AN ANALYSIS OF THE GLOBAL WARMING IMPACT OF HUMBOLDT STATE UNIVERSITY'S REFRIGERANT INVENTORY

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ABSTRACT

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With global warming potentials (GWP) in the thousands to tens of thousands of metric tons of carbon dioxide equivalent ($MTCO_2e$) and the possibility for substantial emissions associated with leaks of refrigerants used in heating, ventilation, air conditioning, and refrigeration (HVACR) equipment, it is important for Humboldt State University (HSU) to document and report greenhouse gas emissions (GHG) associated with refrigerant leaks.

This study has collected data on HSU's HVACR inventory, emphasizing the refrigerant types used, the charges of the equipment (i.e., the amounts of refrigerant in the systems), and the types of equipment. The data were aggregated into a model and paired with typical annual leak rate values for the respective equipment types. The corresponding amount of refrigerant lost through annual leaks was used to estimate a range of GHG emissions.

The HSU campus likely emits between 57 and 429 $MTCO_2e$ annually through refrigerant leaks. This amounts to 1% to 5% of the total 2019 campus GHG emissions. Additionally, it is likely that refrigerated condensing units that use the refrigerant R-404a are the most significant contributor to these emissions.

As HSU progresses towards its carbon neutrality goals and as the global community takes measures to eliminate some of the refrigerants used at HSU, it is increasingly important for the university to take action to better understand and eliminate the use of high-GWP refrigerants. Given the commercial availability of lower-GWP refrigerants, it is HSU's responsibility to determine how to reduce this portion of its environmental impact.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICIES

LIST OF ACRONYMS

AC – Air conditioning

AIM – American Innovation and Manufacturing

CARB – California Air Resources Board

CFC – Chlorofluorocarbons

COP – Coefficient of performance

EIA – Environmental Investigation Agency

EoL – End of life

EPA – Environmental Protection Agency

EU – European Union

GHG – Greenhouse gas

GWP – Global warming potentials

H&DS – Housing and Dining Services

HC – Hydrocarbons

HCFC – Hydrochlorofluorocarbons

HFC – Hydrofluorocarbons

HFO – Hydrofluoroolefins

HSU – Humboldt State University

HVACR – Heating, ventilation, air conditioning, and refrigeration

IPCC – Intergovernmental Panel on Climate Change

IR – Infrared radiation

$MTCO_2e$ – Metric tons of carbon dioxide equivalent

NASA – National Aeronautics and Space Administration

ODP – Ozone depletion potential

SNAP – Significant New Alternatives Policy

UNEP – United Nations Environment Programme

US – United States

UV – Ultraviolet

INTRODUCTION

Humboldt State University (HSU), in its mission to reduce its greenhouse gas emissions and have a net-zero carbon footprint by 2050 (HSU Office of Sustainability, 2016), has so far considered the emissions from the greenhouse gas (GHG) refrigerants in its inventories to be insignificant (Morgan King, personal communication, 2019). Refrigerants are substances that are used in a variety of important applications, from refrigerant systems to propellants to air conditioning. However, they have the potential to contribute serious harm to our environment and accelerate the rate of global warming when they are released into the atmosphere. With annual refrigerant leaks as high as 35% of the total capacity for medium to large commercial refrigeration systems (Intergovernmental Panel on Climate Change [IPCC], 2006), and global warming potentials (GWP) in the thousands of metric tons of carbon dioxide equivalent ($MTCO_2e$), the heating, ventilation, air conditioning, and refrigeration (HVACR) systems at HSU could be a significant contributor to the campus' annual emissions.

This project intends to identify the scale of the contribution that leaked refrigerants make to HSU's greenhouse gas inventory. It is also meant to inform HSU of approaching requirements, assist in compiling a complete refrigerant and refrigeration system inventory, and provide recommendations for the next steps. To narrow this project's scope, its focus is on refrigerants and their associated trends, restrictions, and emissions from leaks and other releases to the atmosphere. Large portions are informed by a

literature review, but the Humboldt-specific information comes from data collected from HSU Facilities Management and HSU's Housing and Dining Services (H&DS).

A literature review was conducted on the trends in commercial refrigerant use globally with a concentration on fugitive leaks. Research was conducted on the refrigerants currently used on-campus and the new generation of low-impact refrigerants. Information was collected on 101 refrigeration and air conditioning systems across 29 buildings at HSU. The current and potential future refrigerants in these units have been compared by GWP, ozone depletion potential (ODP), associated hazards, and system energy efficiency. Published estimates are used to determine a range of possible leak rates for the systems found on campus in cases where data on recharge rates for campus systems are missing. Case studies have been reviewed to inform estimates on price, efficiencies, and success of replacing existing refrigerants with lower ODP and GWP ones.

The focus of this project is on refrigerants. As a result, the energy use of the systems, carbon emissions embedded within the refrigerants and systems (mostly resulting from their manufacturing and transportation), and the energy efficiencies of different configurations may be mentioned. However, these factors do not affect the primary analysis, which focuses on the climate change impact of fugitive emissions of refrigerants used on campus. The outcome of this analysis informs whether or not fugitive emissions from refrigerant leaks contribute a significant amount to the campus' larger emissions inventory.

HSU needs a full accounting of the refrigerants it uses on campus, their environmental impacts, and the regulations restricting their use so the University can adequately assess the situation and take measures to minimize their environmental impact. There is an opportunity to better understand the distribution and use of refrigerants, and the associated emissions, so that HSU can more effectively reduce its carbon footprint, meet its own goals and obligations, and maintain economic feasibility. Additionally, there is a broader incentive for HSU to support the movement, driven by the Montreal Protocol, to eliminate and reduce the use of these environmentally damaging substances. Whether it be adopting low-GWP and ODP alternatives or developing a tighter set of procedures around refrigerants and their tracking, committing to the “greenest” alternative would further support the dedication to environmentalism and sustainability that is already so prominent at this university.

LITERATURE REVIEW

Context is undoubtedly as important in identifying and addressing a potential problem with the fugitive emissions of refrigerants at Humboldt State University as the actual findings and recommendations are. Information that provides context allows one to determine not just whether there is a problem but where the problem lies, why it is a problem, how serious or common the problem is, and what may be done about it. This chapter provides information about what refrigerants are, their associated problems, the work that is being done to address those problems, and available alternatives that can be considered.

What is a Refrigerant?

Refrigerants are substances with specific thermodynamic characteristics that make them effective tools to assist in certain applications. Of the properties associated with refrigerants, it may be their ability to change phase at low temperatures and their compressibility that are most useful. Both properties are needed for many of the applications that they are used in. The phase changes of refrigerants (usually gas to liquid and vice versa) add heat to and remove heat from refrigeration and air conditioning systems, and the pressurization of those refrigerants with vapor compressors adds additional heat energy. The low temperature phase changes of pressurized refrigerant also provide the propellant in hairspray, inhalers, and other aerosols.

Refrigerants are used in applications found in residential, commercial, industrial, medical, and automotive settings (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). The equipment that uses refrigerants can contain amounts of refrigerants (i.e., charges[1]) that range from a few ounces to thousands of pounds (California Air Resources Board [CARB], 2016). This study focuses on heating, ventilation, air conditioning, and refrigeration, so the refrigerant's use as a means to allow for the transfer of heat, rather than the expulsion of some substance, is what will be referred to from now on. Specifically, it is their use as working fluids within vapor-compression refrigeration cycles to take in heat at a low temperature and low pressure and dump heat at a high temperature and high pressure that is relevant here.

Refrigerants, and the vapor-compression cycles they are used in, are important because they incorporate energy from their surroundings, thus using less electrical energy, for instance, to achieve the same outcome (Hundy, 2016). This means that a unit of energy input (as electricity) produces more than one unit of energy output (as heat flow) for something like an electric heat pump. By contrast, a natural gas water heater might only theoretically be able to approach a 1:1 energy balance (or 100% efficiency) and realistically would achieve a lower efficiency depending on energy losses in its system (Afework et al., 2020). In vapor-compression systems, the ratio of energy output to energy input can be multiple times greater than 100%. This is referred to as the system's coefficient of performance (COP) (Hundy, 2016). Only through the use of

[1] Charge is the mass of refrigerant used to operate a certain system, like the quantity of gas in the tank of a car.

refrigerants can external thermal reservoirs (e.g., water bodies or air) be utilized in such a way.

The refrigerant's ability to draw in and release heat through changes in phase (evaporation and condensation, respectively) transfers energy through the systems they work in without requiring more input electricity or fuel (Hundy, 2016). The vapor-compression process can service either direction. Heat can be removed from a desired area like in a refrigerator or air-conditioner (AC), or it can be brought to a desired area with a heat pump, and the effectiveness of this cycle is dependent on the properties of the specific refrigerant used within (Hundy, 2016). More information on vapor-compression cycles along with a diagram illustrating the movement of refrigerant through one of these generalized cycles can be found in Appendix A. Explanation of Refrigeration Cycles.

Different refrigerants are better suited for some applications than others. Table 1 outlines the general criteria that determine the appropriateness of a refrigerant for certain applications and guide the development of new refrigerant types. Toxicity, for instance, is a more serious problem for in-home HVACR equipment than it is for a roof-top unit because of the respective proximities to humans and the differences in the ventilation at each location. Thus, these different scenarios would require different refrigerants to meet the safety requirements of each application.

Table 1. Desirable refrigerant criteria. Adapted from (McLinden & Didion, 1987).

- **Chemical**
  - Stable and inert
- **Health, Safety, and Environment**
  - Nontoxic
  - Nonflammable
  - Does not degrade the atmosphere (i.e., global warming and ozone depletion)
- **Thermal (Thermodynamic and Transport)**
  - Critical point and boiling point temperatures appropriate for the application
  - Low vapor heat capacity
  - Low viscosity
  - High thermal conductivity
- **Miscellaneous**
  - Satisfactory oil solubility
  - High dielectric constant vapor
  - Low freezing point
  - Reasonable containment materials
  - Easy leak detection
  - Low cost

It should be noted that there is no perfect refrigerant and that while many refrigerants exhibit some positive characteristics from this table, they all also display the downsides of one or more (and in some cases many) of these traits as well. Thus, the refrigerants that are deemed desirable may have serious drawbacks associated with their use, but the priorities of the user, industry, or society are such that these traits may be overlooked or worked around to benefit from certain advantageous traits that they might have. Propane, for example, is a refrigerant that is rapidly growing in popularity and use, despite its high

flammability and moderate toxicity, because its environmental impacts are so minimal (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

As defined by Calm (2008), there have been four generations of refrigerant evolution and rejection, each characterized by refrigerant groups with distinct properties. These generations have advanced as responses to changing concerns or priorities with refrigerant safety (Calm, 2008). The refrigerant types that characterized these generations and their summarized descriptions can be found in Table 2. The three most recent generations and refrigerants that are associated with them are the most relevant in this study, as they represent the near past, the currently used, and the foreseeable future in both the refrigerant industry and HSU (Calm, 2008).

Table 2. Summary of the evolution of refrigerant groups from oldest to newest with the refrigerant types that characterize the generations and their descriptions. Adapted from (Calm, 2008).

Generations of Refrigerants	Associated Refrigerant Types	Descriptions
Generation One	• Natural Refrigerants	• "Whatever worked." Used due to abundance and availability. • Include solvents and other volatile fluids like propane, ammonia, carbon dioxide, and even water. • Discarded initially due to high toxicity and flammability.
Generation Two	• Chlorofluorocarbons (CFC), Hydrochlorofluorocarbons (HCFC) & Halons	• A safer and more durable alternative to the former generation. • Popularized because of their effectiveness in a wide variety of applications. • Include saturated organic compounds made up of hydrogen, chlorine, fluorine, and carbon. • Banned due to concerns over ozone depletion.
Generation Three	• Hydrofluorocarbons (HFC) & Blends	• The less environmentally harmful replacement for the previous generation. • Popularized due to similarities in thermodynamic properties and absence of harmful side-effects. • Currently being phased-down due to global warming concerns.
Generation Four	• Hydrofluoroolefins (HFO), Hydrocarbons (HC) & Natural Refrigerants	• The least environmentally hazardous group. • Many of the natural refrigerants from Generation One and a group of unsaturated organic compounds are used here. • Development is ongoing and commercial uptake is still in its early stages.

What is the Problem with Them?

Many refrigerants are made up of chemicals that interact with Earth's atmosphere in ways that may negatively impact its "health." There may also be additional dangers associated with their use, like their flammability, toxicity, and potential for asphyxiation and explosion when leaked or maintained incorrectly (Environmental Protection Agency [EPA], 2016), but the notoriety associated with refrigerants comes from the effects that they have on the environment. There are two main ways that refrigerants negatively affect the environment: stratospheric ozone layer depletion and global warming (EPA, 2020d). In each instance, they pose such a threat that global cooperation to fix damages caused by refrigerants was deemed necessary. The decade- to century-long lifespans of some of these gases and the significant impacts that they have on Earth's atmosphere make them great threats to the condition of Earth's environment and the well-being of its inhabitants (Leahy, 2017).

Ozone Depletion

Though largely a problem of the past now, ozone depletion was a very serious problem caused by refrigerants in our atmosphere that required global organization to fix. Ozone (O_3) is a gas that occurs naturally in the upper part of our atmosphere (the stratosphere) and unnaturally in the lower part of our atmosphere (the troposphere) (EPA, 2020g). The stratospheric ozone layer, unlike the tropospheric layer, is beneficial to humans and life on Earth because it absorbs a wide range of the harmful ultraviolet (UV)

radiation traveling to the Earth's surface from the sun (National Aeronautics and Space Administration [NASA], 1999).

Because some refrigerants (especially CFCs, halons, and HCFCs less so) have a molecular structure that makes them less likely to react in our atmosphere, they can remain stable for many years until they reach our stratosphere (EPA, 2018). Once they reach these upper atmospheric layers, the incoming UV radiation is strong enough to break apart the carbon-chlorine bonds in the gas (EPA, 2018). The chlorine, now free, reacts with the O_3 molecules that make up the ozone layer.[2] Ozone molecules naturally break up in the process of converting UV energy to heat, but there is a balance between their destruction and later reformation (NASA, 1999). A single atom of chlorine can react with and destroy over 100,000 molecules of ozone before it is removed (EPA, 2018), so higher concentrations of it create large imbalances in this natural cycle. The scale of ozone depletion inherent and specific to each refrigerant is referred to as its ozone depletion potential (ODP), and gases that directly deplete the ozone are referred to as ozone-depleting substances (ODS). However, due to their warming effects, all high-GWP refrigerants (as defined in the "Global Warming" section) indirectly contribute to ozone depletion (Hurwitz et al., 2015).[3]

By the 1970s, measured concentrations of atmospheric ozone had begun to decrease annually, and by the 1990s, total global ozone levels had decreased by five percent

[2] This reaction, along with the following reactions, produces oxygen molecules, which do not absorb UV radiation and leaves the chlorine to continue to react.
[3] Stratospheric warming caused by high-GWP refrigerants accelerates the chemical reactions that destroy the ozone layer (Hurwitz et al., 2015).

(National Oceanic and Atmospheric Administration, 2010). This eventually gave way to the Antarctic "ozone hole,"[4] a name that describes an area of the largest and most extreme depletion[5] (reaching 11.5 million square miles at its maximum in 2000) over the South Pole that gained global attention in the 1980s (Leahy, 2017). Scientists began to suggest that chlorine monoxide and bromine monoxide from CFCs and halons were the sources of the depletion (United Nations Environment Programme [UNEP], 2018). By 1987 global recognition over the harms caused by refrigerants gave way to international action (Handwerk, 2010). A depleted ozone layer, even one not as extreme as in the "ozone hole," allows for increased UV radiation to reach the Earth. This would have significant consequences resulting in higher incidences of skin cancers, eye cataracts, more-compromised immune systems, negative effects on watersheds, agricultural lands, and forests, among others (Leahy, 2017).

Global Warming

Unlike ozone depletion, global warming is a problem of the past, present, and future, and all commercial refrigerants (not just chlorinated ones) directly contribute to this. The term global warming refers, generally, to the long-term increase in Earth's average temperatures as a byproduct of greenhouse gas emissions and land-use changes like deforestation (NASA, 2021). It is a topic that gains more and more attention every year as its effects are increasingly recognizable, widespread, and intense. The most well-

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[4] This is not an actual hole, rather a substantial drop in concentrations below historical levels (Handwerk, 2010).

[5] This is due to the Antarctic's higher latitude, particular weather patterns, and extreme cold temperatures (Wuebbles, 2020)

known contributor to this problem, carbon dioxide, has the impact that it does because there are vast amounts of it being emitted all the time and because it lasts in our atmosphere for centuries (Buis, 2019).[6] However, there is a group of other gases, called short-lived climate pollutants, that, because of their incredible warming potentials and projected increase in use, are approaching a level of threat that is likely to match carbon dioxide's (Institute for Governance and Sustainable Development, 2013). Of this group, methane, the main component in natural gas, currently has the greatest impact on global emissions (EPA, 2020b).[7] Many refrigerants have an extremely large potential for global warming impact, and, collectively, they represent a significant contributor to global climate change.

Simply put, the greenhouse gas effect describes the accumulation of molecules in the atmosphere that absorb outgoing infrared (IR) radiation and trap their heat energy close to Earth. The ability of a unit of mass (e.g., kg, ton, etc.) of emitted gas to absorb escaping energy over time, relative to carbon dioxide (the baseline for this metric), is referred to as the gas' global warming potential (IPCC, 2018). This is the unit of measurement used to compare the relative warming impact of GHGs with different atmospheric lifetimes and is dependent on molecular structure and composition. A commonly used refrigerant, R-22, for instance, absorbs much more energy than carbon dioxide, but it lasts in the atmosphere a significantly shorter amount of time. R-22's GWP

[6] The length of time that an increment of a given substance remains in the atmosphere after being leaked or released and before being removed through some chemical or physical process is referred to as that substance's atmospheric lifetime (Armoo & Fagbenle, 2020).
[7] Black carbon contributes more to global warming (Institute for Governance and Sustainable Development, 2013), though since it is a solid particle and not a gas, it is not included here.

is the net effect of its absorption compared to carbon dioxide over a set period of time (EPA, 2017). On a 100-year time period basis, the GWP of R-22 is 1,780 (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). See Appendix B. Expansion on Global Warming Molecules. for more information on the properties of refrigerants that make them highly potent GHGs.

Common time horizons used to compare these impacts include 20-years, 100-years, and 500-years. The time horizon used is a somewhat controversial topic because each gas' associated impact is changed based on the length of its atmospheric lifetime. Currently, the 100-year interval is the standard, though some believe these GHGs should be measured by their 20-year impact to prioritize emissions reductions for gases with shorter lifetimes, as this could help reduce the short-term effects of warming more rapidly (Climate Analytics, 2017).

Many modern commercial refrigerants are considered to be high-GWP substances because they are 150[8] to tens of thousands of times more potent of a GHG than an equal mass of carbon dioxide (CARB, 2021). The global warming impacts and other descriptions of the refrigerants referenced in this study can be found in Appendix C. Refrigerant Descriptions. One of the highest GWP refrigerants, R-12, has a 100-year GWP of 10,300 (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). To put this into perspective, the emissions that would result from dumping ten pounds of R-12 into the atmosphere are equivalent to 103,000 pounds of

[8] A GWP of 150 is the cutoff to be considered high-GWP (CARB, 2021).

carbon dioxide emissions which is roughly equal to driving an average passenger vehicle 116,000 miles, burning 51,500 pounds of coal, or consuming 5,200 gallons of gasoline (EPA, 2020c). Of course, not all refrigerants have this effect, and many are one or more order of magnitude less impactful than R-12. Still, many refrigerants that remain in use today have GWP values thousands of time greater than carbon dioxide. This includes R-12, of which HSU has more than 28 pounds installed right now, with more in reserve.

Table 3. Comparison of various pollutant's GWPs. Adapted from (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

Pollutant	**Global Warming Potential (100-year time horizon)**
Propane (R-290)	<1
Carbon Dioxide (CO_2)	1
Methane (CH_4)	30
R-134a	1,360
R-22	1,780
R-404a	4,200
R-12	10,300

While the potential for impact associated with many of these chemicals is alarming, they are typically not the leading contributor to the emissions that are associated with HVACR equipment. Because of the fossil-fuel-based sources that supply most of the world's energy, it is the electricity consumption of refrigerators, air conditioners, and similar equipment that represent the most emissive of their impacts under normal circumstances (Coulomb, 2010). Still, leaked refrigerants represent an opportunity for considerable emissions reductions on top of the reductions that can occur in relation to their energy use.

What is Being Done About Them?

We know that refrigerants are problematic. Their effects can be intense, globally encompassing, and long-lasting. The unchecked use of these substances in the middle to late 20th century has already caused damages that are expected to take over a century to heal. With the demand for air-conditioning and refrigeration projected to soar as global temperatures rise, populations grow, and wealth in developing countries increases, the role that refrigerants play in the "health" of our atmosphere will become significantly larger if left unrestrained. So, what are we doing about it?

Fortunately, there has been a recognition and movement against the effects that refrigerants have on our ozone layer and a similar movement, occurring within this past decade, that focuses on the warming impact of these substances, as well. However, the high-GWP HFCs that lead the refrigerant market are currently the fastest-growing source of GHG emissions globally (Xu et al., 2013). To appropriately respond to this growing threat, all refrigerant users from national governments and state agencies to private organizations and community mechanics must acknowledge the harm that refrigerants cause and gradually work towards their safer alternatives.

International Action

Globally, much has been accomplished to phase out harmful refrigerants and repair the damage they have caused. The Montreal Protocol on Substances that Deplete the Ozone Layer, which targeted the depleted ozone and the substances that depleted it, is the biggest and most successful instance of this movement (Handwerk, 2010). Though, in its

success, the treaty left a space that was soon filled with other harmful substances. Recently, however, additional rounds of negotiation of the Montreal Protocol have moved to amend this treaty and address the powerful GHGs still in use (UNEP, 2021).

The Montreal Protocol. The Montreal Protocol on Substances that Deplete the Ozone Layer is an international treaty that was established in 1987 to protect the stratospheric ozone layer from harmful ozone-depleting CFCs, HCFCs, and halons (UNEP, 2021). It focuses on eliminating the consumption and production of nearly 100 ozone-depleting chemicals through binding commitments to a time-dependent phase-down schedule and a Multilateral Fund (Leahy, 2017). All countries share the responsibility to eliminate their ODSs equally, though the phase-down schedules are different for “developed” and “developing” countries. The Multilateral Fund was established to assist countries in their transition to non-ODS use. Its clear articulation of the problem and its goals, inclusive negotiation and decision making, and encouragement of cooperation (Rae & Gabriel, 2012) make it an effective model for successfully addressing a global environmental issue.

The Montreal Protocol is widely recognized as the most successful environmental treaty in history (Molina & Zaelke, 2017). It has achieved a 98% reduction in the global abundance of ODSs below 1990 levels, where its absence would have resulted in a tenfold increase, and it has had a profound impact on the health of the environment and of life on Earth (UNEP, 2021). It has prevented an estimated 45 million cataracts, 280 million skin cancer cases, and 1.5 million skin cancer deaths in the United States alone (EPA, 2015). It has also resulted in the prevention of a three-fold increase in the potential

intensity of severe weather like hurricanes and cyclones (Polvani et al., 2016). It has even prevented roughly 1°C of average global temperature increase and up to 4°C of warming in the arctic (Goyal et al., 2019). The stratospheric ozone layer is expected to recover to its 1980 levels globally by the middle of the century, with a full recovery by the end of the century (Eyring et al., 2010). Its success, however, meant that high-GWP refrigerants would fill in as transitional alternatives in lieu of environmentally safer options.

The Kigali Amendment. The Kigali Amendment is an addition to the Montreal Protocol that targets these ODS replacements. This amendment entered into effect on January 1st, 2019, with 104 countries ratifying it so far (United Nations, 2020). The Kigali Amendment works just like the Montreal Protocol with clear phase-down targets that follow set time-tables, offset schedules for developed, developing, and especially hot countries with no reasonable alternative, and a fund to help countries that are in need meet their targets (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). It outlines the 85% phase-down of HFCs by 2036 for “developed” countries and by 2047 for “developing” countries (JMS Consulting & INFORUM, 2018). Like the original protocol, this amendment is expected to have significant impacts on the refrigerant industry and the global environment at large.

Estimates of the Kigali Amendment’s impact vary, but it is generally agreed upon that it will prevent up to another 0.5°C temperature rise because it will mitigate the substantial increase in global HFC consumption expected to occur by 2050 (Xu et al., 2013). HFCs account for less than 1% of the total GHG emissions today, but if their use were left unrestrained, an increase in use, at a rate of 10 – 15% per year (Zaelke et al.,

2018), could potentially push them to account for as much as 45% of total projected carbon dioxide emissions in carbon dioxide stabilization scenarios by 2050 (Velders et al., 2009). The reduction of HFC emissions plays a significant role in the phase-down of short-lived climate pollutants (SLCPs), which is the larger class of potent GHGs that HFCs are included in. The Kigali Amendment is expected to provide a crucial contribution to the ability of the global community to restrict average global temperature rise to below 2°C (Doniger, 2016).

National Action

Though many countries have taken bold initiatives, especially now that so many have ratified the Kigali Amendment, there are a handful of refrigerant-producing countries that are spearheading the way towards widespread use of low-GWP refrigerants. The European Union has so far been the biggest name in the movement towards reducing HFC and ODS emissions and incentivizing next-generation refrigerants, though many other countries, including the US, have begun to follow in their footsteps.

European Union. The European Union (EU) has been a global leader in HFC reductions since 2014 with its F-gas Regulations. These regulations, which are an update to earlier F-gas restrictions set in 2006, outline an HFC reduction goal and phase-down schedule similar to the one outlined by the Kigali Amendment but with an earlier and more aggressive start to its phase-down (European Partnership for Energy and the Environment, 2018). This early uptake has put the EU in a good position for compliance with the Kigali Amendment. For example, by the time "developed" countries reach the 50% reduction milestone to their 85% goal, the EU will only be one year away from its

final goal of 79% reduction below the same 2013 baseline used by the Kigali Amendment (Environmental Investigation Agency [EIA], 2015). This leading approach to natural refrigerants is not new, either. There was a proposed measure, passed by the European Committee in 2005 but later rejected by the European Parliament, which would have fully abolished fluorinated gases (International Energy Agency, 2016). The longer-lived embrace of natural refrigerants is evident when you look at global uptake rates for these replacement refrigerants, as they have become standard options in many end-uses for the EU.

United States. Even with the significant impacts of the Kigali Amendment, the United States (US) has not yet ratified the amendment and, in doing so, has sent mixed messages to the US industry and other countries which saw the US as a leader in the original treaty. Additionally, hesitation on the matter forces a more aggressive phase-down strategy and increases the risk that US industry will lag behind the other nations that have ratified and have already developed working alternatives. Executives urging the ratification of the amendment, citing environmental, economic, and political benefits (JMS Consulting & INFORUM, 2018), sent a letter to the president in May of 2018, but were, at the time, met with more inaction.

With the recent induction of a new president and a Democratic Party led Senate and House of Representatives, there may be a greater inclination towards progressing environmentally-focused legislation. Already, a bill has been passed in December of 2020 to bring the US into compliance with the Kigali Amendment (EIA, 2021). The American Innovation and Manufacturing (AIM) Act, which was included in the 2020

coronavirus relief package, outlines the schedule that dictates the phase-down of HFC refrigerants, returns power to the US EPA to prohibit the use of individual refrigerants, and increases the EPA's authority over the management of refrigerants and leaks (EIA, 2021). This does not mean that the US has ratified the Kigali Amendment, a still important step towards international cooperation and accountability, but it does show progress is being made.

This is by no means the first step made within the US to restrict the use of HFCs. Before 2021, the most significant action towards environmentally friendly refrigerants in the US occurred in 2015 when the EPA issued two new rulings (20 and 21) to its Significant New Alternatives Policy (SNAP) program. This program was established in 1993 to evaluate and regulate the use of ozone-depleting substance replacements (EPA, 2018). Each new chemical proposed as a replacement underwent an assessment that focused on environmental and safety impacts like ODP, GWP, flammability, and toxicity (Natural Resources Defense Council, 2019). All alternatives were determined to be either acceptable or unacceptable for certain uses and were published on a comprehensive list. These new regulations were meant to shape the direction of future HFC refrigerants used in the US while continuing to provide a safe and smooth transition away from the ODS' being phased out.

In 2017, however, the EPA's authority over these alternatives was limited by a federal court's decision. The newest rulings were reversed on the basis that the EPA could not "require manufacturers to replace HFCs with a substitute substance" (EPA, 2018). In other words, EPA had authority over ODS replacements but did not have the

power to require an additional substitution if the switch to HFCs had already taken place, even if the replacement was deemed environmentally unacceptable. The SNAP rules were projected to prevent about 68 million metric tons of carbon dioxide equivalent emissions from HFCs in 2025 (Natural Resources Defense Council, 2019). Though the rulings were vacated, the EPA has maintained its list of evaluated substances, and many states have used these rulings as guidelines while introducing their own refrigerant regulations.

Additionally, the Clean Air Act has established regulation that focuses on the general emissions of refrigerants and prevents against the mishandling and excessive loss of refrigerants. Section 608 is a group of federal legislation within the Clean Air Act that was enacted in 1993 to limit the amount of refrigerant released to the atmosphere and includes laws on the safe and responsible handling of refrigerants and the equipment that utilize them (Cornell Law School, 2020). These laws include certification requirements for technicians and service-people, guidelines for refrigerant leak tests, leak repairs and leak recordkeeping, and reporting requirements, among others. However, Section 608 does not specify the phase-down of any refrigerant group and is only applicable to some equipment and refrigerants.

The most notable state-lead action towards an environmentally-friendly refrigerant transition has come from a group of 24 states that make up the U.S Climate Alliance. California, Washington, Vermont, New York, and others have joined together, with a cumulative 55% of the US population and 60% of US GDP, to greatly reduce the use of short-lived climate pollutants (Natural Resources Defense Council, 2019). Their

formation, in June of 2017, is a direct response to the Trump administration's withdrawal from the Paris Climate Accord (Johnson, 2020). Their objective is to avoid a fragmented, state-by-state movement which would be burdensome for refrigerant manufacturers, distributors, and the refrigeration industry at large, who would have to cater to each state's specific laws (Doniger & Theodoridi, 2020). They coordinate the reduction efforts of these individual states to make the refrigerant transition consistent and easier for manufacturers and, they hope, other regulatory bodies. Of the 24 states that are members of this group, 16 have legislation in place to curb emissions from HFCs by prohibiting HFC-containing products (Doniger & Theodoridi, 2020).

California set the standard for HFC reductions in the US early, with its Senate Bill 1383, which requires the reduction of HFC emissions 40% below 2013 levels (CARB, 2018). With the California Cooling Act (Senate Bill 1013) and regulation approved by CARB, California was able to set restrictions on HFC use, based on the partially vacated SNAP Rules 20 and 21, to meet this goal (CARB, 2018). These senate bills set prohibitions on certain refrigerants for new and retrofitted equipment and require record-keeping, leak repair, and new certification requirements.

Under CARB's newest proposal, refrigerants may not have GWP values above 150 for new stationary refrigeration systems with charges greater than 50 lbs. starting on January 1st of 2022 (CARB, 2019). New stationary air conditioners and new chillers also may not use refrigerants with GWP values above 750 starting on January 1st of 2023 and 2024, respectively (CARB, 2019). Virgin refrigerants with GWPs at or above 1500 are banned from sale, distribution, or import in California (Westbrook, 2018). And a handful

of commonly used high-GWP refrigerants (e.g., R-404a and R-407c) are prohibited starting at varying times depending on the equipment type. California also utilizes its Refrigerant Management Program and F-gas Reduction Incentive Program (Natural Resources Defense Council, 2019).

University Action

HSU is pursuing a "bold and transformational commitment to sustainability" so that it may have a positive impact on the global environment and climate and a lasting influence on its students. It is taking a stand against emissions by developing a Campus Climate Action Plan (HSU Office of Sustainability, 2016). This action plan outlines long-term and short-term goals to meet its mission of sustainable campus operation and social justice- and environmental sustainability-based education. Among other things, the Climate Action Plan (HSU Office of Sustainability, 2016) includes a statement on HSU's commitment to sustainability, a description of the historical, current, and projected emissions at HSU and the sources that contribute to them, and an outline of 50 strategies, and their associated project descriptions, that HSU plans to pursue to curb these emissions.

To effectively reduce its emissions, the campus must, and has been, taking inventory of the greenhouse gases that it is responsible for. The emissions attributed to the campus can be broken up into three categories, referred to as Scope One, Scope Two, and Scope Three. Scope One covers all direct emissions on the campus and includes mobile and stationary combustion (e.g., the campus' vehicle fleet and natural gas for space heating and water heating in buildings) and fugitive emissions from refrigerants. Scope Two are

the indirect emissions not produced at HSU, but ones for which HSU is responsible, such as emissions associated with purchased electricity. Scope Three emissions are associated with a variety of additional activities which are associated with HSU, ranging from vehicle emissions from students, staff, and faulty that commute to campus to emissions associated with management of waste produced on campus. Though HSU considers all three categories and is working to address each, it focuses on the first two more so, in accordance with other California State University GHG reduction programs (HSU Office of Sustainability, 2016). Scope Three emissions will, thus, not be included in further mentions of the campus' reported emissions.

HSU has pledged to achieve three emissions reduction goals on its path to becoming a more sustainable campus.[9] The first goal is that of a reduction in its emissions to the campus' 1990 levels by 2020. HSU appears to have met this goal based on data from 2019 and expected emissions for 2020. The estimation of the 2020 emissions is not yet completed. However, 2019 emissions, as shown in Table 4, amounted to 9,085 $MTCO_2e$ (Humboldt State University, 2020). This is already well below the goal of 12,000 $MTCO_2e$.[10] The second goal requires a reduction of emissions to 80% below HSU's 1990 levels by 2040. This leaves 20 years to eliminate roughly 6,584 $MTCO_2e$. And the third goal is achieving carbon neutrality by 2050. Significant changes in operations are

[9] These goals may change after an update to the CSU sustainability policy that is expected to be released in 2021. This update will likely change the ultimate goal of carbon neutrality to 2045 instead of 2050 (Morgan King, personal communication, 2020).

[10] This number is not known with 100% certainty because complete records were not kept on HSU's emissions in 1990 (Morgan King, personal communication, 2020). The graph referenced in HSU's CAP has its 1990 emissions at just over 12,000 MTCO2e, though it is rounded down here to be conservative.

required to achieve these last two goals. Fortunately, HSU has already made progress and has plans for its future.

Table 4. Breakdown of Scope One and Scope Two emissions at Humboldt State University for the 2019 fiscal year. Data were collected over a period of twelve months starting July 1st, 2018. Adapted from (Humboldt State University, 2020).

Category	Subcategory	Annual Emissions ($MTCO_2e/yr$)
Scope One	Stationary Combustion	5,500
Scope One	Mobile Combustion	220
Scope One	Process Emissions	0
Scope One	Fugitive Emissions	0
	Cumulative	**5,720**
Scope Two	Purchased Electricity	3,365
Scope Two	Purchased Heating	0
Scope Two	Purchased Cooling	0
Scope Two	Purchased Steam	0
	Cumulative	**3,365**
	Total Emissions	**9,085**

However, the sources of emissions that HSU considers are not all-inclusive. Fugitive emissions from refrigerant leaks or losses are omitted because they are believed to contribute insignificantly to the campus' emissions inventory. Since HSU does not have a complete inventory of the equipment and refrigerants they use or a complete record of their leak and recharge rates, refrigerants have the potential to contribute to the campus' emissions considerably more than expected.

Currently, there are detailed refrigerant management compliance plans in place at HSU. The two versions made available by Facilities Management outline the organization's response to Section 608 of the Clean Air Act and amendments to that section that have arisen in recent years (Humboldt State University, 2007; Sine & Busby, 2018). The compliance plans at Facilities Management describe the context to the Section 608 legislation, including a discussion of what refrigerants are, refrigerant nomenclature, various refrigerant characteristics (e.g., boiling point and specific heat capacity), and environmental, health, and safety hazards associated with refrigerants. These plans also describe the requirements and procedures established by the legislation that are relevant to Facilities Management, including contractor requirements, refrigerant inventory processes, leak testing requirements, and the disposal of refrigerant, among others. Finally, they designate which job titles are responsible for the tasks that are required to remain in compliance. For example, two of the Division Refrigerant Supervisor's responsibilities are implementing the Refrigerant Compliance Plan and maintaining the records of refrigerant inventories, usage, and disposal.

These compliance plans are very detailed and appear to be exhaustive in the regulations that are relevant to the refrigerant management at HSU at the time that they were written.[11] Though, neither Facilities Management nor H&DS are in full compliance with the requirements outlined by these plans, they are in compliance with the regulations as they are described in Section 608. The compliance plans do not specify this, but the Section 608 laws apply only to equipment that contain, at their full charge, 50 or more pounds of ozone-depleting refrigerant. So, for the areas where either Facilities Management or H&DS do not meet the listed requirements, they are not required to do so by law because they have no units meeting those characteristics.

Currently, Facilities Management performs routine leak tests on its equipment every year and keeps a record of the names, locations, and characteristics of the equipment it operates, including the full charges of each unit (Mike Dotson, personal communication, 2020). However, it does not keep records of the leaks that are experienced by its equipment nor does it have a log of its service history describing the type of work performed or the amount of refrigerant that was added or removed from each unit (Travis Fleming, personal communication, 2021). Housing and Dining Services now has an inventory of its equipment, as a result of this study. Still, it does not keep records of leaks or of its equipment service history, nor does it perform regular leak checks at this time (Dan Bouchard, personal communication). However, both Facilities

[11] The most recent of these refrigerant compliance plans is an update to the requirements of Section 608 that was written in 2018.

Management and H&DS have expressed their plans to incorporate these tasks into their refrigerant management procedures.

What are Their Alternatives?

This study is being written during the early stages of what appears to be a substantial shift in the types of refrigerants used worldwide. In response to the growing recognition of the global warming impacts associated with the currently used transitional refrigerants (HCFCs and HFCs) and the international support for the Kigali Amendment, which provides a plan to significantly reduce their use, researchers, policymakers, and industry leaders have set their sights on the next generation of refrigerants. Though many refrigerants in this new generation have been known about for decades (e.g., carbon dioxide and propane are among the first refrigerants ever used) and some have been used commercially for years (e.g., ammonia in industrial settings), their latest surge as replacements for harmful HCFCs and HFCs comes with some significant hurdles.

Higher toxicity, flammability, and upfront installation costs, the changing regulatory environment, and the ongoing research, development, and market maturity are among the reasons that these technologies require careful consideration before they can be adopted (Calm, 2008). However, these refrigerants' often negligible or reduced environmental impact, their potential for significant savings in energy consumption, and their status as the only group of refrigerants not targeted by international regulation make them attractive, and in fact, necessary options to consider.

These alternatives can be grouped into two general categories, "natural refrigerants" and fluorinated refrigerants. Natural refrigerants, which include carbon dioxide, hydrocarbons, and ammonia, have negligible GWPs and ODPs but, in many

cases, have safety or technological drawbacks that must be addressed before more widespread implementation is possible (GlobalFACT, 2018). Fluorinated refrigerants, which include HFOs, low-GWP HFCs, and HFC/HFO blends, are a mixed group of reduced GWP refrigerants that do not have the safety hazards of the natural refrigerants. However, they also either do not have GWPs values below the high-GWP threshold (i.e., GWP values below 150) and thus are not considered as long-term solutions or they are not developed enough for efficient use in HAVCR applications (Calm, 2008). There is a need to better understand the strengths and weaknesses of the individual refrigerants and these groups because, as the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) has shown, there are no more “silver bullet” solutions that check as many “ideal refrigerant” boxes as was the case for chemicals like R-22.

It is relevant to describe early on how these refrigerants are categorized with respect to safety. The associated toxicity and flammability of this generation of refrigerants are such that they demand greater attention than their predecessors when considering their fit for an application. Table 5 shows the standard guidelines for classifying a refrigerant by its risk potential.

Table 5. Refrigerant safety classifications. Example refrigerants or refrigerant types, if more widely applicable, are included for each safety class. The first letter of each classification represents the toxicity of the refrigerant and the number indicates the level of flammability. The inclusion of a second letter, "L", in the lower flammability row indicates a maximum burning velocity lower than 10 cm/s. Adapted from (Comstock & Eltalouny, 2020).

Lower Toxicity	**Higher Toxicity**	
A3 (Hydrocarbons)	B3 (No refrigerants)	**Higher Flammability**
A2 (Rarely used)	B2 (Rarely used)	**Lower Flammability**
A2L (Low-GWP, HFC replacements)	B2L (Ammonia)	**Lower Flammability (L)**
A1 (HFCs)	B1 (Rarely used)	**No Flame Propagation**

As can be seen, there are greater toxicity and flammability hazards associated with some of the low-GWP and hydrocarbon refrigerants of this next generation than there are with the HFCs of the current generation. HFCs are generally classified as A1 substances with low flammability and toxicity. Their replacements, however, occupy classifications with greater associated hazards, like A2L, A3, and B2L. Flammability, especially, is a major concern. In fact, the amount of high flammability refrigerants, like hydrocarbons, that can be used in an individual unit are restricted in many areas, including the US (Garry, 2019). Toxicity is a less common concern, generally limited to the use of ammonia, but it is no less dangerous. The differences in safety between these refrigerant types have considerable implications for their adoption in their respective uses.

Though this next generation of refrigerants is still being developed and tested, there are a growing number of low- and moderate-GWP refrigerants commercially available and currently used worldwide that have proved to be the most likely options for future growth. These refrigerants are typically effective replacements for a narrower range of applications than their predecessors. This is largely due to the regulations that presently restrict their acceptable charge ranges, but other limiting factors include lower efficiencies at high ambient temperatures and additional complexities associated with some systems (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). Table 6 summarizes the most promising available options as described by the literature and the applications in which they most efficiently operate. Further descriptions can be found in the sections following.

Table 6. Descriptions highlighting GWP, ODP, safety category, atmospheric lifetime, and suitable applications for popular low-GWP natural and fluorinated refrigerants. Adapted from (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019; EPA, 2020a; Nair & Yu, 2020;).

Refrigerant	100-year GWP	20-year GWP	ODP	Safety Class	Atmospheric Lifetime	Applications
Propane (R-290)	<1	<1	0	A3	12.5 days	Domestic Refrigerators, Stand-alone hermetically sealed, Refrigerated condensing units, Small to medium HVAC, AC chillers
Carbon Dioxide (R-744)	1	1	0	A1	Undefined[12]	Refrigerated condensing units, AC chillers
Isobutane (R-600a)	<1	<1	0	A3	6.0 days	Domestic Refrigerators, Stand-alone hermetically sealed
Ammonia (R-717)	0	0	0	B2L	≤1 day	Industrial refrigeration, AC chillers, Centralized refrigeration
R-32	704	2530	0	A2L	1971 days	AC chillers
R-1234yf	<1	1	<1	A2L	10.5 days	Small to medium HVAC

[12] As EPA (2020a) has stated, the atmospheric lifetime of CO_2 cannot be represented by a single value. The gas is not destroyed over time through chemical or physical properties like the other substances described here. Rather, it is transferred to other reservoirs like the ocean or in plant matter and over time (sometimes thousands of years) is deposited in various ways (e.g., ocean sediments, soil, rocks).

Natural Refrigerants

Though lower-GWP refrigerants and blends may satisfy short-term needs in this transitional period, it must be emphasized that the success of a transition to low-GWP refrigerants is highly dependent on the widespread adoption of natural refrigerants in a broad range of applications. Hydrocarbons, the popular choice for use in nearly all low-charge HVACR equipment categories, have already begun to dominate these markets in most industrialized countries (Zeiger et al., 2014). Carbon dioxide has also already been a part of many successful transitions to low-GWP refrigerants in countries across the world, especially for medium to large-sized equipment.

Natural refrigerants are not drop-in replacements for HFCs, however, and in many cases, substantial design changes are required for their use in existing equipment. As a result, developers must take innovative approaches to modify or redesign existing systems in cases where full replacement is not economically feasible or where other barriers to replacement exist. Transcritical, cascade, secondary loop, and booster systems are a few of the technologies that have been employed globally to aid in achieving more ideal systems with respect to safety, efficiency, cost, and other key factors (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

Popular Options. Carbon Dioxide (R-744) has low flammability, toxicity, and refrigerant cost; it also has zero ODP and a negligible GWP. It has advantageous heat transfer properties, like high thermal conductivity, specific heat capacity, latent heat, and lower dynamic viscosity (Bellos & Tzivanidis, 2019). It also has a high volumetric cooling capacity, meaning that because of its high density, it has a greater ability to

remove heat per unit of volume (Shecco, 2018). This means that less refrigerant is needed to provide the same amount of cooling as a refrigerant with a lower volumetric cooling capacity. It also means that the refrigeration system can be smaller.

However, the high pressures needed in carbon dioxide systems prohibit the use of traditional single-stage compression circuits and prevent retrofits of existing equipment. Cascade and transcritical systems have shown good performances in small, medium, and large applications, especially at low and medium ambient temperatures, though they do require specialized training to operate and maintain (Emani & Mandal, 2018). Currently, the complicated nature of these system designs is seen by some as a barrier (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

Carbon dioxide systems do require specialized valves, piping, and compressors because of their high operating pressures. However, Hillphoenix (2019) has shown that, though upfront equipment costs are higher for transcritical CO_2 booster systems, additional costs, including initial and annual refrigerant costs, refrigeration and electrical installation costs, and annual operational costs are lower across their entire study area. In this same study, it is shown that for smaller systems, this equipment cost is a relatively higher portion of the overall system cost (though still in line with the HFC system equipment costs) and, thus, may be more of a barrier.

Still, carbon dioxide has experienced a surge in use in recent years because of its lower refrigerant cost and higher energy efficiencies compared to HFC systems (Hillphoenix, 2019). Between 2018 and 2020, the US experienced a 76% growth rate in

the number of transcritical CO_2 systems used by various end-users[13], including supermarket/commercial, industrial/manufacturing, and datacenters (Shecco, 2020). Further, the use of transcritical CO_2 systems has grown around the world, with Europe having installed 29,000 units by 2020 and countries like Australia, New Zealand, and South Africa experiencing growth rates of 375%, 150%, and 100%, respectively, since 2018 (Shecco, 2020).

Propane (R-290) has been more successful in a wider range of commercial applications than any other natural refrigerant and is also the refrigerant that exhibits the most similar performance to R-22[14] and the other refrigerants it is expected to replace (Zeiger et al., 2014). Choudhari and Sapali's (2018) literature review showed that for window air conditioning, split air conditioning, and heat pumps, propane exhibited higher energy efficiencies but lower cooling capacity when compared to R-22 under the same conditions. They have also shown that propane exhibits physical and thermodynamic traits that are similar to R-22, with some parameters being advantageous compared to those for R-22, like higher latent heat of evaporation, lower liquid density, lower viscosity, higher thermal conductivity, and higher specific heat. When comparing the two refrigerants in a typical vapor-compression cycle, Choudhari and Sapali (2018) found that R-290 had lower pressure ratios, compressor discharge temperatures, volumetric

[13] This growth rate was developed from a survey collected from 29 end-users.
[14] Refrigerants are commonly compared to R-22, not only because it was the standard refrigerant used in a large array of applications for decades but also because of the high efficiency, safety, and affordability associated with it which contributed to its popularity.

refrigerating capacities, and mass flow rates than R-22 under the same conditions. Coefficients of performance, however, were also lower for propane.

Out of all of the natural refrigerants, propane seems to have the most promising future. It has, so far, had more recognition in studies, reports, and press than any other hydrocarbon and most other low-GWP options. It has also been shown to be more versatile and efficient in a wider-range of applications than any other low-GWP alternative, including AC chillers, split and window AC, and small to medium domestic and commercial refrigeration. Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) has suggested that it has the highest growth in expected production. It has been a commercially available and, in some cases, the standard option for manufacturers in a number of countries, including India and China, for almost a decade, and in Europe and Australia for several years (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). Its use in the US is also growing.

Isobutane (R-600a) is a low toxicity, high flammability, and inexpensive option that is already in use on the HSU campus at the Schatz Energy Research Center and throughout the on-campus residence halls. Its high density reduces the charge mass required to service systems by 45% and 60% when compared to R-134a and R-12, respectively (Johnson, 2019). The low operating pressures required in isobutane systems reduce the noise of the unit and the chance of failures and extend the life of the compressor (Johnson, 2019). However, its high flammability rating is still a major concern. In small applications, isobutane can be used in traditional hermetically sealed

direct expansion circuits but added safety precautions to address this flammability are needed.

Isobutane has also been shown to be the dominant option for new domestic refrigeration applications (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). Globally, more than one billion domestic refrigerators use it currently, and its use was expected to grow to 75% of all new domestic refrigerators and freezers by 2020 (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). It already occupies 95% of new domestic refrigeration in Europe, China, Brazil, and Argentina (Johnson, 2019). Isobutane is especially efficient in medium-, high-, and very high-temperature applications (Johnson, 2019). United States industry has plans to phase out all other refrigerants from use in domestic appliances by 2024 (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). Isobutane is also being considered for other low-charge applications, but domestic refrigeration is the only category where it has been as successful to date.

Ammonia has been a proven and widely used refrigerant in AC chiller and industrial systems for decades. It is said to be one of the most energy and cost-efficient refrigerants available (ICF International, 2011). Its “superior thermodynamic qualities” allow systems using ammonia to have lower charges and smaller pipes and heat transfer areas while providing up to a 15 to 20 percent more efficient service when compared to HCFCs (Kessler, 2016). Though ammonia refrigeration systems come with a high upfront cost, ammonia itself is a naturally occurring and relatively inexpensive substance,

and its high energy efficiency make operational costs low enough that these systems are cost-competitive (ASHRAE, 2017).

While ammonia is well-established and dominant in a few certain equipment categories, it is also largely confined to them. Its high toxicity is a major barrier to its growth in other HVACR applications. It is well suited for medium to large secondary loop and cascade systems where, to reduce risk, its use is removed from populated areas, like roof-tops or central mechanical rooms (ASHRAE, 2017). Kessler (2016) has shown that ammonia is extremely dangerous, resulting in severe burns, respiratory problems, frostbite when in liquid form, and death in high concentrations. Kessler (2016) describes incidents where systems have failed and ammonia has leaked, and the resulting property damage cost between $100,000 and $1,000,000. An additional barrier to its implementation can be found in the lack of technicians trained specifically in its use (ASHRAE, 2017).

Current State. As mentioned before, the natural refrigerant category has had great success to date. Globally, up to 65% of all new commercial refrigeration is installed with low-GWP refrigerants, and uptake has also been substantial for domestic refrigeration (Zaelke et al., 2018). By 2017, the members of Refrigerants, Naturally!, an initiative of international refrigerant-using companies, including Coca-Cola, PepsiCo, Red Bull, and others that are working to eliminate their use of harmful refrigerants, had collectively installed 7.25 million natural refrigerant units across the world (Gkizelis, 2018). In the US alone, some of these companies have begun implementing propane, isobutane, and carbon dioxide in thousands of their vending machines, bottle coolers, and ice-cream

freezers (UNEP, 2019). Major supermarket chains like ALDI, Target, and Whole Foods have converted hundreds of their large, centralized rack systems to transcritical CO_2 systems and CO_2 cascade or secondary loop systems (EIA, 2021). Many supermarkets are even abandoning the standard centralized system designs for individual stand-alone systems, with one US grocery store, H-E-B, being fully supported by self-contained propane units since 2013 (McLaughlin, 2019).[15]

As Lilya (2019) has shown, and as is increasingly evident elsewhere (see above), the acceptance of natural refrigerants as feasible alternatives to HFCs is undeniable. Still, the US has not seen the substantial growth in the use of these products that Europe and other early adopters have. In fact, in a recent EIA study where US supermarkets were ranked on their actions to reduce HFC emissions, all but one chain (ALDI) scored below 50%, with most scoring below 20% (EIA, 2021). This is likely due to the lack, at least until recently, of widespread incentives and regulations promoting these refrigerants and disincentivizing HFCs in the US Such incentives and regulations have been in place in the EU since its first adoption of "F-Gas" legislation in 2006 (European Partnership for Energy and the Environment, 2018).

The reluctance to switch to natural refrigerants, despite their proven advantages, is a complicated issue with many elements to consider. Table 7 presents information about common concerns that users have expressed in the designing of their systems.

[15] This is an interesting case study where no leaks were found for six years. It has been labeled as a great success, though they had not achieved as much energy savings as they had hoped.

While these barriers are quickly becoming less prominent, as Lilya (2019) has shown, they should still be considerations in any development plan.

Table 7. Design challenges to the adaptation of natural refrigerants when compared to HFCs. Adapted from (Lilya, 2019).

- Higher than expected initial investments
- Lack of availability of equipment parts and/or service technicians
- Safety (pressures, toxicity, and flammability)
- Lack of availability of refrigerants
- Unfamiliarity with installation and design requirements
- Compatibility with traditional control systems
- Delays in construction due to the permitting of unfamiliar systems and additional scrutiny of code inspectors

Cost. Cost is an important factor in the decision to convert to natural refrigerant systems, though the information surrounding the topic is vague and highly variable. It is difficult to address the concerns of high upfront investments and new-system transitional costs for the variety of equipment types found at HSU because, as Booten and others (2020) state, data on costs, prices, trading patterns, and production are largely unavailable. This information is often business-sensitive or proprietary, is subject to a dynamic market right now, and is dependent on the specific design requirements of the installation (Booten et al., 2020).

This study has had considerable difficulty finding research that compares HFC refrigerants to natural refrigerants in similar applications where initial and/or ongoing costs are considered. It is possible that this is due to the variability that can be found in the costs for these systems. The location of the system, including the regulations which govern the area and the area's accessibility (especially important with a city as isolated as Arcata), its design and situational requirements, the manufacturer contacted, among other irregularities, can completely change the economics of a decision. Additionally, the changing landscape of the past few years is such that studies that have compared the economics of these systems for one region or over many regions now likely do not reflect current prices or technology.

There has been a fair amount of research comparing the economics of transitions to natural refrigerants in supermarket settings. However, the systems used in supermarkets tend to be large, centralized, distributed, or multiple loop systems, and HSU does not utilize these types of systems. While it is still difficult to find a consensus between these

projects because of the considerable variations in each study's parameters, supermarket refrigeration systems are useful to review to draw attention to patterns that seem to be common in the investments of these systems.

Though not necessarily the case, as Nelson and others (2015) have asserted, natural refrigerant systems tend to have a moderate to significant price premium on their equipment compared to HFC-based systems (Hillphoenix, 2019; Lilya, 2019). These high equipment costs are largely a result of expensive safety measures that are required to reduce the risk of the hazards associated with this category of refrigerants but can also be attributed to the high pressures that CO_2 systems require (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019). Smith (2019) states that the higher upfront equipment investment is a result of not having reached the "tipping point" for these technologies and, thus, not developing the economies of scale necessary to reduce their costs. Still, the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) expects that with increased production capacity and financial incentives, the cost barrier associated with some of these technologies will shortly be overcome.

Generally speaking, these refrigerants and their accompanying equipment are already at parity with their HFC equivalents[16] in terms of energy efficiencies and installation costs (Lilya, 2019). Reports of the energy consumption of these refrigerants when compared to comparable HFC systems differ and are very situationally dependent. For

[16] For the larger supermarket application types, these refrigerants are most often compared to R-404a and R-448a.

CO_2 systems, users have experienced between a 13% decrease in energy consumption and an 18% increase in consumption compared to HFC alternatives (Elbel et al., 2016; Skacanova & Gkizelis, 2018; Lilya, 2019). However, fewer studies have found that CO_2 systems are less energy consumptive than HFCs, as the requirements needed to keep CO_2 systems at operating pressures generally increase their consumption. Alternatively, for hydrocarbons, this study has not found any reports of their operation being more energy consumptive than HFCs. Users of hydrocarbon refrigeration systems have reported energy consumption ranges between 10% and 37% less than their HFC alternatives (Elbel et al., 2016; Peters, 2017; Gaurav & Kuma, 2018; Skacanova & Gkizelis, 2018; Shecco, 2019).

Installation costs can range from 20% more expensive to 22% less expensive than a comparable HFC system (Hillphoenix, 2019; Lilya, 2019). These larger supermarket applications tend to use more expensive and complicated CO_2 systems. However, the much smaller diameter copper piping required for the higher pressures found in CO_2 refrigeration, the generally cheaper electrical costs, and much cheaper refrigerant costs reduce the cost of their installation considerably (Hillphoenix, 2019).

The operational costs of these natural refrigerant systems are often lower than their comparable HFC alternatives. Annual operating and refrigerant costs for these larger systems can range between 8% and 30% less than with HFCs (Airconstruct, 2019; Hillphoenix, 2019). This is due to the price difference between synthetic refrigerants and “natural” refrigerants (Hillphoenix, 2019), the necessary refrigerant charges for both

system types (Shecco, 2018), and the changes in maintenance requirements associated with their use (Zgliczynski, 2018).[17]

When comparing these findings to the many fewer studies on the system types that are more relevant to HSU, the general patterns and inconsistencies in reported successes or drawbacks remain. Elbel and others (2016) have shown that for light commercial refrigeration applications, the system costs of CO_2 and propane systems are “not too different” when compared to the costs of a similar R-134a unit. They go on to say that the slightly higher costs of the CO_2 systems (inferring that the propane systems are either at parity or cheaper than the R-134a units) are expected to drop in the future. Additionally, they have found that for a small-scale glass door merchandiser system, the energy consumption is three percent higher for the transcritical CO_2 unit and nine percent lower for the propane unit when compared to R-134a.

The reasons that users are investing in these natural refrigerants in the short term have as much to do with intangible benefits as they do with tangible ones, it seems. Significant reductions in environmental impacts (mainly due to direct emissions) and reduced risks and troubles related to approaching and uncertain phase-out regulations are often cited as being influential on a prospective user’s decision to transition. As the US Vice President of the ALDI grocery chain (one of few grocery chains leading the transition to low-GWP alternatives) has discussed, the 20 to 30% increase in upfront costs of these systems is a

[17] Namely, there is a considerable reduction in labor costs that comes from being able to vent some of these refrigerants to the atmosphere when repairing or retiring a system. There are still special precautions that one must take to work with natural refrigerants, as they can be deadly, but in well-vented areas, they do not have the same recapture requirements as HFCs.

worthwhile expense because, ultimately, a net gain is expected, especially when considering avoided refrigerant phase-outs and increasing HFC refrigerant costs (Garry & Williams, 2018).

It should be reemphasized that there is a great deal of variation from one project or installation to another. There are many factors that influence the life-cycle costs of natural refrigerant systems. Even in the results of the literature that was reviewed for this study, there are surprising inconsistencies between and within studies. For instance, DC Engineering's (2020) study showed the exact opposite of my findings above. That is, when compared to an HFC baseline system, the equipment and installation costs were lowest for the transcritical CO_2 unit option, while the energy consumption was higher.[18] Finally, even after expanding its study location to observe the differences that geographical region has on price, DC Engineering (2020) indicates that the largest disparity in price estimates was between two manufacturers in the same region. As such, a comprehensive techno-economic analysis is needed to fully understand the effects that situational "quirks" might have on system costs.

Additionally, the specialized equipment that natural refrigerants require to address their safety concerns or higher operating pressures prevent them from being used as "drop-in" replacements or options in retrofits (Emerson, 2011). This means that the use of these refrigerants must come with an entirely new refrigeration system. So, regardless of the differences in costs between natural refrigerant systems and HFC systems, the cost

[18] The DC Engineering study differs somewhat from other studies referenced as it is the only one that has reported both cheaper equipment/installation costs and lower energy efficiencies. One, or the other, of these claims, is common, just not both.

of transitioning to a lower-GWP refrigerant that is better suited as a drop-in will be far less initially because much less will need to be changed. An entity hoping to reduce the impact of their used but still working equipment while also putting off this initial investment may be better suited to low-GWP fluorinated refrigerants. For systems that are reaching the ends of their lives and are in need of replacement, however, natural refrigerants are competitive options.[19]

Safety. Refrigerants with A3, A2, and A2L ratings have been restricted to charges of no more than 150 grams (roughly a third of a pound) since 2017 (Garry, 2019), and to no more than 57 grams previously (Garry, 2018). This greatly limited their use to a few low-charge applications. For reference, charges for domestic refrigerators can range from 28 grams to 185 grams (Sanders, 2017). However, for the units described in the analysis presented here, 150 grams is less than half of the lowest charge reported. Just recently, in 2019, however, the International Electrochemical Commission raised the charge limit on these refrigerants to 500 g for A3 refrigerants and 1,200 g for A2 and A2L refrigerants (just over one and two and a half pounds, respectively) (Garry, 2019). This and future rulings of this nature expand the possible options for these refrigerants and thus pave the way for their more widespread uptake.

[19] They are not so competitive, however, that they warrant completely replacing existing infrastructure before it is retired.

Fluorinated Refrigerants

Hydrofluoroolefins and their mixtures with HFCs dominate the market for lower-GWP fluorinated refrigerants. HFOs are chemicals designed to have desirable refrigerant traits like low-GWPs, flammability, and toxicity, but they lack the efficiencies of other modern refrigerant types. The use of HFOs is largely in conjunction with these other high-GWP refrigerants to optimize for the beneficial qualities respective to each type. In other words, they are mixed to achieve the "best of both worlds." In many cases, a high-GWP refrigerant is mixed with one or more low-GWP refrigerant(s) to maintain the performance, thermodynamic characteristics, and safety of the former while lowering its impact to levels near the latter's.

This group has more potential for drop-in replacements or retrofits than natural refrigerants, but they are currently not seen as a long-term solution. There is much less required to change in a given HFC-based system when considering a transition to an HFO/HFC blend because of their similarities in performance and safety standards. However, even most low-GWP fluorinated refrigerants have GWPs much higher than what is expected to be required of refrigerants moving forward (i.e., values no greater than 150). Though some of these refrigerants, like R-1234yf, have GWP values of one, many others have GWP values in the thousands. For example, R-448a, a suitable replacement for R-22 and other HFC refrigerants, has a GWP of 1400, nearly as high as some of the refrigerants it replaces. Still, they may play an important role in bridging the gap from the worst of an older generation to a still-developing next generation.

Popular Options. Figure 1 shows a general outline of fluorinated refrigerant replacement decisions from the high-GWP refrigerants used at HSU to their lower-GWP alternatives. The placement and specific refrigerants used in each decision are based on literature and are supported by multiple sources. This figure does not include all of the high-GWP replacements for R-12 or R-22, only the ones already used at HSU, nor does it include all of the lower-GWP replacements for these refrigerants. Only the lower-GWP options that had appeared most prolifically in or with the greatest approval from the literature are included. Finally, because this section is focused on fluorinated refrigerants, natural refrigerants are not included in Figure 1.

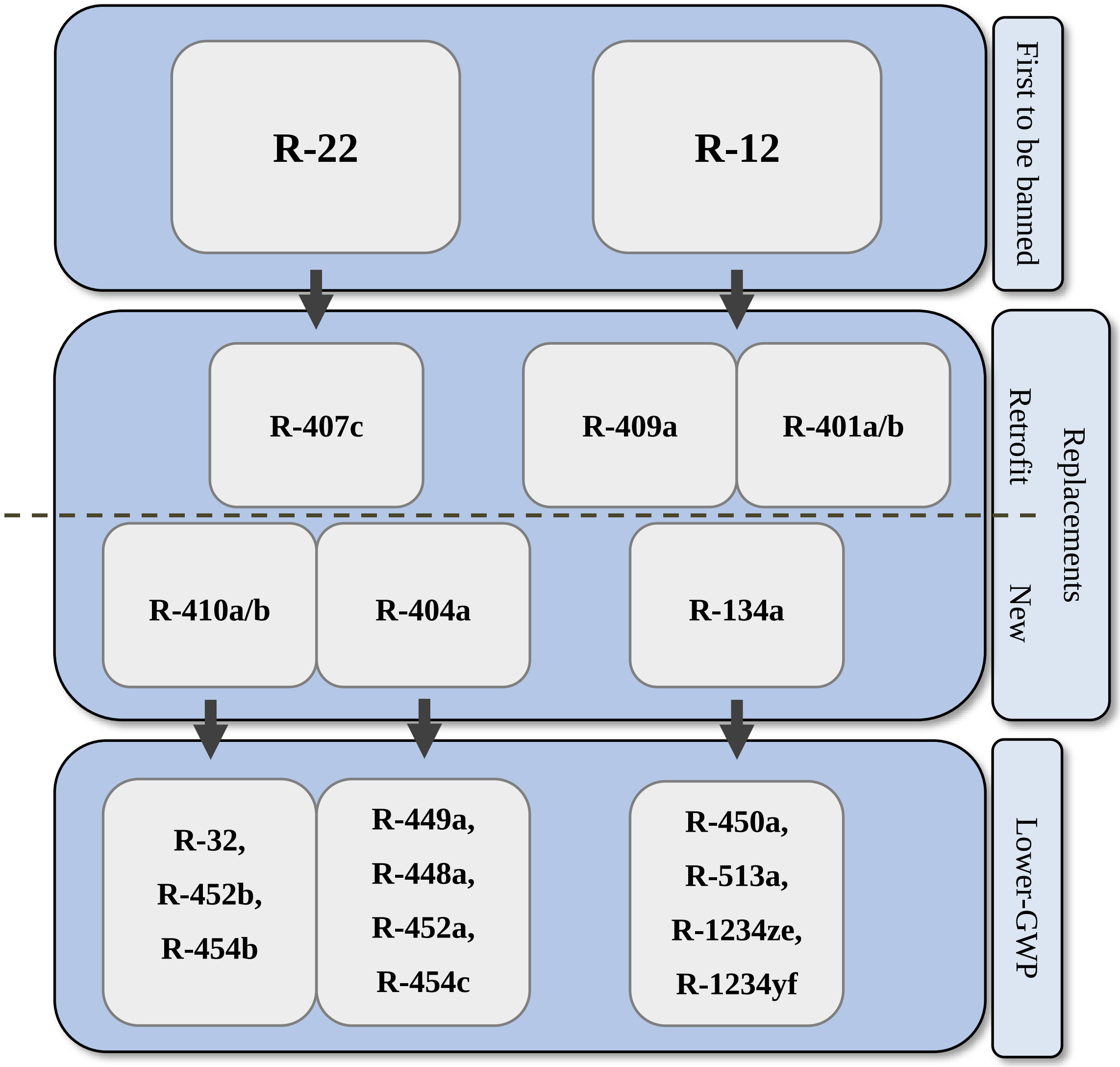

Figure 1. Flowchart showing the progression through time of the most popular fluorinated refrigerant replacement options. Three generations of refrigerants, including those used in retrofit and new equipment replacements, are shown. Retrieved from (Kedzierski et al., 2015; Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019; Hughes, 2018; Pardo & Mondot, 2018; Bobbo et al., 2019; Makhnatch, 2019).

This figure shows that the older generation of HFC refrigerants has typically been replaced with a distinct set of refrigerants and that those refrigerants have their own specific replacement options. The retrofitted refrigerants shown do not have their own replacement options because they were themselves a short-term replacement solution and are likely to have been used to further the lifespans of existing equipment. Thus, replacement options have not been developed for these refrigerants as extensively as they have for the “new equipment” refrigerants (i.e., R-134a, R-404a, or R-410a). Additionally, a full equipment replacement should be considered for existing “retrofit replacements” rather than another retrofit. For the remaining stock, these refrigerants can be considered for either drop-in/retrofit replacements or as options for total equipment replacements.

It seems that most high-GWP HFO/HFC blends are at parity with the HFCs that they replace with respect to operational performances and energy efficiencies (Patenaude, 2018). Unlike with natural refrigerants, many of these refrigerant blends have been designed to match the characteristics of the refrigerants that they are set to replace. For example, R-448a was designed specifically for the replacement of R-404a. Consequently, comparing any two refrigerants can be relatively easy, but a comparison of HFOs as a group of refrigerants to HFCs or natural refrigerants can be difficult. This means that the characteristic of each HVACR application and each system projected to be replaced must be carefully considered. Still, some believe that HVACR operators planning to convert a large number of their systems to safer and more environmentally friendlier alternatives

will find that HFO blends are the quicker, easier, and less expensive option (Patenaude, 2018).

Still, while they might meet short-term demands, HFOs are not long-term solutions to the global refrigerant problems described above. There are a few HFOs and HFO blends that have low-GWPs, like R-454c and R-1234yf, but there are nearly as many popular options that are on par or greater in their GWP values than some of the HFC refrigerants we use now. Additionally, they come with their own environmental hazards. The breakdown of some HFOs can result in a compound called Trifluoroacetic acid that is harmful when inhaled and can cause severe skin burns (Garry, 2021). Trifluoroacetic acid is deposited as acid rain and because of its durability and mobility it can accumulate in bodies of water (Garry, 2021). It may be that HFOs can be used to greatly reduce the direct emissions of a user's refrigeration inventory, but it is reasonable to expect them to be the next refrigerant group targeted for phase-down after HFCs because of their impact.

MATERIALS AND METHODS

This chapter presents this project's inventory process, the model used to calculate the potential impact of refrigerants on campus, the alternative inventories explored, and the uncertainties involved.

Inventory

The refrigerant and refrigeration-system inventory is an aggregate of information and data recorded by HSU's Facilities Management and retrieved in-person through facility tours given by HSU's Housing and Dining Services. It includes descriptions of the 101 HVACR systems operating in 25 buildings on the HSU campus. This inventory is limited to commercial systems and, as is discussed below, does not include personal refrigerators, dormitory refrigerators, or vending machines. This equipment inventory is the base for the GHG emissions analysis that follows.

The Facilities Management Building Service Engineer, Mike Dotson, was generous enough to have provided this study with all of Facilities Management's files on refrigerants used and kept on campus, including their own equipment inventory. These records were made possible largely because of the existence of Facilities Management's record-keeping database, AiM.[20] Housing, & Dining Services, the entity which maintains

[20] AiM is a software package developed by AssetWorks LLC. to meet the unique needs of facilities management entities. It is a multi-faceted product that can include organizational assistance for operations and maintenance, capital planning and project management, space management, real estate and property management, and energy management (AssetWorks LLC., 2020)

and operates the other portion of HSU's refrigeration systems, had until recently operated without AiM. As a result, it does not have data records available that are as comprehensive for its equipment or refrigerants. Fortunately, Dan Bouchard, the H&DS Maintenance Lead, and Ron Lyons, one of H&DS' facilities maintenance mechanics, were both kind enough to host extensive tours through the Jolly Giant Commons, the University Center, the College Creek Community Center, and the three on-campus dining halls, so that information could be collected on the equipment that operates there.

For the in-person data collection, this study focused on recording details like location, type of equipment, type and charge of refrigerants, equipment identifiers like the manufacturer and serial numbers, and lubricant used in an effort to mirror the contents of the spreadsheet already filled out by Facilities Management. Some of this information was easier to find than others. Electrical parameters such as voltages, phase, and frequency, for instance, were clearly labeled on most of the equipment surveyed. The type of refrigerant used by each system was also either included on the system's nameplate or written to the side in marker. The amount of refrigerant charge, however, was absent from most of the split condensing systems because of their constructed-on-site nature and the variability in the lengths of pipework between each system.

Since their charge is dependent on the specific refrigeration system configuration, it was not included on the manufacturer's equipment nameplate where other unit-specific information could be found. There are several direct ways to determine the charge of a system when records are not available. These methods include using gauges to determine relevant operating temperatures and compare them to the temperatures intended for the

system, measuring the lengths and diameters of relevant piping, and removing all of the refrigerant in the system and weighing it (Temple, 2004; Trakref, 2019). However, because of time restrictions and the inability to access installed pipework or remove refrigerant from the system while they were needed for use, none of these direct methods could be used.

Instead, Dan Bouchard and Ron Lyons estimated the refrigerant charge of the units that were without a known charge. These estimates were based on Mr. Bouchard's and/or Mr. Lyons' experience and knowledge surrounding the equipment and assumptions that they had made on the size of the components within each unit. Namely, they were looking at the size of the receiver, which is a storage tank designed to hold excess liquid refrigerant not in circulation and is typically sized proportional to the volume of refrigerant housed within a system (Marchese, 2014). For this study, however, the size of each receiver was visually determined rather than measured, and the corresponding charge was influenced by judgment more than calculation. Thus, there was not a single formula that was applied to each unit. Instead, a set of information and assumptions specific to the individual equipment informed these estimates. Still, the effectiveness of using the receiver size as a quick-estimation technique in the way that this study had is supported by both Mr. Bouchard and Mr. Dotson. [21]

[21] There is evidence that basing charge estimates on receiver size is a method used, or at least taught by the HVACR industry. It is accepted that receivers are generally sized to hold the system's expected charge at, or no more than, 80% of their capacity (Marchese, 2014; Orr, 2018). Thus, it can be inferred that a system's charge is likely to be near 80% of the refrigerant capacity of its receiver. This is supported by a Honeywell (2018) technical bulletin named "Refrigerant Charge Calculation." However, the bulletin also states that rarely is it the case that these receivers are filled to this 80% limit and, in fact, a 30% fill is more common.

The estimation methods used here were not as accurate as would be possible given perfect conditions, but they were based some-what on supported techniques. The cited inaccuracies of receiver-based estimations and the assumptions made by Mr. Bouchard and/or Mr. Lyons about those receivers are sources of uncertainty in this study. It may be that these estimates represent the lower boundary of what the actual charges are, since they are influenced by just one part of the system, the receiver, and do not take into consideration the other areas, like the long stretches of pipework that make up the rest of the system, that may dictate the volume of refrigerant within. The level of uncertainty is reduced in part by the expertise of the operators who are making these estimates and by their familiarity with the systems in question, but it does not eliminate them. An explanation of how these uncertainties factor into the understanding of the results presented in this study is included below.

Model

The two equipment inventories (i.e., Facilities Management's AiM inventory and the results from the Housing and Dining Services tour) were combined, and their systems categorized so that they could be organized into a model and analyzed by their impact. The various systems were split into six classifications based on their general equipment types: (i) Residential Appliance, (ii) Stand-Alone Hermetically Sealed, (iii) Refrigerated Condensing Unit, (iv) Small to Medium Unitary HVAC, and (v) AC Chiller. This was

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This is supported through personal communications with professionals on an HVAC discussion forum, who added that while this 80% estimation is appropriate for sizing a system, it is not accurate for determining the charge within an already operating system because of the tendency to oversize receivers.

done so the charge estimates could be compared to averages and assigned leak rate ranges gathered from the literature. The ODP and GWP of the refrigerant in each system/unit are used to determine the installed and annually leaked quantity of refrigerant in metric tons of carbon dioxide equivalent and metric tons of ODP.

For some portions of this refrigerant inventory, information regarding refrigerant leaks, annual recharge quantities, purchase history, and disposal is unavailable. Since existing data at HSU are limited, published data have been consulted to fill in current information gaps. The typical HVACR equipment characteristics, and specifically the usable lifetime of the equipment and leak rate values at various stages of the equipment's life, shown in Table 8 have been used to estimate HSU's likely refrigerant loss rate. It is assumed that the systems at HSU fall into or are near the same ranges of annual refrigerant loss shown here.

Table 8. Typical equipment characteristics and refrigerant leak rates from literature (each row includes data from the listed source).

Commercial Appliance Type	Source[22]	Average Charge Range (lbs.)	Usable Lifetime (years)	Installation Loss Rate (% of capacity)	Operational Leak Rate (% of capacity/yr)	Charge at EoL (% of capacity)[23]	Recovery Efficiency (% of remaining)	Disposal Loss Rate (% of original)
Domestic Refrigerator	[a][24]	0.1-1	12-20	0.2-1%	0.1-0.5%	0-80%	0-70%	24-100%
Domestic Refrigerator	[c]	0.2	15	0.6%	0.3%	-	-	35%
Domestic Refrigerator	[e][25]	0.34	-	-	1%	85%	-	77%
Domestic Refrigerator	[f]	0.33	14	-	0.5%	91%	31%	63%
Stand Alone Hermetically Sealed	[a]	0.4-13	10-15	0.5-3%	1-15%	0-80%	0-70%	24-80%
Stand Alone Hermetically Sealed	[c]	1	10	1%	1.5%	-	-	40%

[22] [a] (Ashford et al., 2006), [b] (Seidler et al., 2009), [c] (ICF International, 2011), [d] (UNEP Ozone Secretariat, 2015), [e] (CARB, 2016), [f] (ICF International, 2016).

[23] An end-of-life charge of 100% is possible for two reasons: there is assumed to be no operational leaks (only with hermetically sealed units), or maintenance is possible, and the equipment has been recharged before its end-of-life (all other units).

[24] This and the remaining IPCC, 2006 citations in this table have reported leak rates for a wider range of users than the other sources here. In doing so, they have grouped values from "developed" and "developing" countries together. Consequently, the higher end is more accurate for "developing" countries.

[25] This source presents data from the US Environmental Protection Agency's Vintaging Model version 4.4. The original publishing of this data cannot be found.

Commercial Appliance Type	Source[22]	Average Charge Range (lbs.)	Usable Lifetime (years)	Installation Loss Rate (% of capacity)	Operational Leak Rate (% of capacity/yr)	Charge at EoL (% of capacity)[23]	Recovery Efficiency (% of remaining)	Disposal Loss Rate (% of original)
Stand Alone Hermetically Sealed	[d]	0.2-1	-	-	<1%	-	-	-
Stand Alone Hermetically Sealed	[e]	7	-	-	0%	100%	-	100%
Stand Alone Hermetically Sealed	[f]	0.88	10	-	1%	90%	25%	68%
Refrigerated Condensing Unit	[a]	110-4,409	7-15	0.5-3%	10-35%	50-100%	0-70%	15-100%
Refrigerated Condensing Unit	[b]	50-200	-	-	14%	-	-	-
Refrigerated Condensing Unit	[c]	11	14	2%	10%	-	-	15%
Refrigerated Condensing Unit	[d]	2-22	-		5-20%	-	-	-
Refrigerated Condensing Unit	[e]	0-200	-		15%	86-100%	-	20-34%
Refrigerated Condensing Unit	[f]	22	20	2%	12-25%	90%	70-85%	13.5-27%
Small to Medium Unitary HVAC	[a]	1.1-220	10-20	0.2-1%	1-10%	0-80%	0-80%	16-80%
Small to Medium Unitary HVAC	[b]	50-200	-	-	11%	-	-	-

Commercial Appliance Type	Source[22]	Average Charge Range (lbs.)	Usable Lifetime (years)	Installation Loss Rate (% of capacity)	Operational Leak Rate (% of capacity/yr)	Charge at EoL (% of capacity)[23]	Recovery Efficiency (% of remaining)	Disposal Loss Rate (% of original)
Small to Medium Unitary HVAC	[c]	6.6-397	15-18	0.5-1%	3-6%	-	-	20%-30%
Small to Medium Unitary HVAC	[e]	0-50	-	-	10	80%	-	56%
Small to Medium Unitary HVAC	[f]	11-28.6	15-25	-	8%	80%	50-70%	24-40%
AC Chiller	[a]	22-4409	15-30	0.2-1%	2-15%	80-100%	0-95%	4-100%
AC Chiller	[b]	200-2,000	-	-	1%	-	-	-
AC Chiller	[c]	397	18	0.5%	3%	-	-	20%
AC Chiller	[e]	200-2,000	-	-	6.9%	93%	-	20%
AC Chiller	[f]	1,102	23	0.5%	2%	95%	85%	14%

Among other descriptive features, Table 8 also gives typical leak rate values for these general types of commercial appliances using refrigerants on the HSU campus. There are three stages in the life-cycle of HVACR equipment where refrigerants leak. These losses occur when: 1) initially charging new equipment, 2) through normal use and servicing, and 3) through the process of retiring the equipment (also referred to as the equipment's end-of-life or EoL) (IPCC, 2006). The scale of loss in each of these phases is dependent on several variables, including system charge, size, type, age, the frequency of maintenance, any governing regulations, and the manner of disposal.

The leak rate ranges reported here were developed through various studies using large volumes of surveyed units. For example, California Air Resources Board (part of the California Environmental Protection Agency) (2016) averaged leak rates from just under 400,000 condensing unit refrigerators alone. Study areas range from the state of California to various countries around the world. This table is limited, however, in that the youngest dataset it uses was collected in 2014, more than six years ago. This may affect the accuracy of these values.

High, average, and low leak estimates are used to give a more realistic range of HSU's leak rate potential and, thus, its GHG emission values. The three levels of loss (high, average, and low) are obtained from the values presented in Table 8. The highest and lowest leak rate values at each phase of loss (i.e., installation, operation, and disposal) for each equipment type constitute the high and low leak rate scenarios, respectively. For example, the high leak rate scenario for AC Chillers is 1% loss at installation, 15% annual loss through operation, and 100% loss during disposal. The

average leak rate scenario is a calculated average of all of the leak rate values for each equipment category. For example, AC Chillers have an average of 0.6% loss at installation, a 7.3% loss through operation and a 50.6% loss during disposal.

The annual operational leak rates were combined with the installation and EoL leak rates, distributed throughout the equipment's documented average lifetime,[26] to give the estimated average annual loss as a percent of the total system charge. Each system's charge was then factored in to give its annual refrigerant loss rate as a mass per year. Finally, the GWP of the refrigerant used in each system was factored in to give the annual carbon dioxide equivalent impact for each unit. This was repeated for each level of leak estimate and resulted in a three-value range of possible emissions. In other words, the impact calculated for the campus is a function of the GWP values of the refrigerants used, the amount of each refrigerant used, and the leak rates of the equipment types on campus.

The most recent values for GWP and ODP from the 2018 report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) were used to compare the refrigerants used on campus. Over generations of scientific assessment, several sets of values for ODP and GWP have been developed by the World Meteorological Organization and the Intergovernmental Panel on Climate Change (IPCC). These values differ for a number of reasons, including different sources used, updates in research and scientific understanding, and the range of uncertainty associated

[26] This method maintains each units' average total emissions without knowing their individual ages or actual total lifetimes. However, it will inflate annual emissions in years when few units are retired and deflate emissions when many are retired.

with each value (UNEP, 2016). The set of values used in this report, however, reflects the most complete (including HFC blends) of the recent scientific assessments. The Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) pulls its data from the World Meteorological Organization (2018), the IPCC (2014), the World Meteorological Organization (2011), and the IPCC (2007).

The California Air Resources Board uses a different set of values than were chosen for use here, and it is important to understand the implications of this choice. CARB currently uses IPCC (2007), the fourth IPCC Assessment Report, in its studies and regulation. Since CARB is the agency in charge of all of California’s air pollution control, these are also the values, then, that the California State University system, and thus, HSU, must use. So, it would be reasonable to use this report as the main reference in this study. However, the fourth IPCC Assessment Report is the second most recent, and even the most recent is somewhat dated as it was published more than six years ago (2014). This study has prioritized the use of data that reflects the most up-to-date scientific knowledge over using the somewhat outdated values used by CARB. The multiple reports that are considered as potential options for use are compared by their percent difference in values and in results.

This study also reports its results using the 100-year time horizon, though a section that shows the impact of using the 20-year horizon is also included. These 100-year values are far more often what will be found in reports concerning refrigerant pollution, and they are what CARB references, so complying with regulations will mean using these values. However, the difference between the two time-horizons is in the

priorities of those using them. Here, and perhaps in other global settings, it may be wise not to set sights so far off.

The 100-year horizon prioritizes the distant future and how the effects of something are felt over that time period. But now, in 2021, with the extreme impacts of climate change already felt all over the world, it seems irresponsible to disregard the high impact that a substance can have on the climate in the shorter-term. Most of the refrigerants in this report have atmospheric lifetimes shorter than 20 years. HSU has pledged carbon neutrality by 2050 (30 years from now) (HSU Office of Sustainability, 2016). And it is far more important to focus on curbing the fuel to climate change by the middle of this century rather than at the end, as it may be too late by then. Still, it is important to use what will be most useful by the affected parties at HSU. Nonetheless, the near-term outlook is important, and the results using a 20-year time horizon value set show the seriousness of the issue.

Projections

Multiple emissions scenarios are considered based on economic, technological, and practical feasibility. These scenarios give a sense of what the impact would look like if the refrigerants used on campus today were replaced with alternatives. Three pathways of commercially available replacement options for HSU's current inventory are outlined below to do this. The replacement pathways will be compared based on their respective GHG emissions and the nature of the replacement (i.e., drop-in refrigerants vs. full equipment replacements). This is an informed look at what the next steps for HSU's

HVACR systems could be and a chance to consider how upcoming action might affect future campus GHG emissions.

The replacements that were selected for this analysis are currently accepted as the most suitable alternatives for each refrigerant that they are replacing, based on recent literature. These replacements were chosen based on assumptions made about the refrigeration requirements rather than the equipment types alone. For some equipment types, there is a greater variety of proposed replacements because there is such a large variety of current refrigerants which are distinctly suited for one application over another. Though there are many refrigerants that are available and are discussed as appropriate options in the literature for a given application, the ones chosen for this analysis were those that were discussed most often and were found to have received more positive assessment than others. Table 9 below specifies the refrigerants that were chosen as replacements for the current inventory, outlines the high, moderate, and low, replacement pathways explored, and presents the associated GWP impacts of those refrigerants.

Table 9. Chosen replacements for HSU's current refrigerant inventory by equipment category. This table is meant to show which refrigerants were used in the projected emissions analysis. The three "replacing" refrigerants that are shown for each existing refrigerant make up the high, moderate, and low scenarios/pathways. The placement of each "replacing" refrigerant is based on the literature informing Figure 1 and the Natural Refrigerants sub-section.

Equipment Type	Existing Refrigerant	Existing Refrigerant 100-year GWP	Replacing Refrigerant	Replacing Refrigerant 100-year GWP
Stand Alone Hermetically Sealed	R-22	1,780	R-448a/R-449a	1400
Stand Alone Hermetically Sealed	R-22	1,780	R-454c	150
Stand Alone Hermetically Sealed	R-22	1,780	R-290	1
Stand Alone Hermetically Sealed	R-134a	1,360	R-513a	600
Stand Alone Hermetically Sealed	R-134a	1,360	R-450a	570
Stand Alone Hermetically Sealed	R-134a	1,360	R-290	1
Stand Alone Hermetically Sealed	R-404a	4,200	R-448a/R-449a	1400
Stand Alone Hermetically Sealed	R-404a	4,200	R-454c	150
Stand Alone Hermetically Sealed	R-404a	4,200	R-290	1
Stand Alone Hermetically Sealed	R-410a	2,100	R-32	704
Stand Alone Hermetically Sealed	R-410a	2,100	R-454b	490
Stand Alone Hermetically Sealed	R-410a	2,100	R-290	1
Refrigerated Condensing Unit	R-12	10,300	R-134a	1360
Refrigerated Condensing Unit	R-12	10,300	R-513a	600
Refrigerated Condensing Unit	R-12	10,300	R-290/R-744	1
Refrigerated Condensing Unit	R-22	1,780	R-448a/R-449a	1400
Refrigerated Condensing Unit	R-22	1,780	R-454c	150
Refrigerated Condensing Unit	R-22	1,780	R-290/R-744	1
Refrigerated Condensing Unit	R-134a	1,360	R-513a	600
Refrigerated Condensing Unit	R-134a	1,360	R-450a	570

Equipment Type	Existing Refrigerant	Existing Refrigerant 100-year GWP	Replacing Refrigerant	Replacing Refrigerant 100-year GWP
Refrigerated Condensing Unit	R-134a	1,360	R-290/R-744	1
Refrigerated Condensing Unit	R-401a	1,100	R-513a	600
Refrigerated Condensing Unit	R-401a	1,100	R-450a	570
Refrigerated Condensing Unit	R-401a	1,100	R-290/R-744	1
Refrigerated Condensing Unit	R-401b	1,200	R-513a	600
Refrigerated Condensing Unit	R-401b	1,200	R-450a	570
Refrigerated Condensing Unit	R-401b	1,200	R-290/R-744	1
Refrigerated Condensing Unit	R-404a	4,200	R-448a/R-449a	1400
Refrigerated Condensing Unit	R-404a	4,200	R-454c	150
Refrigerated Condensing Unit	R-404a	4,200	R-290/R-744	1
Refrigerated Condensing Unit	R-409a	1,500	R-513a	600
Refrigerated Condensing Unit	R-409a	1,500	R-450a	570
Refrigerated Condensing Unit	R-409a	1,500	R-290/R-744	1
Refrigerated Condensing Unit	R-410b	2,200	R-32	704
Refrigerated Condensing Unit	R-410b	2,200	R-454b	490
Refrigerated Condensing Unit	R-410b	2,200	R-290/R-744	1
Small to Medium HVAC	R-22	1,780	R-32	704
Small to Medium HVAC	R-22	1,780	R-454b	490
Small to Medium HVAC	R-22	1,780	R-290	1
Small to Medium HVAC	R-407c	1,700	R-32	704
Small to Medium HVAC	R-407c	1,700	R-454b	490
Small to Medium HVAC	R-407c	1,700	R-290	1
Small to Medium HVAC	R-410a	2,100	R-32	704
Small to Medium HVAC	R-410a	2,100	R-454b	490

Equipment Type	Existing Refrigerant	Existing Refrigerant 100-year GWP	Replacing Refrigerant	Replacing Refrigerant 100-year GWP
Small to Medium HVAC	R-410a	2,100	R-290	1
AC Chiller	R-22	1,780	R-32	704
AC Chiller	R-22	1,780	R-454b	490
AC Chiller	R-22	1,780	R-717	0
AC Chiller	R-407c	1,700	R-32	704
AC Chiller	R-407c	1,700	R-454b	490
AC Chiller	R-407c	1,700	R-717	0

These refrigerants are categorized into high, moderate, and low replacement categories based on their GWP values. The explored pathways are limited here to three GWP value ranges. The high scenario GWP values include values from 600 to 1,400. The moderate scenario is a range of refrigerants with GWP values from 150 to 600. The low scenario is limited to GWP values of 1. The relevance of these limits comes mostly from the exclusion of R-452a, an HFO refrigerant blend shown in Figure 1 to be a suitable option to replace R-22 and some of its HFC alternatives. However, because its 100-year GWP, 2100, is higher than most of the refrigerants it would be replacing, this study has chosen to exclude it from consideration in its replacement pathways.

Uncertainty

It is important to recognize the uncertainty in any analysis performed within a project. The data collected for the HSU refrigerant inventory represents an initial point of error/uncertainty. There is a level of uncertainty associated with every charge value reported. The Facilities Management data are assumed to be well-known. However, given the nature of the estimates made about the equipment charges collected with H&DS and because information on the collection of Facilities Management's charges was unavailable due to COVID-19 restrictions, this study assumes a plus/minus 20% uncertainty for each charge entry.[27] The estimated charges described above that are not

[27] It was the intention of this study to corroborate this with an explanation from Facilities Management about their charge measurements, but this information was inaccessible due to COVID-19 related difficulties. This error value should be updated, however, with a more accurate value of uncertainty related to charge measurements.

well-known are, at least, confined to a portion of the H&DS side of the inventory. While they do make up 53% of the H&DS units, they only account for 22% of the total reported campus inventory.

A propagation of uncertainty was performed to show how the errors and uncertainty in this study have affected its results. This meant multiplying each refrigerant charge by its stated uncertainty, multiplying that value (in pounds) to the global warming impact of the lost refrigerant per year (in tons of carbon dioxide equivalent / pounds of refrigerant), squaring that product, and taking the square root of the sum of each of those entries. This resulted in a standard deviation, or a range of possible values around the total emissions in which the true result might lie. This standard deviation was then doubled to give a 95% confidence interval. This was repeated for each leak estimate range in each refrigerant scenario. The general formula used in this error analysis can be found in Equation 1.

Equation 1. Propagation of uncertainty. Retrieved from (Harvard University, 2007).

$$\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2 + (\delta c)^2 + \cdots + (\delta z)^2}$$

where:

- δQ is the uncertainty around the cumulative impact of the reported units, and
- δa- δz are the uncertainties in the calculated impact of each individual unit.

This propagation is dependent on a few assumptions made about the values used within the model. Specifically, it assumes that the GWP values and the leak rates used are known without any uncertainty. Both of which, however, have a level of uncertainty

associated with them.[28] It also assumes that there is no correlation between the measurements of refrigerant charge for each system and that the impact of each system is a function of the leaked refrigerant alone.

Some assumptions were made about the natural refrigerants chosen to constitute the low scenario replacements, as shown in Table 9. This refrigerant selection, and, in general, the inclusion of natural refrigerants as options for approaching use within about the next five years assumes that they will have developed and proliferated throughout the US by then. HSU may be a school that is willing to try new things, but it is unlikely it is in a position to be the first school to try a new, potentially dangerous refrigerant. This is a reasonable assumption to make, especially with the new pro-low-GWP refrigerant laws that have passed this year, in 2021, alone. The natural refrigerants used with reported GWP values that are "less than one" (but not zero) have been given GWP values of one in this analysis to reduce difficulties in calculations.

Ozone depletion is an aspect of refrigerant use that is important but, ultimately, it is outside of the project's scope. The notoriety of refrigerants may, indeed, be more a consequence of the effects they have had and continue to have on Earth's atmospheric ozone layer than their global warming impacts. Additionally, some of the worst offenders of this ozone depletion, especially R-12, are still used on the HSU campus. However,

[28] The uncertainty associated with GWP values for a refrigerant is defined by their atmospheric lifetimes, as stated in IPCC (2014). Their lifetime ranges can be grouped into centuries, decades, or years, with the shortest periods having the most uncertainty. Refrigerants with century-long lifetimes can be assumed to have an uncertainty range of 30%, decade-long lifetimes of 35%, and short-lived gases of 50%. This means that for a refrigerant with a stated life of 500 years, the actual life may be anywhere between 350 and 650 years. This is consistent with World Meteorological Organization (2014), which states that GWPs for the 100-year time-horizon have uncertainties of roughly ±35% with higher uncertainties attributed to shorter-lived gases, and IPCC (1996), which states that typical uncertainties for GWPs are on the order of 35%.

metric tons of ozone depletion potential emitted is a metric that is not easily comparable on a small scale. Ozone depletion seems to be exclusively reported on the national or global scales. This study has been unable to find any universities, businesses, or other similarly sized organizations that report their ozone depletion, nor has it found any that specify the refrigerants lost each year so that their associated ozone depletion could be calculated. Consequently, the current analysis is focused on global warming impacts.

This study does not include or pursue the emissions from dorm refrigerators, dorm minifridges, office minifridges, and vending machines. The number of refrigerators and minifridges in the on-campus residence halls, some 210 refrigerators, and 653 minifridges, may indicate that they could, collectively, have a substantial emissions profile. Interestingly enough, though, they all operate using isobutane, a hydrocarbon refrigerant with a negligible GWP (Dan Bouchard, personal communication, 2020). So, when this low-GWP is coupled with each unit's small charge[29] and low operational leak rates, the result is a negligible global warming impact.[30] The descriptions and counts of refrigerants and equipment are still included for reference and context. However, they will not be included in any emissions analysis here.

Previously collected information regarding office minifridges and vending machines, were unavailable at the time of this study and may be non-existent. There were

[29] Assumed to be 0.3 lbs. for refrigerators and 0.15 lbs. for minifridges.
[30] Assuming a charge of 0.15 lbs. and a set of loss rate values reflecting the Domestic Refrigerator equipment category, as described in Table 8, the most that a given mini-fridge would lose in a year is 0.01 lbs. of refrigerant. When converted to tons and when the GWP of isobutane is factored in, the resulting emissions in $MTCO_2e$ are 0.00. Even when all of the hundreds of housing mini-fridges and refrigerators are totaled, their cumulative associated emissions are still only 0.01 $MTCO_2e$.

also no clear rules allowing or disallowing faculty and staff from owning personal minifridges in their own offices or other workspaces. It was the intention of this study to collect data through an inventory exercise of a subset of offices and then extrapolate from this effort to cover the whole campus to provide an estimate that could be used to examine their contribution. With the restrictions and lack of accessibility brought on by the COVID-19 pandemic, however, it was not possible to collect this information. When Andrea Alstone, the Energy Planner/Analyst at HSU Facilities Management was questioned about the contribution of these minifridges and vending machines she mentioned that she thought they would probably play a minimal role when compared to the rest of the campus' inventory. It is likely that this is the case, especially because minifridges are shown above as being responsible for small amounts of emissions per year.

Finally, it was the intention of this study to compare known refrigerant recharge data to published data to gauge the campus' general positioning within the range of leak rates developed here, but that comparison was not possible as of the writing of this report. In early communications with Mike Dotson, he had mentioned the existence of logs kept by Facilities Management that detail the exchanges of refrigerants into and out of equipment that they manage. These logs could have been used to identify patterns of recharge frequency and quantity over some number of years at HSU. Priority would have been placed on the ranges of recharge rates within the individual equipment types, as that would most align with the leak rates from the literature described above. Trends in equipment age and size would also have been a focus. Unfortunately, this was

unachievable due to the COVID-19 pandemic and the restrictions and busyness which it brought to HSU Facilities Management and the world.

Knowing the frequency of leaks and the average percentage of refrigerant lost for a given equipment type annually would certainly improve the accuracy of the emissions analysis. As will be shown below, the emissions calculated are so heavily influenced by the rates of refrigerant loss, that the information based on recorded data would likely eliminate the need to estimate annual emissions, at least for the current inventory. Still, my results are based on leak rate values that have been measured for similar systems in a wide variety of settings, providing a reasonable estimate of what can be expected for typical systems of the respective types. The values should be updated, however, with data collected at HSU when that becomes possible again.

HSU INVENTORY

In order to know whether high-GWP refrigerant use at HSU is a problem, one must first look at the individual pieces, the impact of the refrigerants themselves, the regulations governing them, the equipment using them, and the entities that manage them. These pieces provide clues as to what, if anything, is problematic, whether something should or can be done about it, and what should be done. Understanding the refrigerants and the technology using them can highlight possible hazards or areas with higher-than-normal impact. Knowing where and how much of each refrigerant is used also allows for a better understanding of the courses of action that can be taken when considering their possible replacement. Questions like, “who is in a position to address these problems and how big of a fix will it be?” are as important as identifying the problem itself. The following section is intended to cover some of these details.

Refrigerants Used on Campus

Table 10 lists the eleven different types of refrigerants currently used on campus with their respective refrigerant category, GWP, ODP, and atmospheric lifetime. Refrigerants are grouped into six categories: CFCs, HCFCs, HFCs, HCFC blends, HFC blends and HCs. Most of the refrigerants used are zeotropic blends, which are mixtures of two or more refrigerants designed to match certain properties of the refrigerants used before them while also complying with regulations (UNEP Compliance Assistance Programme, 2016). All but one of these refrigerants have high-GWPs, with the highest at

10,300 and the lowest at 1,100. Only half deplete the ozone directly with ODPs between 0.02 and 0.73. However, because of their warming effects, they all indirectly deplete the ozone layer (Hurwitz et al., 2015).

Table 10. Refrigerants used at Humboldt State University and their corresponding impacts. Adapted from (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

Refrigerant	Type	100-year GWP	20-year GWP	ODP	Atmospheric Lifetime
R-12	CFC	10,300	10,800	0.73	102 years.
R-22	HCFC	1,780	5,310	0.034	12 years.
R-134a	HFC	1,360	3,810	0	14 years.
R-401a	HCFC Blend	1,100	3,500	0.02	-
R-401b	HCFC Blend	1,200	3,800	0.03	-
R-404a	HFC Blend	4,200	6,600	0	-
R-407c	HFC Blend	1,700	4,100	0	-
R-409a	HFC Blend	1,500	4,400	0.03	-
R-410a	HFC Blend	2,100	4,400	0	-
R-410b	HFC Blend	2,200	4,600	0	-
R-600a	HC	<1	<1	0	6 days

All of the refrigerants used, with the exception of R-600a, are either banned or are at some point in the process of being phased down. R-12, and now, R-22 and the refrigerants that contain it (i.e., R-401a, R-401b, and R-409a) have all been banned for production and import (in “developed” countries) since 1996 and 2020, respectively, as a

result of the Montreal Protocol (EPA, 2020e; EPA, 2020f). R-22, R-401a, R-401b, and R-409a have also all been banned in new equipment since 2010 (EPA, 2020f).[31]

The use of these "banned" refrigerants is still legal. However, the equipment affected will have to be serviced with recycled and reclaimed refrigerant rather than new refrigerant, as no new refrigerant can be produced nor imported (EPA, 2020f). The extension of any existing unit's cooling capacity qualifies that unit as "new equipment", and thus, disqualifies it from using even reclaimed supplies of any of these banned refrigerants (EPA, 2020e). Otherwise, existing equipment can still be operated like normal until refrigerant reserves run out.

The rest of the refrigerants used here are not regulated nationally or globally, as the Kigali amendment does not target individual refrigerants. Even the new AIM act leaves out specific refrigerant restrictions, and although their bans had been scheduled in earlier federal legislation, those rules have been vacated. Still, in California, all of these remaining refrigerants have been prohibited for use in new equipment as of or before January 1st of 2021 (CARB, 2018). Additionally, R-404a has been banned from all retrofitted equipment since 2019 (CARB, 2018). Currently, only R-134a, R-407c, R-410a, and R-410b are available for retrofitted equipment from the list. However, all but R-134a have GWP values that are as high or higher than the refrigerant they are most likely to replace, R-22.

[31] The extension of any existing unit's cooling capacity qualifies that unit as "new equipment", and thus, disqualifies it from using any of these banned refrigerants. under these rules.

The distribution of refrigerants across the campus and their estimated cumulative installed totals in pounds is tabulated in Table 11 and illustrated in Figure 2. R-22, R-407c, R-404a, and R-410a are the refrigerants with the most installed capacity on campus at 483, 260, 141, and 142 lbs. respectively, accounting for 89% of the total installed mass. Three refrigerants alone (R-22, R-407c, and R-404a) are estimated to account of 78% of the total Nearly all of this capacity is operated by Facilities Management with the exception of R-404a, which is used predominantly by H&DS. Moreover, 72% of the total mass of refrigerants used on campus are under the supervision of Facilities Management. In total, there are about 1,260 lbs. of refrigerant used at HSU.

Table 11. Quantities of installed refrigerants at Humboldt State University and their corresponding operators. Values are given in pounds. Percent totals are given to show each refrigerant's relative abundance on campus.

Refrigerant	Facilities Management	Housing & Dining Services	Total	Percent of Total
R-12	28	-	28	2%
R-22	451	32	483	40%
R-134a	14	2	16	1%
R-401a	8	8	16	1%
R-401b	-	2	2	0%
R-404a	60	181	241	20%
R-407c	210	50	260	22%
R-409a	-	15	15	1%
R-410a	140	3	143	12%
R-410b	-	2	2	0%
R-600a[32]	-	54	54	-
Totals (excluding R-600a)	**911**	**295**	**1,206**	

[32] The installed amount of R-600a is included for reference. However, because the domestic refrigerator equipment category is excluded from the following emissions analysis, the refrigerant type which it exclusively uses is also excluded from the total quantities given here.

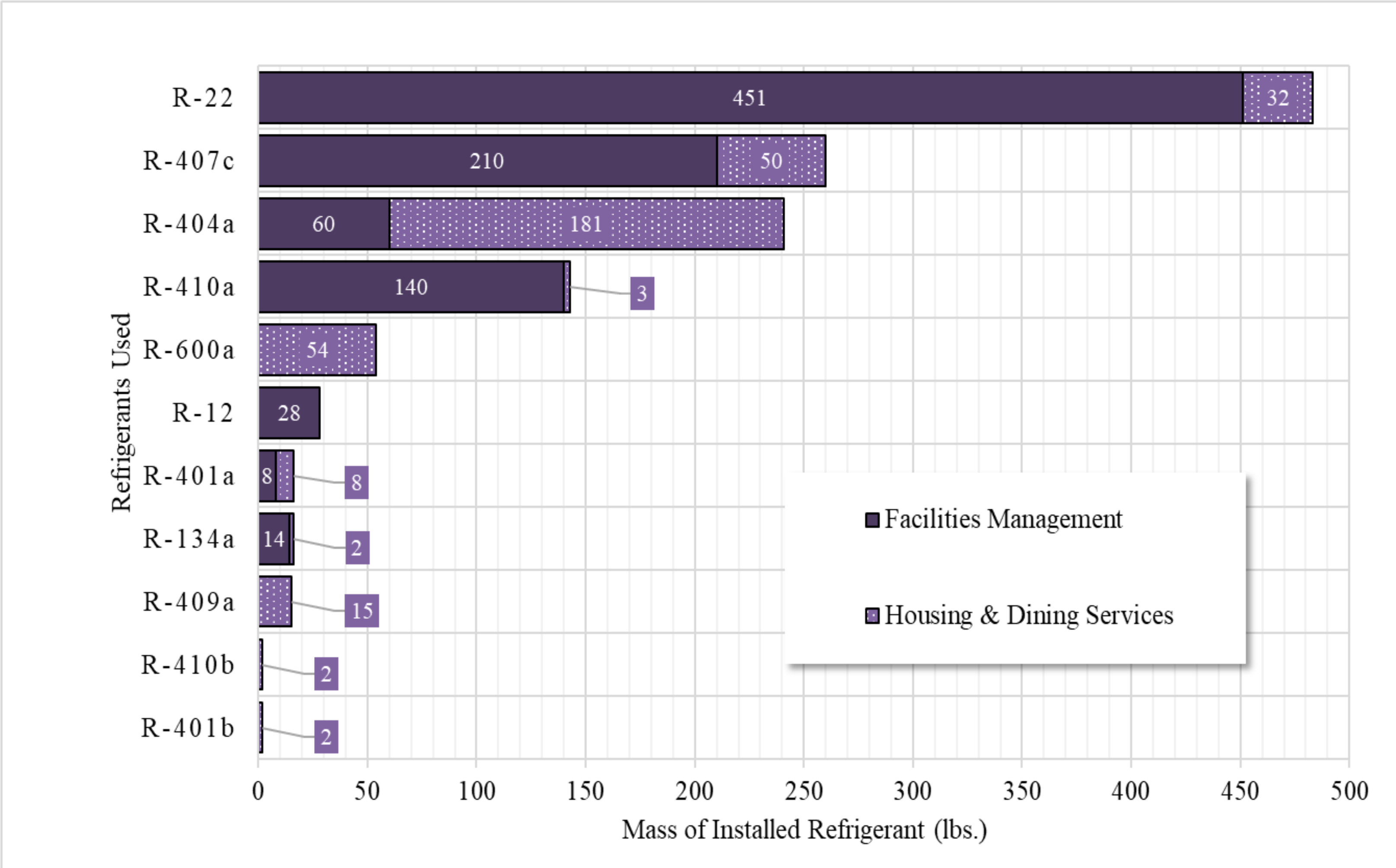

Figure 2. Comparison of the installed masses of each refrigerant currently used at Humboldt State University. Data are shown for systems managed by Facilities Management and Housing and Dining Services.

Figure 3 shows the distribution between the two organizations spatially by highlighting the 25 buildings on the HSU campus which contain the refrigerants and HVACR equipment included in this project[33]. These buildings include four dining areas: the Jolly Giant Commons, the College Creek Marketplace, the Depot, and Windows Café; six non-classroom buildings: the HSU Library, the greenhouse, the fish hatchery, Student and Business Services, Facilities Management, and the Toddler Center; and sixteen classroom buildings: Seimens Hall, Theater Arts, Founders Hall, Van Metre Hall, Art A, Gist Hall, Jenkins Hall, Science A, Science B, Science C, Science D, Wildlife and Fisheries, Harry Griffith Hall, Natural Resources, Forestry, and Behavioral and Social Sciences.

[33] Though it is true that only 25 buildings are included in this inventory, one building is divided so that both Facilities Management and H&DS operate out of it. This division is shown in Figure 3 at points "b" – The Depot / Windows Café – and "e" – University Center.

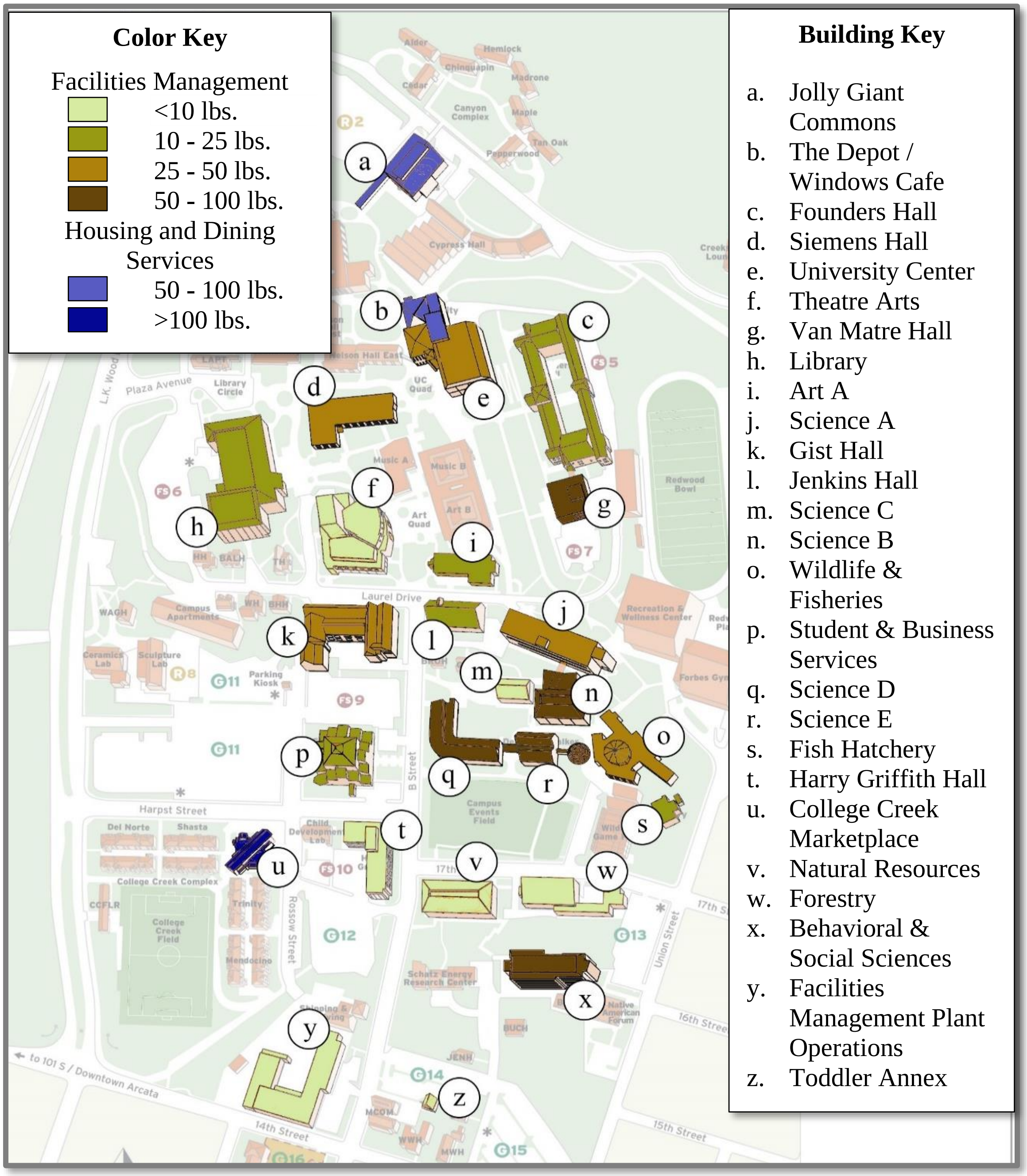

Figure 3. Map of the Humboldt State University campus highlighting the buildings which house HVACR equipment. These buildings are categorized into six groups based on the amount of refrigerant installed within each building and whether they are operated by Facilities Management or Housing and Dining Services. See alternative text for a listing of the buildings within each group. Not pictured in this figure are the HSU marine lab, cell tower, and KHSU transmitter site.

Application Descriptions

There are five general categories of refrigeration and air conditioning applications on campus: domestic refrigeration, stand-alone hermetically sealed systems, refrigerated condensing units, small to medium unitary HVAC, and AC chillers. Each category satisfies HSU's many needs in different ways, and they also contribute differently to the impact that HSU has on the environment. Table 12 shows a count of each equipment type by operator. Below are brief descriptions for these equipment categories. The category descriptions help inform where HSU's equipment fits in each category, what can and cannot be easily changed and when, what is contributing more or less to GWP, and what can be done about it. These descriptions also provide much of the equipment-specific information used in the analysis of this study.

Table 12. Quantities of installed equipment types at Humboldt State University and their respective operators. Values are given in number of units.

Application	Facilities Management	Housing & Dining Services	Total
Domestic Refrigeration[34] (excluded from analysis	-	863	863
Stand-Alone Hermetically Sealed	7	5	12
Refrigerated Condensing Units	14	28	42
Small to Medium Unitary HVAC	40	2	42
AC Chillers	5	-	5
Total (excluding Domestic Refrigeration)	**66**	**38**	**101[35]**

[34] The number of installed domestic refrigerators is included for reference. However, because the domestic refrigerator equipment category is excluded from the following emissions analysis, it is also excluded it from the total quantities given here.
[35] This includes three units not represented in the following emissions analysis here. One heat pump that was included in the Facilities Management inventory, but not filled out, and two split condensing units that were inaccessible on the H&DS equipment tours.

Domestic Refrigerators

The domestic refrigerator category describes most non-commercial or industrial refrigeration. They include residential refrigerators, minifridges, coolers, and freezers. Figure 4 shows an example of a basic refrigerator. These are standard units that can be found at homes, offices, and dorm rooms. These individual units are self-contained, factory built, and hermetically sealed (meaning airtight). This equipment type has the lowest refrigerant charge (commonly under 1 lb.) of any equipment category mentioned here because of its smaller cooling duty and minimal pipework. Because its compressor is sealed, there are few operational leakages associated with these systems. The main source of emissions for this equipment type is at the end of its life due to equipment failure or inappropriate disposal methods, including not following end-of-life (EoL) recovery procedures (UNEP Ozone Secretariat, 2015). Common refrigerants include R-134a and R-600a. Lifespans around 15 years can be expected.

Figure 4. Example of a domestic refrigerator. Retrieved from (Best Buy, 2021).

Stand-Alone Hermetically Sealed

The stand-alone hermetically sealed equipment category describes small commercial refrigeration systems, similar to domestic refrigerators that are commonly used in retail food operations. Figure 5 shows an example of a common stand-alone hermetically sealed unit. Like domestic refrigerators, these units are also individual, self-contained, factory built, and hermetically sealed. They include food display cases, growth chambers, stand-alone refrigerators/freezers, and ice makers. Their charges can be much higher than domestic refrigerators[36], but when compared to other equipment they are still relatively low. Like with any hermetically sealed equipment, operational emissions are almost negligible, but end-of-life (EoL) emissions can be very high. Popular refrigerants used in this category include R-12, R-22, R-404a, and, most recently, hydrocarbons. A typical lifetime of about ten years can be expected (ICF International, 2011).

Figure 5. Example of a stand-alone hermetically sealed commercial refrigerator. Retrieved from (Amazon, 2020).

[36] Based on the data from (Ashford et al., 2006), the charge range for a stand-alone hermetically sealed unit is 0.4-13 pounds. The upper limit of this category is 13 times greater than the upper unit for domestic refrigerators from the same study (i.e., one pound).

Refrigerated Condensing Units

The refrigerated condensing unit equipment category describes medium-sized, split-refrigeration units also used in many retail food settings, though in larger applications than stand-alone units. An example of the display portion of a common refrigerated condensing unit can be found in Figure 6. There are several labels that refer to this type of system, including small commercial refrigeration systems, medium to large refrigeration, remote condensing units, and commercial refrigeration. They are characterized by a "split" design with their evaporator in the refrigerated space and compressor(s), receiver, and condenser in a separate area removed from the sales space. Examples include walk-in coolers, freezers, larger display cases, and other small to medium refrigeration equipment.

Figure 6. Example of a refrigerated condensing unit display case. Retrieved from (Alibaba, 2021).

The UNEP Ozone Secretariat (2015) puts the typical charge range between 2 and 22 lbs. while CARB (2016) puts it at 50 to 200 lbs. The considerable higher charge for this category is due to the much longer lengths of refrigerant pipework needed to connect the two remote elements of the system. The opportunity for leakage is much higher in these systems due to the longer lengths of pipework necessary for their site-specific construction and the ability for operators to perform maintenance. Because access to the refrigerant held in these systems is not restricted, there is a much better outlook for refrigerant recovery associated with them. Since condensing units can be recharged with refrigerant, it is possible that they have a full charge at the end of their life, but a charge anywhere between 50% to 100% can be expected. This full charge, however, allows for the opportunity that all the refrigerant is released during disposal (Ashford et al., 2006). This equipment category has a possible average lifespan of about 20 years. Popular refrigerants used include R-12, R-22, R-134a, R-404a, and a variety of other zeotropic blends.

Small to Medium Unitary HVAC

The small to medium unitary HVAC category describes the lower end of the commercial comfort heating and cooling covered here. Because of its lower cooling capacity, this category includes equipment used in residential applications or ones that are very similar. Examples include self-contained AC units, ducted and non-ducted split AC systems, and packaged roof-top units. Figure 7 shows an example of one of these packaged HVAC units. A range of refrigerant charge between 0 and 200 lbs. is common for these systems (IPCC, 2006), though ICF International (2011) reported a range as high

as 400 lbs. This range combines both small and medium HVAC systems which are sometimes split in reports but are more often grouped. Because of their shorter piping, annual operational leak rates for this equipment type are relatively low and recovery efficiencies at EoL are relatively high. Popular refrigerants used in this category include R-12, R-22, R-134a, R-407c, R-410a, and now, hydrocarbons. Typical lifetimes are between 15 and 25 years (ICF International, 2016).

Figure 7. Example of a medium sized packaged HVAC unit. Retrieved from (Trane, 2020).

AC Chillers

The AC chiller category generally represents the higher end of commercial comfort cooling and heating at HSU. The word "generally" is used because at HSU, heat pumps, which are essentially chillers operating in reverse, fit more neatly in the small to medium HVAC equipment category because of their smaller applications, heating capacity, and charge. However, because it is the same type of system, it is subject to the same

conditions as the higher capacity chillers. Examples include package chillers and air source heat pumps. Figure 8 gives an example of a packaged chiller.

Figure 8. Example of a packaged AC Chiller. Retrieved from (Carrier, 2021).

The chiller equipment category has the highest charge range of any category used at HSU. The typical charge range commonly falls within 200 to 2,000 lbs. (ICF International, 2011; CARB, 2016; ICF International, 2016), though Ashford and others (2006) define it more broadly as being between 22 and 4,409 lbs. Annual operational leak rates for chillers are in line with those reported for the smaller HVAC category. Disposal leak rates are also comparable to smaller HVAC equipment, though they have the potential to be much higher and lower. One can expect a lifetime of about 20 years for these units. Popular refrigerants include R-12, R-22, R-134a, R-407c, R-410a, and ammonia.

RESULTS

The following chapter presents the estimated emissions associated with HSU's current refrigerant inventory and a few of the available pathways that the University it could pursue moving forward to reduce these emissions. The contributions of the refrigerant types, the equipment types, and the set of values used to compare the impacts of each refrigerant are also discussed.

Current Emissions

Figure 9 shows the range of estimated annual emissions at HSU for the current inventory along with benchmarks for reference. The high, average, and low leak rate possibilities used to develop this range cover a wide array of possible situations. This is shown by the variation in emissions for each scenario. The current inventory is expected to emit between 429 ±15 $MTCO_2e$ and 57 ±2 $MTCO_2e$ annually, with an average[37] of 224 ±8 $MTCO_2e$ annually. That correlates to 295 lbs., 36 lbs., and 154 lbs. of annual refrigerant loss, respectively, over the range of different refrigerant types at HSU. This range of greenhouse gas emissions is on the order of the emissions associated with the staff commuting and solid waste disposal categories at HSU, which in 2019 amounted to about 408 and 183 $MTCO_2e$, respectively (Humboldt State University, 2020). Information is needed from Facilities Management to compare their known recharge rates to these estimates of loss.

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[37] Based on calculated average leak rates from the literature

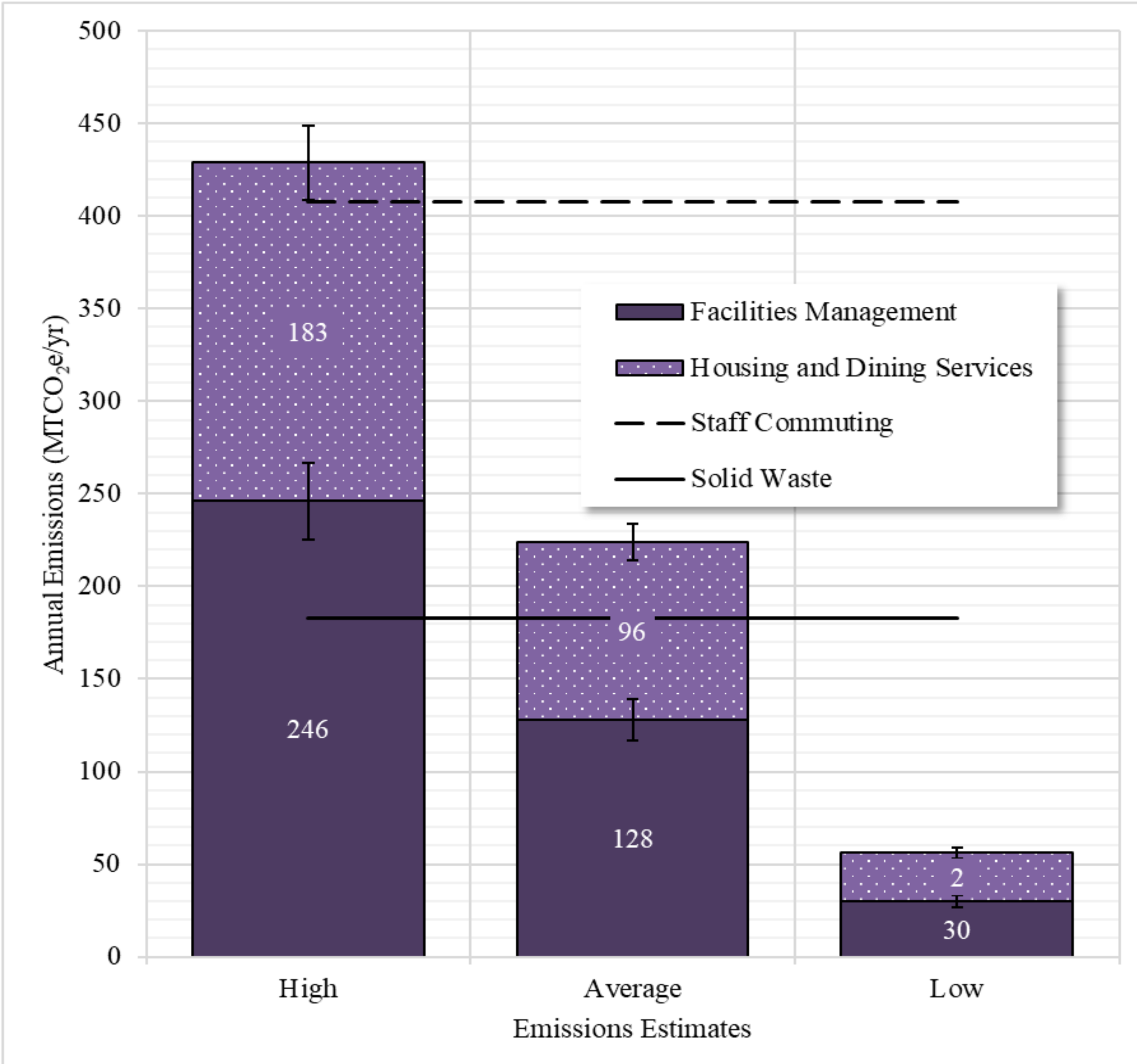

Figure 9. Estimated annual emissions associated with fugitive refrigerant leaks at Humboldt State University. Data are shown for systems managed by Facilities Management and Housing and Dining Services. Emissions estimates are given in metric tons of carbon dioxide equivalent per year ($MTCO_2e$/yr). Amount of released refrigerant is calculated based on the charges of each reported/surveyed heating, ventilation, air conditioning, and refrigeration unit and reported average annual leak rates for each unit type in the literature. These annual values for the high, average, and low ends of the leak rate spectrum were then converted to annual emissions using the global warming potentials of each refrigerant. There is a 20% uncertainty assigned to each charge datum, and error bars are included to show a 95% confidence interval. The reported emissions from two additional emissions sources for 2019 at Humboldt State University, staff commuting, and solid waste, are included for comparison.

Figure 9 also shows what these emissions ranges look like when they are categorized by the campus entity that manages them. Facilities Management's systems account for an estimated 57%, 57%, and 53% of the emissions in the high, average, and low emissions scenarios, respectively. As a reference, if we look back at Table 11 and Table 12, we find that Facilities Management operates 66% of the total units on campus and those units contain 72% of the total mass of the refrigerants on campus.

Table 13 details HSU's 2019 emissions inventory and is broken down by emissions source categories and subcategories. The emissions from this inventory total 9,085 $MTCO_2e$.[38] Emissions from fugitive refrigerants could contribute between 1% and 5% to this inventory, depending on the equipment's leak rates.

[38] This only includes emissions from Scope 1 and 2 sources. Although Scope 3 is acknowledged as a group of emissions associated with campus, it is not included in the total emissions reported in the campus' inventory.

Table 13. Comparison of HSU's reported emissions for the 2019 year using 100-year and 20-year time horizon GWP values. Emissions sources are organized into groups (e.g., commuting) and sub-groups (e.g., student commuting) based on origin. They are also classified by their scope. Data for HSU’s 2019 emissions inventory were retrieved from (Humboldt State University, 2020). The 100-year and 20-year GWP values were retrieved from (Intergovernmental Panel on Climate Change, 2014). Emissions values are given metric tons of CO_2 equivalent per year ($MTCO_2e/yr$).

Scope	**Source**[39]	**Totals 100-Year**	**Totals 20-Year**
One	Direct Transportation: University Fleet: B20 Fleet	13	13
One	Direct Transportation: University Fleet: Diesel Fleet	36	36
One	Direct Transportation: University Fleet: Gas Fleet	170	170
One	On-Campus Stationary: LPG (Propane)	20	20
One	On-Campus Stationary: Natural Gas	5,317	5,347
One	Cogeneration: Natural Gas	164	165
Two	Electricity, Steam, and Chilled Water: Electricity	3,365	3,377
Three	Commuting: Faculty Commuting: Automobile	221	221
Three	Commuting: Faculty Commuting: Bike	0	0
Three	Commuting: Faculty Commuting: Carpool	26	26
Three	Commuting: Faculty Commuting: Public Bus	11	11
Three	Commuting: Faculty Commuting: Walk	0	0
Three	Commuting: Staff Commuting: Automobile	349	351
Three	Commuting: Staff Commuting: Bike	0	0
Three	Commuting: Staff Commuting: Carpool	41	41
Three	Commuting: Staff Commuting: Public Bus	18	18
Three	Commuting: Staff Commuting: Walk	0	0
Three	Commuting: Student Commuting: Automobile	1,268	1,271
Three	Commuting: Student Commuting: Bike	0	0
Three	Commuting: Student Commuting: Carpool	131	132
Three	Commuting: Student Commuting: Public Bus	226	226
Three	Commuting: Student Commuting: Walk	0	0
Three	Directly Financed Outsourced Travel: Air: Faculty / Staff	1,102	1,102
Three	Electricity, Steam, and Chilled Water: T&D Losses	169	170
Three	Solid Waste: Landfilled Waste: CH4 Recovery and Flaring	183	549

[39] Emissions sources attributed to H&DS are not included as they are recognized as auxiliary to the campus.

Compared to this inventory, emissions from fugitive refrigerant leaks, under the average leak scenario, are greater than 71% of the individual emissions source subcategories for Scope One and Scope Two emissions. In fact, fugitive refrigerants have the potential to contribute more on average to HSU's emissions inventory than all but two emissions subcategories: 1) On-Campus Stationary Sources (Natural Gas); 2) Electricity, Steam, and Chilled Water (Electricity). When emissions associated with the Scope One, Two, and Three categories are considered, the percent of emissions subcategories that the average refrigerant emissions scenario is greater than increases to 76%.

The current refrigerant fugitive emissions impact of the campus can be broken down further by looking at the equipment and refrigerants used. Further analysis looks at the impact of each refrigerant used within their equipment. This can help determine what the campus' "problems areas" are so that HSU can tackle the pieces of its inventory that will have the largest impact on its emissions profile.

Table 14 shows the relative impact of each equipment type on campus. Each category has a separate listing for the respective operators. These subcategories are analyzed to show their relative contribution to each equipment category and to the total emissions. It should be noted that Facilities Management is responsible for the greater percentage of emissions in every category except refrigerated condensing units, which it splits roughly 40/60 with H&DS. Recalling the number of units owned by each party given in Table 12, there is a similar pattern where Facilities Management is responsible for a greater percentage of the total equipment in each category except refrigerated condensing units.

Table 14. Relative contributions of refrigerant fugitive emissions by equipment type and operator at Humboldt State University. Emissions estimates are divided to show the respective impact of each equipment type. These equipment type categories are further divided to show H&DS' and Facilities Management's contribution to the impact of each equipment type. The high, average, and low emissions estimates are given in metric tons of CO_2 equivalent per year ($MTCO_2e$/yr). The respective contributions are given as a percentage of the total emissions for the campus and of the impact of the individual equipment type. Values may not add up to totals due to rounding.

Equipment	Operator	High ($MTCO_2e$/yr)	% of Total	Ave. ($MTCO_2e$/yr)	% of Total	Low ($MTCO_2e$/yr)	% of Total	% of Equip
Stand-Alone Hermetically Sealed	**Housing & Dining Services**	2	<1%	1	<1%	<1	1%	23%
Stand-Alone Hermetically Sealed	**Facilities Management**	5	1%	3	1%	1	2%	77%
	Total	**7**	**2%**	**4**	**2%**	**1**	**3%**	**-**
Refrigerated Condensing Units	**Housing & Dining Services**	175	41%	91	41%	25	45%	57%
Refrigerated Condensing Units	**Facilities Management**	130	30%	68	30%	19	33%	43%
	Total	**305**	**71%**	**159**	**71%**	**44**	**78%**	**-**
Small to Medium Unitary HVAC	**Housing & Dining Services**	7	2%	4	2%	1	1%	10%
Small to Medium Unitary HVAC	**Facilities Management**	61	14%	33	15%	7	13%	90%
	Total	**67**	**16%**	**36**	**16%**	**8**	**15%**	**-**
AC Chillers	**Housing & Dining Services**	-	-	-	-	-	-	-
AC Chillers	**Facilities Management**	50	12%	25	11%	3	5%	100%
	Total	**50**	**12%**	**25**	**11%**	**3**	**5%**	**-**

The refrigerated condensing unit category is overwhelmingly the largest contributor to the campus' emissions. It contributes roughly 305, 159, and 44 $MTCO_2e$/yr in the high, average, and low scenarios, respectfully. This works out to be between 71% and 78% of all direct refrigerant emissions across all scenarios. The Small to Medium Unitary HVAC category is the second most emissive at between 15% and 16% of total emissions. AC Chillers are the third most emissive with between 5% and 12%. And Stand Alone Hermetically Sealed is the least emissive equipment type with about 2% of total direct emissions.

Table 15 shows the contribution of each refrigerant type to the campus' inventory. Unlike equipment type, this comparison is more dependent on the operator. For Facilities Management, the greatest impact is shared by R-22 and R-12, though R-404a, R-407c, and R-410a all have reasonably high contributions as well. For H&DS, the greatest contribution is by far R-404a, with 157, 82, and 23 $MTCO_2e$ annually in the high, average, and low scenarios, respectively. R-404a contributes 86% of the GWP-weighted emissions associated with the refrigeration systems managed by H&DS. In each case, the impact of R-404a is a full magnitude higher than any other refrigerant used by H&DS. Further, R-404a contributes a cumulative 48% to the total emissions associated with fugitive refrigerants across the campus.

Table 15. Relative contributions of refrigerant fugitive emissions by refrigerant type and operator at Humboldt State University. Emissions estimates are divided to show the respective impact of each refrigerant type. These refrigerant type categories are further divided to show H&DS' and Facilities Management's contribution to the impact of each refrigerant type. The high, average, and low emissions estimates are given in metric tons of carbon dioxide equivalent per year ($MTCO_2e/yr$). The respective contributions are given as a percentage of the total emissions for the campus under the average emissions estimate. Values may not add up to totals due to rounding.

Operator	Refrigerant	High ($MTCO_2e/yr$)	Ave. ($MTCO_2e/yr$)	Low ($MTCO_2e/yr$)	Ave. % of Total
Facilities Management	R-12	61	32	9	14%
Facilities Management	R-22	75	39	9	18%
Facilities Management	R-134a	4	2	1	1%
Facilities Management	R-401a	2	1	<1	0%
Facilities Management	R-401b	-	-	-	0%
Facilities Management	R-404a	46	24	7	11%
Facilities Management	R-407c	36	18	2	8%
Facilities Management	R-409a	-	-	-	0%
Facilities Management	R-410a	23	12	3	5%
Facilities Management	R-410b	-	-	-	0%
	Totals	**246**	**128**	**30**	**57%**

Operator	Refrigerant	High ($MTCO_2e/yr$)	Ave. ($MTCO_2e/yr$)	Low ($MTCO_2e/yr$)	Ave. % of Total
Housing and Dining Services	R-12	-	-	-	0%
Housing and Dining Services	R-22	12	6	2	3%
Housing and Dining Services	R-134a	<1	<1	<1	0%
Housing and Dining Services	R-401a	2	1	<1	0%
Housing and Dining Services	R-401b	<1	<1	<1	0%
Housing and Dining Services	R-404a	157	82	23	37%
Housing and Dining Services	R-407c	7	4	1	2%
Housing and Dining Services	R-409a	5	3	1	1%
Housing and Dining Services	R-410a	<1	<1	<1	0%
Housing and Dining Services	R-410b	1	<1	<1	0%
	Totals	**183**	**96**	**26**	**43%**

Table 16 shows the relationship between the refrigerants used on campus and the equipment categories in which they are used. This table adds evidence to the previous two by showing that most of the emissions on campus are coming from the Refrigerated Condensing Unit category and from the five refrigerants described above. However, it also narrows the problem area even further, showing that the greatest contributions are coming from the refrigerants with the greatest impact potentials that are used in the equipment types with the highest leak rates. R-12, with a GWP of 10,300, and R-404a, with a GWP of 4,200 (the two highest GWP values on campus), are almost exclusively used by the refrigerated condensing unit category, which has the highest annual equipment leak rate, at 35% of the total unit charge. However, it is the use of R-404a in refrigerated condensing units that makes the greatest contribution to these emissions with a cumulative 47% of all emissions being attributable to the combination of the two. The impact that is shown in this table still follows the same patterns of relative contributions that the previous two tables have shown.

Table 16. Relative contributions of refrigerant fugitive emissions by refrigerant within each equipment type and operator at Humboldt State University. Emissions estimates are divided to show the respective impact of each refrigerant type used in each equipment type. These emissions categories are further divided to show H&DS' and Facilities Management's contribution to the impact of each category. The high, average, and low emissions estimates are given in metric tons of CO_2 equivalent per year ($MTCO_2e/yr$). The respective contributions are given as a percentage of the total emissions for the campus under the average emissions estimate. Values may not add up to totals due to rounding.

Operator	Equipment	Refrigerant	High ($MTCO_2e/yr$)	Average ($MTCO_2e/yr$)	Low ($MTCO_2e/yr$)	Ave. % of Total
Facilities Management	**Stand Alone Hermetically Sealed**	**R-22**	5	3	1	1%
Facilities Management	**Stand Alone Hermetically Sealed**	**R-134a**	-	-	-	0%
Facilities Management	**Stand Alone Hermetically Sealed**	**R-404a**	-	-	-	0%
Facilities Management	**Stand Alone Hermetically Sealed**	**R-410a**	-	-	-	0%
Facilities Management	**Refrigerated Condensing Units**	**R-12**	61	32	9	14%
Facilities Management	**Refrigerated Condensing Units**	**R-22**	18	9	3	4%
Facilities Management	**Refrigerated Condensing Units**	**R-134a**	4	2	1	1%
Facilities Management	**Refrigerated Condensing Units**	**R-401a**	2	1	<1	0%
Facilities Management	**Refrigerated Condensing Units**	**R-401b**	-	-	-	0%
Facilities Management	**Refrigerated Condensing Units**	**R-404a**	46	24	7	11%
Facilities Management	**Refrigerated Condensing Units**	**R-409a**	-	-	-	0%
Facilities Management	**Refrigerated Condensing Units**	**R-410b**	-	-	-	0%
Facilities Management	**Small to Medium Unitary HVAC**	**R-22**	38	21	5	9%
Facilities Management	**Small to Medium Unitary HVAC**	**R-407c**	-	-	-	0%
Facilities Management	**Small to Medium Unitary HVAC**	**R-410a**	23	12	3	6%
Facilities Management	**AC Chillers**	**R-22**	14	7	1	3%
Facilities Management	**AC Chillers**	**R-407c**	36	18	2	8%

Operator	Equipment	Refrigerant	High (MTCO$_2$e/yr)	Average (MTCO$_2$e/yr)	Low (MTCO$_2$e/yr)	Ave. % of Total
Housing and Dining Services	**Stand Alone Hermetically Sealed**	**R-22**	-	-	-	0%
Housing and Dining Services	**Stand Alone Hermetically Sealed**	**R-134a**	<1	<1	<1	0%
Housing and Dining Services	**Stand Alone Hermetically Sealed**	**R-404a**	1	1	<1	0%
Housing and Dining Services	**Stand Alone Hermetically Sealed**	**R-410a**	<1	<1	<1	0%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-12**	-	-	-	0%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-22**	12	6	2	3%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-134a**	-	-	-	0%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-401a**	2	1	<1	0%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-401b**	<1	<1	<1	0%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-404a**	155	81	22	36%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-409a**	5	3	1	1%
Housing and Dining Services	**Refrigerated Condensing Units**	**R-410b**	1	<1	<1	0%
Housing and Dining Services	**Small to Medium Unitary HVAC**	**R-22**	-	-	-	0%
Housing and Dining Services	**Small to Medium Unitary HVAC**	**R-407c**	7	4	1	2%
Housing and Dining Services	**Small to Medium Unitary HVAC**	**R-410a**	-	-	-	0%
Housing and Dining Services	**AC Chillers**	**R-22**	-	-	-	0%
Housing and Dining Services	**AC Chillers**	**R-407c**	-	-	-	0%

The magnitude of these fugitive emissions cannot be attributed solely to the refrigerant used or the equipment type, but rather the combination of the two together. It is more of an unfortunate coincidence rather than a mistake that the most emissive refrigerants are paired with the equipment with the greatest leak rates. For the applications that this equipment serves, especially with bigger units and greater cooling demands, these high-GWP refrigerants were the thermodynamically most appropriate and most efficient fits. The lower temperature demands of the commercial refrigeration equipment categories require refrigerants with specific characteristics like extremely low boiling points to meet those needs. It seems to be the case that those more extreme characteristics go hand in hand with more extreme GWP values. It also just so happens that those applications are the ones with the longer lengths of pipework and more potential for leaks.

Projected Emissions

Figure 10 compares the emissions from HSU's current inventory to three possible emissions pathways, which are outlined as potential next steps here. These pathways signify the possible responses to current and approaching refrigerant regulations. Since all of HSU's current refrigerants (excluding R-600a) are banned for use to some degree, this study has outlined alternatives for each refrigerant used and categorized them by GWP. These pathways are described in Table 9 above. They represent the high, moderate, and low emissions choices that the campus could make when deciding to replace its existing stock. These scenario groups are meant to show a comparison

between the emissions from business-as-usual and, alternatively, the early adoption of current or upcoming refrigerant bans.

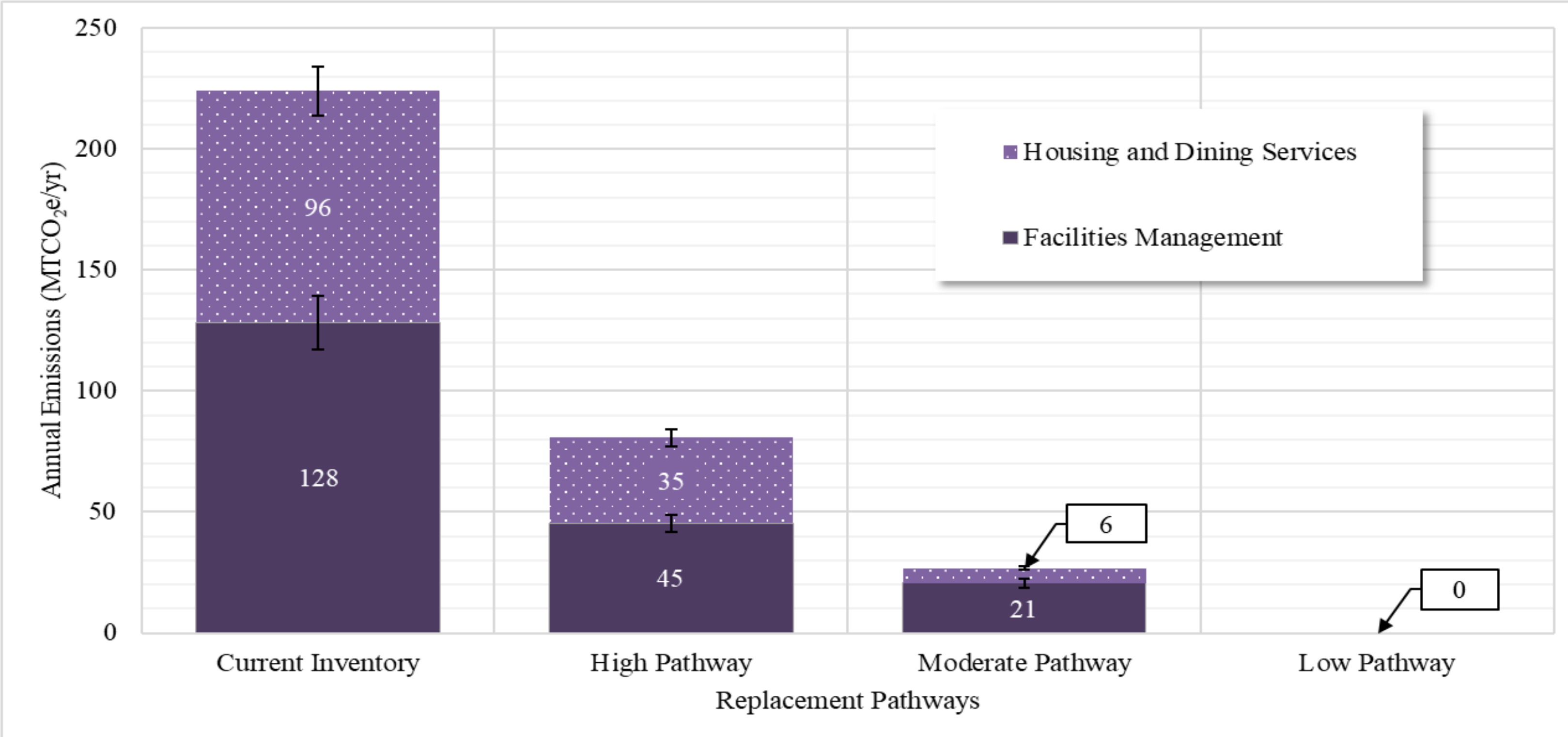

Figure 10. Comparison of the estimated annual emissions associated with fugitive refrigerants from HSU's current HVACR equipment inventory to three possible replacement pathways. The current inventory and the three proposed inventories represent the averages of their set of emissions estimates as they have all been calculated using averages of the equipment leak rate values given in Table 8. This graph is intended to show the associated emission of HSU's future refrigerant options. Emissions estimates are shown for systems managed by Facilities Management and Housing and Dining Services. Estimates are given in metric tons of carbon dioxide equivalent per year ($MTCO_2e/yr$). Refrigerants were chosen based on their regulatory status and their level of favorability as replacements for each existing refrigerant at HSU. There is a 20% uncertainty assigned to each charge datum, and error bars are included to show a 95% confidence interval. Callout boxes are included to indicate the emissions where numbers do not fit.

Though the benefits of a complete replacement like the one shown here are likely to be drawn out over time as units are incrementally replaced, the potential emissions reductions are substantial. The result of an instantaneous replacement of HSU's existing refrigerant stock with even the most environmentally harmful of their more favorable alternatives is a decrease in emissions associated with refrigerant use by 64%. Further, an 88% reduction can be achieved through the moderate emissions pathway. All of HSU's fugitive emissions from refrigerants can be eliminated when the low emissions pathway is pursued. Even without the use of natural refrigerants, HSU can reduce its refrigerant emissions to a point where they might reasonably be considered negligible.

Alternatives

The GWP values and time-horizon used have a substantial effect on the outcome of these emissions calculations. As mentioned above, this report uses the 100-year GWP values from the Refrigeration, Air Conditioning, and Heat Pumps (2019) assessment report to be consistent with the most recent available science regarding GWP values. However, the California Air Board Resource uses the IPCC (2007) fourth assessment report, and many argue for the use of the 20-year time-horizon when discussing short-lived pollutants. Table 17 shows the impact that these choices have on the results reported here.

Table 17. Comparison of the emissions estimates for the HSU campus using different GWP reference data. The estimates made in this project are based on the 100-year GWP values given by the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019), but there are other reasonable references on which they could be based. This table looks at the difference that using one reference over another makes. Emissions estimates are given in metric tons of carbon dioxide equivalent per year ($MTCO_2e/yr$).

	High Estimate ($MTCO_2e/yr$)	**Ave. Estimate ($MTCO_2e/yr$)**	**Low Estimate ($MTCO_2e/yr$)**
100-Year GWP Values (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019)	429	224	57
100-Year GWP Values (IPCC, 2007)	424	224	56
Percent Change	-1%	0%	-2%
20-Year GWP Values (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019)	831	433	106
Percent Change	94%	93%	86%

There is very little difference between the results using the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) GWP values and the ones using IPCC (2007) values, with less than a two percent difference between the two. Further, there is very little difference between the GWP values themselves in these reports, or with older reports, for that matter. When considering the high-GWP refrigerants discussed in this project (found in Table 10). GWP values for the respective refrigerants change by one to nine percent from IPCC (2007) to the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019). Most of the GWPs have decreased from the fourth assessment report (IPCC, 2007) to the one used here (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

There is a smaller difference, between one and five percent, from the most recent IPCC (2014) assessment report to the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019) report. There is a larger difference between the GWP values reported in the second IPCC assessment report (IPCC, 1996) and the more recent reports. For example, the differences range from four to twenty-nine percent between the second assessment report and the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (2019).

The time horizon used, unlike the GWP reference values, has a very large influence on the emissions reported. The emissions estimates for refrigerant leaks at HSU almost double when the time-horizon used is switched from 100-years to 20-years. There is between an 86% and 94% difference between the two sets of results. While there is uncertainty regarding where HSU falls in the range between the low, average, and high

emissions cases, once 20-year GWP values are considered the emissions are sufficiently high to indicate a need for action in any case.

To compare the emissions from refrigerant leaks with GWP values of a shorter time-horizon to the campus' emissions, the latter must be converted first. Table 13 above shows what HSU's overall 2019 emissions inventory would look like if it were calculated with GWP values under a 20-year time horizon. This recalculation only increased the total emissions by 3%. However, refrigerant emissions, as we have seen in Table 17, nearly double across all estimates.

The switch to a 20-year time horizon does not result in large changes in HSU's overall emissions because most of HSU's emissions are in the form of carbon dioxide from natural gas and electricity use. The GWP value for carbon dioxide is not dependent on the time frame considered, as it is the baseline for the metric and always has a GWP of one. Considerable emissions from methane, the only short-lived gas recognized in HSU's inventory, can be found for four emission sources. Those four sources can be seen as experiencing the largest increases in their total emissions when a 20-year time horizon is considered. This is because methane's GWP increases from 28 to 84 when considering a 20-year time horizon (Intergovernmental Panel on Climate Change, 2014).

Like methane, there is a considerable increase in the GWP values of many individual refrigerants. Thus, the contribution of emissions from refrigerant leakage increases. Because few other emissions in the inventory increase, the relative contribution of refrigerant emissions also increases. Under a 20-year time-horizon, estimated refrigerant fugitive emissions remain greater than 71% of HSU's emissions source subcategories.

However, estimated refrigerant emissions account for nearly twice the relative impact they had under the 100-year time horizon. They are estimated to contribute between 1% and 9% of the total emissions from the campus under the 20-year time horizon.

DISCUSSION

The following chapter presents a comparison of the emissions estimates presented in this study to other schools who have noted fugitive emissions in their own inventories. The outlook of HSU’s refrigerant inventory and the applications and/or equipment that may be suitable for low GWP replacements are also discussed.

Is This Range of Emissions Reasonable?

As noted previously the results presented here are based on leak rate values that were collected from the literature rather than through measurements at HSU. This raises the question of whether the range of estimated emissions is consistent with expectations for other universities. As a point of comparison, six universities’ GHG emissions inventories and/or climate action plans have been reviewed focusing on cases where refrigerant fugitive emissions are covered, to see how they line up with what is presented here. The universities reviewed are California State Polytechnic University Pomona, California State University Los Angeles, North Carolina State University, University of California Berkeley, University of North Carolina Wilmington, and University of Virginia. The information in these reports concerning refrigerants is summarized in Table 18. There are some common trends that are of relevance to this project.

Table 18. Summary of reviewed universities' climate action plans. The total emissions column represents the emissions from the Scope One and Scope Two emissions categories. Data for emissions are given $MTCO_2e$. The contribution of refrigerants to the total emissions for each campus is given as a percentage.

University	Source	Total Emissions ($MTCO_2e$)	Scope One Emissions ($MTCO_2e$)	Emissions Associated with Refrigerants ($MTCO_2e$)	Percent Contribution to Total Emissions
California State Polytechnic University Pomona	(California State Polytechnic University, Pomona, 2019)	36,002	11,971	729	2%
California State University Los Angeles	(California State University, Los Angeles, 2019)	18,098	3,382	185	1%
North Carolina State University	(North Carolina State University, 2021)	173,236	105,346	2,484	1%
University of California Berkeley	(UC Berkeley, 2021)	147,004	144,684	779	1%
University of North Carolina Wilmington	(Ponder et al., 2014)	39,828	10,423	1,466	4%
University of Virginia	(Pettit, 2019)	227,390	94,136	1,699	1%

The most important of these trends is that refrigerants at each university account for between less than 1% and 4% of the total emissions. For the reports that clearly described/differentiated their emissions categories (i.e., Scopes One, Two, & Three), refrigerants accounted for 1% to 14% of their Scope One emissions, though only one university, the University of North Carolina Wilmington, reported a value above 6%.

The range of emissions from fugitive leaks reported here makes up between 1% and 5% of HSU's 2019 emissions. This is between 1% and 8% of the Scope One category, which is the category that accounts for the largest share of HSU's GHG emissions. The HSU values are therefore within a range that is consistent with values reported by other universities.

The range of reported emissions from other universities can be made easier to compare to the values given here by scaling their emissions associated with refrigerant leaks to a level that is proportional to the ratio between HSU's total emissions and their total emissions. For example, North Carolina State University's emissions for 2017 totaled 173,236 $MTCO_2e$ and their emissions associated with fugitive refrigerants totaled 2,484 $MTCO_2e$. If their total emissions were scaled to be equal to HSU's 2019 emissions (i.e., 9,085 $MTCO_2e$) and the ratio between their total emissions and the emissions associated with refrigerants was kept, their adjusted refrigerant emissions would be 130 $MTCO_2e$.

The adjusted fugitive refrigerant emissions for the universities described here ranged between 68 and 334 $MTCO_2e$. The range of emissions estimated for HSU is between 57 and 429 $MTCO_2e$, with an average of 224 $MTCO_2e$. Figure 11 shows this comparison

more fully by presenting each university's adjusted emissions alongside the three emissions estimates for HSU's inventory. An average for the six reviewed universities, 143 $MTCO_2e$, is included in this figure, as well. The low and average estimates for HSU's emissions match the values reported by other universities, while the high-end value for HSU falls somewhat outside values reported elsewhere.

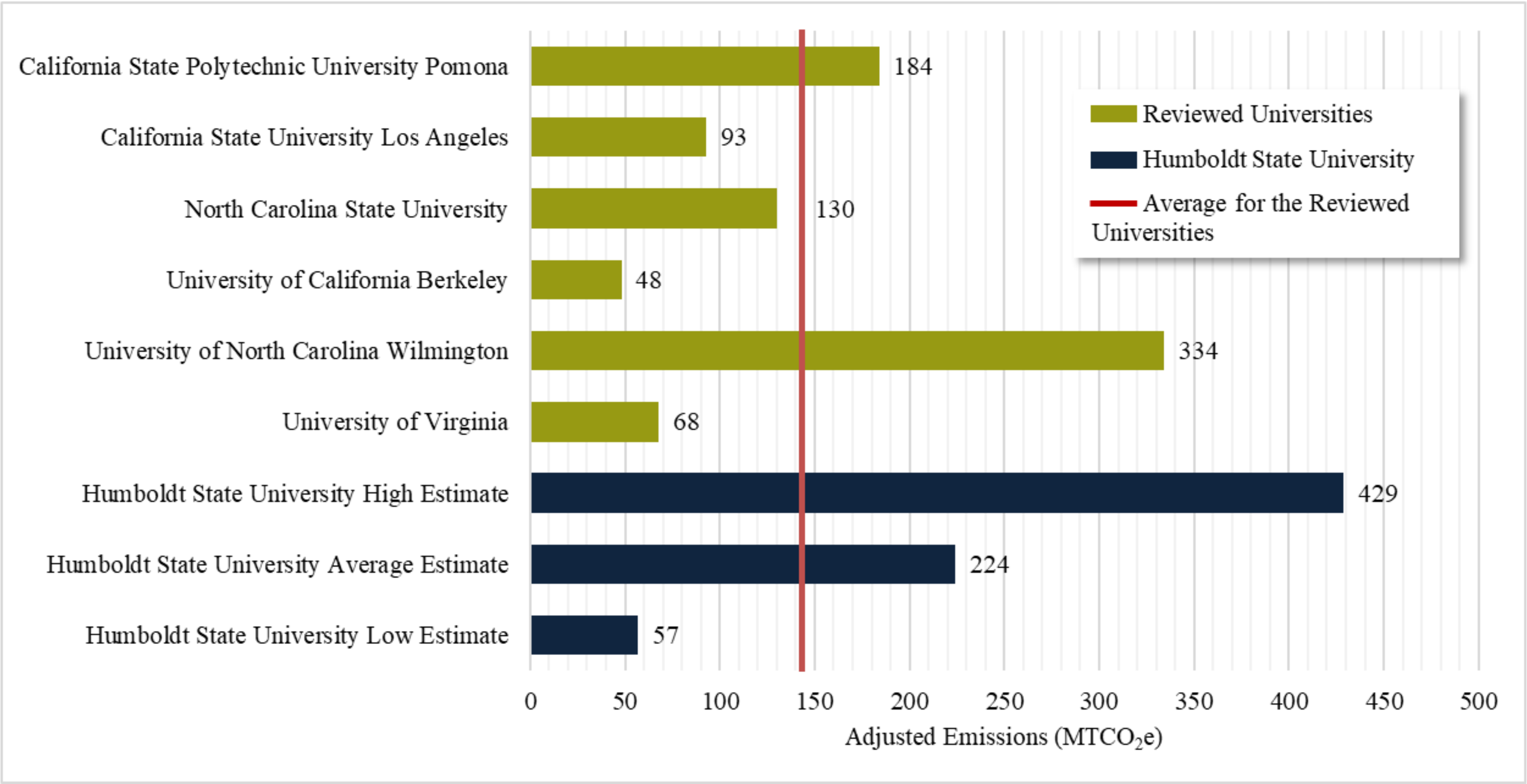

Figure 11.Comparison of the adjusted emissions associated with fugitive refrigerants at six universities to the emissions range estimated for Humboldt State University. The total emissions at each university have been scaled down to match HSU's recorded 2019 emissions (i.e., 9,085 $MTCO_2e$) and the emissions related to refrigerant leaks have been scaled proportional to the original ratio between the two emissions categories (i.e., total emissions and refrigerant emissions). An average for the adjusted emissions at the six universities has been included. Values are given in metric tons of carbon dioxide equivalent.

The maintenance personnel in charge of these systems were convinced in their conversations that the leakage of refrigerants at HSU was minimal and practically non-existent. The error in this study from their perspective would likely be that the leak rates associated with each equipment type were too high. However, they were unable to provide any real evidence that this was the case. In fact, during my survey of the H&DS equipment, one stand-alone hermetically sealed refrigerator was out of service because it experienced a leak and all of the refrigerant inside had escaped.

It may be that HSU's actual emissions associated with refrigerant loss are somewhat closer to the lower end of the range of emissions reported here. It is no surprise that if there were 295 lbs. of refrigerant being lost annually,[40] it would be a noticeable problem not just because of the emissions but also for the loss of the regular function of the equipment, the cost of new refrigerant, and the reductions in energy efficiency. This type of annual refrigerant loss would likely be known to the staff governing it, and those interviewed for this study were convinced that leaks are uncommon and do not amount to high refrigerant losses each year.

The leak rates used in this report to analyze the HVACR equipment at HSU are based on literature values, and it is possible that HSU has leak rates that are lower or higher than the ones used here. Discussions with Dan Bouchard indicate that he believes that the actual leak rates at HSU are lower than the values reported in the literature. He states that H&DS has years where there are no leaks across their entire inventory and that

[40] The amount of loss needed by the HSU campus to result in the high end of the emissions reported here.

it would take a "complete rupture" of their largest system to produce the amount of refrigerant loss to make up even the lowest boundary of the emissions range (Dan Bouchard, personal communication, 2020).

The emissions range reported above for the current inventory incorporates the one-time losses that occur at the installation and the disposal of the equipment in a way that they appear proportionally in the annual values. Thus, they could seem greater than expected to anyone keeping track of refrigerant lost through operation alone. Also, since the refrigerant losses reported here and their corresponding emissions are annual averages, it is likely that there is a good deal of variation from one year to the next around these values.

The true leak rate values for the HVACR equipment at HSU will remain uncertain, unfortunately, until there is ongoing and comprehensive record-keeping completed by both Facilities Management and H&DS. Fortunately, there are already upcoming changes that will aid in this management, like the movement to electronic record-keeping and annual inventory leak searches by H&DS (Dan Bouchard, personal communication, 2020). Additionally, there are operational and EoL procedures already used at HSU which address the problems with refrigerant management that might lead to the higher limits of these ranges. This project should, in any case, show what is possible for the current situation at HSU and how important good refrigerant management is.

HSU's Refrigerant Outlook

Knowing now that this is a reasonable estimate for the range of refrigerant-related emissions at HSU, there are a number of "next-steps" available to the school to address them. The first of which should be a period of data collection and re-analysis. The comparison above to other universities normalizes the range of emissions presented here; however, there are positions within that range that would demand more or less attention (i.e., if subsequent study confirms that HSU's fugitive refrigerant emissions fall near the lower end of the estimated annual emissions, this may indicate that there is not a significant problem with refrigerant leaks and that little is in need of change or vice versa).

The second next step is a consideration of the potential to replace HSU's "worst offenders," or the R-12, R-22 and, R-404a refrigerants. Replacing these refrigerants and/or the associated equipment should take priority over the others because of their considerable contribution to HSU's negative environmental impacts, though with the current status of almost all of the refrigerants used on campus, there needs to be an inventory-wide effort made towards upcoming replacements.

The importance of record-keeping cannot be understated here. Currently, there are no available refrigerant fugitive emissions records kept by either H&DS or Facilities Management. They are not, after all, mandated by CARB or the EPA to keep them. Current refrigerant laws specify that all equipment containing 50 or more pounds of refrigerant at full charge must have regular leak inspections, and invoices must be kept

when any refrigerant is added to a unit (EPA, 2021). However, all but one unit at HSU is under 50 pounds when charged. Both the Facilities Management and H&DS teams have already expressed their intention to begin keeping records and have acknowledged its importance, as well.

Until then, with no ongoing tracking of these chemicals, it seems unlikely that either party would be fully aware of the true scale of refrigerant loss. Small ongoing problems may go unnoticed for longer periods of time, and it may be that these otherwise unnoticeable leaks add up over the entire inventory through time. Without records it is not possible to document leak rates for refrigeration systems on campus. Record-keeping is also the only way to get a more accurate picture of HSU's emissions from fugitive leaks.

Next, there are a number of factors that should be considered with respect to carrying out the replacement of R-12, R-22 and, R-404a, some of the most used refrigerants on campus. These three refrigerants are collectively used in 70% of the current equipment inventory. In other words, transitioning away from the worst substances currently used at HSU would mean replacing or retrofitting, in some way, 71 of the 101 units operating on campus now. This includes 31 Refrigerated Condensing Units, 29 Small to Medium Unitary HVAC units, 9 Stand Alone Hermetically Sealed units, and 2 AC Chillers.

The business-as-usual option replaces the refrigerants in these units with HFCs like R-134a and R-407c in retrofits where possible and with HFO blends like R-448, R-449a, R-32 through retrofit or replacement. These replacements would likely occur when R-12, R-22, and R-404a eventually become unavailable, or too expensive, and supplies are

exhausted. While all of these replacements still constitute a moderate to high-GWP pathway, they are also allowed by current and upcoming legislation and, in some cases, have lower environmental impacts than the ones that they are replacing.

This business-as-usual approach includes easy and relatively inexpensive refrigerant switches with noticeable reductions in associated emissions. The properties of the replacement refrigerants may be similar enough in nature to the existing ones to allow their operators to retain a sense of familiarity with the refrigerant itself and the equipment's servicing demands. It is a safe and reasonable option, especially if the actual leak rates are determined to be lower than the values from literature used in this analysis.

But what of the rapidly developing next generation of natural refrigerants? Is it wise to commit such a large portion of the HVACR equipment inventory to refrigerants that are still considered to be moderate to high-GWP now when there is the potential for a better-suited option right around the corner? It seems that the current development of this next generation is better suited for some equipment types than others. In order to eliminate the most problematic areas of HSUs refrigerant inventory in the short-term, as they are required, there can and should be a mixed approach. For instance, the moderate-GWP business-as-usual option may work well for the Refrigerated Condensing Units and AC Chiller replacements, while the low-GWP option is better suited for the Stand-Alone Hermetically Sealed units and Small to Medium HVAC equipment. The appropriateness of each option is dependent on safety, cost/ease of replacement, and the availability of a suitable low-GWP replacement.

Dan Bouchard has mentioned that he would like to stay away from natural refrigerants as much as possible to avoid their flammability and toxicity dangers. This is a completely reasonable perspective that prioritizes the immediate safety of the people servicing the equipment, the students benefiting from the equipment, and the buildings that house the equipment above what may be fairly modest global warming environmental impacts associated with fugitive refrigerant emissions from the equipment. While wanting to avoid the use of natural refrigerants for these reasons is a clear and good sentiment, there are options like using hermetically sealed equipment, outdoor staging locations, and better venting/air circulation that reduce the risks associated with them. The low charge limits and heightened safety measures required for equipment using high flammability and toxicity refrigerants can lower this risk even further.

Natural refrigerant systems may not cost much more than HFC systems for long, but a completely new system will always cost more in the short term than a retrofit or component replacement involving a switch to a similar but less impactful HFC. This is especially true for the built-on-site units, which require replacement of more equipment. It is less true, for instance, with factory packaged equipment like the hermetically sealed units. Studies have found that there was a short return on investment for some natural refrigerant technologies (Hillphoenix, 2019), that some system types were more energy-efficient than their HFC counterparts (Elbel et al., 2016; ICF International, 2011; Peters, 2017; Choudhari & Sapali, 2018; Gaurav & Kuma, 2018; Skacanova & Gkizelis, 2018; Shecco, 2019), and that there was a net benefit, through reductions in environmental impact, avoided risks regarding regulation uncertainty, and increasing HFC refrigerant

costs (Garry & Williams, 2018) such that even when their energy consumption was greater, they were a worthwhile investment. But, currently, transitioning entirely to natural refrigerants may not be the most cost-effective investment to make for reducing emissions at this time compared to other options (such as measures to reduce natural gas use on campus).

In many ways the natural refrigerants and other low-GWP options discussed above are commercially ready worldwide and in the US While there are some barriers that must be overcome to use them, many are not as concerning as they seem, and even more are expected to be overcome shortly. Still, while natural refrigerants have proven to be commercially ready for some system categories, their success has not translated to every equipment type. The smaller and larger ends of the HVACR equipment world have experienced enough technical development to where refrigerants like isobutane and ammonia are standard and favorable options for use. Middle-ground equipment like split condensing units and some medium to large HVAC units do not necessarily have a clear or favorable natural refrigerant alternative available. Carbon dioxide is a promising option for both, but this and other suggested options require more from a system design in terms of complexity, understanding, and cost (at the moment) than an HFC-based system would.

Despite considerable effort, only one university was found, California State Polytechnic University, Pomona, that mentioned transitioning to lower-GWP refrigerants as a considered emission-reducing method (California State Polytechnic University, Pomona, 2019). And it seems that only one university, the University of the West Indies

in Jamaica, has made that transition to a portion of its main commercial HVACR inventory (Lobnig, 2010).[41] Nevertheless, an outcome of this project is that the range of estimated fugitive refrigerant emissions at HSU do not make up a large enough portion of the greater campus' emissions to warrant a complete transition to natural refrigerants in the near term. This may be why few other universities have made the switch themselves. It may also be the case that universities have prioritized more cost-effective options for reducing their emissions, like reconsidering the source(s) of their electricity or focusing on building heating options.

Still, HSU has the opportunity to adopt these technologies where their adoption is practical. And there are even more opportunities where at first glance, their adoption seems impractical. It is my suggestion that all stand-alone hermetically sealed equipment be replaced with units that use R-290. Any outside HVAC equipment should also be considered for a natural refrigerant replacement, especially those with low to medium charge. Finally, there are reach-in split condensing unit display cases at each dining facility that could potentially be removed and replaced with hydrocarbon-based stand-alone hermetically sealed units.

Retrofits for equipment using R-12, R-22, and R-404a, where possible, should be considered immediately so that their impact on the university's emissions can be reduced while also prolonging their lifetime. All of the complete equipment replacements should occur at the end of the existing equipment's lifetimes so as to avoid generating

[41] Though, it is unclear if other universities have discreetly transitioned their entire residence hall refrigerator stock to hydrocarbons, like HSU has.

unnecessary waste. The portion of the HSU inventory that is considered to be unsuitable for natural refrigerant replacement in the short term should be replaced with low to moderate HFO blends or, if needed, higher-GWP HFCs and HFO blends. We have seen that even the transition to high-GWP HFO blends is one that would result in considerable emissions reductions.

CONCLUSION AND RECOMMENDATIONS

Fugitive refrigerants are likely to be a greater source of emissions for the HSU campus than is currently acknowledged by the university. This project has identified that refrigerants lost through the installation, operation, and disposal of HVACR equipment at HSU may be responsible for between 57 $MTCO_2e$/yr and 429 $MTCO_2e$/yr with an average of 224 $MTCO_2e$/yr, depending on the leak rate value used for these systems. This amounts to between 1% and 5% of the total GHG emissions recorded for the campus in 2019. This project has also found that the portion of the refrigerated condensing unit equipment category that uses the refrigerant R-404a is likely to be the most significant contributor to those emissions. These units are responsible for roughly 47% of all estimated annual emissions from fugitive refrigerants.

This project has identified what are likely to be the problem areas with respect to refrigerant emissions. It has aggregated the current HVACR and refrigerant inventory on campus. It has described the individual environmental impact potentials for each refrigerant and has estimated their cumulative impact at HSU. And it has considered what general next step options are available to the university and what their benefits and drawbacks are. Still, of equal importance is what HSU's response to this information can and should be. In other words, what is the next course of action for HSU to meet emissions goals, current regulations, and global trends?

There are three things that this study has identified as priority recommendations for HSU. They are:

- Updating the inventory presented here with more accurate charge data, measured leak rates, and uncertainty values. Some of the information that is critical for accurately calculating the emissions associated with refrigerant leaks was unavailable, for a number of reasons, during the course of this project. With more attention and time given to the subject, this analysis can be updated and reconsidered.
- Eliminating the use of the R-12, R-22, and R-404a refrigerants. Nearly all of the refrigerants used on campus are either currently banned from use or have approaching bans, but these three contribute a disproportionately large amount to HSU’s refrigerant fugitive GHG emissions. These refrigerants also contribute to ozone depletion, and their replacement would have corresponding benefits in this regard.
- Acknowledge direct refrigerant emissions in future campus emissions reports. Currently, these emissions are considered to be “de minimis” or insignificant, but the full picture is still not yet known. There is a potential for fugitive emissions to contribute as much, or more, to HSU’s emissions inventory as emissions sources already included as lower-level priorities in published reports. Careful documentation and reporting of refrigerant fugitive emissions could help generate a better understanding of the full impact of this GHG emissions source.

Given the range of possible emissions for the equipment and refrigerants currently used on the HSU campus, the number of similarly emissive activities or byproducts at HSU that have received recognition in HSU's Climate Action Plan, and the necessity for greater coordination and organization with respect to campus refrigerant management and planning for the next generation of refrigerants and equipment, this study recommends that a more detailed analysis is warranted. For HSU to contribute to the historical success and current push in eliminating the use of these environmentally destructive substances, it must fully consider the emissions associated with their use on campus. While these refrigerants affect the entire campus, their divided management makes a comprehensive analysis of their use difficult. A lack of records in some areas further complicates this. However, HSU has the opportunity to play an important role in the future of refrigerants and their own campus sustainability by staying informed about upcoming trends in their regulation and use and complying with current phase-out mandates.

If it is discovered upon further analysis of data collected by HSU's refrigerant operators that HSU falls in the lower portion of the estimated emissions range reported here, then it will have benefitted from better understanding a portion of its operation that is potentially harmful, and it will be in a better position to comply with upcoming regulation by transitioning to lower-GWP alternatives. It is true that the emissions from the refrigeration and air conditioning sector are dominated by the impact of their energy consumption rather than fugitive leaks. However, reducing leaks through updated management procedures will keep system charges optimized and eliminate wasted energy. Updating equipment and equipment infrastructure will both increase energy

efficiencies and decrease leak potential. Even a partial transition to low-GWP alternatives would further increase energy efficiency, decrease leaks, and eliminate the damage associated with the leaks, as well. There are, then, multiple options that can be taken with refrigerants which will lead to a reduced emissions inventory.

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APPENDICES

Appendix A. Explanation of Refrigeration Cycles

Figure A.1. shows a simplified version of a vapor-compression cycle. This cycle can be described as follows: the refrigerant enters the evaporator as a low-temperature, low-pressure liquid. Air or water from a reservoir interacts with the coils containing refrigerant in the evaporator. The refrigerant, with its low boiling point, changes phase to a vapor and, in the process, absorbs heat energy from the reservoir. It then enters position “a” as a high-temperature, low-pressure, vapor. The refrigerant then moves through the compressor, which adds energy to the refrigerant through pressurization. The refrigerant leaves the compressor and enters position “b” as a high-temperature, high-pressure, vapor. As the refrigerant travels through the coils in the condenser it interacts with another reservoir, which is also often air or water, and is cooled to the point that it changes phase back to a liquid. Through its phase change, the refrigerant releases its heat energy. The refrigerant leaves the condenser as a low-temperature, high-pressure liquid at position “c”. Finally, the expansion valve reduces the pressure on the refrigerant where it is then able to restart its cycle at position “d” as a low-temperature, low-pressure liquid.

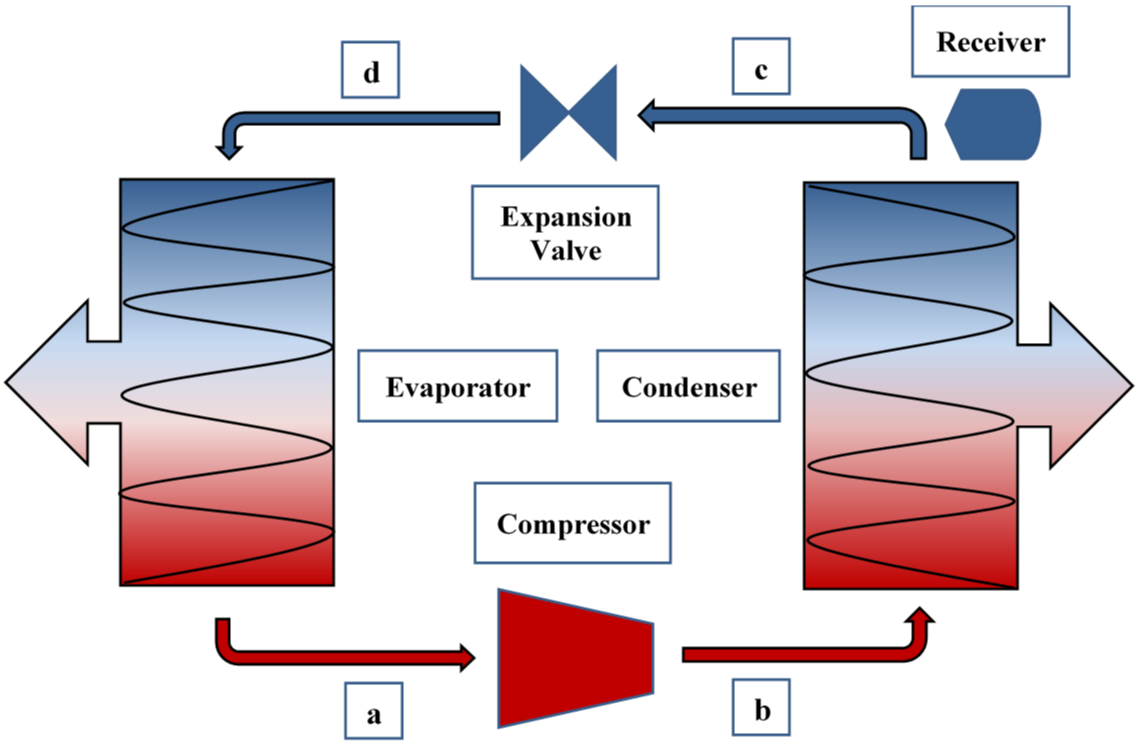

Figure A.1. Depiction of a generalized vapor-compression cycle for a single-stage HVACR unit. Arrows show the movement of refrigerant inside the system and colors indicate the relative temperatures of the refrigerant. Labels are included to indicate points of interest within the cycle.

This vapor-compression cycle can service either direction. All refrigeration and air conditioning generally work where the evaporator is in the area where cooling is desired (e.g., the inside of a house) and the reservoir that interacts with the evaporator is air. The condenser is in an area where it can interact with air or water that is external to the first reservoir. In the example of a domestic AC unit, the condenser is typically outside of house and its heat rejection is directed towards the outside air. For heating systems, the cycle is opposite. Heat is absorbed by the evaporator at an external reservoir and rejected to the area where heating is desired.

The equipment surrounding these cycles is much more complex than how it is described above. In reality, there may be multiple evaporators connected to one system where cooling is desired in separate areas, like in some commercial refrigeration applications. There may also be more than one of these vapor-compression cycles liked together so that two refrigerants are utilized separately, and a greater range of temperatures can be reached.

The correct sizing of each component in the system is also crucial and is fine-tuned specifically to the refrigerant(s) in use and the application at hand. The receiver, for instance, must be sized to hold a systems total charge and be no more than 80% filled (Orr, 2018). Since the receiver acts as a storage tank for the system and moderates the amount of refrigerant being used at any given time to meet changing system demands, under-sizing it could result in pressure-related problems in the system which could cause damage to other mechanical components or affect normal operation (Marchese, 2014)

Appendix B. Expansion on Global Warming Molecules.

The details of how greenhouse gases contribute to global warming are difficult to conceptualize. Terms like global warming potential (GWP) and atmospheric lifetime are important, though, to understand in order to get a better appreciation of the lasting and intense global warming effects of refrigerants. This section is a discussion of what molecular level characteristics of refrigerants make them highly potent greenhouse gases.

Molecules vibrate. Some molecules have many different, and sometimes complex, ways in which they can vibrate; carbon dioxide, for instance, has three different modes of vibration (University Corporation for Atmospheric Research, 2012). Depending on the structure and modes in which it vibrates, a molecule can interact with passing waves of electromagnetic radiation (University Corporation for Atmospheric Research, 2012). Certain gases have molecular structures that allow them to absorb specific ranges of wavelengths of outgoing infrared (IR) radiation because of these vibrational interactions. The absorption of this radiation causes the vibration of the molecule to increase.

Because these molecules are energized and vibrating more, there are more collisions between them, which increases their thermal energy and raises their temperature (American Chemical Society, 2021). These molecules also eventually release their IR energy, which can then be released back into space or re-absorbed by other surrounding molecules (University Corporation for Atmospheric Research, 2012). An increase in number of these heat-absorbing molecules in the atmosphere leads to more warming. This is because outgoing radiation is trapped and because of the heat generated by the

increase in molecular collisions. This is the general process behind what is known as the greenhouse gas effect.

The GWP of a gas is dependent on the amount of time that the molecule remains intact in the atmosphere and the vibrational interactions between the molecule and outgoing infrared radiation (IR) while it is intact. The amount and strength of this IR absorption are dependent on the range in which IR waves interact with the molecule (American Chemical Society, 2021). Molecules that interact with wavelengths not absorbed by water vapor or carbon dioxide (the two most abundant GHGs in Earth's atmosphere (Dlugokencky et al., 2016) tap into radiation that would otherwise be lost to space and, thus, have the potential to make significant contributions to atmospheric warming (American Chemical Society, 2021). The length of time that these substances remain in our atmosphere is dependent on the efficiency of two general processes: physical removal, through absorptions at Earth's surface, and chemical removal, including UV light and hydroxide reactions (Solomon & Wuebbles, 1994). Most refrigerants have characteristics that make them, in each of these three ways, significantly more potent of GHGs in the short-term and long-term than carbon dioxide (Bera et al., 2009).

Specifically, it is the chemical bonds with chlorine (Cl) or fluorine (F) in the molecular structure of these refrigerants which make them such effective global warming agents. Bera and others (2009) have shown that molecules with these bonds, and especially with carbon-fluorine bonds, have vibrational modes that allow them to strongly absorb IR radiation in the "atmospheric window" of wavelengths not already absorbed by

CO_2 or H_2O. As the number of these bonds within a molecule increases, the range of IR wavelength absorption narrows to be more situated within the atmospheric window (Bera et al., 2009). Additionally, these fluorine bonds do not readily react with molecules in the atmosphere that remove and break up GHGs (i.e., hydroxide (OH^-)), so molecules containing them have much longer lifespans (Bera et al., 2009).

Unfortunately, the some of the refrigerants that are most widely and heavily used have many of these bonds that make them so effective at absorbing IR radiation and so resistant to being broken down. For instance, the refrigerant R-12 has a chemical formula of CCl_2F_2 (National Library of Medicine, 2021). Each atom of carbon has four bonds, and they are all either chlorine or fluorine, the two elements which intensify the effects of a greenhouse gas. Since the breakdown of chlorine is also a contributor to ozone depletion, as well as global warming, it is exclusive as a chemical constituent to the chlorofluorocarbons and hydrochlorofluorocarbons of the earlier refrigerant generations. Fluorine, however, is a component of even the approaching generation of lower-GWP refrigerants and can be found in hydrofluoroolefins.

Appendix C. Refrigerant Descriptions

Descriptions for the refrigerants referenced in this study can be found in Table C.1. These descriptions include each refrigerant's name, type, chemical formula or composition, safety classification, global warming potentials under various time horizons, ozone depletion potential, and atmospheric lifetime, where they are available.

Table C.1. Master list of all the refrigerants referenced in this study. Adapted from (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019).

Name	Refrigerant Type	Chemical Formula/ Composition	Safety Class	100-year GWP	20-year GWP	ODP	Atmospheric Lifetime
R-12	CFC	CCl_2F_2	A1	10,300	10,800	0.73	102 years.
R-22	HCFC	$CHClF_2$	A1	1,780	5,310	0.034	12 years.
R-32	HFC	CH_2F_2	A2L	704	2,530	0	5.4 years.
R-134A	HFC	CH_2FCF_3	A1	1,360	3,810	0	14 years.
R-290 (Propane)	HC	$CH_3CH_2CH_3$	A3	<1	<1	0	12.5 days
R-401A	HCFC Blend	R-22/152a/124 (53/13/34)	A1	1,100	3,500	0.02	-
R-401B	HCFC Blend	R-22/152a/124 (61/11/28)	A1	1,200	3,800	0.03	-
R-404A	HFC Blend	R-25/143a/134a (44/52/4)	A1	4,200	6,600	0	-
R-407C	HFC Blend	R-32/125/134a (23/25/52)	A1	1,700	4,100	0	-

Name	Refrigerant Type	Chemical Formula/ Composition	Safety Class	100-year GWP	20-year GWP	ODP	Atmospheric Lifetime
R-409A	HFC Blend	R-22/124/142b (60/25/15)	A1	1,500	4,400	0.03	-
R-410A	HFC Blend	R-32/125 (50/50)	A1	2,100	4,400	0	-
R-410b	HFC Blend	R-32/125 (45/55)	A1	2,200	4,600	0	-
R-448a	HFO Blend	R-32/125/1234yf/134a /1234ze(E) (26/26/20/21/7)	A1	1,400	3,100	0	-
R-449a	HFO Blend	R-32/125/1234yf/134a (24.3/24.7/25.3/25.7)	A1	1,400	3,100	0	-
R-450a	HFO Blend	R-1234ze(E)/134a (58/42)	A1	570	1,600	0	-
R-452a	HFO Blend	R-1234yf/32/125 (30/11/59)	A1	2,100	4,000	0	-
R-452b	HFO Blend	R-32/125/1234yf (67/7/26)	A2L	710	2,100	0	-

Name	Refrigerant Type	Chemical Formula/ Composition	Safety Class	100-year GWP	20-year GWP	ODP	Atmospheric Lifetime
R-454b	HFO Blend	R-32/1234yf (68.9/31.1)	A2L	490	1700	0	-
R-454c	HFO Blend	R-32/1234yf (21.5/78.5)	A2L	150	540	0	-
R-513a	HFO Blend	R-1234yf/134a (56/44)	A1	210	710	0	-
R-600a (Isobutane)	HC	$CH(CH_3)_2CH_3$	A3	<1	<1	0	6 days
R-717 (Ammonia)	Natural	NH3	B2L	0	0	0	<1 day
R-744 (Carbon Dioxide)	Natural	CO_2	A1	1	1	0	Undefined[42]
R-1234ze	HFO	$CF_3CH{=}CHCl$	A2L	<1	4	0	16.4 days
R-1234yf	HFO	$CF_3CH{=}CH_2$	A2L	<1	1	0	10.5 days

[42] As Environmental Protection Agency (2020a) has stated, the atmospheric lifetime of CO_2 cannot be represented by a single value. The gas is not destroyed over time through chemical or physical properties like the other substances described here. Rather, it is transferred to other reservoirs like the ocean or in plant matter and over time (sometimes thousands of years) is deposited in various ways (e.g., ocean sediments, soil, rocks).