrigerants vary in their MIE with 30–100 MJ for R-32, 5000–10 000 MJ for R-1234yf, and 61 000 to 64 000 MJ for R-1234ze.[25] Accordingly, although these refrigerants are classified as mildly flammable (A2L), they have a low BV and require a considerable energy amount to ignite, leading to a low probability for these refrigerants to ignite in normal operating conditions.[26] Another potential drop-in replacement for the R-410A is the R-447a, which has a low GWP of 572 with a negligible ODP as it contains 28.5% R-1234ze (E), which has a very low ODP. R-447A is classified as A2L, which means nontoxic with low flammability. It showed higher COP over R410A at low temperatures and more improvement at high ambient temperatures. On the contrary, though R-290 is a highly flammable refrigerant, it is considered a low GWP and high-efficiency refrigerant. R-290 has a higher COP than R-410A in both cooling and heating, a lower compression ratio, and around 60% of R-410A volumetric capacity, indicating the requirement for a larger compressor when R-290 is used. It also showed a better response to adding IHX with a COP improvement of 8–13% compared to just 3–6% for R-410A. However, the current regulations limit the use of R-290 to 988 g due to safety concerns related to its flammability,[27] which means that this refrigerant will not be applicable for medium- or large-charge applications, but it may be useful for small residential applications, in the future.

4.4. The Effect of IHX on Refrigerant Performance

This section presents and discusses the effect of including an IHX in a medium-capacity refrigeration system at different evaporating and condensing temperatures. To properly study

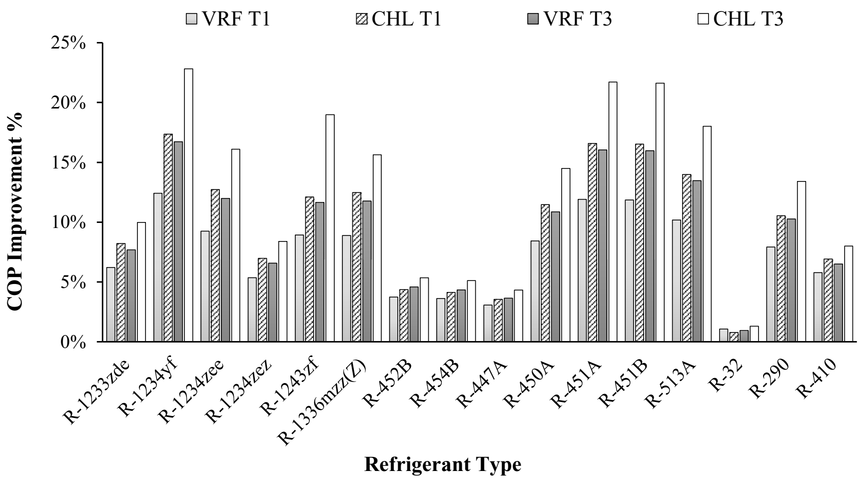

Figure 4. The effect of IHX on the cycle COP for different applications.

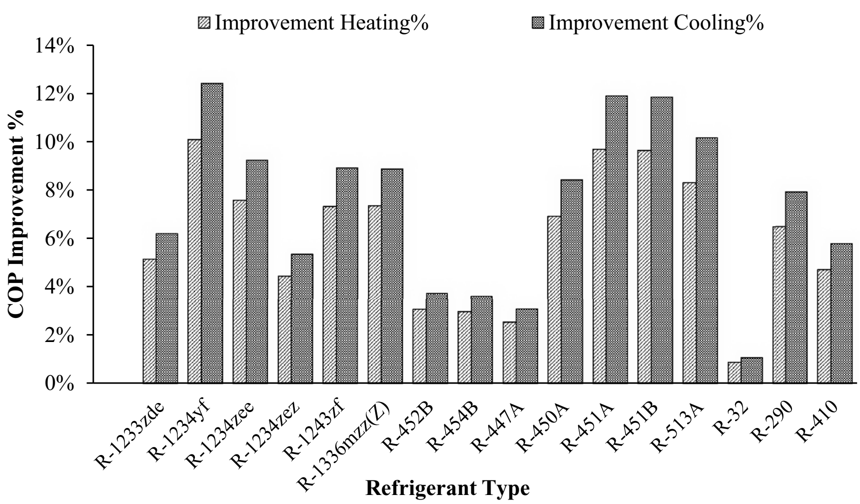

Figure 5. The COP improvement percentage for heating and cooling (VRF @ T1 conditions) by adding IHX.

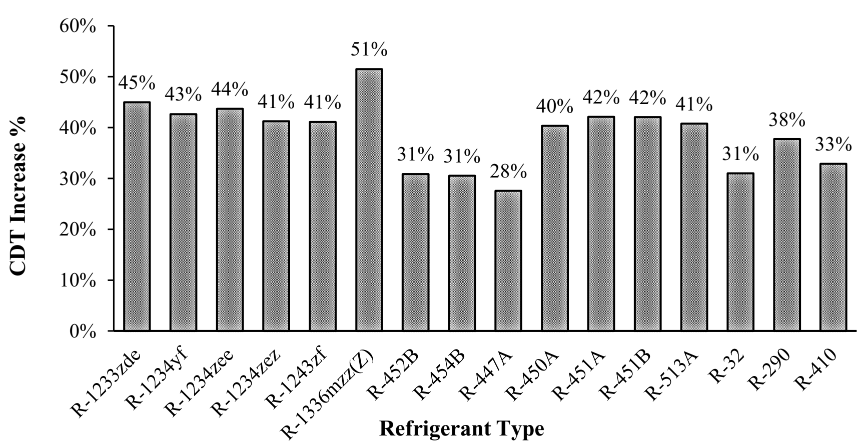

Figure 6. IHX impact on the CDT.

the cycle with and without the IHX, all options with IHXs were designed to present a relatively high heat exchange effectiveness of around 80%. The effect of the IHX in the VCC's main operating and energetic parameters has been analyzed, and results using both refrigerants have been compared. As shown in **Figure 4**, the IHX improves the COP for all refrigerants in this study. However, the improvement is more significant for the T3 cycles and the fluids with higher molar heat capacity. Notably, the benefits of the modified cycle exceed the cycle efficiency as the IHX showed a lower compression ratio of 3–6% for different refrigerants and cycle operating temperatures.

The effect of IHX on the cycle COP is more significant in cooling than in heating. **Figure 5** shows the COP improvement percentage compared to the basic cooling cycle for both cooling and heating; the difference in the IHX performance could be referred to as the stage where the heat exchange is taking place, as in the cooling case, the heat exchange process takes place before the expansion. In contrast, it takes place after expansion in heating. After expansion, the density of the fluid decreases, and so does the volumetric heat capacity, which affects the efficiency of the IHX and its impact on the cycle performance improvement.

The IHX increases the fluid temperature at the compressor suction, reducing the density, which is directly related to the IHX influence on the refrigeration cycle performance and could result in a negative or positive impact on the cycle performance. Notably, it also increases the CDT and could elevate it to more than 100 °C for some refrigerants, including R-32, R-454B, R-452B, R-477A, and, in some cases, R-410A. This indicates that using IHX is not very beneficial for these refrigerants. The rate of change in the CDT varies between refrigerants, as shown in **Figure 6**, and it is highly dependent on the refrigerant specific volume at the vapor state. In conclusion, we can say that the IHX is recommended with many fluids, including R-1234yf, R-1234zee, R-1234zf, R-1336mzz, R-450A, R-451A, R-451B, and R-513A; in contrast, it is not recommended for R-452B, R454B, R-447A, and R-32.

However, this is based on the temperature ranges applied in this study, and the impact might differ for other temperature ranges. In addition, the IHX showed better performance for a wide operating temperature range, such as in the case of chilled water applications and especially at T3 climate standards, where the temperature lift is the highest, as shown in Figure 4. It shows that as the cycle temperature lift increases, the IHX impact increases. However, the IHX impact on the CDT has to be noted, as it might cause issues with the system components and affect the system's reliability.

Table 6. Refrigerants LTEC and TEWI in moderate and hot climates.

Fluid	VRF		CHL	
	LTEC [kWh]	TEWI	LTEC [kWh]	TEWI
Moderate climate				
R-1233zde	687 722	7 530 749	893 985	9 789 283
R-1234yf	776 247	8 500 059	954 406	10 450 868
R-1234zee	737 401	8 074 807	933 893	10 226 334
R-1234zez	685 081	7 501 713	898 012	9 833 289
R-1243zf	739 816	8 101 021	938 548	10 277 129
R-1336mzz(Z)	703 570	7 704 166	891 398	9 760 871
R-452B	754 306	8 277 274	1 010 464	11 078 681
R-454B	751 796	8 249 716	1 009 260	11 065 441
R-447A	743 549	8 163 311	1 003 582	11 006 383
R-450A	736 600	8 086 282	940 110	10 310 614
R-451A	773 060	8 469 998	954 944	10 460 627
R-451B	772 708	8 466 625	954 944	10 461 017
R-513A	759 887	8 342 251	953 869	10 462 055
R-32	737 081	8 096 344	1 019 584	11 184 692
R-290	747 980	8 196 003	956 561	10 478 845
R-410A	777 494	8 591 859	1 020 505	11 237 167
Hot climate				
R-1233zde	734 498	8 042 941	908 930	9 952 932
R-1234yf	864 308	9 464 324	988 075	10 819 538
R-1234zee	805 809	8 823 866	960 946	10 522 568
R-1234zez	731 539	8 010 422	914 942	10 018 671
R-1243zf	809 626	8 865 447	938 288	10 274 284
R-1336mzz(Z)	759 660	8 318 352	904 966	9 909 434
R-452B	832 600	9 134 590	1 067 993	11 708 618
R-454B	828 799	9 092 897	1 065 251	11 678 539
R-447A	814 850	8 944 056	1 055 191	11 571 497
R-450A	804 915	8 834 336	969 606	10 633 596
R-451A	859 704	9 418 746	988 747	10 830 773
R-451B	859 195	9 413 665	988 747	10 831 163
R-513A	839 578	9 214 866	987 739	10 832 929
R-32	808 050	8 873 460	1 074 709	11 788 319
R-290	819 447	8 978 570	989 758	10 842 350
R-410A	868 962	9 593 433	1 117 285	12 296 905

4.5. Refrigerants Environmental Assessment

Assessing the environmental impact of refrigerants is critical to developing sustainable cooling solutions and mitigating climate change. These assessments help identify refrigerants with lower GWP and minimal ODP, guiding the industry toward more sustainable alternatives. Such evaluations are essential for ensuring compliance with international agreements like the Kigali Amendment to the Montreal Protocol and for supporting global efforts to reduce greenhouse gas emissions. **Table 6** shows the TEWI and the LTEC of different refrigerant options in T1 and T3 conditions. As shown, the long-term environmental impact is driven by the indirect impact of the refrigerant, which means more energy is consumed throughout the system's life span and, hence, more carbon dioxide is emitted to the environment.

Figure 7 and **8** present the lifetime energy and environmental performance of the different refrigerant options at moderate and hot climate conditions. The figures clearly show that the TEWI was highly dependent on the system energy consumption, and the TEWI followed almost the same trend of LTEC. However,

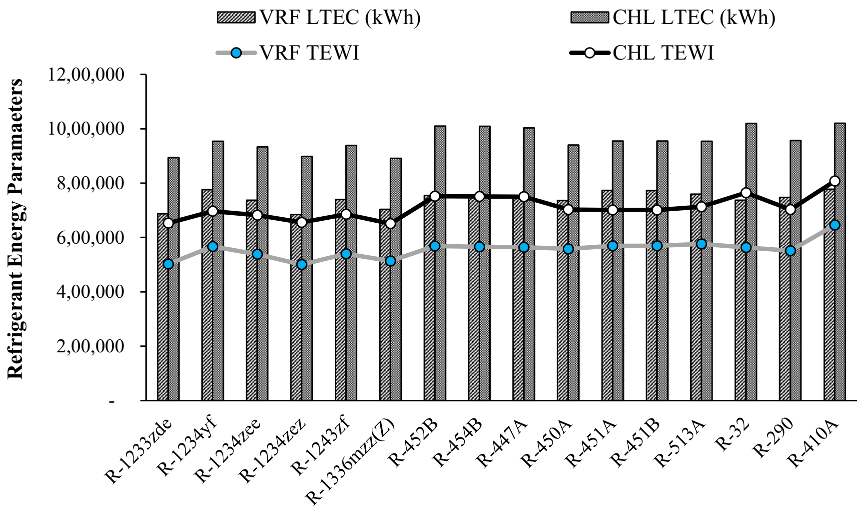

Figure 7. The LTEC and its impact on TEWI for VRF and CHLs at T1 conditions.

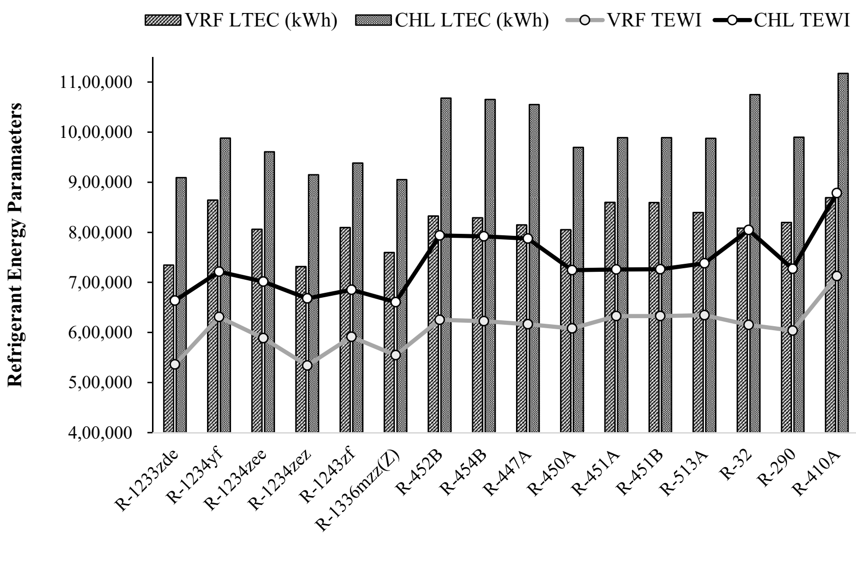

Figure 8. The LTEC and its impact on TEWI for VRF and CHLs at T3 conditions.

this was not the case for R-410A, as the energy consumption was not the highest, but the TEWI was. The reason for that is its relatively high GWP, which increased the direct impact and hence the TEWI. The refrigerant's TEWI is highly affected by the refrigerant's direct impact, which is represented by the refrigerant's GWP. Also, it depends on the leakage rate of the refrigerant to the environment.

Conversely, it is also dependable on the indirect impact driven by the cycle SEER. The indirect environmental impact could be significant throughout the system's lifetime. However, it is not clearly shown in Figure 7 due to the very close SEER of the refrigerants, hence the LTEC values for the refrigerants in this study. The indirect impact of the refrigerant is highly dependent on the carbon dioxide emission factor where the system is used, as the carbon dioxide emission factor indicates the amount of CO_2 emitted for every kWh of refrigerant. Even the slightest improvement in the system COP could lead to a significant reduction in the TEWI. Figure 6 shows the GWP and TEWI of different refrigerants compared to R-410A as a baseline, as shown in the figure. All the proposed refrigerants could achieve a better environmental performance than R-410A, and the refrigerant with the highest TEWI value was R-32, which has less than 33% TEWI compared to R-410A.

The most suitable refrigerants for replacing R-410A without significant system component changes are R-452B, R-454B, and R-447A, as detailed in Section 4. These refrigerants exhibit strong environmental performance compared to R-410A, with a TEWI reduction of 22–27%. Additionally, refrigerants such as R-1233, R-1234yf, R-1234zez, R-1243zf, and R-1336mzz have notably low GWP and higher SEER. Their direct environmental impact is negligible compared to R-410A, with only minor direct contributions to TEWI. **Table 7** provides an analysis of the direct and indirect environmental impacts. For most low-GWP refrigerants, the direct impact, based on their GWP, represents an insignificant portion of their TEWI, as low as 0.014% for R-1243zf. In contrast, R-410A demonstrates a much higher direct impact, with about 11% of TEWI for VRF systems and 7% for CHLs, indicating that its environmental footprint is dominated by refrigerant leakage.

Critically, the trade-offs between different refrigerants reveal that while some of the alternatives perform exceptionally in terms of environmental impact, they may come with challenges related to mild flammability and system design adjustments. For instance, R-447A, which shows strong performance in standard and high ambient temperatures, has a higher direct environmental impact of 3.481% in VRF systems, which is significantly higher than that of R-452B or R-454B. This suggests that although R-447A offers strong thermodynamic performance, it requires careful consideration in applications where refrigerant leakage risk is high.

Ultimately, while most alternatives proposed are viable, particularly for CHL applications, the choice of refrigerant for VRF systems remains more constrained, necessitating a careful balance between environmental performance, safety, and system efficiency.

Table 8 presents a comparison between these refrigerants against R-410A. The refrigerant's TEWI at T1 and T3 conditions was 77–88% in the case of VRF and 81–95% in the case of the CHL, compared to R-410A. At the same time, it did not change significantly in T3 conditions, which proves the importance of the indirect impact of the refrigerants on total environmental performance represented by energy consumption. Moreover, it comprises the need to move with renewable resources for power generation to reduce the carbon emission index and, hence, the indirect environmental impact. The indirect environmental impact of the refrigerants is related to their energy efficiency; according to the TEWI methodology, the direct impact of these refrigerants was found to be between 0.05% and 32% compared to R-410A as shown in Table 8, which is very low; however, that did not contribute much to the TEWI, which shows the importance of reducing the indirect impact of refrigerants since it has a more significant impact on the TEWI especially where the carbon emission index is high. To estimate the environmental impact of a vapor compression-based cooling system, the value of the energy consumption should be estimated throughout the lifetime of the system, and accordingly, the CO_2 emissions that result from operating the system should be estimated during its entire life span; Table 7 shows the energy and environmental analysis of different refrigerants over an estimated lifetime of 15 years.

The results show that with a minor change in the COP of the system, a reasonable amount of CO_2 emissions can be reduced. For instance, around 1500 kg of CO_2 can be saved during the system's lifetime using more efficient refrigerants such as R-1233zde or R-1234zez. Also, it should be noted that by increasing the renewable energy share in power generation, the indirect impact of the refrigerant decreases as it is directly related to the carbon dioxide emission factor calculated by $CO_2\,kWh^{-1}$ produced (**Table 9**).

Figure 9 shows the amount of CO_2 that could be saved throughout the system lifetime for systems operating with different refrigerants compared to an R-410A system. Notably, the CO_2 emissions are higher when the temperature lift is higher, driven by greater energy consumption. Hence, the savings throughout

Table 7. The direct and indirect portion of the total environmental weighted impact of different refrigerants.

Fluid	VRF			CHL		
	Indirect impact	Direct impact	Direct [%]	Indirect impact	Direct impact	Direct [%]
R-1233zde	536 184	188	0.035	663 519	150	0.023
R-1234yf	630 945	150	0.024	721 295	120	0.017
R-1234zee	588 240	263	0.045	701 491	210	0.030
R-1234zez	534 023	75	0.014	667 907	60	0.009
R-1243zf	591 027	38	0.006	684 950	30	0.004
R-1336mzz(Z)	554 552	75	0.014	660 625	60	0.009
R-452B	607 798	17 625	2.818	779 635	14 100	1.776
R-454B	605 023	17 550	2.819	777 633	14 040	1.773
R-447A	594 840	21 450	3.481	770 289	17 160	2.179
R-450A	587 588	20 513	3.373	707 812	16 410	2.266
R-451A	627 584	4988	0.788	721 786	3990	0.550
R-451B	627 213	5475	0.865	721 786	4380	0.603
R-513A	612 892	21 488	3.387	721 049	17 190	2.329
R-32	589 876	25 313	4.115	784 538	20 250	2.516
R-290	598 196	5625	0.932	722 523	4500	0.619
R-410A	634 342	78 300	10.987	815 618	62 640	7.132

Table 8. Direct and total environmental impact versus R-410A.

Moderate climate				
Fluid	VRF		CHL	
	TEWI versus R410a [%]	DEWI versus R410a [%]	TEWI versus R410a [%]	DEWI versus R410a [%]
R-1233zde	78	0.24	81	0.24
R-1234yf	88	0.19	86	0.19
R-1234zee	83	0.34	84	0.34
R-1234zez	77	0.10	81	0.10
R-1243zf	84	0.05	85	0.05
R-1336mzz(Z)	80	0.10	81	0.10
R-452B	88	22.51	93	22.51
R-454B	88	22.41	93	22.41
R-447A	87	27.39	93	27.39
R-450A	86	26.20	87	26.20
R-451A	88	6.37	87	6.37
R-451B	88	6.99	87	6.99
R-513A	89	27.44	88	27.44
R-32	87	32.33	95	32.33
R-290	85	7.18	87	7.18

Hot climate				
Fluid	VRF		CHL	
	TEWI versus R410a [%]	DEWI versus R410a [%]	TEWI versus R410a [%]	DEWI versus R410a [%]
R-1233zde	75	0.24	76	0.24
R-1234yf	89	0.19	82	0.19
R-1234zee	83	0.34	80	0.34
R-1234zez	75	0.10	76	0.10
R-1243zf	83	0.05	78	0.05
R-1336mzz(Z)	78	0.10	75	0.10
R-452B	88	22.51	90	22.51
R-454B	87	22.41	90	22.41
R-447A	86	27.39	90	27.39
R-450A	85	26.20	82	26.20
R-451A	89	6.37	83	6.37
R-451B	89	6.99	83	6.99
R-513A	89	27.44	84	27.44
R-32	86	32.33	92	32.33
R-290	85	7.18	83	7.18

the system's lifetime could be as high as 155 000 kg of CO_2 for some refrigerants. However, the best-suited refrigerants to replace R-410A were found to be in the range of 7000 and 45 000 kg in CO_2 emissions savings, which is still significant considering the huge number of systems installed worldwide. That proves that considering the current carbon dioxide index, the indirect impact of the refrigerant is more significant than the direct impact, and even the smallest improvement in the system COP could lead to a significant saving over the system lifespan.

Table 9. Lifetime CO_2 emission production for different refrigerants.

Fluid	CO_2 produced [kg]			
	VRF T1	CHL T1	VRF T3	CHL T3
R-1233zde	502 037	652 609	536 184	663 519
R-1234yf	566 661	696 717	630 945	721 295
R-1234zee	538 303	681 742	588 240	701 491
R-1234zez	500 109	655 549	534 023	667 907
R-1243zf	540 066	685 140	591 027	684 950
R-1336mzz(Z)	513 606	650 721	554 552	660 625
R-452B	550 643	737 639	607 798	779 635
R-454B	548 811	736 760	605 023	777 633
R-447A	542 791	732 615	594 840	770 289
R-450A	537 718	686 280	587 588	707 812
R-451A	564 334	697 109	627 584	721 786
R-451B	564 077	697 109	627 213	721 786
R-513A	554 718	696 324	612 892	721 049
R-32	538 069	744 296	589 876	784 538
R-290	546 025	698 290	598 196	722 523
R-410	567 571	744 968	634 342	815 618

5. Validation and Calibration of the COP Results

To validate the COP results generated by the numerical simulation in this study, we compared them with previous experimental and numerical studies. The COP results of various refrigerants compared to R-410A under different climate conditions align well with findings from previous research. Refrigerants such as R-1233zd(E) have been reported to offer slightly improved COP compared to R-410A in CHL systems, particularly under high-temperature conditions, due to their low GWP.[28] Similarly, R-1234yf and R-1234ze(E), recognized for their low GWP, exhibit performance that is either comparable to or slightly below R-410A, with R-1234ze(E) excelling in low-temperature applications.[29] R-1234ze(Z), on the other hand, has been shown to provide comparable or marginally better COP in medium-pressure systems.[30] For R-454B and R-452B, studies indicate a notable improvement in COP under high ambient conditions, with R-454B consistently outperforming R-452B.[31] Refrigerants like R-447A demonstrate comparable or improved efficiency relative to R-410A, making them suitable for VRF systems in low ambient conditions.[30] Conversely, R-450A and R-451A/B, while designed for medium-pressure systems, generally display a reduced COP compared to R-410A, although they still meet minimum efficiency benchmarks.[28]

R-513A, an alternative refrigerant with lower GWP, shows a slight reduction in COP compared to R-410A.[32] However, R-32 is widely recognized for its superior cooling capacity and higher COP relative to R-410A, although it has limitations such as a higher discharge temperature.[31] Finally, R-290 exhibits excellent COP in both VRF and CHL systems under all climate conditions due to its thermodynamic properties and low GWP, though its high flammability poses safety concerns.[33] These findings substantiate the trends observed in this study and

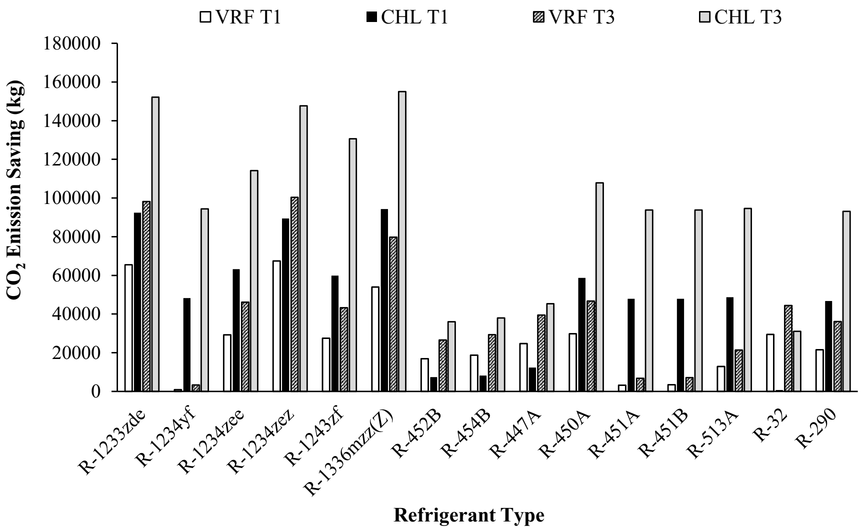

Figure 9. CO_2 emission saving versus R-410A for different applications.

emphasize the viability of several low-GWP refrigerants as alternatives to R-410A. **Table 10** compares the results from this study with the findings of previous studies:

This comparison validates the trends observed in this study, confirming that refrigerants like R-32, R-454B, and R-290 offer higher efficiency, while others, such as R-1234yf and R-1234ze(E), provide acceptable COP with low environmental impact.

6. Applications, Trade-Offs, and Future Directions

The findings of this study on low-GWP refrigerants have practical applications across various industries, including residential and commercial HVAC systems, refrigeration, and industrial cooling. By identifying refrigerants with lower environmental impacts and comparable or improved performance characteristics to R-410A, this work supports the development of energy-efficient and sustainable cooling systems. The integration of IHXs demonstrated in this study enhances system efficiency, which can benefit applications requiring high energy performance, such as data centers and healthcare facilities. Furthermore, the adoption of low-GWP refrigerants is instrumental in meeting regulatory standards, such as those outlined in the Kigali Amendment and European F-Gas regulations, while advancing global climate goals.[34,35]

Table 10. Comparison of the COP with previous research findings.

Refrigerant	COP versus R-410A (chart)	COP versus R-410A (referenced Studies)	Comments
R-1233zd(E)	Slightly better	Slightly better in CHL systems under high-temperature conditions.[28]	Matches well; suitable for T3 conditions in CHLs.
R-1234yf	Comparable	Comparable or slightly below.[29]	Similar results confirm its viability for low-GWP applications.
R-1234ze(E)	Comparable	Slightly below R-410A in high temperature; excels in low temperature.[29]	Consistent with studies, particularly for specific temperature ranges.
R-1234ze(Z)	Comparable to better	Comparable or better in medium-pressure systems.[30]	Matches well for medium-pressure applications.
R-454B	Better	Better than R-452B and R-410A under T3 conditions.[31]	Results align well; recommended as an alternative refrigerant.
R-452B	Comparable	A slight improvement over R-410A but less efficient than R-454B.[31]	Consistent; slightly less efficient than R-454B.
R-447A	Comparable	Comparable or improved performance relative to R-410A.[30]	Matches findings; viable for VRF systems.
R-450A	Slightly lower	Reduced COP compared to R-410A; still meets efficiency benchmarks.[28]	Consistent; moderate efficiency alternative.
R-451A/B	Slightly lower	Lower COP but meets minimum efficiency requirements.[28]	Results align with studies.
R-513A	Slightly lower	A slight reduction in COP compared to R-410A.[32]	Matches well; suitable for systems prioritizing low GWP.
R-32	Better	Higher COP with better cooling capacity; higher discharge temp.[31]	Consistent; widely recognized as a leading alternative.
R-290	Better	Excellent COP; safety concerns due to flammability.[33]	Matches; promising but limited by safety considerations.

However, transitioning to low-GWP refrigerants involves inherent trade-offs. Many alternatives, such as R-1234yf and R-290, offer excellent performance but come with challenges such as flammability, toxicity, and material compatibility. For example, flammable refrigerants require modifications to system designs, safety measures, and compliance with fire safety regulations, which can increase implementation costs.[28] Similarly, the adoption of natural refrigerants like propane may be limited in large-scale applications due to safety concerns and charge limitations. Additionally, retrofitting existing systems to accommodate alternative refrigerants often requires compatibility with existing lubricants, seals, and components, posing operational challenges.[36] Another critical concern lies in the decomposition pathways of these refrigerants, especially HFOs such as R-1234yf. Under high temperatures or when exposed to combustion or degradation in the atmosphere, HFO refrigerants may break down into hazardous by-products, such as TFA, which has been found to accumulate in water systems and is considered persistent in the environment.[37] This raises questions about the long-term ecological impact of some low-GWP refrigerants, potentially offsetting their short-term benefits. Future research must therefore prioritize a holistic assessment of refrigerant impacts, considering both operational emissions and degradation products. Future research should aim to address these trade-offs and environmental concerns through innovative approaches. For instance, the development of hybrid refrigerant blends that balance performance, safety, and environmental impact could offer tailored solutions for specific applications.[38] Advanced system designs, such as microchannel heat exchangers and enhanced IHX configurations, can mitigate some of the operational challenges associated with low-GWP refrigerants. Additionally, comprehensive life cycle assessments, incorporating manufacturing, operation, and EOL disposal, should be conducted to validate the environmental benefits of alternative refrigerants.[39] Sensitivity analyses on leakage rates, ambient temperature variations, and energy consumption across diverse climate zones can provide deeper insights into the practical applicability of these refrigerants. The future direction should also explore the integration of new refrigerant blends and propose suitable applications to the best-performing refrigerants to optimize energy efficiency further. Efforts should also focus on the development of refrigerants with lower environmental persistence, ensuring minimal long-term impact on ecosystems. Collaboration between researchers, manufacturers, and policymakers will be critical in ensuring that the transition to low-GWP refrigerants is both technically feasible and environmentally responsible. By addressing the trade-offs, managing decomposition risks, and advancing innovative solutions, this scption of sustainable refrigerant technologies.[40]

7. Conclusion

In this study, we conducted a comprehensive simulation analysis to identify suitable replacements for R-410A in medium-sized refrigerant charge applications. The investigation focused on 15 promising low-GWP refrigerants, evaluating their potential to meet energy efficiency, safety, and environmental standards. By examining alternative refrigerants, new techniques, and cautious handling practices, we aimed to significantly reduce the use of high-GWP HFCs both in the short and long term. Our findings align with the global trend toward adopting lower GWP alternatives in commercial and residential air conditioning systems. Based on our analysis, the most promising candidates for replacing R-410A in medium and large refrigerant charge applications include R-452B, R-454B, and R-477A. The conclusions drawn from this study highlight the advantages and considerations of these refrigerants and underscore the ongoing efforts to develop sustainable HVAC solutions.

The below points can summarize the reason for that: 1) These refrigerants have close operating cycle parameters to R-410A; 2) R-452B and R-454B could be excellent direct or indirect drop-in alternatives for the current systems designed to work on R-410A; 3) R-32 performs excellently compared to all other refrigerants with cycle parameters close to R-410A. However, it is mildly flammable, and industry standards limit its application to small- and medium-charge systems; 4) R-452B, R-454B, and R-477A could be suitable for larger refrigerant charge applications where R-32 cannot be used due to lower BV; and 5) The current flammability classification scheme could be improved to differentiate between mildly flammable refrigerants based on their BV and the minimum energy ignition requirements as R-32, R-452B, R454B, and R-477A are all classified as A2L; however, their burning velocities and MEIs vary.

Researchers, equipment manufacturers, and chemical producers are actively working to develop new alternatives that can replace high-GWP refrigerants globally. While significant progress has been made, and many low-GWP alternatives are under development, challenges remain. Collaborative efforts between industry and researchers could help bridge the gap and accelerate the adoption of these alternatives. Although HFOs and their blends offer numerous advantages over traditional HFC refrigerants, they also present some notable disadvantages. A major concern with HFOs is their potential decomposition when overheated, which can produce toxic and acidic substances. Many refrigerants can serve as replacements for R-410A in stationary large-charge equipment, such as rooftop units and CHLs. However, these alternatives often have lower volumetric capacities, which may necessitate larger compressors and heat exchangers. Despite the drawbacks and risks associated with HCs, HFOs, and HFO blends, natural refrigerants remain a strategic choice. Even if they require compromises in equipment cost or size, their environmental benefits are crucial and align with broader sustainability goals.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

hydrochlorofluoroolefins, hydrofluoroolefins, internal heat exchangers, low-global warming potential refrigerants, R-410A alternatives, refrigerant cycle efficiencies, total environmental weighted impacts

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[1] M. Phagare, HVAC system market report 2024 (Global edition). Cognitive Market Research, www.cognitivemarketresearch.com/hvac-system-market-report (accessed: March 2023).
[2] A. Cascini, M. Gamberi, C. Mora, M. Rosano, M. Bortolini, *J. Cleaner Prod.* **2016**, *112*, 448.
[3] H. W. Stanford, *Analysis and Design of Heating, Ventilating, and Air-Conditioning Systems*, CRC Press, Boca Raton, FL **2019**.
[4] M. Molina, F. S. Rowland, *Nature* **1974**, *249*, 810.
[5] H. Wang, L. Zhao, R. Cao, W. Zeng, *J. Cleaner Prod.* **2021**, *296*, 126491.
[6] M. O. McLinden, J. S. Brown, R. Brignoli, A. F. Kazakov, P. A. Domanski, *Nat. Commun.* **2017**, *8*, 14476.
[7] K. Uddin, S. Arakaki, B. B. Saha, *Environ. Sci. Pollut. Res.* **2020**, *28*, 2934.
[8] O. B. Tsvetkov, Y. Laptev, A. A. Nikitin, V. Mitropov, A. V. Sharkov, Y. A. Rakhmanov, *IOP Conf. Ser.: Mater. Sci. Eng.* **2020**, *826*, 012017.
[9] I. G. Franco, D. F. M. Pico, D. D. D. Santos, E. P. B. Filho, *J. Build. Eng.* **2022**, *47*, 103847.
[10] I. H. Bell, P. A. Domanski, M. O. McLinden, G. T. Linteris, *Int. J. Refrig.* **2019**, *104*, 484.
[11] S. Saran, M. Gurjar, A. Baronia, *Therm. Sci. Eng. Prog.* **2023**, *29*, 113.
[12] J. Xu, P. Zhang, Y. Wang, *Energy Convers. Manage. X* **2023**, *11*, 7.
[13] H. Zhao, F. Li, Q. Chen, *Int. J. Refrig.* **2023**, *138*, 79.
[14] Y. Lin, Z. Qian, M. Dong, *Energy Convers. Manage. X.* **2023**, *29*, 102.
[15] R. Smith, J. Taylor, D. Walker, *Case Stud. Therm. Eng.*, *19*, 122 **2023**.
[16] Z. Wang, Y. Li, S. Huang, *Appl. Sci.* **2023**, *33*, 156.
[17] International Organization for Standardization, *ISO 817:2014-Refrigerants — Classification*, International Organization for Standardization, Geneva, Switzerland **2014**.
[18] UNEP Ozone Secretariat, Background material on HFC management fact sheet 10: Water chillers for air-conditioning. UNEP Ozone Secretariat **2015**, ozone.unep.org/sites/ozone/files/Meeting_Documents/HFCs/FS_10_Water_chillers_for_air-conditioning_Oct_2015.pdf (accessed: April 2024).
[19] Clean Energy Regulator, EERS release 2022–23, www.cleanenergyregulator.gov.au/OSR/EERS/eers-current-release (accessed: February 2024).
[20] National Institute of Standards and Technology, Refrigerant properties, www.nist.gov/srd/refprop, Gaithersburg, MD (accessed: September 2023).
[21] I. Dincer, M. A. Rosen, *Exergy Analysis of Heating, Refrigerating and Air Conditioning: Methods and Applications*, Elsevier, Amsterdam, Netherlands **2015**, pp. 43–97.
[22] R. Hendron, *Building America House Simulation Protocols*, National Renewable Energy Laboratory, Golden, CO **2010**.
[23] Energy Rating - Australian Government, Seasonal energy efficiency ratio, www.energyrating.gov.au/industry-information/publications/seasonal-energy-efficiency-ratios-seer-calculator (accessed: January 2024).
[24] A. Mota-Babiloni, J. Navarro-Esbrí, Á. Barragán-Cervera, F. Molés, B. Peris, *Int. J. Refrig.* **2015**, *52*, 21.
[25] Y. Wang, Z. Wang, M. Sun, J. Guo, J. Zhang, *Sci. Total Environ.* **2021**, *780*, 146631.
[26] J. L. Pagliaro, S. Davis, *Sci. Technol. Built Environ.* **2020**, *26*, 588.
[27] M. Vender, Flammable charge limits on the move again. HVAC&R News **2020**, www.hvacrnews.com.au/legislation_updates/flammable-charge-limits-on-the-move-again/ (accessed: February 2024).
[28] Natural Refrigerants, Higher hydrocarbon charges unanimously approved in IEC standard for home ACs and heat pumps **2022**, naturalrefrigerants.com/higher-hydrocarbon-charges-unanimously-approved-in-iec-standard-for-home-acs-and-heat-pumps/ (accessed: January 2025).
[29] J. M. Calm, G. C. Hourahan, *ASHRAE J.* **2021**, *63*, 22.
[30] P. A. Domanski, S. F. Yana Motta, J. Wojtusiak, *HVAC&R Res.* **2020**, *16*, 411.
[31] K. Saito, *Refrig. Sci. Technol.* **2019**, *2019*, 104.
[32] S. Bhattacharyya, T. Pal, *Energy Build.* **2022**, *260*, 111962.
[33] I. L. Maclaine-cross, E. Leonardi, *Int. J. Refrig.* **2020**, *115*, 32.
[34] S. Wongwises, N. Chimres, *Appl. Therm. Eng.* **2018**, *149*, 254.
[35] Z. Luo, X. Wang, Y. Zhang, *Therm. Sci. Eng. Prog.* **2023**, *40*, 101271.
[36] J. Stene, *Energy Policy* **2022**, *162*, 112733.
[37] L. Kuijpers, M. Spatz, J. Stene, *Energy Build.* **2020**, *211*, 109819.
[38] V. Papadimitriou, B. Miller, R. Portmann, *Environ. Sci. Technol.* **2022**, *56*, 9104.
[39] A. Hafner, O. Kaarstad, D. Wight, *Int. J. Refrig.* **2024**, *147*, 110.
[40] P. Goncalves, D. Silva, S. Almeida, *J. Cleaner Prod.* **2023**, *374*, 134920.
[41] E. Granryd, *Int. J. Refrig.* **2001**, *24*, 15.
[42] M. Zhang, J. Muehlbauer, in *Int. Refrigeration and Air Conditioning Conf.* Purdue University, West Lafayette, IN **2012**.