Assessing the Opportunities for Low Global Warming Refrigerants at UBC

Prepared by:

Esteves Bengui

Claire Pam

AnnaMaria Zubieta

Prepared for: Prof. Tony Bi and the UBC Campus and Community Planning

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Statement of Contribution

Esteves Bengui: Responsible for going through the data provided on UBC's current operations, researching regulations concerning refrigerants, and writing sections 4.1 and 4.2.

Claire Pan: Responsible for researching 1st generation refrigerants and writing the executive summary and section 4.3.

AnnaMaria Zubieta: Responsible for researching 4th generation refrigerants, conducting the LCA, and writing sections 1, 2, 3, 4.4, 4.5, 5, and 6.

All members were responsible for references and appendix organization.

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Executive Summary

This project aims to provide evidence-based recommendations on the most suitable heat pump refrigerant technologies for the University of British Columbia (UBC) to adopt in support of its campus-wide decarbonization strategy. To achieve this, a comprehensive evaluation was conducted covering: technoeconomic considerations, environmental impacts, safety and health, economic feasibilities. The analysis includes both conventional and emerging refrigerants, spanning synthetic options such as HFCs and HFOs, as well as natural refrigerants like CO_2, ammonia, and propane.

Particular attention was given to the Canadian regulatory landscape, including the Montreal Protocol, the Kigali Amendment, and federal policies such as SOR/2016-137 and SOR/2022-110. These regulations collectively signal an accelerated phase-down of high-GWP HFCs, raising concerns about the long-term availability and legal compliance of HFC-based systems—many of which are currently in use at UBC.

To assess potential alternatives, a consequential life cycle assessment (LCA) was performed across three scenarios: continued reliance on HFCs, transition to HFOs, and a full shift to natural refrigerants. The results indicate that propane (R-290) demonstrates the most favourable overall performance due to its low environmental footprint, high efficiency, economic viability, and compatibility with both residential and district-scale applications. While CO_2 and ammonia offer strong thermodynamic advantages, they require significant upfront investment and more stringent safety measures. HFOs serve as a transitional solution but present uncertainties in terms of long-term environmental impact and high cost.

In all, the report recommends that UBC prioritize the adoption of natural refrigerants, particularly R-290, in future heat pump installations. HFOs may serve as interim replacements in existing systems until natural alternatives are feasible. This strategy supports UBC's climate commitments and ensures resilience under evolving regulatory and market conditions.

1. Introduction

Heat pumps are a low carbon technology that has been proposed as a possible solution for the decarbonization of many heating systems. They function based on a refrigeration cycle and use electrical power to extract heat from a source and transfer it to where it is needed. Since they rely on heat transfer rather than generation, heat pumps are far more efficient than boilers or electric heaters and can be cheaper to run [1]. They can also be run using clean electricity, which can significantly reduce its carbon footprint.

However, one main challenge of heat pumps is their requirement of a refrigerant. These chemical compounds must have key thermodynamic properties to be able to function with the heat pump's refrigeration cycle, including low boiling points to absorb heat at low temperatures, high stability, and low corrosivity to prevent damage to the equipment [2]. These specific technical requirements make it difficult to find suitable chemical compounds that can act as refrigerants without compromising other environmental, health, and safety concerns. For example, many refrigerants used in these technologies can have high ozone depletion potential (ODP), flammability/toxicity risks, and potential for water and food system contamination [2]. As refrigerant leakage is common in these systems, such concerns have continued to grow as heat pumps have become more and more common. In particular, concerns about the Global Warming Potentials (GWP) of these refrigerants have gained attention in recent years. Many refrigerants have been found to have GWP several thousand times more potent than carbon dioxide [2], which, if leaks are significant enough, could offset some of the environmental benefits gained using the heat pump. Such impacts have also introduced regulatory risks, as many refrigerants are in the process of being phased out in various jurisdictions [2]. Therefore, there is a need for an in-depth study into the current refrigerant technologies available, as well as their advantages and disadvantages. In particular, as UBC's campus utilizes many heat pumps for its buildings, there is a need for an evaluation of how refrigerant risks may impact the campus community and sustainability, as well as how regulatory risks could impact potential heat pump investments made by the university.

This study aims to review and assess heat pump refrigerants, with an emphasis on heat pump operations at the UBC Vancouver campus. The project's specific objectives are to identify and list the most used refrigerants along with emerging alternatives, to evaluate the listed refrigerants in terms of environmental impact, regulatory compliance, safety, economic feasibility, and technical performance, and to formulate evidence-based recommendations on which heat pump and refrigerants technologies UBC should adopt or prioritize to achieve its decarbonization goals.

2. Background of Heat Pump Refrigerants

Refrigeration using a thermodynamic cycle was developed in the mid-1800s [2]. In this era, the main constraints on refrigerants were simply that they should be available and work in the equipment of the time. Thus, most of the refrigerants identified in these early years were naturally occurring substances such as ammonia, propane, carbon dioxide, and sulfur dioxide. However, although these substances had reasonably good thermodynamic properties, many are associated with high flammability, acute toxicity, and/or high-pressure requirements that compromised the safety of workers at the time [2]. These refrigerants are known as First Generation Refrigerants. Despite their challenges, many of these refrigerants have resurfaced in popularity in recent years, as their health and safety risks can now be more easily managed with evolving technologies [3].

In the 1920s, chlorofluorocarbons (CFCs) were discovered as a group of compounds with excellent thermodynamic properties suitable for refrigeration [2]. As these were synthetic compounds, variations in their flammability and acute toxicity could be varied based on the degree of chlorination and fluorination [2]. Shortly thereafter, hydrochlorofluorocarbons (HCFCs) were also discovered. This led to the Second Generation of refrigerants, prioritizing 'safety and durability' [2]. Although these refrigerants dominated the market until the 1980s, their fame was cut short due to the discovery of their high ozone depletion potential (ODP). This resulted in many accords and legislations passing to limit their use, encouraging the search to continue for alternative refrigerants.

In the 1980s, hydrofluorocarbons (HFCs) began to rise in popularity as promising alternatives. These compounds, known as Third Generation refrigerants, had little to no ODP and comparable performance. However, HFCs have extremely high global warming potentials (GWP) [2]. As talks of climate change and greenhouse gas emissions have become more common in the past years, these GWP concerns have been elevated and have resulted in imposed limitations on their use as well.

Finally, the Fourth Generation of refrigerants was developed in the 2010s and consists of hydrofluoroolefin compounds (HFOs). These compounds have zero ODP and low GWP, addressing the main concerns of their second and third generation counterparts [4]. They also have low acute toxicity and relatively low flammability in comparison to First Generation refrigerants [4]. However, some concerns have been raised about potential degradation into chronically toxic compounds. Though more research into toxicity is required, it suggests a new concern that may soon limit the widespread use of this refrigerant class.

Figure 1 below summarizes the evolution of heat pump refrigerants over the years, as well as the concerns associated with each generation.

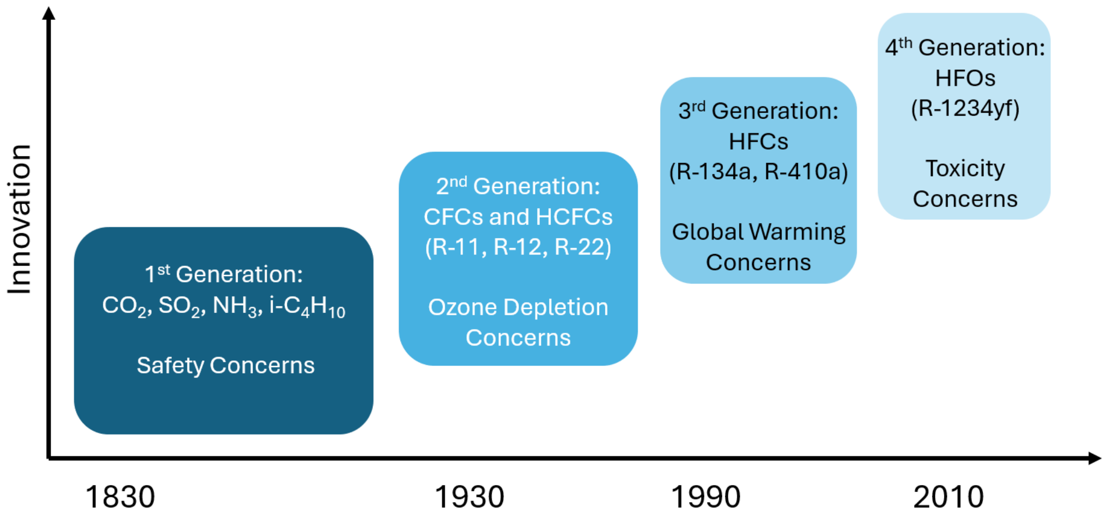

Figure 1. Evolution of heat pump refrigerants, adapted from Arora et al. [5]

3. Research Methodology and Methods

This research study will start with an initial literature review of UBC's operations, regulatory frameworks, and potential refrigerants. The purpose of this review will be to provide a high-level overview of critical challenges associated with UBC's heat pump operations, as well as opportunities for improvement. After this literature review, a quantitative comparison of three operational scenarios at UBC will be conducted using a consequential Life Cycle Analysis (LCA). The LCA will be performed between the base-case scenario of current refrigerants used at UBC, a scenario in which all refrigerants are replaced by fourth-generation synthetic refrigerants, and a scenario in which all refrigerants are replaced by a first-generation natural refrigerant. Within each of the latter two categories, an internal LCA will be performed (i.e., between all synthetic refrigerants and all natural refrigerants) to determine which refrigerant candidates will move on to the final analysis. Note that laboratory-scale refrigeration will be considered out of scope for this project.

3.1 Functional Unit

The functional unit proposed is "per year of UBC's heat pump operations". This general functional unit is chosen to allow for a more comprehensive analysis, as it facilitates comparison across refrigerants with different parameters while still focusing on the UBC context.

3.2 System Boundary

The LCA will include the cradle-to-gate of each refrigerant, including their manufacture and usage. Disposal of the refrigerants will not be included in the analysis due to uncertainties in their incineration or reclamation (see Section 4). Furthermore, the energy required for manufacturing will not be considered due to a lack of data (see Section 4.4.2 Environmental Considerations). The LCA system boundary is summarized in Figure 2 below.

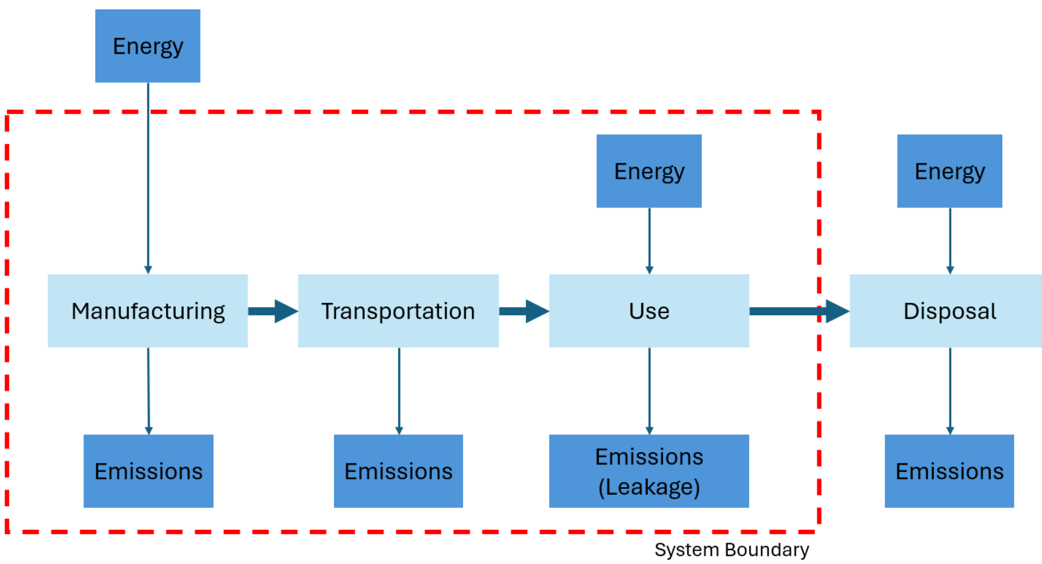

Figure 2. System boundary of refrigerant impact assessment

3.3 Impact Categories

The LCA will include the impacts of global warming, ozone depletion, short-term and long-term toxicity, flammability, and cost. The cost impact will include refrigerant costs as well as any capital costs and changes in electricity costs that may occur. During this analysis, a combined quantitative and qualitative approach will be used to weigh each impact factor, considering trade-offs to reach a final recommendation for the most suitable heat pump refrigerant for UBC.

3.4 Data Collection

In terms of research methods, basic data relevant to UBC's heat pump equipment and operations will be provided by the client for LCA purposes. Data related to refrigerant performance, environmental impacts, and regulatory frameworks will be obtained through a comprehensive literature review. Primary sources will include peer-reviewed articles, industry databases, leading heat pump manufacturers, patents, and trade organizations. No primary data collection will take place by the student team.

4. Literature Review and Life Cycle Inventory

4.1 Regulatory Considerations

Governments worldwide have recognized the need to address the environmental impact of chemical refrigerants. This recognition has led to the implementation of specific regulations governing the manufacture, use, and disposal of these substances. The primary regulation agreed upon at a global level is the Montreal Protocol of 1987, along with its subsequent amendments. Additionally, various federal and local regulations have been introduced in response to the Montreal Protocol and to achieve country-specific objectives.

4.1.1 Montreal Protocol

The 1987 Montreal Protocol was introduced with the primary goal of phasing out the production and consumption of ozone-depleting substances (ODS), which were identified as the principal cause of the ozone hole in the atmosphere [6].

Chlorofluorocarbons (CFCs), which were the primary components of heat pump refrigerants at the time, were identified as major contributors to Ozone-Depleting Substances (ODS) in the atmosphere. HFC represented a major improvement in terms of ozone depletion potential, as their ODP values are zero or close to zero in many cases. However, their high GWP values range between 12 to 14,000 (see Appendix D: Table of Third Generation Refrigerant Properties) [7].

4.1.2 Kigali amendment

The 2016 Kigali amendment to the 1987 Montreal protocol was established to reduce the production and consumption of HFC due to its high GWP values. Unlike the original Montreal Protocol, which mandated the complete elimination of ozone-depleting substances (ODS), the Kigali Amendment stipulates a progressive reduction in hydrofluorocarbons (HFCs).

The amendment aims to globally decrease HFC production and consumption to 15% of the levels recorded between 2011 and 2013. Another goal is to replace the high GWP refrigerants for alternative low GWP [8]. Figure 6 below provides a relative classification of high and low GWP for the purpose of the amendment. See Appendix A: Table of GWP for refrigerants impacted by the Kigali Amendment for a comprehensive list and classification.

The phase-down timeline is being implemented in stages, similar to the approach used for ODS, with different starting points and reference periods for developed and developing countries. Figure 3 below presents an overview of the HFC phase-out schedule as outlined in the original amendment. Canada, as a signatory of the amendment, is part of the non-article 5 early start timeline [9].

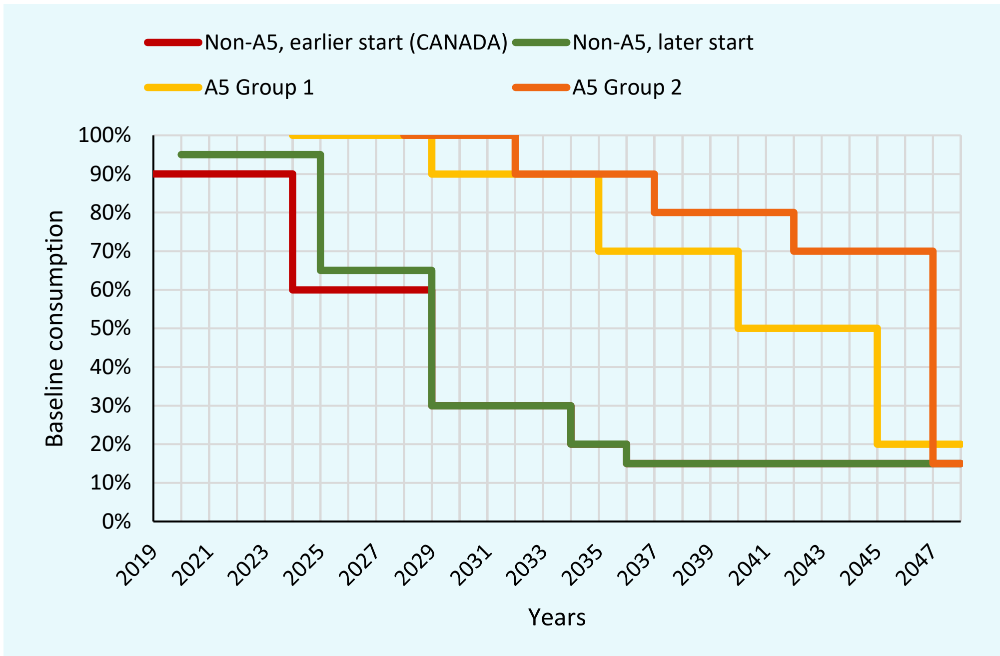

Figure 3. Kigali amendment HFC phase-down timeline, adapted from [10]

The Kigali Amendment is anticipated to significantly decrease HFC emissions worldwide and maintain global temperature changes below 0.1 degrees Celsius [8]. The graphs below illustrate the global effects of the protocol.

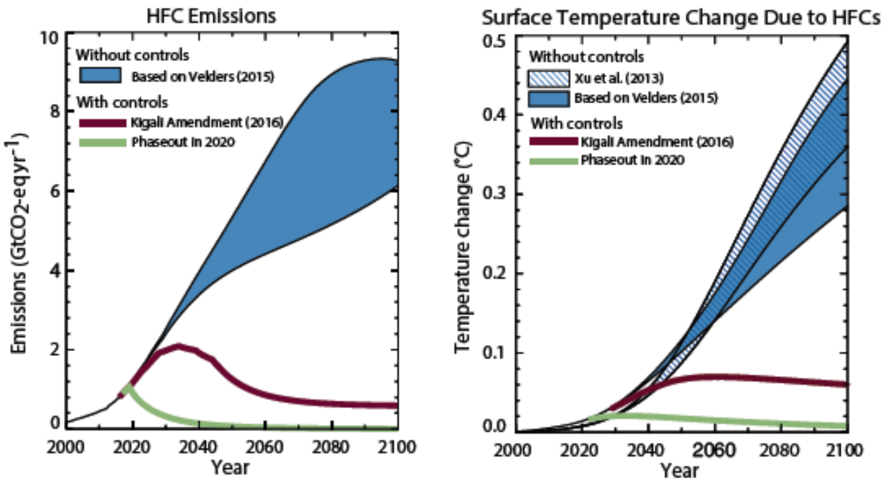

Figure 4. Scenario HFC emissions and global average surface-temperature response [11]

The importance of the complete implementation of the Montreal Protocol and the Kigali Amendment is shown by Figure 5 below. The chart demonstrates that the use of low GWP refrigerants will result in a minimal increase in CO_2 equivalent emissions when compared to the total refrigerant emissions by mass.

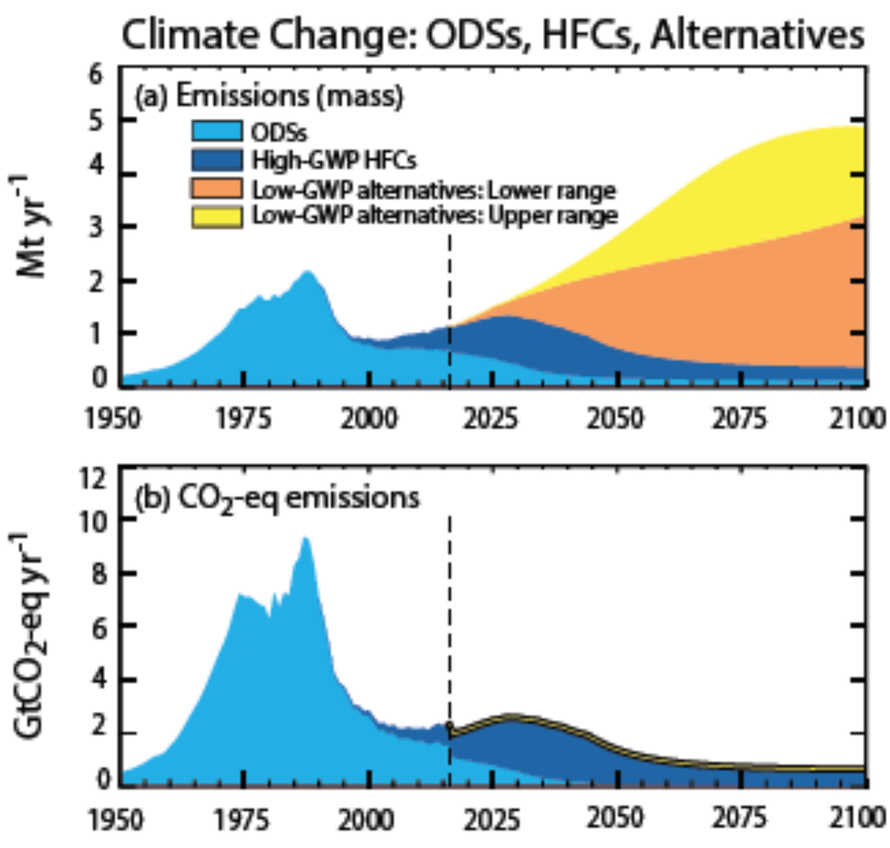

Figure 5. Scenario emissions for ODS, HFC, and low GWP alternatives [11]

Under the Amendment, the following key responsibilities are required as part of the implementation:

- Implement national legislation to facilitate the Kigali Amendment.
- Establish systems for monitoring and reporting the usage of hydrofluorocarbons (HFCs).
- The implementation of a licensing and quota system for the production and importation of hydrofluorocarbons (HFCs)
- Implementing a system for the verification of imports of HFCs and equipment containing HFCs.

4.1.3 Federal regulations

Canada's obligations under the Montreal Protocol are detailed in two key legislative frameworks. The first is the 2016 Ozone-Depleting Substances and Halocarbon Alternatives Regulations (SOR/2016-137), which were revised by the 2017 amendment (SOR/2017-216) to incorporate the provisions of the Kigali Amendment.

The second regulation, the Federal Halocarbon Regulations (SOR/2022-110), outlines comprehensive guidelines for the installation, operation, testing, and reporting requirements for equipment that utilizes halocarbon refrigerants.

4.1.3.1 SOR/2016-137

Regulation SOR/2016-137 covers ODS and HFC. Therefore, it establishes controls for importing, exporting, and manufacturing HFC refrigerants as well as products and equipment containing HFC. The regulation also defines consumption allowances and specifies the process for destroying refrigerants, mostly for CFC and other ODS [12].

To address the Kigali amendment, the regulation implemented a phase-down of consumption of the bulk HFCs and a product specific control [12]. For the phase-down of consumption, the regulation established a limit in the import of bulk HFC, since Canada does not produce those chemicals. These limits are aligned with the Kigali HFC phase-down timelines.

Table 1 below provides the most updated version of the federal government HFC consumption phase-down importation limits in tonnes of CO_2-eq.

The values represent the amount of HFC import that will be allowed to enter Canada. The regulation does not put any limitation on the recycling and reuse of the existing fluid. Therefore, any equipment using existing HFC refrigerant at its end of life the refrigerant can be recycled and put back into the overall country inventory for use [13].

Table 1. Baseline consumption allowance as per SSOR/2016-137, adapted from [13]

Period	HFC Consumption allowance (% Base line)	Maximum allowable HFC consuption (tonnes CO2e) as per SOR 2022-177
(2011 0-2013) Base line		
2019 to 2023	90%	16 207 916
2024 to 2028	60%	10 805 277
2029 to 2033	30%	5 402 639
2034 to 2035	20%	3 601 759
2036	15%	2 701 319

The product specific controls are targeted at products and equipment that are manufactured or imported that contain or are operated using HFC or its blends. It is important to mention that it also includes the production of different blends of HFC in country [12].

The regulation does not define specific HFC that are banned or provide any alternatives refrigerant for replacement. The regulation just provides limitations on refrigerant uses based on its GWP value. Therefore, HFC use are allowed if they are within the limits provided by its specific equipment and use. Appendix B: Product specific control with GWP limits and implementation dates provides the description and product specific controls by use and the time when the controls start [12].

It is also important to notice that the use and sale of equipment and product manufactured or imported before the control dates are not restricted [12].

4.1.3.2 SOR/2022-110

The SRR/2022-110 regulations address the emissions of HFCs by existing equipment. It places a limit on emissions during all phases of the equipment operations from installation, testing, calibration, and decommissioning and recycling activities [14]. The regulation is particularly concerned with reporting during these activities. SOR/2022-110 therefore establishes clear inventory reporting, activity logging, and release reporting requirements that always need to be maintained during the full lifecycle of any heat pump operation [14]. This legislation is closely aligned with BC provincial regulation 387/99, that addresses refrigerant emissions during operations activities.

4.1.3.3 Other legislation

The European Union has revised and approved the last amendment of its F-gas regulation (EU) 2024/573 in late 2024, in which it will seek to completely phase-out HFC by 2050 [15].

4.2 Current UBC Operations

The heat pumps currently installed throughout the campus operate using one of five third-generation refrigerants, as shown in figure 5. These refrigerants fall within the GWP range that the amendment specifies should be phased down. For details of the leakages associated with each of these refrigerants, see Appendix C: UBC Operations Leakage Data.

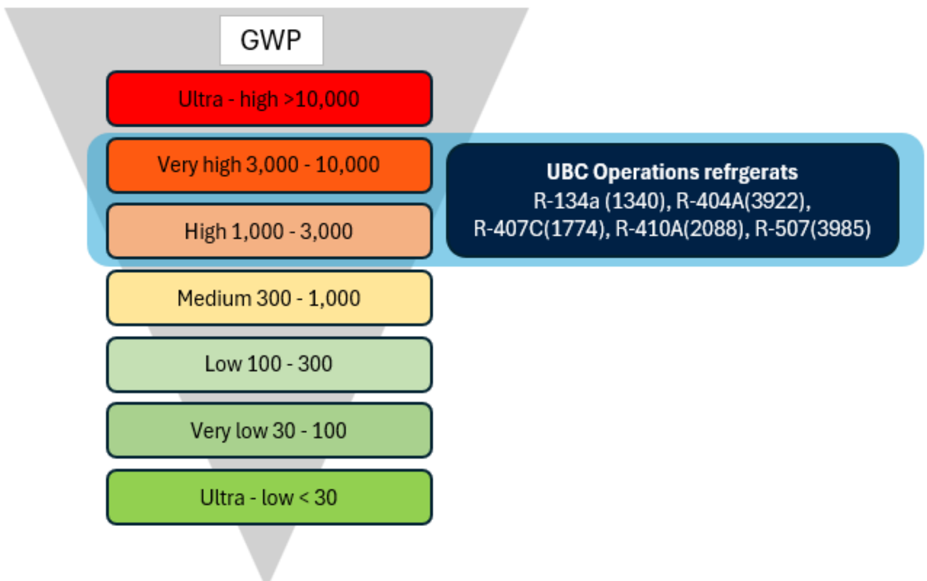

Figure 6. GWP spectrum for the Kigali amendment emissions calculations with relative placement of UBC refrigerant in use, adapted from [16]

4.2.1 Regulatory impact

The regulations described above do not have an immediate direct impact on UBC heat pump operations. Legacy equipment is exempt if installed prior to the implementation dates of the new regulations or the GWP limits.

The first impact on the UBC will occur when new equipment is needed for new buildings or to replace the current old equipment. At that time, the approach will depend on whether there is existing equipment on the market that meets UBC requirements, either imported or manufactured before the restrictions, or new equipment that uses HFC but within established limits.

Regardless of options, UBC's solution to continue using HFC equipment will be affected by bulk import limits, restricting refrigerant availability in the country.

4.3 Natural Refrigerant Alternatives

Natural refrigerants, also known as first generation refrigerants, are substances that occur naturally in the environment and have zero or minimal direct environmental impact [17]. Commonly examples include Carbon Dioxide (CO_2, R-744), Ammonia (NH_3, R717), Propane (R-290), Isobutane (R-600A), water, and air.

4.3.1 Performance Considerations

Since heat pumps rely on the phase change of refrigerants to absorb or release heat, the boiling point of a refrigerant is a critical technoeconomic factor. Water, with its high boiling point at atmospheric pressure (100 °C), and air, whose main components nitrogen and oxygen extremely low boiling points (−196 °C and −183 °C, respectively), are generally unsuitable for use in domestic heat pumps. This is due to their phase-change temperatures falling well outside typical operating ranges [18, 19].

Therefore, from a performance perspective, only the following four natural refrigerants are capable of industrial use: carbon dioxide (CO_2, R-744), ammonia (NH_3, R-717), propane (R-290), and isobutane (R-600A).

4.3.2 Environmental Considerations

Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) are primary reasons for shifting to natural refrigerants. Natural refrigerants have minimal environmental impact. Unlike HFCs (e.g., R-134a, R-410A), which have high GWPs, natural refrigerants do not contribute to ozone depletion and have negligible global warming effects (see Appendix E: Table of Natural Refrigerant Properties) [19, 20].

For details of manufacturing emissions associated with natural refrigerant production, see Appendix I: General Data used for LCA. In general, first-generation refrigerants have much lower manufacturing carbon intensities than those of third-generation refrigerants.

4.3.3 Safety Considerations

Table 2 lists the safety classifications of key natural refrigerants based on ISO 817.

Table 2. Safety Classification of first-generation refrigerants, adapted from [19].

Flammability	**Refrigerant Classification**	
Highly flammable	A3-HCs (R-290, R-600a)	B3
Flammable	A2	B2

Mildly flammable	A2L	B2L-Ammonia (R-717)
Non flammable	A1-CO_2 (R-744)	B1
Toxicity	Low Toxicity	High Toxicity

As shown above, some major downsides of first-generation refrigerants are their significant safety risks. Mitigating these risks is important for domestic applications. This can be done by identifying all the risks for each specific refrigerant and controlling them with various technical and organizational measures.

4.3.3.1 Flammability

Among natural refrigerants, hydrocarbons (R290, R600a) pose the most significant flammability risk. They are classified as A3 refrigerants, meaning they have high flammability but low toxicity. However, with the advancement of technology, flammability concerns can be well-mitigated in heat pump systems today. Therefore, flammability is not a reason to reject a substance for refrigerant purposes. To mitigate fire hazards, hydrocarbon-based heat pumps must include safety measures such as leak detection, proper ventilation, and explosion-proof components [20].

In Canada, the use of hydrocarbon refrigerants such as R-290 (propane) and R-600A (isobutane) in heat pump systems is governed by the CSA B52-13 Mechanical Refrigeration Code, which states that refrigerant amounts must not exceed 3 kg (6.6 lb). They must also be inspected by an approved testing laboratory [21]. If these regulations are followed, hydrocarbons can be safely used as refrigerants.

4.3.3.2 Toxicity

Ammonia is classified as B2L, indicating high acute toxicity. Exposure to 300 parts per million (ppm) is immediately dangerous to life and health [22]. In contrast, hydrocarbons and CO_2 pose minimal health risks. Aside from this, Ammonia is corrosive to materials like copper and its alloys. This necessitates the use of compatible materials in system components and the installation of pressure-relief valves, which must be replaced or recertified at intervals not exceeding five years [21].

To mitigate health risks, according to CSA B52-13, indoor ammonia systems must be housed in dedicated machinery rooms with proper ventilation, leak detection, and emergency controls. Ammonia vapor detectors must also automatically initiate ventilation and alarms when concentrations reach or exceed 300 ppm. System components must be constructed from materials resistant to ammonia's corrosive effects, mainly certain grades of steel. Furthermore, operators must be adequately trained and certified to handle ammonia systems [21].

4.3.3.3 High Pressure

CO_2 (R-744) is classified as an A1 refrigerant, indicating low toxicity and non-flammability. This makes it a highly attractive choice for heat pump applications. In addition to its outstanding safety profile, CO_2 has an exceptionally low GWP of 1. However, one of the most distinctive thermodynamic characteristics of CO_2 is its relatively low critical point at 31 °C, which causes the system to operate in a trans critical cycle. As a result, heat is typically released at high temperatures and pressures, often exceeding 100 °C and up to 10 MPa. A comparison of operating pressures across different refrigerants is shown Figure 7. While CO_2 heat pump systems demonstrate high efficiency in cold climates (typically below 5 °C), their performance tends to decline in warmer regions, presenting a notable operational challenge.

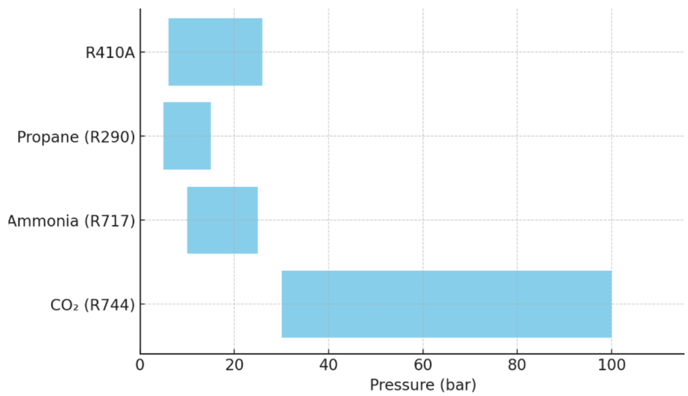

Figure 7. A comparison of operating pressures across different refrigerants

High-pressure operation requires the use of durable system components and reinforced piping, which substantially increases overall system costs. Stringent safety measures and continuous monitoring are also essential. Furthermore, the high heat rejection temperature of CO_2 systems can typically raise water temperatures up to 90 °C. This makes them less suitable for domestic applications and more appropriate for large-scale systems such as district heating or centralized hot water supply [19, 23].

4.3.4 Cost and Availability

Natural refrigerants cost significantly less per unit mass than synthetic alternatives. For example, one imperial pound of carbon dioxide refrigerant might cost as little as $1.58 USD, while the same amount of an HFC could cost more than $40 [19]. These cost savings can be significant for large, leak-prone equipment. However, despite these friendly market prices, the initial capital investments of natural refrigerant heat pumps can be higher than those of their synthetic counterparts because of the need for risk mitigation [19]. Due to their improved system designs, enhanced material resilience, and additional safety measures, low GWP refrigerant-based systems generally cost more than conventional refrigerant systems, making businesses hesitant, as ordinary residents are unwilling to bear excessively high heating costs. Hydrocarbons, however, often offer slightly lower-cost investments due to their lower acute toxicity and lower pressure requirements [19].

Overall, CO_2 and ammonia systems have high initial capital costs but offer long-term efficiency benefits, while hydrocarbons provide a cost-effective solution for residential and commercial applications. For detailed cost data, see Appendix E: Table of Natural Refrigerant Properties.

4.3.5 Suitable Applications

Hydrocarbons are particularly well-suited for small-scale heat pumps. With proper risk management measures in place, they can also be applied in collective systems, such as blocks of houses or apartment complexes, and in industrial settings.

Carbon dioxide is ideal for applications requiring higher supply temperatures, including domestic hot water and central heating systems with stratified thermal buffers. It is commonly used in both small and large heat pumps, has been widely adopted in Europe, Asia, and emerging markets in North America.

Ammonia, due to its toxicity and flammability, is generally not recommended for residential heat pump use. Instead, it is primarily deployed in industrial and commercial systems where stringent safety protocols can be ensured.

It is crucial to note that natural refrigerants cannot simply be retrofitted into existing heat pump systems. Each application requires specific safety-focused design modifications to ensure proper and secure operation.

4.4 Synthetic Refrigerant Alternatives

4.4.1 Technoeconomic Considerations

As a response to the phase out of third generation refrigerants, many HFOs were developed and optimized to replace specific HFCs or CFCs. This was done by synthesizing compounds with similar parameters such as critical temperature and boiling point. In particular, the ability of one refrigerant to directly replace another in an existing system is mainly dependent on their normal boiling points being similar [24]. This is because the normal boiling point of the refrigerant will dictate the upper and lower temperatures at which the heat pump must operate [24]. Therefore, using a refrigerant with a similar boiling point will minimize changes to the operational changes of the system, which can prevent the need for material or equipment changes. However, some second or third generation refrigerants have properties that cannot be closely replicated by a pure HFO. For this reason, many fourth-generation refrigerants are also blends of HFCs and HFOs, created to match the performance of a given CFC or HFC as closely as possible [24]. As seen in the comprehensive table in Appendix F: Table of pure HFO refrigerant properties and Appendix H: Table of fourth generation refrigerant blends' properties, the COPs and volumetric capacities (Q_v) are very close to those of the replaceable HFC, highlighting the negligible difference in performance. Therefore, by selecting an appropriate fourth generation refrigerant, the HFC refrigerants being utilized at UBC could be replaced with a fourth-generation refrigerant with no changes to existing heat pump equipment.

Since second and third generation refrigerants are directly retrofittable by certain fourth generation refrigerants, capital cost investments into new equipment can be avoided. This is a major advantage of utilizing fourth generation refrigerants in comparison to first generation refrigerants. However, the market price of the fourth-generation refrigerants themselves can be up to 4 times higher than their third-generation counterparts (see Appendix H: Table of fourth generation refrigerant blends' properties). Nevertheless, as fourth generation refrigerants are still relatively new and manufacturing methods are continuously improving, the price of these compounds is expected to drop significantly in the coming years [25].

4.4.2 Environmental Considerations

As fourth generation refrigerants emerged from a need to address the environmental challenges of their second and third generation counterparts, their environmental impacts are quite low. The low GWP of HFOs is attributed to their lower atmospheric lifetime (most on the order of days) [26]. This shortened lifespan is due to the high reactivity between olefins and the radical species in the troposphere, resulting in a low accrual in the stratosphere [26]. Most HFOs have GWPs on the order of 102, significantly lower than those of HFCs, which are often in the thousands. However, fourth generation refrigerant blends can have higher GWPs due to their

HFC content (see Appendix H: Table of fourth generation refrigerant blends' properties. Nonetheless, GWP values in this range still present significant environmental risk and may be subject to regulation in some contexts and jurisdictions (see Section 4.1 Regulatory Considerations). Therefore, HFOs considered to be leading in the global warming potential category are those with GWP under 10 – namely, R-1224yd(Z), R-1233zd(E), R-1234ze(E), R-1234yf, and R-1336mzz(Z). In terms of Ozone Depletion Potential, HFOs are considered to have a negligible impact, resulting in ODP values of 0.

Due to their relatively recent development, there is limited data available regarding the impacts of HFO refrigerants during their manufacturing stage. However, three patents published within the last 10 years outline some industrial synthesis routes that can be used to produce multiple HFOs [27, 28, 29]. In general, HFOs are produced by subjecting HFCs to dehydrofluorination under high temperature and with a catalyst (see Figure 8). Carbon dioxide is produced as a side-product of the reaction, but the HFC feed should also be diluted with carbon dioxide to maximize conversion. Based on the data available, it is estimated that 1.9 mol CO_2 are produced per mol of HFO produced on average, and 97% of the CO_2 can be captured for reuse in the feed [28]. From this, it is estimated that 1.02 g CO_2 are released per g HFO during the HFO manufacturing process. Additionally, while there is evidently a large amount of heat input required for this process due to the high temperatures needed, there was no data available on typical heat inputs or even typical reactor materials used for such processes. For these reasons, environmental impacts related to heating were not included in the analysis.

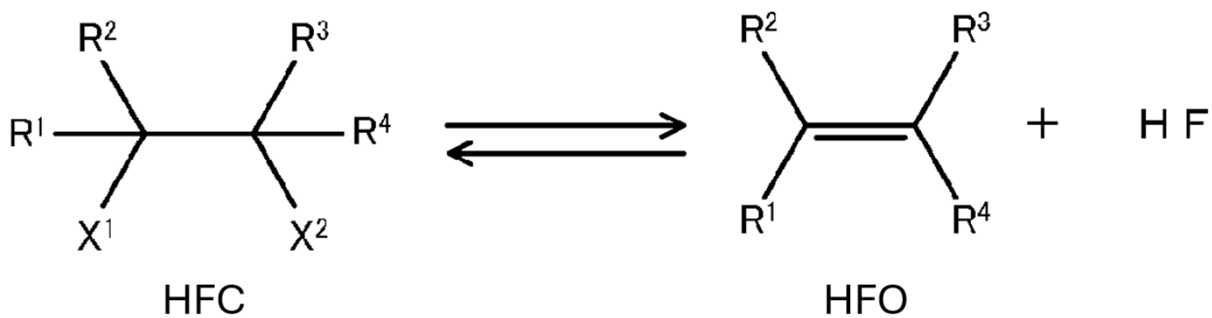

Figure 8. HFO Synthesis from HFCs [28]

In terms of disposal, the vast majority of fourth generation refrigerants are reclaimed at the end of a heat pump's life [30]. This is because the purity of the refrigerant is not significantly altered during the operation of the heat pump [30]. The first points of failure of a heat pump are often its electrical and mechanical components; while refrigerants leaks are common, the integrity of the refrigerant itself within the system is not significantly impacted [31]. The small amount of refrigerant that is deemed no longer suitable for use after a heat pump's disposal will be incinerated or potentially purified for reuse [30]. However, the percentage of fourth generation refrigerants reclaimed, incinerated, and purified vary widely between jurisdictions, and concrete data is not available for this new class of refrigerants. For this reason, refrigerant disposal was not included in this analysis.

4.4.3 Safety Considerations

In general, HFOs are more flammable than their third-generation counterparts. The reason for this is that there is a trade-off between a compound's global warming potential and flammability. The heightened reactivity that shortens the compounds' lifetimes also translates to a higher reactivity in the presence of heat, i.e. flammability. Most HFOs are classified with a flammability of 2L, higher than that of most HFCs and CFCs (classified as 1), but lower than those of many 2nd generation refrigerants (classified as 2 or 3). Nevertheless, flammability classifications of 2L present safety considerations that may require additional controls and redundancies to mitigate them depending on the location of the heat pumps [32].

For adequate heat pump operation with HFOs, moderate to high pressure ratios are required. Generally, pressure ratios around 2-3 are common for such refrigerants. However, some fourth-generation refrigerants require pressure ratios of up to 12 in some contexts (see Appendix H: Table of fourth generation refrigerant blends' properties). Nevertheless, these pressure considerations are much lower than those of some first-generation refrigerants, particularly carbon dioxide (see Section 4.3.3.3 High Pressure). While the pressure ratios can be higher than those of some second or third generation refrigerants, they are not so significant such that major changes need to be made to existing heat pump equipment [24].

4.4.4 Health Considerations

In terms of short-term toxicity, HFOs are not very acutely toxic. As seen in Appendix F: Table of pure HFO refrigerant properties and Appendix H: Table of fourth generation refrigerant blends' properties, most fourth generation blends have toxicity ratings of 'A'. However, a major concern of HFOs is that they can decompose in the atmosphere to form trifluoroacetic acid (TFA). Additionally, some HFOs such as R-1234yf produce hydrofluoric acid (HF). TFA is categorized as a Per- and PolyFluoroAlkyl Substance (PFAS) which is persistent, prone to accumulation in water and in the human body, and may result in health impacts such as liver damage, reproductive harm, and carcinogenicity [33]. The Cancer Slop Factor (CSF) for TFA is 0.07 $(mg/kg/day)^{-1}$ [34]. In contrast, HF is an acutely toxic compound, with a permissible exposure limit (PEL) of 3 ppm over 8 hours and no reported CSF [35]. However, as the breakdown of HFOs is estimated to occur within a few days after exposure to atmospheric gases, the acute toxicity of daughter compounds is not believed to be significant [26]. Therefore, the long-term toxicity impact of HFOs considered in the analysis will be limited to that due to TFA produced.

4.4.5 Regulatory Considerations

As the development of fourth generation refrigerants was inspired by the need to find low ODP, low GWP refrigerants, they are not impacted by the Montreal Protocol, Kigali Amendment, or any resulting federal and provincial regulations. However, their long-term toxicity concerns have inspired regulations in other jurisdictions. In the EU, five countries put forward a proposal in 2023 to the European Chemicals Agency (ECHA) to amend the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) regulation [36]. The aim of the proposal is to reduce the emission of PFAS into the environment. The proposal specifically names the following HFOs: R1234yf, R1234ze, and R1233zd [36]. Therefore, should the proposal come into effect, fourth-generation refrigerants containing these compounds could become restricted. Nonetheless, the proposal is still in the review stages, and policy makers are deciding on how best to mitigate the risks of these refrigerants (i.e., through increased monitoring, a phase-down approach, or a complete phase-out) [37]. The proposal will also not affect Canadian jurisdictions. However, such a regulation may inspire similar actions to be taken by other countries, including Canada, in coming years.

5. Impact Assessment (Life Cycle Analysis)

5.1 General Approach

Using the leakage data of refrigerants at UBC, an average leakage rate for each refrigerant was estimated. This was done by averaging the four years of available data (see Appendix C: UBC Operations Leakage Data). It is assumed that the leakage rate is equivalent to the amount of refrigerant that must be replaced in the heat pump systems each year. From this, the global warming impact and ozone depletion impact during the use phase (Scope 1) can be calculated by multiplying the GWP and ODP data and the average leakage rate. Likewise, the background manufacturing global warming impact (Scope 2) can be calculated based on these average leakage rates and the manufacturing intensity data in kg CO_2-eq. per kg refrigerant. The estimated refrigerant cost can also be calculated by multiplying the average leakage rates and the market prices. For estimates of capital costs, these values were converted into an equivalent annual cost using a discount rate of 5% and an estimate heat pump lifetime of 10 years.

Variations in COP were accounted for using an estimated cost of electricity; an estimated 15 buildings on UBC campus utilize heat pumps, with an estimated heat requirement of 1.5 MW per building [38, 39]. Due to a lack of other data, it was assumed that the proportion of refrigerants used to satisfy this total heating requirement is equivalent to the proportion of average leaks observed. Therefore, the electricity requirement (W) corresponding to each refrigerant can be calculated as follows:

$$COP = \frac{Q}{W} \rightarrow W = \frac{Q}{COP},$$

$$where\ Q\ is\ the\ proportion\ of\ the\ heating\ demand\ based\ on\ the\ leakage\ proportion.$$

Furthermore, the electricity price in BC is estimated to be 0.1352 CAD/kWh [40]. Using a conversion rate of 0.70 USD per CAD, the price of electricity can then be determined. Additionally, using an electricity intensity factor of 9.9 tCO_2-eq. per GWh, the global warming impact due to electricity requirements (Scope 2) can be calculated [41].

Transportation emissions were estimated assuming all refrigerants were purchased from Koura, a multinational refrigeration company that manufactures a variety of HFOs and HFCs. Their manufacturing facility is in St. Gabriel, Louisiana, USA, which is located 4344 km from UBC [42]. Although they manufacture a limited number of natural refrigerants, the same manufacturing location was assumed for this category for simplicity. It was assumed that all refrigerants would be delivered by transport truck, with an average transportation emission intensity of 75.39 g/km/tonne [43]. No reverse trip was considered for transportation.

To evaluate the flammability and short-term toxicity impacts, a more qualitative approach was taken for simplicity. The ASHRAE designations for refrigerants, as described in Table 2, were used to classify each refrigerant in terms of flammability and toxicity (a toxicity of A was translated to a score of 1, and a toxicity of B was translated to a score of 2). These classifications were simply multiplied by the leakage in kg/year to obtain a yearly impact. In contrast, the long-term toxicity of refrigerants, specifically the fourth-generation refrigerants, was assessed using the CSF of TFA (see Section 4.4.4 Health Considerations). It is assumed that only HFOs can degrade into TFA based on the literature that was consulted; therefore, this CSF was also multiplied by the percentage of HFO content for fourth generation refrigerant blends. This was then multiplied by an average intake factor for North America of 37.8 mg/kg body weight [44] and finally multiplied by the emission converted into kg/day. The calculation is summarized by the equation below, with the units in brackets:

$$Carcinogenic\ Impact\ [-] = \%\ HFO * CSF\ [1/(mg/kg/day)] * iF\ [mg/kg] * emission\ [kg/day]$$

Note that there was not a specific regulatory impact included in the analysis. However, as explained in Section 4.2.1 Regulatory impact, it is possible to operate using first, third, or fourth generation refrigerants without being in direct contradiction of regulatory requirements due to the phase-down approach of the Kigali amendment. Therefore, it is believed that the environmental impact indicators give a sufficient insight into the regulatory risks associated with each option, since all regulations currently in place are concerned with either global warming impact or ozone depletion impact.

5.2 Weighting Factors

The weighing of the impact factors was decided by the team using a hierarchical approach. First, the impacts were separated into three categories: environmental, techno-economic, and social. Environmental impacts were given the largest weight of 65%, as most existing regulations are concerned with this category. From this, the global warming impact was given a 40% weight, and the ozone depletion impact was given a 25% weight. This is because the focus of the project was to look at low global warming potential refrigerants, and therefore it was thought that this impact was the most relevant. The techno-economic impact category was given a 20% weight in total, and the social impact category was given a 15% weight. This was done because, as a public institution, it is likely that cost would be a primary concern for UBC. Under the social impact category are the long-term health, short-term health, and flammability (safety) indicators. The long-term health impact was given a slightly higher weight in comparison to the other two impacts, as it is believed that short-term health and safety impacts can be well mitigated using engineering controls and safety protocols. The weighting factors are summarized in Figure 9 below:

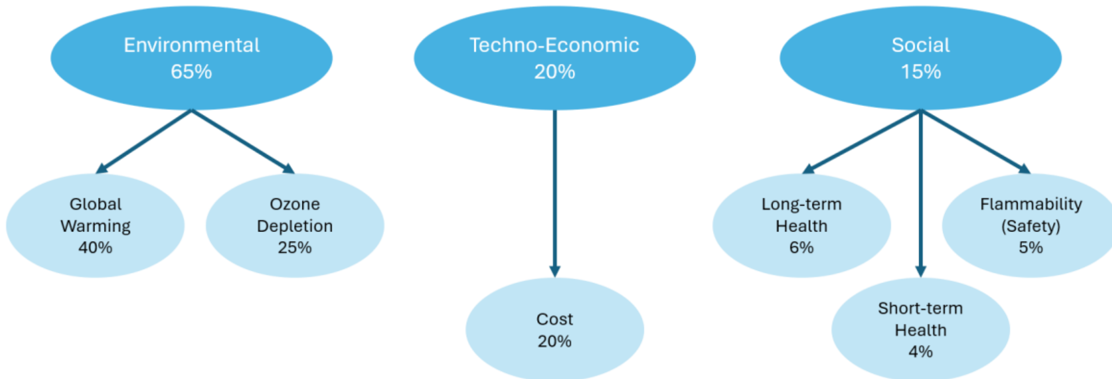

Figure 9. Consequential LCA Weighting Factors

Note that prior to weighing, all scores were normalized from a scale of 1 to 10, with 10 representing the highest impact of the compared options. Normalization was done according to the equation below:

$$Normalized\ score = \frac{Impact}{Max\ Impact\ in\ Category} * 10$$

5.3 Internal LCA for Natural Refrigerants

As outlined in the methodology, internal LCAs were carried out prior to the final LCA comparing current UBC operations to both first and fourth generation alternatives. For the natural refrigerants, the purpose of this LCA is to select the preferred natural refrigerant that will move on to the final LCA. Therefore, for the purposes of this analysis, it is assumed that should UBC decide to shift to 1st generation refrigerants, all refrigerants currently used would be replaced by a single natural refrigerant. While this may be a very simplified approach to the analysis, it makes sense on some level as a transition to 1st generation refrigerants would require the existing heat pumps at UBC to be replaced with equipment that is compatible with natural refrigerants. Furthermore, since many of these 1st generation refrigerants are more suited to large-scale, centralized systems, it makes sense that all currently used refrigerants would be replaced by a single refrigerant. For example, on the UBC Okanagan campus, a single CO_2 heat pump is used to supply all heat pump-related heating demands [39].

The normalized results of the internal LCA for natural refrigerants are summarized in Figure 10 below. Calculation details are available in Appendix J: Natural Refrigerant Internal LCA Data and Calculations.

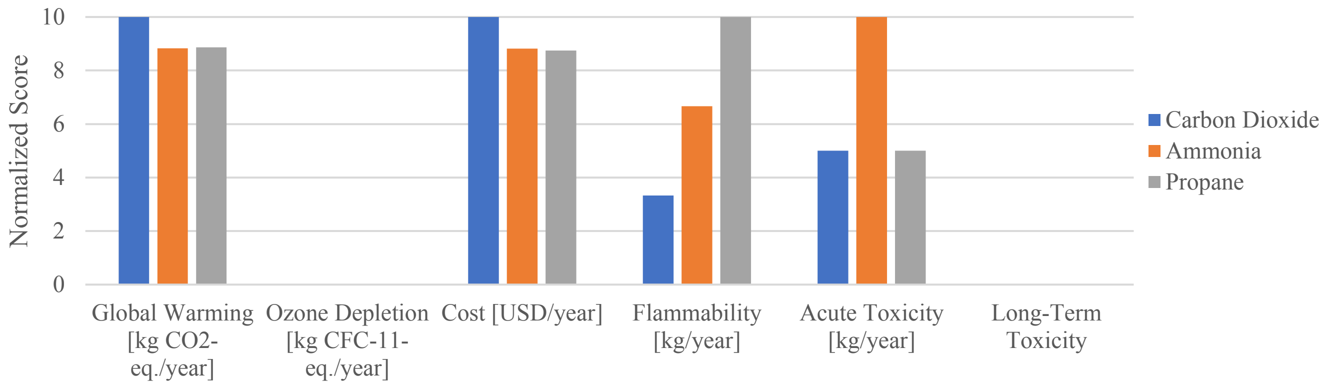

Figure 10. Normalized Scores of Internal LCA for First Generation Refrigerants

After applying the weighting factors, it is found that propane is ranked as the first-generation refrigerant having the lowest impact, with ammonia as a close second.

5.4 Internal LCA for Synthetic Low GWP Refrigerants

For fourth-generation refrigerants, the aim of the internal LCA was to select the best replacement for each third-generation refrigerant currently in use at UBC. Since each fourth-generation refrigerant can only replace certain third-generation counterparts, the first step of this analysis was to identify which fourth-generation refrigerant could replace each refrigerant in use at UBC (see Appendix H: Table of fourth generation refrigerant blends' properties). From this, the preferred fourth generation replacement for each third-generation refrigerant was determined using the same approach and weighting factors.

Figure 11 through Figure 15 below summarize the normalized results of the internal LCA for fourth-generation refrigerants. Calculation details are available in Appendix K: Synthetic Refrigerant Internal LCA Data and Calculations.

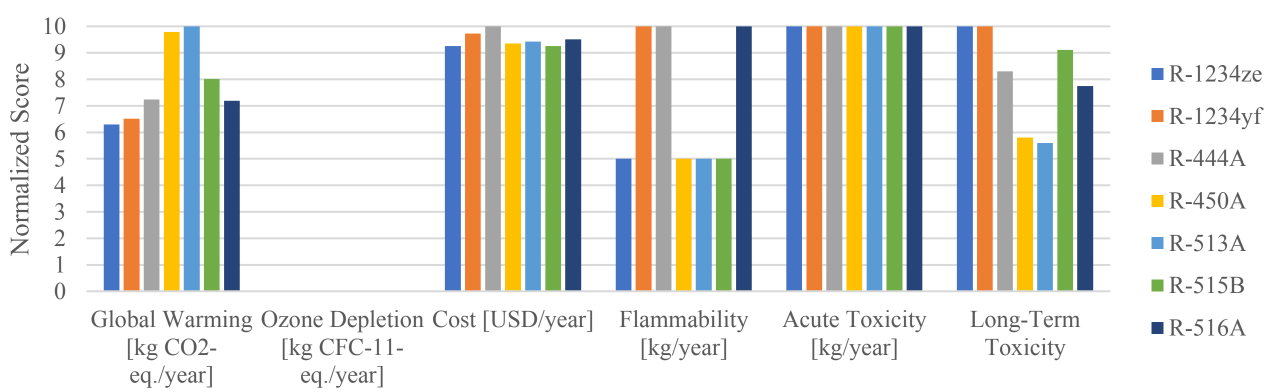

Figure 11. Normalized Scores for R-134A Fourth Generation Replacements

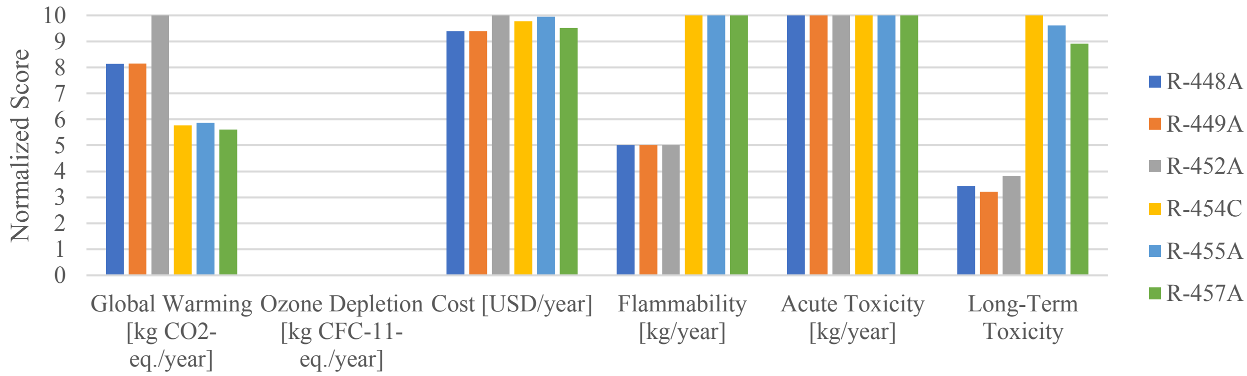

Figure 12. Normalized Results for R-404A Fourth Generation Replacements

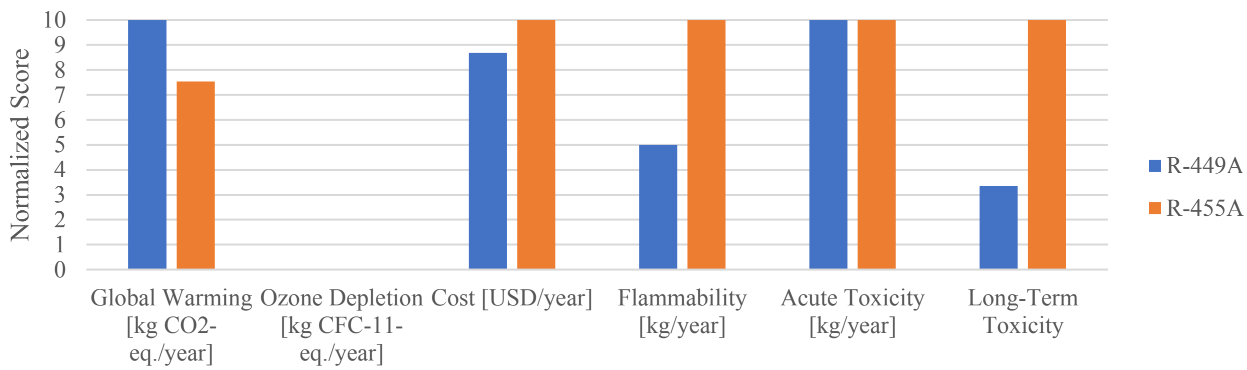

Figure 13. Normalized Results for R-407C Fourth Generation Replacements

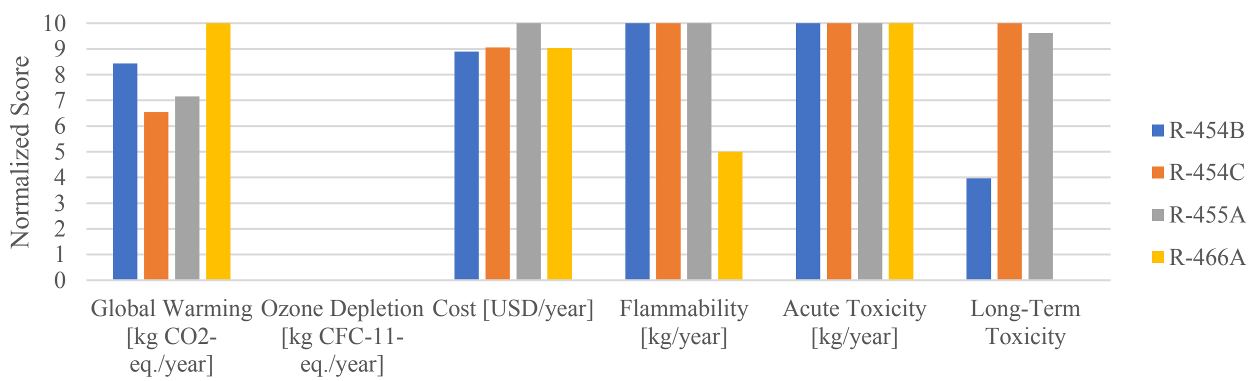

Figure 14. Normalized Results for R-410A Fourth Generation Replacements

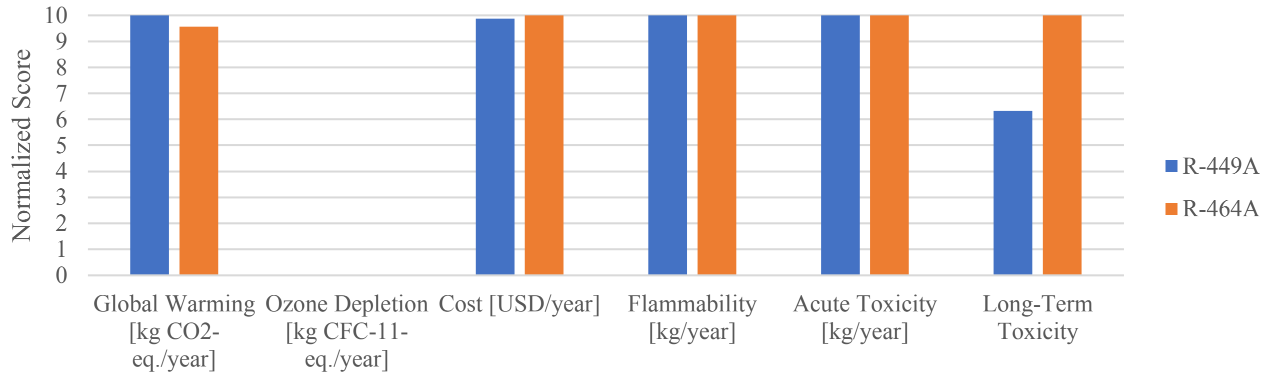

Figure 15. Normalized Scores for R-507 Fourth Generation Replacements

After applying the weighting factors, the fourth-generation refrigerant selected to replace each HFC in use at UBC is summarized in Table 3 below:

Table 3. Fourth generation refrigerant replacements for HFCs at UBC, as decided by the LCA

R-134A Replacement	R-404A Replacement	R-407C Replacement	R-410A Replacement	R-507 Replacement
R-234ze	R-457A	R-455A	R-454C	R-449A

5.5 Overall LCA

Based on the results of the internal LCA, the base case scenario of current UBC operations was compared to a replacement with the fourth-generation refrigerants in Table 3 (Scenario 1), and a complete replacement of all refrigerants with propane (Scenario 2). The normalized results of analysis are summarized in Figure 16 below.

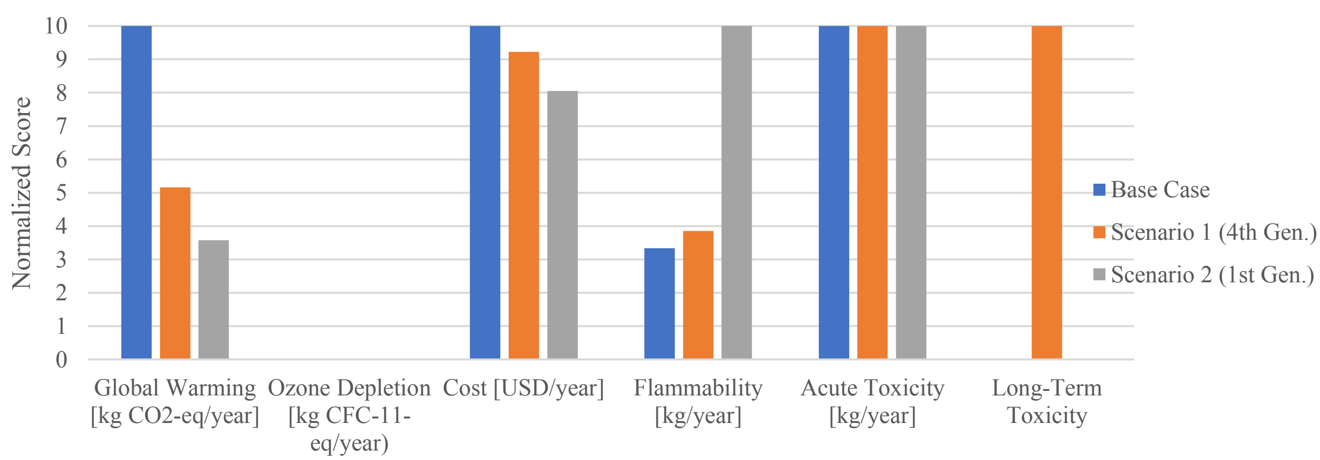

Figure 16: Normalized Final LCA Results

As expected, the results indicate that the base case scenario has the highest global warming impact. Much of this is attributed to the high GWP of the HFCs currently in use at UBC, although their manufacturing carbon intensity also plays a role. All cases have negligible ozone depletion impact and identical acute toxicity impact. Also expected are the superior flammability impacts of the natural refrigerant, and the superior long-term toxicity impact of the fourth-generation refrigerants. Interesting, however, are the cost results of the analysis. The data used suggests that, even despite the high capital costs incurred by the natural refrigerant scenario, the adjusted cost per year of operations would be the lowest. This is mainly due to the higher average COP of propane as a refrigerant; although the differences may not seem large, even small improvements in COP can make a great difference due to the large power requirements of the heat pumps at the university. Thus, the high capital investment for these systems is compensated by the electricity savings incurred during their lifetime.

6. Interpretation and Recommendations

The results of the LCA above suggest that UBC should prioritize first-generation refrigerants on their decarbonization journey, with propane appearing to be the most favourable option. This is in accordance with much of the literature that was consulted during this project, which suggests that heat pumps with natural refrigerants have been growing in popularity due to technological advances that improve safety risk mitigation [3]. Furthermore, many sources have also suggested propane as the best candidate for residential heat pump systems [2, 3, 20]. While fourth-generation refrigerants result in a lower impact score than the base case, the analysis still shows them to be inferior to the propane scenario. HFOs and their blends could therefore be used as transitional tools in preparation for the large capital investments that first-generation refrigerants would require.

However, it is important to consider the limitations associated with the impact assessment. One main uncertainty in the analysis is associated with the economic analysis. Many of the capital costs and refrigerant market prices obtained are preliminary and have been estimated based on a variety of sources. As available information on costs can be limited, it is crucial for a more detailed economic analysis to be conducted using UBC's suppliers. Similarly, the transportation analysis conducted was very preliminary and based on the refrigerants all being sourced from one supplier. These calculations should be redone using UBC's chosen suppliers.

Additionally, many assumptions were made about the heat pump power demand at UBC, as this data was not available for the study. The assumption that the proportion of leaks at UBC is equivalent to the proportion of refrigerants in use may not be valid whatsoever, and proper data on the powers and refrigerants used by each heat pump is critical to refine the analysis.

Furthermore, there is much uncertainty associated with the long-term toxicity of fourth generation refrigerants, as their degradation pathways into TFA has not been studied extensively. This is one of the reasons why a low weighting factor was placed on this impact category. In terms of acute toxicity and flammability, these impacts were done on a qualitative level due to time limitations (i.e., permissible exposure limits (PEL) and Lower Flammability Limits (LFL) were not used to differentiate between compounds, and they were simply categorized as having "low" or "high" toxicities and flammabilities). In a subsequent analysis, these factors should be investigated in more detail.

In addition, more thought should be given to the weighting factors in a subsequent analysis to ensure they are representative of the priorities of UBC. A sensitivity analysis could be conducted for a better understanding of how the weighting factors impact the results of the analysis.

Finally, the number of scenarios considered in the analysis were quite limited. In a subsequent analysis, a methodology should be developed to consider scenarios where only a portion of heat pump systems are retrofitted/replaced, or potentially scenarios where heat pump systems are gradually replaced with natural refrigerant heat pumps as they reach their end of life. In these cases, the disposal of the systems and refrigerants could be valuable to include.

Nevertheless, our recommendation is for UBC to consider replacing existing systems with natural refrigerant heat pumps, particularly those systems that are close to reaching their end of life. These systems, while requiring high capital investment, are shown to pay off over time due to their high COPs, low regulatory risk, low environmental impacts, and low cost of refrigerant. In addition, it is believed that many of the acute health and safety risks posed by these systems can now be well mitigated with emerging technologies. Therefore, these risks are far less of a concern in comparison to when these refrigerants emerged in the late 1800s.

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8. Appendices

Appendix A: Table of GWP for refrigerants impacted by the Kigali Amendment

Group	Fluid	GWP
HFCs	HFC-23	14 800
	HFC-32	675
	HFC-41	92
	HFC-125	3 500
	HFC-134	1 100
	HFC-134a	1 430
	HFC-143	353
	HFC-143a	4 470
	HFC-152a	124
	HFC-227ea	3 220
	HFC-236cb	1 340
	HFC-236ea	1 370
	HFC-236fa	9 810
	HFC-245fa	1 030
	HFC-365mfc	794
	HFC-4310mee	1 640
HCFCs	HCFC-22	1 810
	HCFC-123	77
	HCFC-124	609
	HCFC-141b	725
	HCFC-142b	2 310
CFCs	CFC-11	4 750
	CFC-12	10 900
	CFC-113	6 130
	CFC-114	10 000
	CFC-115	7 370
HFOs	HFO-1234yf	4
	HFO-1234ze	7
	HFO-1233zd	4
	HFO1336mzz	9
Other	Ammonia	0
	CO_2	1
	Propane	3
	Iso-butane	3
	Pentane	3
	Propylene	2

Blend	GWP
R-401A	1 182
R-401B	1 288
R-402B	2 416
R-403A	3 124
R-403B	4 457
R-404A	3 922
R-407A	2 107
R-407C	1 774
R-407F	1 825
R-408A	3 152
R-409A	1 585
R-409B	1 560
R-410A	2 088
R-411A	1 597
R-412A	2 826
R-413A	2 053
R-415A	1 507
R-415B	546
R-416A	1 084
R-417A	2 346
R-418A	1 741
R-419A	2 967
R-420A	1 536
R-421A	2 631
R-421B	3 190
R-422A	3 143
R-422B	2 526
R-422C	3 085
R-422D	2 729
R-423A	2 280
R-424A	2 440
R-425A	1 505
R-426A	1 508
R-427A	2 138
R-428A	3 607
R-429A	13
R-430A	94
R-431A	37
R-432A	2
R-434A	3
R-433B	3
R-433C	3
R-434A	3 245
R-435A	26

Blend	GWP
R-436A	3
R-436B	3
R-437A	1 805
R-438A	2 265
R-439A	1 983
R-440A	144
R-441A	3
R-442A	1 888
R-444A	93
R-444B	296
R-445A	135
R-446A	461
R-447A	583
R-448A	1 387
R-449A	1 397
R-449B	1 412
R-450A	605
R-451A	149
R-451B	164
R-452A	2 140
R-452B	698
R-453A	1 765
R-454A	239
R-454B	466
R-454C	148
R-455A	148
R-456A	687
R-457A	139
R-458A	1650
R-459A	460
R-459B	145
R-460A	1352
R-461A	2103
R-502	4 657
R-507A	3 985
R-508A	13 214
R-508B	13 396
R-510A	1
R-511A	9
R-512A	189
R-513A	631
R-513B	596
R-514A	7
R-515A	939

Note: The color code is as per figure 4 in main report. From *GWP, CO2(e), and the Basket of HFCs: Kigali Fact Sheet 3.* UN Environment Programme.

Appendix B: Product specific control with GWP limits and implementation dates

SCHEDULE 1.1

(Subsections 64.4(1) and (2) and 65.02(1))

Products Containing or Designed to Contain an HFC Used as a Refrigerant

	Column 1	Column 2	Column 3	Column 4
Item	Product	Use	Date	Global Warming Potential (GWP) Limit of Refrigerant Used in Product
1	Stand-alone medium-temperature refrigeration system: self-contained refrigeration system with components that are integrated within its structure and that is designed to maintain an internal temperature ≥ 0°C	(a) Commercial or industrial	January 1, 2020	1 400
		(b) Residential	January 1, 2025	150
2	Stand-alone low-temperature refrigeration system: self-contained refrigeration system with components that are integrated within its structure and that is designed to maintain an internal temperature < 0°C but not < -50°C	(a) Commercial or industrial	January 1, 2020	1 500
		(b) Residential	January 1, 2025	150
3	Centralized refrigeration system: refrigeration system with a cooling evaporator in the refrigerated space connected to a compressor rack located in a machinery room and to a condenser located outdoors, and that is designed to maintain an internal temperature at ≥ -50°C	Commercial or industrial	January 1, 2020	2 200
4	condensing unit: refrigeration system with at a cooling evaporator in the refrigerated space connected to a compressor and condenser unit that are located in a different location, and that is designed to maintain an internal temperature at ≥ -50°C	Commercial or industrial	January 1, 2020	2 200
5	chiller: refrigeration or air-conditioning system that has a compressor, an evaporator and a secondary coolant, other than an absorption chiller	Commercial or industrial	January 1, 2025	750
6	mobile refrigeration system: refrigeration system that is normally attached to or installed in, or operates in or with a means of transportation	Commercial or industrial	January 1, 2025	2 200

Appendix C: UBC Operations Leakage Data

	GHG Emissions (tons)						Amount of refrigerants leak (kg)				
Calendar Year	HFC R -134a (tCO2e)	HCF R-404a (tCO2e)	HCF R-407c (tCO2e)	HFC R-410a (tCO2e)	HFC R-507 (tCO2e)		HFC R -134a (kg)	HCF R-404a (kg)	HCF R-407c (kg)	HFC R-410a (kg)	HFC R-507 (kg)
2020	138	5	0	683	176		97	1	0	327	44
2021	552	4	0	18	0		386	1	0	9	0
2022	33	100	0	125	8		25	14	0	65	1
2023	397	656	37	90	0		305	90	23	47	0

Appendix D: Table of Third Generation Refrigerant Properties

Refrigerant	Safety Class (Toxicity and Flammability)	GWP (100-year)	COP (average)	ODP (100-year)	Normal Boiling Point (°C)	Market Price (USD/lb)	Reference
R-134A	A1	1430	4.5	0	-26.1	$27.00	[45], [46], [47]
R-404A	A1	3922	1.8	0	-46.0	$37.50	[45], [46], [48]
R-407C	A1	1774	2.0	0	-43.6	$42.50	[45], [46], [49]
R-410A	A1	2088	4.8	0	-48.6	$21.00	[45], [46], [50]
R-507	A1	3985	1.8	0	-46.7	$40.00	[45], [46], [51]

Appendix E: Table of Natural Refrigerant Properties

Refrigerant	Safety Class (Toxicity and Flammability)	Pressure Ratio	GWP (100-year)	COP	Market Price	Estimated Capital Investment [CAD/MW]	Reference
CO_2 (R-744)	A1	Up to 100	1	2.4-3.5	$2.00-5.00	$36,000	[19], [45], [70], [71]
NH_3 (R-717)	B2L	Up to 25	0	3.0-4.0	$4.00-6.00	$30,000	[19], [45], [70], [71]
Propane (R-290)	A3	Up to 15	<5	3.5-4.5	$7.00-10.00	$14,782	[19], [45], [70], [71]
Isobutane (R-600a)	A3	No data	<5	3.0-4.0	$7.00-10.00	No data	[19], [45], [70], [71]

Appendix F: Table of pure HFO refrigerant properties

Refrigerant	Safety Class (Toxicity and Flammability)	Pressure Ratio	GWP (100-year)	Replaceable HFC Refrigerants	COP relative to replaceable HFC	Qv relative to replaceable HFC	Normal Boiling Point (C)	Market Price	Retro-fittable at UBC?	Reference
R-1132a	A2	~4.4	3	R-23, R-508, R-170	~1.416 (R-170)	>0.80 (R-508)	-83.0	No data	No	[54], [55], [56]
R-1224yd	A1	3.1	1	R-123	0.977	1.55	14.6	No data	No	[24]
R-1233zd	A1	2.7	3.88	R-123	0.990	1.39	29.0	No data	No	[24]
R-1234ze	A2L	2.7	7	R-134A	0.993	0.74	-19.0	$52.50	Yes	[24]
R-1234yf	A2L	2.5	4	R-134A	0.957	0.94	-29.5	$121.88	Yes	[24]
R-1336mzz	A1	~5.0	18	R-245fa	0.950	0.88	33.4	No data	No	[53], [57], [58], [59]

Appendix G: List of refrigerant blends and their compositions

Refrigerant	Description	Composition (mass)
R-404A	HFC Blend	R-125/143a/134a (44/52/4)
R-407C	HFC Blend	R-32/125/134a (23/25/52)
R-410A	HFC Blend	R-32/125 (50/50)
R-444A	HFO/HFC Blend	R-32/152a/1234ze(E) (12/5/83)
R-445A	HFO/HFC Blend	R-744/134a/1234ze(E) (6/9/85)
R-448A	HFO/HFC Blend	R-32/125/1234yf/134a/1234ze(E) (26/26/20/21/7)
R-449A	HFO/HFC Blend	R-32/125/1234yf/134a (24.3/24.7/25.3/25.7)
R-450A	HFO/HFC Blend	R-134a/1234ze(E) (42/58)

R-452A	HFO/HFC Blend	R-32/125/1234yf (11/59/30)
R-454B	HFO/HFC Blend	R-32/1234yf (68.9/31.1)
R-454C	HFO/HFC Blend	R-32/1234yf (21.5/78.5)
R-455A	HFO/HFC Blend	R-744/32/1234yf (3.0/21.5/75.5)
R-457A	HFO/HFC Blend	R-32/1234yf/152a (18/70/12)
R-464A	HFO/HFC Blend	R-125/R-1234ze/R-227ea/R-32 (27/40/6/27)
R-466A	HFC/halomethane Blend	R-32/125/13I1 (49/11.5/39.5)
R-502	HFC/CFC Blend	R-22/115 (48.8/51.2)
R-513A	HFO/HFC Blend	R-1234yf/134a (56/44)
R-514A	HFO Blend	R-1336mzz(Z)/1130(E) (74.7/25.3)
R-515B	HFO/HFC Blend	R-1234ze(E)/227ea (91.1/8.9)
R-516A	HFO/HFC Blend	R-1234yf/134a/152a (77.5/8.5/14.0)

Appendix H: Table of fourth generation refrigerant blends' properties

Refrigerant	Safety Class (Toxicity and Flammability)	Pressure Ratio	GWP (100-year)	Replaceable HFC Refrigerants	COP relative to replaceable HFC	Qv relative to replaceable HFC	Normal Boiling Point (°C)	Market Price	Retro-fittable at UBC?	Reference
R-444A	A2L	~4.2	88	R-134A	0.918	0.74	-30.0	$47.52*	Yes	[60], [61]
R-445A	No data	No data	117	No data	No data	No data	-49.2	No data	No	[63]
R-448A	A1	10.9	1494	R-404A	1.058	0.98	-46.3	$33.13	Yes	[24]
R-449A	A1	10.9	1504	R-404A, R-507A	1.058	0.97	-45.9	$33.62	Yes	[24], [53]
R-450A	A1	5.2	643	R-134A	0.980	0.85	-23.6	$34.38	Yes	[24], [46]
R-452A	A1	10.5	2292	R-404A	0.995	0.96	-47.1	$48.62	Yes	[24]
R-454B	A2L	2.7	531	R-410A	1.027	0.97	-50.7	$40.00	Yes	[24]
R-454C	A2L	3.0/11.2	166	R-410A / R-404A	0.942/1.022	0.62/0.83	-45.8	$102.39*	Yes	[24], [53]
R-455A	A2L	3.0/10.4	166	R-410A/R-404A/R-407C	0.923/1.004	0.68/0.91	-52.0	$98.79*	Yes	[24]
R-457A	A2L	11.5	159	R-404A	1.050	0.77	-42.8	$91.40*	Yes	[24]
R-464A	A1	3.5	1288	R-404A/R-507A	1.046	0.711	-46.5	$49.96*	Yes	[2], [62]
R-466A	A1	2.7	808	R-410A	1.009	0.98	-51.7	$26.63*	Yes	[24]
R-513A	A1	2.5	673	R-134A	0.972	1.01	-29.6	$37.90	Yes	[24], [53]
R-514A	B1	No data	2	R-123	~1	~1	29.0	No data	No	[24]
R-515B	A1	2.5	322	R-134A	0.989	0.74	-19.0	$30.92	Yes	[24], [52]
R-516A	A2L	2.7	153	R-134A	0.975	0.99	-29.6	$97.26*	Yes	[24]

*Market price not readily available, so it was estimated using a weighted average of the blend components

Appendix I: General Data used for LCA

Item	Value	Units	Reference
Discount Rate	5	%	[64]
Compounding Periods per Year	1	-	[64]
UBC Vancouver Buildings with Heat Pumps	15	-	[38]
Estimate of Heat Pump Power Per Building	1.5	MW	[39]
Manufacturing Intensity of CO2	105	kWh/tCO2	[65]
Manufacturing Intensity of NH3	2	kg CO2-eq./kg NH3	[66]
Manufacturing Intensity of Propane	72	g CO2-eq./MJ	[67]
Manufacturing Intensity of R-134A	10.48	kg CO2-eq./kg R-134A	[68]
Manufacturing Intensity of R-404A	10.09	kg CO2-eq./kg R-404A	[68]
Manufacturing Intensity of R-407C	10.15	kg CO2-eq./kg R-407C	[68]
Manufacturing Intensity of R-410A	10.35	kg CO2-eq./kg R-410A	[68]
Manufacturing Intensity of R-507	10.04	kg CO2-eq./kg R-507	[68]
Manufacturing Intensity of HFOs	1.09	mol CO2/mol HFO	[28]
Carbon Intensity of Vancouver’s Electricity	9.9	t CO2-eq./GWh	[41]
Propane HHV	50.4	MJ/kg	[69]
Electricity Price BC Hydro	0.1352	CAD/kWh	[40]
Manufacturing Site Distance from UBC	4344	km	[42]
Transport Truck Emissions	75.39	g CO2-eq./km/tonne	[43]

Appendix J: Natural Refrigerant Internal LCA Data and Calculations

RAW DATA

Refrigerant	COP	GWP	ODP	Cost (USD/year)	Manufacturing Intensity (kg CO2-eq./kg refrigerant)	Electricity GWP Impact (kg CO2-eq./year)	Transport GWP Impact	GWP SUM (kg CO2-eq./ye.	Flammability	Acute Toxicity	Long-term Toxicity
CO2	3	1	0	$ 6,315,753.46	0.0010395	650950.344	122.4828158	651447.2156	1	1	0
NH3	3.4	0	0	$ 5,567,924.35	2	574367.9506	122.4828158	575238.4334	2	2	0
Propane	3.4	5	0	$ 5,526,537.54	3.6288	574367.9506	122.4828158	577717.6046	3	1	0
MAX				$ 6,315,753.46				651447.2156	3	2	0

Refrigerant	Capital Cost (USD)	Lifetime (yr)	Equivalent Annual Cost (USD/yr)	Refrig. needed (lb/year)	CAPEX per refrigerant (USD/lb)	Market Price (USD/lb)	Electricity Costs (USD/yr)	Electricity Cost (USD/lb)
CO2	$ 378,000.00	10	$ 48,952.73	824.67	$ 59.36	$ 1.58	$ 6,217,848.00	$ 7,539.80
NH3	$ 315,000.00	10	$ 40,793.94	824.67	$ 49.47	$ 2.38	$ 5,486,336.47	$ 6,652.77
Propane	$ 155,211.00	10	$ 20,100.53	824.67	$ 24.37	$ 3.80	$ 5,486,336.47	$ 6,652.77

Appendix K: Synthetic Refrigerant Internal LCA Data and Calculations

R-134A Replacements	COP	GWP	ODP	Cost (USD/lb)	Electricity Costs (USD/year)	Electricity GWP Impact	Manufacturing GWP Impact	Transport GWP Impact	Cost Sum (USD/year)	GWP Sum (kg CO2-eq./year)	Flammability	Acute Toxicity	Long-Term Toxicity
R-1234ze	4.4685	7	0	$ 52.50	$ 2,268,603.23	237501.4718	6.216372257	66.56318802	$ 2,292,131.96	238997.0014	1	1	0.07
R-1234yf	4.3065	4	0	$ 121.88	$ 2,353,942.53	246435.6965	6.216372257	66.56318802	$ 2,408,565.04	247321.476	2	1	0.07
R-444A	4.131	88	0	$ 47.52	$ 2,453,946.63	256905.1869	6.216372257	66.56318802	$ 2,475,241.25	274863.9664	2	1	0.0581
R-450A	4.41	643	0	$ 34.38	$ 2,298,696.94	240652.0016	6.216372257	66.56318802	$ 2,314,102.75	371414.5311	1	1	0.0406
R-513A	4.374	673	0	$ 37.90	$ 2,317,616.26	242632.6765	6.216372257	66.56318802	$ 2,334,601.76	379492.706	1	1	0.0392
R-515B	4.4505	322	0	$ 30.90	$ 2,277,778.57	238462.044	6.216372257	66.56318802	$ 2,291,626.91	303981.3236	1	1	0.06377
R-516A	4.3875	153	0	$ 97.26	$ 2,310,485.13	241886.1144	6.216372257	66.56318802	$ 2,354,071.84	273056.1439	2	1	0.05425
MAX			**0**						**$ 2,475,241.25**	**379492.706**	**2**	**1**	**0.07**

R-404A Replacements	COP	GWP	ODP	Cost (USD/lb)	Electricity Costs (USD/year)	Electricity GWP Impact	Manufacturing GWP Impact	Transport GWP Impact	Cost Sum (USD/year)	GWP Sum (kg CO2-eq./year)	Flammability	Acute Toxicity	Long-Term Toxicity
R-448A	1.9044	1494	0	$ 33.13	$ 694,028.74	72658.29701	0.81049872	8.67859524	$ 695,964.32	112258.7861	1	1	0.0189
R-449A	1.9044	1504	0	$ 33.62	$ 694,028.74	72658.29701	0.81049872	8.67859524	$ 695,993.52	112523.7861	1	1	0.01771
R-452A	1.791	2292	0	$ 48.62	$ 737,972.27	77258.7721	0.81049872	8.67859524	$ 740,813.54	138006.2612	1	1	0.021
R-454C	1.8396	166	0	$ 102.39	$ 718,475.94	75217.68908	0.81049872	8.67859524	$ 724,459.11	79626.17817	2	1	0.05495
R-455A	1.8072	166	0	$ 98.79	$ 731,356.98	76566.21338	0.81049872	8.67859524	$ 737,129.67	80974.70248	2	1	0.05285
R-457A	1.89	159	0	$ 91.40	$ 699,316.58	73211.88403	0.81049872	8.67859524	$ 704,657.13	77434.87313	2	1	0.049
MAX			**0**						**$ 740,813.54**	**138006.2612**	**2**	**1**	**0.05495**

R-407C Replacements	COP	GWP	ODP	Cost (USD/lb)	Electricity Costs (USD/year)	Electricity GWP Impact	Manufacturing GWP Impact	Transport GWP Impact	Cost Sum (USD/year)	GWP Sum (kg CO2-eq./year)	Flammability	Acute Toxicity	Long-Term Toxcity
R-449A	2.116	1504	0	$ 33.62	$ 624,625.87	65392.46731	0.81049872	8.67859524	$ 626,590.65	105257.9564	1	1	0.01771
R-455A	1.846	166	0	$ 98.79	$ 715,985.01	74956.91269	0.81049872	8.67859524	$ 721,757.70	79365.40178	2	1	0.05285
MAX			**0**						**$ 721,757.70**	**105257.9564**	**2**	**1**	**0.05285**

R-410A Replacements	COP	GWP	ODP	Cost (USD/lb)	Electricity Costs (USD/year)	Electricity GWP Impact	Manufacturing GWP Impact	Transport GWP Impact	Cost Sum (USD/year)	GWP Sum (kg CO2-eq./year)	Flammability	Acute Toxicity	Long-Term Toxicity
R-454B	4.87825	531	0	$ 40.00	$ 58,788.66	6154.620865	0.17586293	1.88309142	$ 59,295.81	9209.929819	2	1	0.02177
R-454C	4.8545	166	0	$ 102.39	$ 59,076.27	6184.731535	0.17586293	1.88309142	$ 60,374.51	7141.290489	2	1	0.05495
R-455A	4.38425	166	0	$ 98.79	$ 65,412.73	6848.099272	0.17586293	1.88309142	$ 66,665.30	7804.658227	2	1	0.05285
R-466A	4.79275	808	0	$ 26.63	$ 59,837.41	6264.415886	0.17586293	1.88309142	$ 60,174.99	10912.47484	1	1	0
MAX			**0**						**$ 66,665.30**	**10912.47484**	**2**	**1**	**0.05495**

R-507 Replacements	COP	GWP	ODP	Cost (USD/lb)	Electricity Costs (USD/year)	Electricity GWP Impact	Manufacturing GWP Impact	Transport GWP Impact	Cost Sum (USD/year)	GWP Sum (kg CO2-eq./year)	Flammability	Acute Toxicity	Long-Term Toxicity
R-449A	1.9044	1504	0	$ 33.62	$ 2,933,253.54	307084.1232	3.425504023	36.67934592	$ 2,941,557.52	475572.2281	1	1	0.01771
R-464A	1.8828	1288	0	$ 49.96	$ 2,966,904.63	310607.0768	3.425504023	36.67934592	$ 2,979,242.14	454903.1817	1	1	0.028
MAX			**0**						**$ 2,979,242.14**	**475572.2281**	**1**	**1**	**0.028**

Appendix L: Overall LCA Data and Calculations

BASE CASE:	Refrigerant	Leak (kg/yea	% Leak	GWP - Use (kg CO2-eq/year	ODP Impact - Use (kg CFC-11-eq/year)	Cost (USD/year)	Electricity Costs (USD/year)	Flammability (kg/year)	Acute Toxicity (kg/year)	LT Toxicity (CSF*iF*Emission)	GWP Electricity (kg-CO2/year)	GWP Manufacturing (kg CO2-eq./y	GWP Transport (kg CO2-eq./ye.	Total GWP	Total Cost (USD/year)
	R-134A	203.25	54%	290647.5	0	$ 12,100.88	$ 2,252,723.01	203.25	203.25	0	235838.9615	2130.06	66.56318802	528683.0847	$ 2,264,823.89
	R-404A	26.5	7%	103933	0	$ 2,191.29	$ 734,282.41	26.5	26.5	0	76872.47824	267.3426	8.67859524	181081.4994	$ 736,473.70
	R-407C	26.5	7%	47011	0	$ 2,483.46	$ 660,854.17	26.5	26.5	0	69185.23041	268.9591	8.67859524	116473.8681	$ 663,337.63
	R-410A	5.75	2%	12006	0	$ 266.26	$ 60,375.95	5.75	5.75	0	6320.795628	59.5125	1.88309142	18388.19122	$ 60,642.21
	R-507	112	30%	446320	0	$ 9,878.72	$ 3,103,382.25	112	112	0	324895.0024	1123.92	36.67934592	772375.6017	$ 3,113,260.97
	SUM				0			374	374	0				1617002.245	$ 6,838,538.39

OPTION 1:	Refrigerant	Leak (kg/yea	% Leak	GWP - Use (kg CO2-eq/year	ODP Impact - Use (kg CFC-11-eq/year)	Cost (USD/year)	Electricity Costs (USD/year)	Flammability (kg/year)	Acute Toxicity (kg/year)	LT Toxicity (CSF*iF*Emission)	GWP Electricity (kg-CO2/year)	GWP Manufacturing (kg CO2-eq./y	GWP Transport (kg CO2-eq./ye.	Total GWP	Total Cost
(Synthetics)	R-1234ze	203.25	54%	1422.75	0	$ 23,528.73	$ 2,268,603.23	203.25	203.25	1.473423288	237501.4718	6.216372257	66.56318802	238997.0014	$ 2,292,131.96
	R-457A	26.5	7%	4213.5	0	$ 5,340.56	$ 699,316.58	53	26.5	0.134474795	73211.88403	0.81049872	8.67859524	77434.87313	$ 704,657.13
	R-455A	26.5	7%	4399	0	$ 5,983.17	$ 301,467.37	53	26.5	0.145040671	31560.80534	0.81049872	8.67859524	35969.29444	$ 307,450.54
	R-454C	5.75	2%	954.5	0	$ 337.57	$ 59,076.27	11.5	5.75	0.032721596	6184.731535	0.17586293	1.88309142	7141.290489	$ 59,413.85
	R-449A	112	30%	168448	0	$ 8,303.98	$ 2,933,253.54	112	112	0.205416592	307084.1232	3.425504023	36.67934592	475572.2281	$ 2,941,557.52
	SUM				0			432.75	374	1.991076941				835114.6875	$ 6,305,211.00

OPTION 2:	Refrigerant	Leak (kg/yea	% Leak	GWP - Use (kg CO2-eq/year	ODP Impact - Use (kg CFC-11-eq/year)	Cost (USD/year)	Electricity Costs (USD/year)	Flammability (kg/year)	Acute Toxicity (kg/year)	LT Toxicity (CSF*iF*Emission)	GWP Electricity (kg-CO2/year)	GWP Manufacturing (kg CO2-eq./y	GWP Transport	Total GWP	Total Cost
(Natural)	Propane	374	100%	1870	0	$ 23,235.71	$ 5,486,336.47	1122	374	0	574367.9506	1357.1712	122.4828158	577717.6046	$ 5,509,572.19
	SUM														
	MAX				0			1122	374	1.991076941				1617002.245	$ 6,838,538.39

WEIGHTED

Scenario	GWP (kg CO2-eq/year)	ODP Impact (kg CFC-11-eq/ye	Cost (USD/year)	Flammability (kg/year)	Acute Toxicity (kg/year)	Toxicity (CSF*iF*Emission)	SUM
Base case	4	0	2	0.166666667	0.4	0	6.5667
Scenario 1	2.06583433	0	1.844022988	0.192847594	0.4	0.6	5.1027
Scenario 2	1.429107736	0	1.611330337	0.5	0.4	0	3.9404