Variable Refrigerant Flow (VRF) Refrigerant Management Market Assessment

Final Report

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Executive Summary

This report seeks to examine the impact of Variable Refrigerant Flow (VRF) technology in the context of California's energy and environmental policy objectives and evaluate the suitability of continuing to incentivize VRF technology within utility energy efficiency portfolios, considering its impact on greenhouse gas (GHG) emissions and refrigerant usage. Over the past decade, VRF systems have gained significant popularity across the California market, incentivized by California's utilities mainly as a strategic electrification and decarbonization solution, capable of meeting the state's stringent energy efficiency requirements and providing a primary path to replacing fossil fuel-based heating and cooling equipment. Market adoption has also been driven by the technology's purported energy-saving potential, zoning controllability, design flexibility, and ability to handle California's high cooling demand while also providing heating capabilities.

As California aims to achieve net-zero emissions by 2045, the increasing use of heat pumps has become a growing environmental concern due to the largely unknown and unquantified emissions impact of refrigerant leaks across all HVAC systems. There is a greater risk for VRF technology that requires a high-charge volume of high global warming potential (GWP) refrigerant—several thousand times more potent than carbon dioxide.

The California Air Resources Board (CARB) has implemented a ruling on hydrofluorocarbons (HFCs) – a type of synthetic greenhouse gas commonly used as refrigerants — known as the Short-Lived Climate Pollutants (SLCP) Strategy — that supports the transition away from high-GWP HFCs to lower GWP and alternative technologies and advanced heat pump systems. However, this does not currently affect the regulatory acceptability or dissuade market adoption of VRF technology.

As such, the key objectives of this report are to (1) estimate the existing stock of refrigerants in California buildings' HVAC systems by equipment type; (2) calculate the potential impact of these systems leaking on the State's emissions reduction goals; (3) review current policy objectives to drive heat pump adoption and the requirements to reduce refrigerants; (4) cross-examine the emissions and efficiency impact of VRF technology against these policies and HVAC technology alternatives; and (5) identify and recommend actions needed to ensure utility efficiency incentives align and support CARB's policy to reduce GHG emissions and HFC refrigerant-based HVAC specifically.

A range of approaches—including both primary and secondary research methodologies—were employed to gather insights and knowledge about the current market conditions, policy objectives, technological advancements, and stakeholder perspectives on this topic. This involved the review and analysis of publicly available information including building stock data, HVAC equipment descriptions, case studies, and training materials alongside interviews with industry stakeholders— equipment installers, manufacturing representatives, and independent engineering and technology experts. In addition, a conceptual building system comparison exercise was conducted to assess the difference between similar cooling load-dominated HVAC system designs (including VRF) relative to system refrigerant charge reduction and integration of leak detection opportunities as well as overall refrigerant emissions impact and energy efficiency.

The findings in this report indicate that the total refrigerant load across California's building stock for existing HVAC systems (residential and commercial combined) is 58,217,452 pounds, with residential buildings accounting for 48,866,000 pounds of refrigerant, and

commercial buildings accounting for 9,351,452 pounds of refrigerant. Further, based on informed leak rate assumptions, this report estimates the annual GHG impact of refrigerant leaks across these sectors to be approximately two million metric tons (MMT) of CO2e, with the largest contribution coming from residential central air conditioning (CAC) systems and commercial packaged single-zone air conditioning (AC) systems.

Overall, this report's analysis suggests that that the operating efficiency of VRF technology may not be as advertised, and that given the challenges in independently verifying the efficiency and leak rates of VRF systems in real-world installations, there is a need to suspend VRF incentives and further examine the next generation VRF systems against HFC reduction targets set by California Air Resources Board (CARB) and consideration of alternative and emerging HVAC systems that can safely use near zero GWP refrigerants like R-290 as solutions for space heating and cooling decarbonization in the future.

Abbreviations and Acronyms

Acronym	Meaning
AIM	American Innovation & Manufacturing
AC	Air Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Btu	British Thermal Unit
CARB	California Air Resources Board
CEC	California Energy Commission
CEE	Consortium for Energy Efficiency
CFC	Cholorfluorocarbons
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
CPUC	California Public Utilities Commission
CAC	Central Air Conditioning
DOAS	Dedicated Outside Air Systems
ERV	Energy Recovery Ventilators
EPA	Environmental Protection Agency

ETS	Emissions Trading Scheme
FCU	Fan Coil Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCFC	Hydrocholofluorocarbons
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation, and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kWh	Kilowatt-hour
LPG	Liquid Petroleum Gas
MT	Metric Tons
MMTCO2e	Million Metric Tons of Carbon Dioxide Equivalent
NREL	National Renewable Energy Laboratory
NEEP	Northeast Energy Efficiency Partnership
PTAC	Packaged Terminal Air-Conditioner
PTHP	Packaged Terminal Heat Pumps

RTU	Rooftop Units
SLCP	Short-Lived Climate Pollutants
SEER2	Seasonal Energy Efficiency Ratio 2
VRF	Variable Refrigerant Flow
VRV	Variable Refrigerant Volume

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Introduction

Heating and cooling building indoor spaces, or “space conditioning,” is accomplished using equipment commonly referred to as “HVAC,” or “heating ventilation and air conditioning” equipment. Fuel combustion is a common means of heating in California, but increasingly both heating and cooling are provided across all California climate zones by equipment that uses electricity to extract heat from outdoor air for heating and remove heat from indoors for cooling. This electrically driven “heat pump” equipment includes many configurations of components such that space conditioning needs can be met across various building types. For a given building, more than one design approach and several alternative versions of heat pumps could meet ventilation needs and space conditioning needs. Other configurations provide ventilation and space conditioning using separate heat pump systems. All these various equipment types and configurations use refrigerants to absorb, move, and release heat without onsite fuel combustion. The type and relative amount of refrigerant used by different heat pump equipment has become an important consideration for utilities because most all current options have a high greenhouse gas (GHG) impact, a metric increasingly applied to energy efficiency policy. Installing, operating, servicing, and end-of-life handling of most all current heat pump equipment regularly releases the refrigerants they contain, which is now recognized as a significant and avoidable source of GHG. Reducing the use of high-GHG refrigerants, efficiently using lower global warming potential (GWP) refrigerants and choosing equipment that can use ultra-low GHG refrigerants are the main means of reducing the total GHG effect of heat pump and cooling equipment. High GWP HVAC may “electrify” a building but fail to “decarbonize” that building.

California legislation and regulation increasingly requires that buildings reduce or eliminate fuel combustion. To address this challenge, heating using electric heat pumps has moved to the center of energy and environmental policy, including utility incentives. It is important to note that this technology will drive increasing amounts of refrigerant use as the number of heat pumps installed increases. California now requires that the emissions of past-generation and currently sold high carbon dioxide equivalent (CO2e) refrigerants classed as short-lived climate pollutants (SLCPs) be dramatically reduced, which creates a tension between thermal electrification and GHG reduction mandates, putting the use of even mid-GWP heat pumps into question. For some time now, utilities have been offering incentives to increase the use of heat pumps due to their electricity-driven fuel source and increasing amounts of renewable electricity on the grid. However, the recent regulation targeting high-GWP refrigerant types will change the heat pump environment over the next several years because it puts the GHG implications of utility energy efficiency portfolios into question. A clash of environmental policy with energy efficiency metrics now forces utilities to include consideration of the CO2e impacts of refrigerants use and emissions as regards to whether they are best advancing California’s “decarbonization” requirements.

This report examines a specific form of heat pump system that uses refrigerants that flow through a network of piping not seen in other heat pumps. Widely used in Japan for over thirty (30) years , such systems are called Variable Refrigerant Volume (VRV) by Daikin and Variable Refrigerant Flow (VRF) by other manufacturers. VRF systems have gained acceptance in the United States (US) over the last 20 years. This examination of VRF technology in the context of both the policy driving heat pump adoption and the requirements to reduce refrigerant releases to the atmosphere despite increasing numbers of heat pumps aims to optimize net GHG reductions and more fully align utility incentives to California policy objectives during a transition period to replacement refrigerants with much lower or alternatively, ultra-low GWP.

Background

The net effect of atmospheric heating and climate change is not caused solely by carbon dioxide (CO2) from such sources as fossil fuel combustion and electricity generation. The California Air Resources Board (CARB) is charged by a series of laws to reduce total GHG including a law specifically requiring steep reductions of non-CO2 SLCPs that are powerful climate forcers with shorter lifetimes: the GHGs methane and hydrofluorocarbons (HFCs), and anthropogenic black carbon. “Fluorinated gases – especially HFCs – are the fastest growing source of GHG emissions both in California and globally” (CARB n.d.).

To meet California’s overall GHG reduction policy target of net zero emissions by 2045, space heating/cooling equipment must not only efficiently use electricity and displace prior fossil fuel burning but also reduce releases of environmentally damaging high GWP refrigerants, primarily HFCs (CARB 2020a). The US Environmental Protection Agency’s (EPA) American Innovation & Manufacturing (AIM) Act has begun the process to progressively reduce “the production and consumption of HFCs in the United States by 85 percent over the next 15 years.” This “phase down” mechanism comes in several steps: the first 10 percent reduction happened in 2022 with the second step being a further 30 percent reduction in 2024) (EPA 2023). CARB regulation of HFC use sets a limit of 100-year GWP of 750 which will mandate a change away from the most common HVAC refrigerants of R-410A and R-134a during the current transition period of 2023-2025 for new equipment. This mandated transition applies to most residential and commercial HVAC equipment by the end of 2024 and to VRF by end of 2025. The regulations do not require a change to a specific lower-GWP alternative but do require that new units sold in California contain a percentage of reclaimed HFC refrigerant as a means of using new sales to drive refrigerant reclamation from end-of-life equipment.

As heat pumps gain popularity to provide heating and cooling, refrigerant use will also increase. Choices among what heat pumps are incentivized and what refrigerants they contain allow for alternative paths where increased use of refrigerants does not have to equate to increasing CO2e emissions. CARB regulation set an upper limit for GWP in new HVAC equipment that allows for mid-GWP A2L refrigerants to be used, such as R-454B and R-32. CARB did not set a lower limit, so a transition to HVAC equipment that uses near-zero GWP R-290 could become a market choice immune to CARB action, such as lowering the current limit if HFC emissions reductions fall short. Indeed, new automotive HVAC and low-pressure chillers are already being manufactured using an ultra-low GWP refrigerant, R-1234yf, avoiding this GWP regulatory risk. Heat pumps with all refrigerants outside the building such as air-to-water heat pumps of residential scale already use R290 in many global markets, virtually eliminating GWP from refrigerants use at each unit installed. With impacts of climate change such as damage from wildfires increasing costs to California utilities and ratepayers the recognition that avoiding CO2e emissions such as those from SLCPs and avoidable use of even mid-GWP HFCs is likely to increase in importance and can prompt further action by CARB (CARB. 2020a).

Among available heat pump technologies, refrigerant is used in different ways resulting in more or less “refrigerant efficiency,” as described by a May 2023 presentation to the Consortium for Energy Efficiency (CEE) by Daikin. In it, Daikin argued that the metrics applied by energy efficiency policy were not responsive to requirements exerted by environmental regulations such as the federal AIM Act and CARB HFC regulations and that efficiency policy needs to increasingly consider the refrigerant efficiency of how any given specific heat pump equipment meet metrics such as Seasonal Energy Efficiency Ratio 2 (SEER2), the current seasonal energy efficiency rating method. Daikin presented data showing how some equipment within the category of three-ton residential heat pumps were more efficient in their use of operating energy (electricity consumed) but much less efficient in their use of the “increasingly scarce resource” of HFC refrigerant that is becoming less available under the AIM Act phasedown. While all conventional heat pump designs use similar components, Daikin presented internal market information showing that only the US market has not adopted variable speed compressors and continues to use single and two-stage compressors. Units using these “on-off” compressors meet energy efficiency standards such as SEER2 by increasing their coil surface area and refrigerant charge. Daikin also explained that SEER2 does not consider the efficiency of variable capacity due to variable speed compressors under low load demand conditions The authors argue: “All HVAC industry stakeholders must recognize the convergence of energy and environmental drivers. Future policies and initiatives should consider goals and constraints from both sets of drivers” (Daikin 2023). The specifics of the presented equipment analysis are relevant to a current market gap in the commercial roof top segment discussed in this report where variable speed compressor-based Roof Top Units (RTUs) are not generally available and low ambient capability to cover 100 percent of California heating loads is not offered in heat pump only designs that might displace gas-furnace/air conditioning-only RTUs dominating the state’s commercial building stock. However, the larger point of energy efficiency metrics and incentives being unresponsive or in conflict with environmental regulation relative to refrigerants is the center point of this market assessment. In fact, Daikin asserts that refrigerant efficiency must be considered in what specific HVAC equipment is incentivized via energy efficiency metrics to VRF technology.

VRF Definition

This report examines the comparative advantages and disadvantages of one form of HVAC equipment referred to herein by the most common term in the market: VRF technology in the context of California’s legal requirement to reduce total HFC emissions. When the Variable Refrigerant Volume (now also known as VRF) approach was invented in the early 1980’s, the system was sometimes referred to a as a “connected air conditioner” (initially, it was cooling only) because the managed direct flow of refrigerant to and among distributed inside terminal units was the key innovation that made the approach workable (Daikin 2008, 6). As defined by the industry standards organization American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): “Variable-refrigerant-flow (VRF) HVAC systems are a direct-expansion (DX) heat pump technology platform.... These systems are thermodynamically similar to unitary and other common DX systems and share many of the same components.... VRF systems transport heat between an outdoor condensing unit and a network of indoor units located near or within the conditioned space through refrigerant piping installed in the building. Attributes that distinguish VRF from other DX system types are multiple indoor units connected to a common outdoor unit (single or combined modules), scalability, variable capacity, distributed control, and simultaneous heating and cooling" (ASHRAE 2020). To clarify, many VRF systems act only as heat pumps and are not designed to provide simultaneous heating and cooling—only some can. The actual operation in this "heat recovery" mode is dependent on the nature of the building and whether different areas served require heating while others require cooling for any significant number of hours per year.

In early 2023, a patented variation of VRF called "Hybrid VRF" which uses the same outdoor units as their traditional VRF but employs a different Hybrid Circuit Controller that transfers energy from the main refrigerant circulation to the water side of the unit, and thereafter circulates heated or cooled water as needed to up to 16 indoor fan coil units (FCUs). Multiple circuit controllers can be connected to multiple outdoor units, allowing the same range of capacity as the other VRF systems. Hydronic distribution connecting to indoor units reduces the total amount of refrigerant needed by up to 20 percent. While traditional VRF requires selecting components and piping design to enable heat recovery capability as an option, it is inherently a capability provided by the hydronic distribution and Hybrid Circuit Controller.

Key to understanding the California-specific challenges brought by refrigerant use in heat pumps is that California policy and regulation necessarily shape the technologies incentivized through utility energy efficiency and GHG reduction portfolios. Among all states, California has a unique legal structure driving action by HVAC manufacturers, distributors, and installers through the CARB regulation of refrigerant use in both manufacturing of new equipment and servicing of existing HVAC equipment. The California Public Utility Commission (CPUC) provides regulatory oversight of electricity and gas utilities much like other states' utility regulation bodies. However, the California Energy Commission (CEC) acts "as the state's primary energy policy and planning agency" providing "a cohesive approach identifying and solving California's pressing energy needs and issues" via the Integrated Energy Policy Report (CEC 2023).

On HVAC trainer Bryan Orr's HVACR School Podcast, Emerson's Rajan Rajendran noted that half of all refrigerants manufactured each year are going to replace leaked refrigerant—an issue that is potentially at odds with California's HFC reduction policy ambitions; "Bryan, I don't know if this is a statistic you know, but more than 50 percent of all the refrigerant produced in any given year goes to servicing leaks" (Rajendran 2022). Recent legislation directly addressed the need to reduce the significant GHG contribution from high GWP refrigerants and promote the reclamation of previously deployed refrigerants via mandated reuse of reclaimed refrigerants by manufacturers and installers: Senate Bill (SB) 1206 directly prohibited the sale of newly manufactured or "virgin" R410A and R-134a, the most commonly used refrigerants in space heating and cooling. The law also forces using reclaimed material to service existing HVAC equipment (Turpin 2022). California SB 1383 puts into law a specific mandate to reduce HFC gases by 40 percent below 2013 levels by 2030 (Lara 2016). This bill required CARB, "no later than January 1, 2018, to approve and begin implementing that comprehensive strategy to reduce emissions of SLCP to achieve a reduction in methane by 40 percent, HFC gases by 40 percent, and anthropogenic black carbon by 50 percent below 2013 levels by 2030, as specified."

These requirements are incorporated into recently finalized CARB rulemaking imposing an upper limit of 750 GWP on new manufacture of HVAC equipment, starting on January 1, 2023, for some equipment and extended to 2026 for VRF equipment. This CARB ruling also introduces the "R4" program, implementing a minimum percentage of reclaimed high GWP (above 750) refrigerants in new HVAC equipment sold in California during this 2023–2026 period. The project team believes California has logically placed HFCs with other short-lived climate-forcing agents. While other states are in the early stages of moving from purely energy metrics-based utility incentives, California's state legislation and CARB rulemaking *make the likelihood of HFC emissions from a given type of HVAC equipment a necessary consideration in shaping utility portfolios* because equipment that contributes to HFC emissions are subject to additional CARB actions, representing a clear risk to measure lifetime.

Objectives

The purpose of the research for this report is to assess the appropriateness vs. risk to utility energy efficiency portfolios of including VRF technology in incentivized measures. We examine VRF use in HVAC systems as an emerging technology within a market alongside potential alternative HVAC technologies with a focus on the potential for high GWP refrigerant leaks and the longer-term suitability and adaptability of each technology. The findings were developed in response to the following research questions:

1. What is the total stock of existing HVAC refrigerants in California buildings and how can it be reasonably estimated?
2. What existing Hydrochlorofluorocarbons (HCFC) and HFC bearing equipment types will require replacement and refrigerant capture to achieve the state's net HFC emissions reduction and building decarbonization goals? Does VRF help or hurt in this regard?
3. What evidence of measured third-party verified efficient heating and cooling using VRF is readily available? How feasible is it to verify VRF operating efficiency as installed? What is the efficiency in low demand conditions and how is it achieved?
4. What markets are manufacturers selling VRF into most successfully and why?
5. Is there readily available market data on VRF penetration from recent years to indicate future trends? Can we discern the degree to which VRF systems represent a segment of those systems with less than 50 pounds of refrigerant charge not subject to federally required HFC leak reporting and repair?
6. What technology, if any, could be applied to reduce net leaks of refrigerant in new or existing VRF systems? Is it feasible to apply leak detection after a VRF system is installed?
7. What is the technology roadmap for reducing the GWP of refrigerant and/or amount of refrigerant in VRF systems? Can the potential points of failure that cause leaks be reduced in number?
8. Do we need VRF to electrify California buildings? What alternative technologies or applications of HVAC to California buildings could offer a potentially lower use of high GWP refrigerant or easier "future-proofed" transition to lower or ultra-low GWP refrigerant-based heating and cooling?

The project team started with the widely held premise that VRF heat pump technology is gaining market share and the fact that marketing of VRF systems often cites energy efficiency and building decarbonization as a reason for building owners and equipment specifiers and installers to choose VRF systems. HVAC and refrigeration equipment manufacturers have historically externalized responsibility for the net impact on atmosphere of GHG emissions from high-GWP refrigerants leaks in systems that require installers to make field connections. Packaged systems with only factory-made refrigerant line connections benefit from more warranty protection. Once equipment delivery is accepted, system owners and installers bear all direct costs from refrigerant leaks in VRF systems to the extent that leaks occur during a warranty period unless the component failure is proven (Helbing 2022). In exploring the questions above, this report seeks to review the market options for the commercial HVAC segments in which VRF competes in the context of HFC policy and the absence of something like an Extended Producer Responsibility mechanism funding a highly effective program for leak repair and end-of-life refrigerants recovery.

Methodology & Approach

Primary Data Sources and Methodology

To help inform this project's stated Objectives described above, the project team implemented the following research methodologies:

- Conducted a secondary review of publicly available equipment descriptions, trainings, market data, application information, and case studies.
- Interviewed industry stakeholders.
- Performed a conceptual application scenario.
- Conducted a building stock and HVAC analysis.

Information on these sources and methodologies is described in more detail below.

Primary and Secondary Research

Key project research objectives were to understand VRF systems relative to refrigerant emissions impacts and verified energy efficiency, the current market for VRF, and emerging or existing alternative technologies. This was done by searching publicly available equipment descriptions and trainings, market data, application information (such as case studies); and direct interviews with VEIC engineering and other engineering resources, equipment installers, manufacturer representatives, and manufacturers.

We primarily identified stakeholders through networking to gain introductions to key personnel, prioritizing the leading manufacturers of VRF/HVRF or alternative emerging technologies, as well as cold calling identified installers and manufacturer representatives. A research service that identifies other stakeholders was initially employed to interview self-identified construction and building managers to assess their familiarity with HVAC technology and view its dimensions of value from their standpoint. However, familiarity with heat pumps was very low, and we found no experience with VRF in a small sample, so this effort was discontinued.

The project team made its subject matter expert engineering and HVAC program staff available to the project. These engineers were asked to share their experience with VRF and other relevant technologies and applications to help frame the research questions (see Objectives). These engineers also participated in interviews and provided analysis of the information gathered. Outside independent technology expert evaluators from Steven Winters Associates and Taitem Engineering were also consulted on the likelihood and experience with leaks in VRF systems, best practices, and the questions of whether and how it is possible to independently verify their energy efficiency. Additionally, several other manufacturer subject matter experts were consulted on hydronics primarily and HVRF.

To illustrate how other approaches might be compared to VRF and HVRF, we performed a conceptual application scenario at one of the most common large building types where this technology is installed: a primary school. This comparison focused on addressing load diversity, good quality active ventilation, reducing total refrigerant charge, and the likelihood of refrigerant leaks as well as the relative feasibility of applying leak detection. All system scenarios examined met the baseline objective of eliminating on-site fuel combustion for space heating and cooling.

Building Stock & HVAC Analysis

The project team also analyzed likely refrigerant emissions from existing equipment installed in California, described below, including seeking to estimate the potential shift to VRF technology and its implications for total net HFC emissions reductions required by law. For this analysis, the project team assessed the total quantity of refrigerants within California building stocks and estimated the potential impact of leaks. demonstrates the thought process and methodology for this analysis. The figure also shows the general method of the calculation approach to estimate the GHG impact from HVAC refrigerants. The data sources have been identified where applicable.

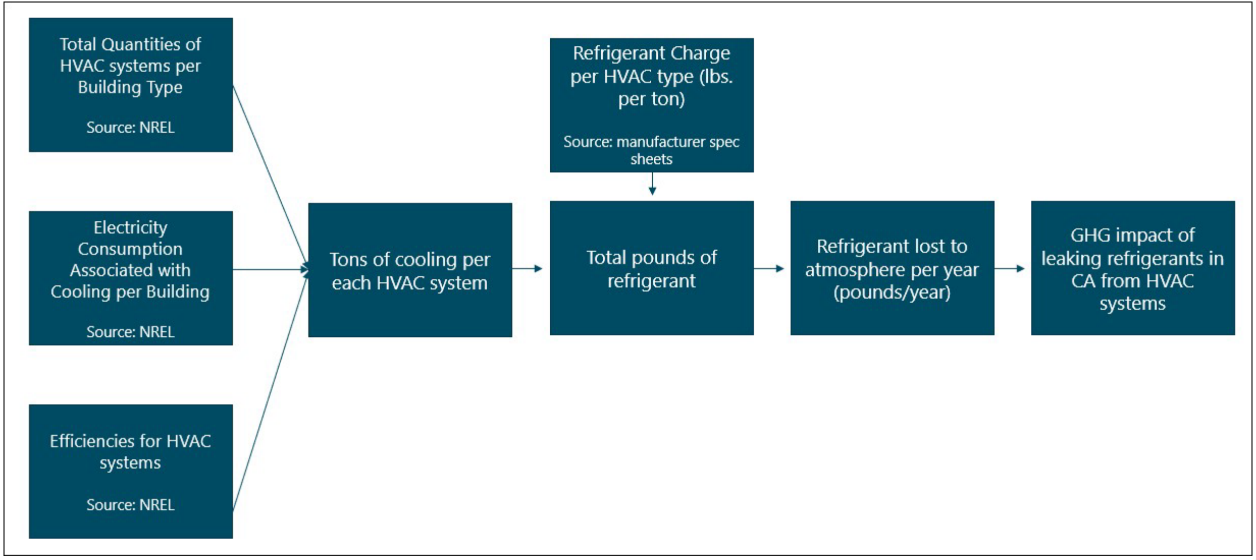


Figure 1: Calculations of likely refrigerant emissions flowchart.

By leveraging existing data from the National Renewable Energy Laboratory (NREL), the existing building stock and HVAC system were identified in California for both the residential and commercial sectors (Wilson, et al. 2022). This also included associated efficiencies and annual cooling energy consumption to help determine the total pounds of refrigerant. CARB staff responsible for their GHG inventory work suggested that the GWP value of R-410A (2,088 pounds CO2e per pound R-410A) be used to convert the millions of pounds of refrigerant estimate in California's building stock into millions of metric tons (MMT) of CO2e, the metric both SB 1383 and CARB use in refrigerants policy and regulation (Kohli 2023).

Findings

Review of Market for VRF, Hybrid VRF, and Alternative Technologies Relative to Refrigerant Emissions

California’s goal of net decarbonization of buildings requires a series of HVAC design considerations that include the equipment lifetime and embodied carbon equivalent of the refrigerant used in the applied HVAC design, not just the elimination of fossil fuels for heating. With recent CARB regulation driving an increasing recognition of refrigerant considerations and, thus, available equipment and refrigerants, the understanding of what long-term decarbonization means is evolving, including the implications to long-held conventions incorporated into utility-sponsored incentive programs.

A key stated benefit of VRF technology has historically been the increased operating efficiency it lends itself to in some HVAC systems, in particular heat pumps. The project team’s research to date has led us to conclude that operating efficiency will not be realized as advertised. There are reasons to view current R-410A systems as a risk to utility energy efficiency portfolios, which can be avoided.

This risk stems from the difficulty of independently verifying the operating efficiency and leak rates of VRF as installed in the field, anecdotal evidence that the many points of failure inherent in VRF design can lead to persistent leaks over time, and the prospect that VRF systems using R-410A are not assured of replacement refrigerant stocks as they do leak or require repairs. Various alternative system types, including HVRF, centralized hydronic systems, and distributed small units already being demonstrated as capable of using near-zero GWP R-290 to “solve” the refrigerants emissions problem for space heating/cooling decarbonization.

CARB may revise its current HFC reduction measures in ways that will negatively impact the regulatory acceptability of VRF systems using R-410A and R-32 and with potential risk to utility energy efficiency portfolios. Importantly, CARB references the Intergovernmental Panel on Climate Change (IPCC) AR4 report for its GWP values associated with individual refrigerants. The most recent

IPCC AR6 report updates the GWP values for R-32 from 675 to 771, just over the regulatory cut-off of 750 (see above). Notably, R-454B's value is much lower, so we attached a short-term risk value to R-32 systems and not R-454B VRF systems in this regard. That said, the net result of the US phasedown regulatory approach is that decarbonization policy and other drivers will increase the total deployment of high-GWP, and somewhat lower GWP HFC refrigerants, in heat pumps of all types. As the cycle of more dire climate reports is published and estimates of more damaging weather events continue, additional laws may be instituted, and potentially more pressure will be on utilities to align their energy efficiency incentives with the more aggressive CARB policy to reduce GHG emissions and HFC refrigerant-based HVAC specifically. This may mean that the likelihood is high for California utilities currently incentivizing systems with VRF to eliminate those incentives because they will be contrary to increasing net CO2e reduction metrics.

Additional findings are described below and are summarized by the relevant questions outlined in the Objectives section.

Specific Findings by Questions from Objectives

1) What is the total stock of existing HVAC refrigerants in California buildings and how can it be reasonably estimated?

KEY FINDINGS:

- Data regarding refrigerants deployed currently is dated, though useful.
- The total refrigerant in California's building stock for existing systems, residential and commercial combined, is estimated at 58,217,452 pounds (48,866,000 pounds from residential and 9,351,452 pounds from commercial).

The project team used NREL's datasets on residential and commercial buildings to identify by type, number of floors, square footage, and HVAC system used. The analysis calculated the relationship between building characteristics and system size to establish the estimated pounds of refrigerant by building category (residential vs. commercial), building type, or market segment (NREL 2023). We note that the CEC's "California Commercial End-Use Survey" (CEUS) was last issued in 2006, and an updated CEUS was scheduled to be published in 2022 and then January 2023 but has again been delayed. When that data is released, it will likely be the most up to date.

The analysis estimates that the total amount of refrigerant in California residential equipment is 48,866,000 pounds. The graph in Figure 2 below shows the refrigerant amounts by category of residential property and equipment type. The largest segment by far is central air conditioning (CAC) in Single Family Detached residences, at approximately 35 million pounds of refrigerant.

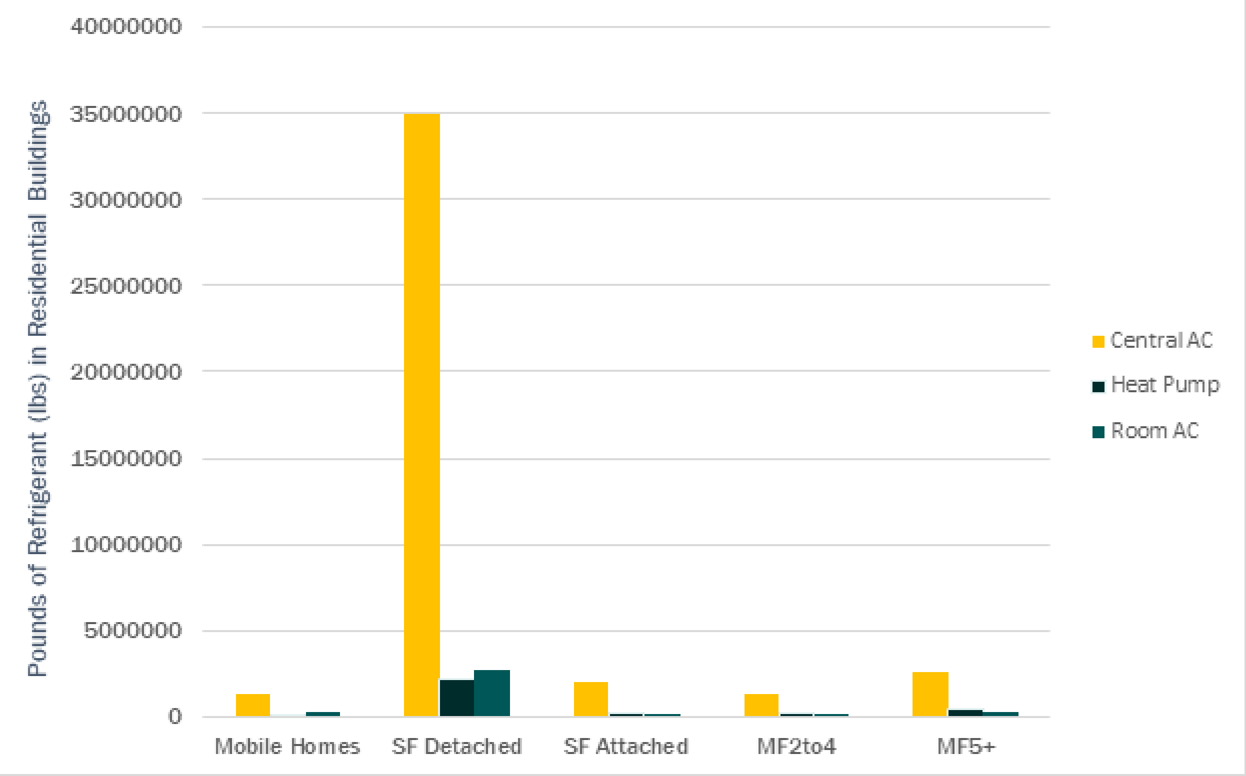


Figure 2: Pound (lbs.) of refrigerant by residential building and HVAC type in California.

An image of a central air conditioner outside condenser units and refrigerant line sets penetrating a masonry wall is shown in Figure 3 below. The refrigerant line sets typically connect to evaporator coils in indoor air handler units and ductwork to circulate cooled and dehumidified air.

Figure 3: Image of CAC outside condenser units and refrigerant line sets penetrating masonry wall (courtesy of Efficiency Vermont).

More recent residential data might show an increase in heat pumps relative to CACs. Some portions of the heat pump market will have a similar visual appearance and coil configuration as the units pictured above; others use horizontal air flow and appear more rectangular. Single-phase "Mini VRF" is a relatively new entrant to the residential market and, as such does not appear in the data categories above.

The NREL Commercial Buildings dataset for California yields a total estimated refrigerant of 9,351,452 pounds in existing commercial HVAC equipment. Commercial buildings are far more diverse in size and function than residential buildings. As a result, there are many more considerations to design and build an HVAC system for the owner's commercial purpose. Commercial HVAC equipment markets have many design approaches in common use that can serve the owner's purpose in very different ways. Building codes incorporating the design requirements embodied in ASHRAE Standards 15 and 34 become particularly relevant regarding refrigerant and equipment choices. Mechanical ventilation design attention and code enforcement are uncommon in residential markets but a core consideration in commercial markets.

Figure 4 shows the total pounds of refrigerant found in commercial buildings. The buildings with the highest refrigerant totals are primary school buildings (such as primary schools), followed by warehouses, secondary schools (i.e., high schools), and retail strip malls. The graph below only shows total pounds of refrigerant by building category. While building types have varying intensities of HVAC use, the main driver of total pounds of refrigerant is the number of buildings in each category and their size, as seen below.

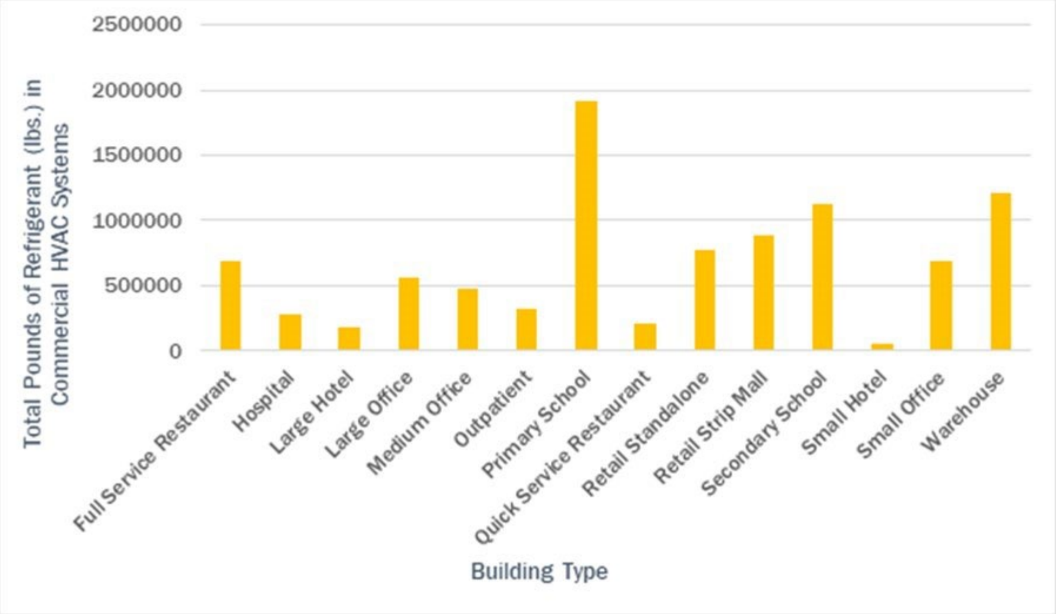


Figure 4: Total pounds of refrigerant by building category.

Among building types, Hospitals have the largest average size, and Small Office buildings are the greatest in number.

Table 1: Building Type by Quantity and Average Square Foot

Building Type	Quantity	Average Square Foot
Full-Service Restaurant	18,031	10,910
Hospital	479	516,545
Large Hotel	1,252	183,936
Large Office	1,037	403,230
Medium Office	5,860	92,867
Outpatient	6,810	78,600
Primary School	6,777	92,611
Quick Service Restaurant	9,713	15,101
Retail Standalone	16,432	27,315

Retail Strip Mall	16,234	31,215
Secondary School	2,092	78,082
Small Hotel	1,844	45,569
Small Office	53,482	9,401
Warehouse	29,256	57,732

Two rows are highlighted in Table 1: the Medium Office and Primary School categories were reviewed more closely because they are relatively large and represent a large number of buildings. By contrast, Small Office and Warehouse are much more prominent in number, but VRF market participants cited neither category as being successful verticals for VRF equipment. Their fundamental structure leads these two building types to be dominated by packaged single-zone air conditioning RTUs, usually with integrated gas furnaces for heating, as a much lower cost approach.

2) What existing CFC/HCFC/HFC–bearing equipment types will require replacement and refrigerant capture to achieve the state's net HFC emissions reduction and building decarbonization goals? Does VRF help or hurt in this regard?

KEY FINDINGS:

- Building electrification is a key strategy for reducing total GHG emissions; however, the impact of HFC refrigerants emissions from buildings' HVAC systems can only be estimated at this time.
- The replacement of aging existing units creates the greatest opportunity to reduce HVAC related refrigerant emissions, including HFC emissions, if the refrigerants are correctly captured at that point and if the replacement units use lower GWP refrigerants.
    - The largest amount of refrigerant needing recovery overall is in existing residential CAC units.
    - The largest amount of refrigerant needing recovery in the commercial building stock is for existing packaged single-zone air conditioning units.
- Data regarding refrigerants deployed currently is dated. While this data is too dated to reflect market penetration of VRF systems accurately, it was useful for some estimating.
- Data regarding refrigerant leak rates is sparse and insufficient to provide accurate analysis, forcing the use of broad estimates. Across our research, we did not find anyone who knows the leak rate of HVAC equipment and learned that little study effort has gone into finding out.
- For a given capacity, VRF systems will have more refrigerant per ton, and HVRF will have up to 20 percent less than traditional VRF but still more than other HVAC equipment types. On a same capacity basis, shifting from other equipment types to VRF requires more refrigerant and thus requires more refrigerant-bearing piping and joints made in the field, representing more points of failure that can leak refrigerant.
- The negative effect on meeting California's mandated HFC reduction targets from VRF taking market share from other less-refrigerant-intensive system types is a source of risk to utility

energy efficiency portfolios because CARB can take further actions to force GWP reductions if its reduction targets are not met.

  - This risk is greatest for the 2023-2026 period, during which current CARB rules allow VRF using R-410A to be sold and relatively less risk for VRF based on R-32 and again less risk for VRF based on R-454B due to reduced GWP of those refrigerants.

California SB 1383 and CARB regulation of HFC refrigerants use in new equipment manufacture seek to force a net reduction of 7.5 million metric tons of CO2 equivalent (MMTCO2e) below 2013 levels by 2030. To successfully meet this mandate, CARB, CEC, and California's utilities will need to collaborate over the coming years to align policy and action such that the incentivized HVAC equipment considered in this report and even commercial refrigeration equipment not considered here support this mandate.

As reflected in the figure below, the project team's review of California's building stock and commercial HVAC equipment by type shows that decades of investment have predominantly gone to the lowest cost equipment that performs space conditioning and delivers fresh air in a simple-to-install package, primarily small and medium-sized packaged single zone AC or RTUs and through-wall packaged terminal air conditioners or heat pumps (PTAC/PTHP).

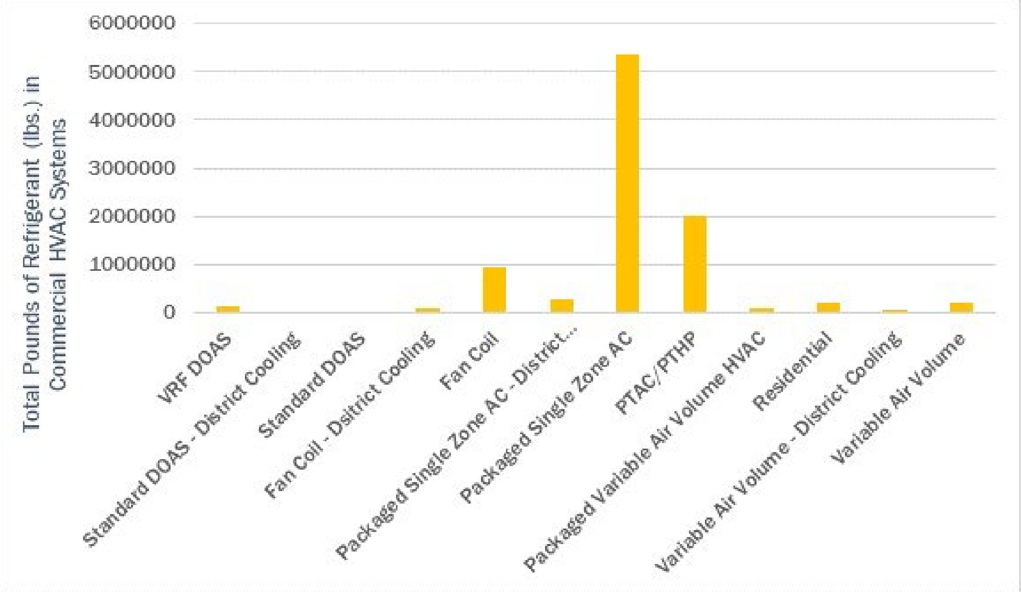


Figure 5: Pounds (lbs.) of refrigerant by commercial HVAC type in California.

RESULTS OF REFRIGERANT EMISSIONS ESTIMATION ANALYSIS

The project team found that the types of refrigerants used across the HVAC landscape vary from site to site. Based on field observation and literature review, R-410A is currently the most used refrigerant. At the recommendation of CARB staff, for the purpose of this study, we used the GWP of R-410A (100-year GWP = 2,088) for the calculations to convert the pounds of refrigerant by category and total into CO2e GHG impact in MT.

Figure 6: Example of commercial two- to five-ton packaged Single Zone AC Unit of RTU (AAONRQ).

The biggest impact was seen with CAC systems in residential buildings and packaged single-zone AC units in commercial buildings. This finding was driven based on the quantities those buildings and systems represent in California. Figure 7 below shows the total GHG impact from HVAC systems in the commercial sector, *assuming only the low-end assumption of 3.5 percent system leak rate*. Predictably, the largest impact from an HVAC system is the packaged single-zone AC systems due to their high prevalence.

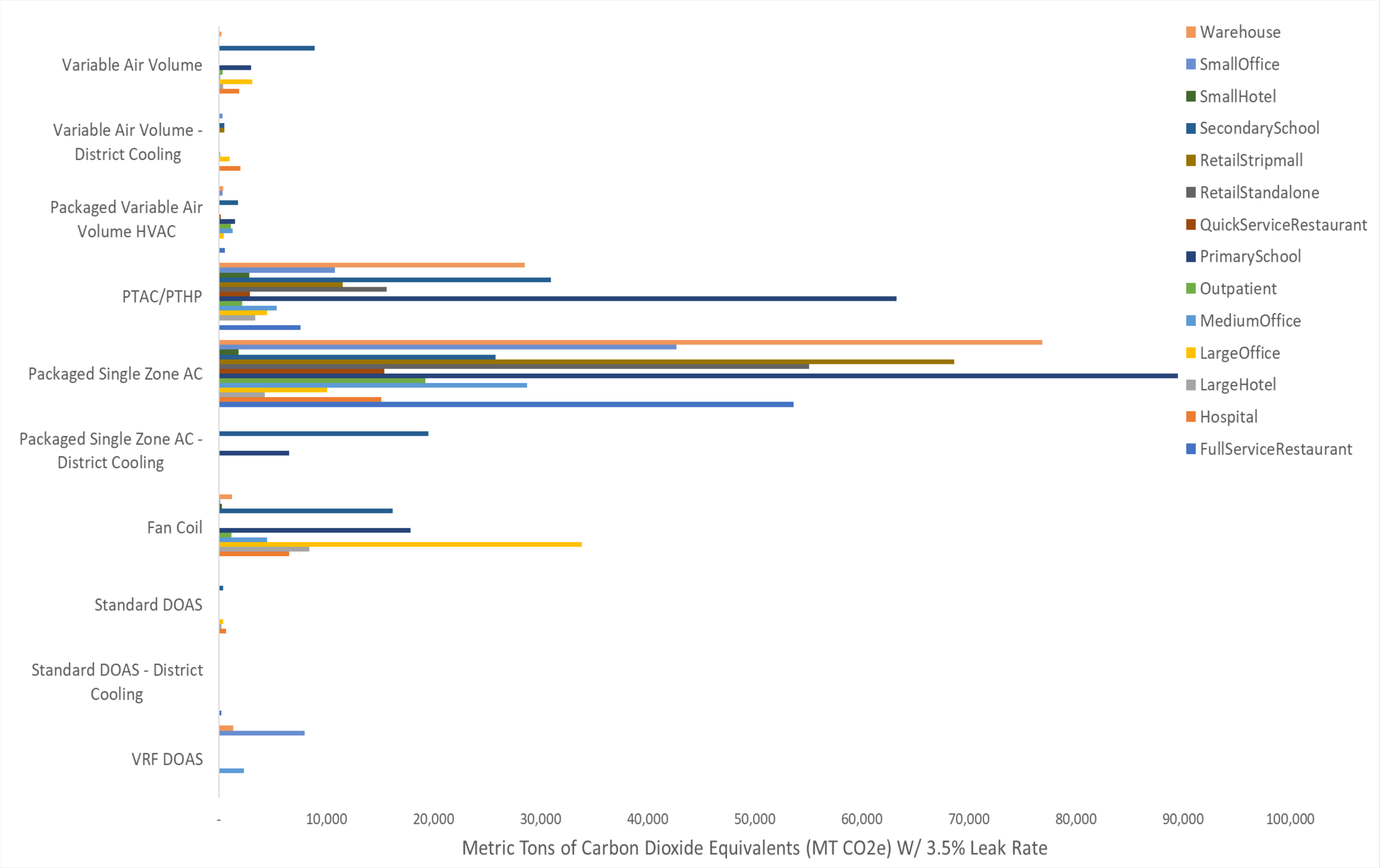


Figure 7: Total GHG impact from HVAC systems.

Using the conversion rate described above, the total pounds of refrigerant estimated to exist in California's residential building stock becomes the equivalent of 46,239,649 MT of CO2e.

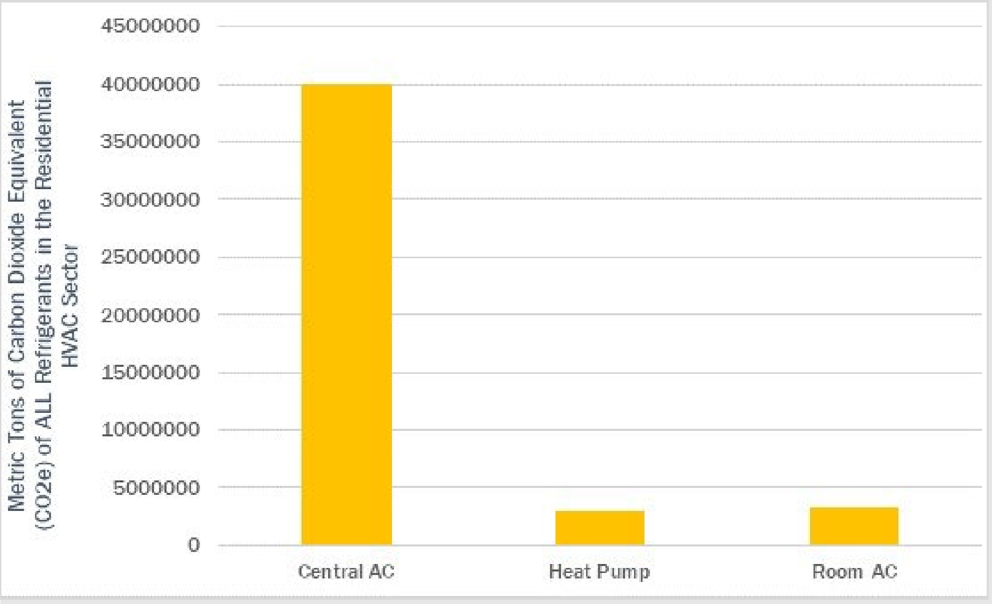


Figure 8: Metric tons of CO2e by HVAC unit type.

The leak rates of HVAC systems can vary greatly for reasons of:

- Design/inherent points of failure
- Manufacturing defects
- Mishandling of equipment or piping prior to installation
- Less than perfect installation at points of failure, such as flare joints or brazed (soldered) joints
- Less than perfect installation procedure, including pressure testing, leak testing, triple evacuation, and refrigerant handling and charging procedure
- Damage while in use after installation
- Less than perfect decommissioning and refrigerant recovery at end of life

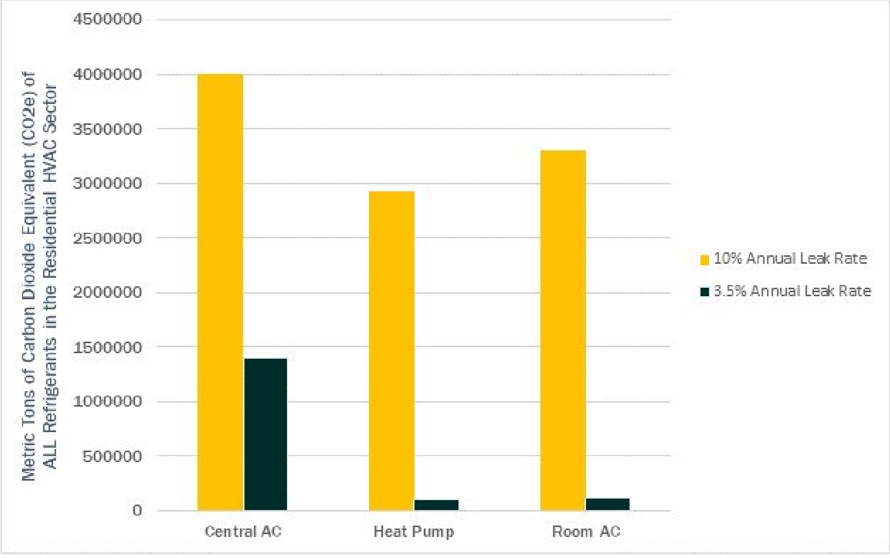


Figure 9: Metric tons of CO2e with 3.5% and 10% leak rates by HVAC unit type.

There are few available studies attempting to document or estimate failure rates and leak rates. While this is an important area lacking data, the project team found a few sources. CARB estimates leaks to be between two and ten percent (Gallagher 2016). In the United Kingdom, the Department for Environment, Food and Rural Affairs (U.K. 2019) estimates leakage rates that range from three to 17 percent. The IPCC puts estimates in the range of one to five percent for residential and commercial AC units and as high as 25 percent for industrial and commercial equipment (Devotta, et al. 2005). The EPA's GreenChill program confirms the 25 percent estimate to be an average leak rate for grocery store refrigeration systems, potentially due to the long length of the refrigerant lines on site (ICF 2005). Preliminary studies have estimated the leak rate for commercial heat pumps once installed to range from three to 7.5 percent (Sabine 2009). We acknowledge that different systems experience different leak rates and established 3.5 percent as the most conservative leak rate estimate used and 10 percent as the highest leak rate estimate to estimate refrigerants emitted to the atmosphere. Given Mr. Rajan Rajendran's statement that half of all refrigerants produced each year are used to service leaks in existing systems, it is possible that leak rates in HVAC equipment substantially exceed 10 percent. In particular, this higher leak rate may well underrepresent the actual leak rate by 100 to 200 percent, given experience with higher-duty commercial refrigeration equipment leak rates. As such, it is important to emphasize that no good data sets or dispositive studies on leak rates were identified through this research effort.

For the analysis, the project team applied three different annual leak rates to the estimated total CO2e of the pounds of refrigerant in existing systems in the range of lowest at 3.5 percent to 10 percent. Overall, the annual GHG impact from leaking refrigerants (3.5 percent leak rate and a GWP of 2,088) in the commercial and residential HVAC sector in the state of California is approximately two million MT CO2e. This is the equivalent to the emissions of 415,505 gasoline-powered passenger vehicles driven for one year (EPA 2023). The largest contributors identified in this study are CACs in single family detached homes (in residential) due mostly to the high prevalence of those items in California and packaged single-zone AC systems in primary schools (in commercial).

The table below highlights the total amount of emissions related to leaking HVAC refrigerants in California. The 2030 column is a summation of the GHG impact since 2022. Because average leak rates can vary, 3.5 percent, five percent, and ten percent are shown based on the leak rate ranges estimated by other research (EPA 2023). Because California SB 1383 aims to reduce HFC gases by 40 percent below 2013 levels by 2030, the eight-year sum total of GHG emissions are shown for different leak rates, illustrating the importance of all available measures and opportunities to reduce, repair and avoid leaking refrigerants from our HVAC systems.

Table 2: GHG Impact (in MT CO2e) by Leak Rates

Leak Rate	2022 Commercial (Annual)	2022 Residential (Annual)	2030 (8-year Accumulation)

3.5%	309,987	1,618,388	15,426,995
5%	442,838	2,311,982	22,038,564
10%	885,676	4,623,965	44,077,129

It is entirely reasonable to view the above-projected leak rates as significantly *under*estimated due to the following factors:

- NREL data is out of date and updated CEC data remains unavailable as of April 2023. This means the estimate does not account for the rapid growth of heat pump deployment in the last decade and underestimates existing high-GWP bearing HVAC equipment.
- The 10 percent leak rate is based on true estimates, not actual data. As noted, HVAC leak rates may well be higher, closer to the refrigeration leak rates of 25 percent or more based on much better data.

High-GWP refrigerants cannot simply be substituted for by lower-GWP refrigerants because refrigerants are matched to the compressor and other system components, leaving the system owner a choice of repairing a leaking system and paying for new refrigerant to be charged into the system or buying an entirely new system. As the less expensive choice is often repeated repair, the result is that a poorly installed or often-repaired system can see the original refrigerant charge of anywhere between three pounds to up to 50 pounds of refrigerant being *leaked and replaced many times over its lifetime* with no legal requirement to track how often it is leaking and recharged. In the case of the most popular refrigerants of recent vintage, R-22 (HCFC) and R-410A (HFC), anything less than a fully resolved leak in a single system causes a minimum of dozens to thousands of MT of CO2e to be literally pumped into the atmosphere over a few years of less-than-correct service. This greatly increased potential points of failure inherent in VRF systems versus the currently predominant packaged rooftop units (RTUs) cannot be understood to be anything but an increase in total refrigerant use per capacity ton and increased risk of refrigerant emissions. California SB 1206 bans the sale of bulk R-410A (as one of the refrigerants over a 1,500 GWP limit) in 2030. There is no companion measure requiring the recovery of R-410A above current levels, representing another source of risk to the servicing of R-410A-based units in only seven years, or half the expected service life normally applied to VRF systems in energy efficiency calculations.

In order to service refrigerant loss in equipment, and in addition to all the process skills listed above, technicians must also have the skill and specialized equipment to detect and locate the source of the leak. Once identified, the replacement of a leaking part (such as an evaporator coil) or a leaking connection often involves all the same procedures used in installation because remaining refrigerant must be removed or “recovered” into a specialized container, the repair made, then pressure testing, evacuation of contaminants and test of negative pressure, then weighing in and providing replacement refrigerant with further leak testing. The leak servicing processes, and especially the identification of slow leaks or leaking points in inaccessible spaces within a building, are made more difficult when the line sets are longer and have more potential points of failure such as many joints and connections to many individual indoor fan coil, air handler coils, and “cassettes” (a form of fan coil) that could each be a leak source. During interviews for this project, one Southern California installation company system designer related how a large VRF system installed in a hospital had well over 1,000 linear feet of refrigerant piping and one 200-foot section had a persistent leak somewhere, month after month, since installation. Despite revisiting the installation repeatedly, the leak persisted, costing his company significant amounts of money because all such warranty work is a cost to the installer in systems with field-installed piping and connections. Unlike a common residential or small commercial split direct exchange or DX system which usually has one outdoor unit serving one indoor fan coil or other unit transferring refrigerant energy to indoor air flow and four connections for the two pipes in the refrigerant line set, a VRF system can have hundreds of connections all along its distribution system branches spanning up to 3,000 feet in line set length meaning 6,000 or 9,000 feet of total pipe.

Considering the research, the project team views a lack of any enforceable mandate to recover refrigerant from the small units that use most of the total as a general market risk and source of uncertainty in coming years to the sale and lifetime of operation of HFC-bearing HVAC equipment. With VRF systems representing the greatest risk among all system types. CARB’s R4 program does not require actual recovery of refrigerant, despite the limited prior success using economics to force reclaim of chlorofluorocarbons (CFCs) or HCFCs. Instead, the use of 15 percent recovered and reclaimed HFC refrigerant is required in the sale of new units in the interests of creating a market to incentivize recovery of HFCs. While it remains uncertain what exact response to the AIM Act by manufacturers will be, shifting to lower GWP refrigerants for VRF earlier than 2026 would allow more unit sales under a given market actor’s allocation of total HFC GWP.

Viewed in the context of California’s HFC emissions reduction requirement and CARB’s ability to add programs and regulation as needed to realize its 7.5 million MT CO2e emissions reduction, near term regulatory options include:

- Mandating the recovery of refrigerants from all HVAC units.
- Adopting the state of Washington’s approach to record keeping and leak repair requirements enforcement for units with 50 pounds of HFC refrigerants charge.
- Expanding the requirements for record keeping and leak repair for commercial HVAC and refrigeration units of less than 50 pounds charge.
- Moving the date for ending bulk sales of refrigerants over 1,500 GWP closer to present than 2030.
- Adopting IPCC AR6 values for refrigerants, triggering immediate reclassification of R-32 as above the current regulatory threshold of 750.

3) What evidence of measured third-party verified efficient heating and cooling using VRF is readily available? How feasible is it to verify VRF operating efficiency as installed? What is the efficiency in low demand conditions and how is it achieved?

KEY FINDINGS:

- VRF efficiency is promoted by manufacturers, but we found a very little data from studies of installed systems (see Appendix 3). VRF efficiency and performance claims rely on descriptions of features (e.g., variable speed inverter compressors) or the optional capability to perform heat recovery among indoor units, but with a lack of data demonstrating whether or to what extent a building might seasonally benefit from heat recovery. No party has so far been able to point us to studies demonstrating VRF efficiency being equal to or better than other inverter driven heat pumps.

- Unlike packaged heat pumps, single or multi-head heat pumps, or hydronic systems of any scale, the nature of VRF systems makes reliable measurement of their operating efficiency extremely difficult and costly to achieve. No standard methodology to measure in-field operating performance and efficiency has been identified and no field-verified datasets are available to provide the basis for modeling accuracy for VRF systems.

The project team asked Daikin, Mitsubishi, and Trane representatives along with an independent Daikin manufacturer representative if they could provide any third-party or independent reviews documenting the as-built operating performance of traditional VRF systems. No such studies were acquired as a result of these requests. Two notable studies by third parties were identified. These are reviewed in Appendix C in more detail. They confirm a reliance on estimation methods, the difficulty of measurement and verification for VRF in the field and multiple issues cited in this market analysis. VEIC is engaged with the Northeast Energy Efficiency Partnership (NEEP) under an ongoing US DOE project attempting to collect data on multiple installed VRF systems, creating direct experience with the substantial challenge of measurement and verification. There are many features inherent to VRF systems that cause this measurement and verification challenge.

4) What markets are manufacturers selling VRF into most successfully and why?

KEY FINDINGS:

To date, no manufacturer contacted has been willing to share any form of market data, which is a common, known market characteristics research barrier. However, installer and manufacturer representative interviews and VRF manufacturer marketing and training materials yielded consistent lists of market segments or “verticals” where VRF is having success:

- Hospitality
- Multifamily Residential / College Dormitories and Senior Living
- Class-A Offices and Government Buildings
- K-12 Schools
- Taller buildings in dense urban areas

Features leading to the selection of VRF systems over other options commonly cited included:

- For large hydronic-based systems using chillers for cooling, the avoided maintenance of cooling towers and chillers is regularly mentioned through use of the short-hand phrase “the chiller killer.”
- For multifamily residential, dormitories, senior living, and hospitality/hotels, the ability to individually zone living spaces or rooms is most often cited.

5) Is there readily available market data on VRF penetration from recent years to indicate future trends? Can we discern the degree to which VRF systems represent a segment of those systems with less than 50 pounds of refrigerant charge not subject to federally required HFC leak reporting and repair?

KEY FINDINGS:

There is not. As described in responses to Objective question #1, the CEC's most recent CEUS report is delayed and we have not been able to locate any other robust available primary data source, or even substantiated secondary information.

6) What technology, if any, could be applied to reduce net leaks of refrigerant in new or existing VRF systems? Is it feasible to apply leak detection after a VRF system is installed?

KEY FINDINGS:

- The leak detection system equipment market continues to lack a truly inexpensive and no maintenance low-concentration physical leak detection solution that could be applied to VRF. In particular, the project team found that existing systems are too costly and the vast footprint of VRF refrigerant piping makes current third-party systems infeasible for VRF.
- What refrigerant leak detection technology is available varies to serve three segments: ○ Life Safety type leak detection has a high-threshold based on potential human asphyxiation before sounding any alarm due to high-concentration leaks. This detection type can be required in certain building types, notably hotels.
    - Example: Bacharach MVR-SC Gas Detection system provides physical gas detection at levels that provide life-safety alarms indicating accumulating refrigerant within a space from up to 100 sensors to one central controller.
    - Equipment Shut-off Interlock is triggered by lower concentration leaks within the main equipment cabinet. The advent of A2L refrigerants is driving manufacturers to include leak detection sensors to shut-off and interlock leaks near the compressor and accumulator, but these are not a system appropriate for other applications.
    - Low Concentration Leak Detection systems consist of two options:
        - Physical air sampling type systems provide low-concentration detection and alarms early enough to prompt repairs before catastrophic refrigerant loss, such as for commercial refrigeration.
        - Software-based system condition monitoring types, which are also available for commercial refrigeration systems. These systems use anomalies and trends analysis to predict or identify refrigerant leaks.
- In the EU market, but not the US market as of May 2023, a VRV leak detection system was introduced that is of this software-based type of system. Publicly available information on this system contrasts its ability to detect refrigerant losses as "low" as 33 percent of total charge versus other systems 50 percent of total charge loss within an entire VRV system before an alarm is triggered. If this becomes available in the US market, it seems an important development as the first manufacturer-offered leak detection effort (Daikin 2022).

Commercial refrigeration is a large segment of the equipment base using high GWP HFC refrigerants, including the application of low-concentration physical leak detection systems. All the same refrigerant management issues exist in HFC refrigerant-bearing commercial refrigeration equipment, however there are fully commercialized and high-performing alternative equipment that use ultra-low GWP R-290 (propane) and CO2 itself, which have GWP of less than 0.2 and 1 CO2e, respectively. This report does not review refrigeration equipment and therefore does not address total HFC emissions from refrigerant-bearing equipment.

Notably, the CARB regulation of HFC refrigerants applies to commercial refrigeration and achievement of targeted net reduction of HFC emissions may expand efforts to apply leak detection to more large commercial refrigeration systems. These are underutilized in the refrigeration sector due to the complexity and expense of maintenance for physical systems. The high value of food loss when refrigeration systems leak and lose cooling capacity maintains customer interest and some investment in physical systems. Because the relationship of energy efficiency and cooling capacity is relatively linear in commercial rack refrigeration system footprints are manageable, VEIC has found success in their use applied in leak detection and repair programs, yielding kilowatt (kW) and kilowatt-hour (kWh) savings and GHG emission reductions. That linear relationship of refrigerant loss to capacity loss led to several software-only systems monitoring solutions that have some track record of avoiding catastrophic losses by predicting events.

Relative to VRF, we asked equipment manufacturers if their communications and data management inherent to their systems could be adapted to similarly predict refrigerant leaks based on system operation profiling or even detect leaks in progress. This question requires further investigation, but the early response from Mitsubishi at the sales engineering level is that this is not possible. In addition to Mitsubishi’s perspective, our review of the application of available physical leak detection systems to VRF was quickly abandoned: existing systems are too costly and the vast footprint of VRF refrigerant piping makes current third-party systems infeasible for VRF.

7) What is the technology roadmap for reducing the GWP of refrigerant and/or amount of refrigerant in VRF systems? Can the potential points of failure that cause leaks be reduced in number?

KEY FINDINGS:

- VRF systems core features relate to managing the flow of relatively larger amounts of refrigerant (vs. other DX systems) per capacity ton across a large area within the conditioned space through a connected piping network. The project team has not been able to identify a technology roadmap pathway that would allow an even lower GWP refrigerant to be used than the R-32 and R-454B systems used outside the US and anticipated in response to the AIM Act and CARB regulation. While new solutions may be developed relative to using an ultra-low GWP refrigerant, our research shows that the path available to small, distributed units—namely any A3 or R-290 specifically—seems unlikely to be available to traditional VRF due to large refrigerant volumes and large piping systems within occupied spaces. However:
    - It is possible that HVRF would have a path to using A3 ultra-low GWP refrigerants, but the current regulatory landscape makes this a low likelihood.
    - For applications where VRF is desirable, HVRF achieves a meaningful level of reduced total GWP per capacity ton.
- Manufacturer representatives that the project team spoke with explained that Trane, Mitsubishi, and several others (Johnson Controls 2021) chose the lower-GWP A2L refrigerant R-454B as the best alternative for most of their next-generation products, including HVRF systems, to be sold in the US through Mitsubishi Electric Trane US (METUS). Trane is in the midst of a years-long

> evaluation process to investigate which lower-GWP refrigerants might be appropriate for various equipment types to succeed R-454B in future.

Mitsubishi’s Matthew Blocker, HVRF Product Manager, confirmed that neither VRF nor HVRF outdoor units using R-410A could be updated to use R-454B, nor could the next-generation CARB-compliant R-454B outdoor units be used while retaining the previous R-410A branch circuit controllers or indoor units because of the difference in refrigerant behavior, equipment certifications being specific to each refrigerant and ASHRAE Standard 15 and 34 considerations being changed by the new refrigerant. Mr. Blocker noted, “For example, the A2L classification of 454B means the new outdoor units have vented cases that won’t pool any refrigerant inside and the previous ones aren’t vented; we didn’t need that before” (Blocker 2023). The project team asked whether any part of an HVRF system could be retained in a switchover from R-410A to R-454B; he explained that the outdoor and circuit controller section would have to be new units and hydronic piping downstream from the circuit controllers could likely be reused. In traditional VRF, “a refrigerant change is changing the whole system most likely.”

The project team’s research found that Daikin is not only the originator of the VRV approach and largest manufacturer globally in the segment, but also produces its own R-32 refrigerant for its equipment. Other equipment manufacturers do not also make refrigerant. Daikin did not respond to our questions to date. In its published refrigerants policy Daikin states its conclusion that R-32 is “the best choice for lowering GWP” and discounts the prospect of other refrigerants being suitable to existing equipment types (Daikin 2020).

In California, the A2L classification of R-32 and R-454B has triggered a need to revise codes and standards to allow their use in HVAC and refrigeration equipment, as explained in CARB’s rulemaking: “The term “Codes and Standards” is industry speak for a combination of safety standards and building codes that govern the safe use of appliances and systems in buildings (CARB 2020a).” The net result of the conflict of CARB’s GWP limit and California’s Codes processes was CARB granting an extension in time for compliance: “… the California Building Code is anticipated to be finalized in 2023 and released by January 1, 2024, with an effective date of July 1, 2024, in advance of the 2025 deadline for AC equipment. VRF equipment has a compliance date of January 1, 2026, which is aligned with the effective date of the next California Building Code update, following the July 1, 2024, update” (CARB 2020b).

8) Do we need VRF to electrify California buildings? What alternative technologies or applications of HVAC systems to California buildings could offer a potentially lower use of high GWP refrigerant or easier “future-proofed” transition to lower or ultra-low GWP refrigerant based heating and cooling?

KEY FINDINGS:

The VRF approach has features that can simultaneously be considered advantages in some respects such as design and purchasing convenience and disadvantages in others such as relative value to reducing total embodied and operating carbon equivalent emissions. The project team’s review of system features common to traditional VRF and HVRF, as well as those features HVRF improves upon, corroborates the refrigerant leaks risk posed by traditional VRF. Given potential further CARB action and unknown availability of reclaimed R-410A beyond 2030 that will be necessary to maintaining VRF that has leaked, the presumed measure life of R-410A based VRF has come to be at risk. As a result of this risk and the lack of data and third-party evaluations demonstrating claimed energy efficiency in as-built systems in occupied buildings, VRF energy efficiency incentives may be an unwarranted investment of ratepayer dollars. Additionally, VRF is likely not needed to electrify California buildings given alternative heat pump and heat recovery equipment options. The Total System Benefit metric should be revised to distinguish the refrigerant burden of alternative HVAC more clearly by taking VRF out of the "Unitary" category in the ACC Calculator for all VRF larger than 60,000 British Thermal Units (Btu) capacity.

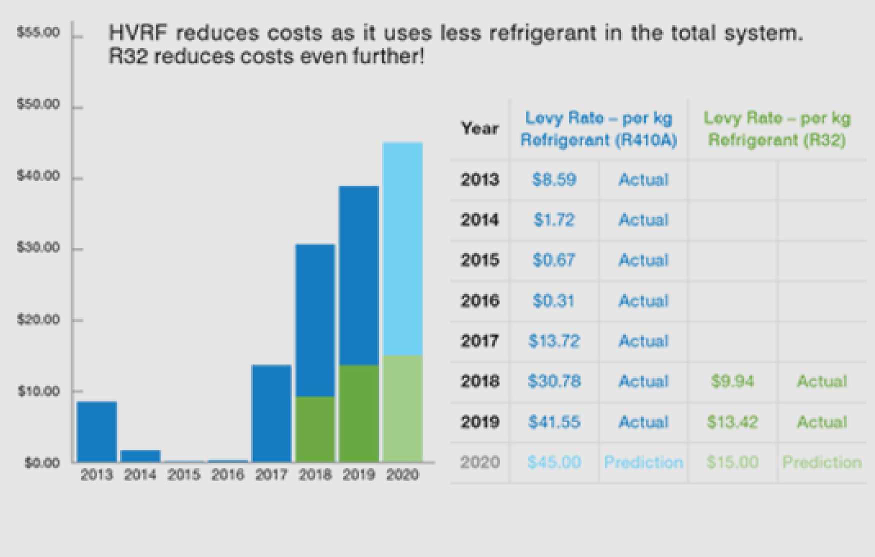
Additional findings include:

- From a technology roadmap view relative to refrigerants, existing or new large systems designed around hydronic two-pipe or four-pipe distribution are durably future-proofed, according to an expert HVAC consulting engineer and a manufacturer engineering product manager interviewed for this report. More specifically, large systems (over 300 tons) were dominated by piping systems carrying water and ductwork carrying air as the default HVAC design approaches until the advent of larger VRF systems. The source of heating or cooling can be removed and replaced with a different, more efficient, or lower-GWP source at any time and does not need to be from the same manufacturer as other components such as indoor piping or terminal fan coils and air handler units because water separates those components.
- The recent manufacturer effort to market Mini-VRF as a desirable alternative to other heat pump application approaches seems well established. This report’s refrigerant estimation work identified the overwhelming share of existing refrigerant deployed in Central AC systems in single family residences that will need to be replaced by heating-capable heat pumps to meet California’s decarbonization targets. This raises the importance of examining whether shifting market share to residential Mini-VRF could have negative impacts relative to meeting California’s targeted HFC reduction goals, whether those impacts are significantly different from the total line set lengths of multiple single-indoor or multi-head DX heat pumps, and potential refrigerant emissions reductions from air-to-water heat pumps as an hydronic distribution alternative that eliminates field-made refrigerant line connections and field added refrigerant. This area bears further examination.
- For large systems with existing hydronic distribution and boilers for heating and chiller/cooling towers for cooling, VRF is not necessary or necessarily desirable. The expanded offerings of air-to-water heat pumps—10- to 30-ton capacity range for modular and up to 270-ton capacity non-modular—allow a lower-refrigerant-per-capacity-ton option that can eliminate or minimize the use of both boilers and cooling towers while preserving existing emitters. As future versions of these heat pumps using lower or ultra-low refrigerants become available, the current R-410A versions can be unbolted and replaced. Overall embodied carbon should be lower when the interior renovation of removing and replacing refrigerant piping and emitters is avoided by the use of hydronic distribution with a service life that can double the expected life of VRF systems, and all sources of heating/cooling and emitters of heating/cooling can be replaced as needed independent of each other.
    - Heat recovery chillers and water-to-water heat pumps can also be employed to increase hydronic systems’ cooling capacity and produce domestic hot water or heating.
    - Applying low-concentration threshold leak detection local to heat recovery chillers or water-to-water heat pumps located indoors is clearly feasible, though not common currently.
    - With all refrigerants contained in only factory-made circuits at outdoor modular or large unit heat pumps within a limited area, leaks are far less likely than in VRF systems containing

dozens or hundreds of field-made piping joints, the feasibility of applying low-concentration leak detection to prompt repairs is higher but unproven in the field. Additionally, occupant exposure potential is eliminated because all refrigerant is outdoors, allowing their technology roadmap to potentially include near-zero GWP A3-classed refrigerants such as R-290.

- HVRF systems incorporating hydronic distribution replacing most of the length of a traditional VRF systems refrigerant piping and reducing total refrigerant charge by up to 20 percent with no loss in efficiency was developed in response to taxes on refrigerant use and regulation or high GWP elsewhere in the world and reduces all the identified refrigerants leak risk and charge size as well as ASHRAE Standard 15 occupant-safety application considerations.
- The need for dedicated outside air systems (DOAS) to provide ventilation with attendant need for ductwork distribution of ventilation air remains as either an existing pre-requisite or additional cost if using VRF systems. Such separate DOAS can be partially integrated in some VRF system indoor emitters, but the additional heat pump capacity needed to temper outside air then adds to the total refrigerant and refrigerant piping needed, thus adding points of failure and potential for leaks relative to other rooftop DOAS central units.
- Distributed small, packaged heat pump equipment that incorporates ventilation, especially those incorporating heat recovery cores are an emerging technology now available from significant manufacturers:
    - Heat-pump only RTUs from the leading manufacturers of traditional gas furnace/packaged AC RTUs creates a ready path for eliminating fuel combustion in most existing commercial systems. A literature review showed that these tend not yet to incorporate inverter driven compressors but do have other energy efficiency features such as variable speed fans and economizers. Further development to increase the efficiency of such units could have a large impact on creating simple conversion to electric heating and cooling. Lower-GWP versions using R-454B and R-32 are required under CARB regulation one year sooner than VRF.
    - New “through-wall” inverter-driven heat pump packaged unit ventilators with nominal cooling from 7,000 Btu/h to 36,000 Btu/h cooling capacity could be an important market development brought forward primarily for commercial applications in direct competition to VRF. These eliminate the need for field installed refrigerant piping connections and addition of refrigerant charge, are small enough to have already been demonstrated as near-zero R-290 units in one case and are commercially available using R-32.
    - For commercial applications with zone diversity that requires simultaneous heating and cooling, the use of distributed packaged heat pumps of either RTU or through-wall design can satisfy this need. The incremental efficiency of optional heat recovery VRF systems is logical, but the project team found no data to support the efficiency claims during those hours of the year where the demand occurs.

A MARKET RESPONSE: “HYBRID VRF” BY MITSUBISHI / MITSUBISHI ELECTRIC TRANE US (METUS)



HVRF reduces costs as it uses less refrigerant in the total system.
R32 reduces costs even further!

Year	Levy Rate – per kg Refrigerant (R410A)		Levy Rate – per kg Refrigerant (R32)	
2013	$8.59	Actual		
2014	$1.72	Actual		
2015	$0.67	Actual		
2016	$0.31	Actual		
2017	$13.72	Actual		
2018	$30.78	Actual	$9.94	Actual
2019	$41.55	Actual	$13.42	Actual
2020	$45.00	Prediction	$15.00	Prediction

Figure 10: HVRF costs by year.

Outside the US market, the global manufacturers of VRF equipment have been contending with government actions to reduce the volume of refrigerants used and their GWP per pound for at least a decade (Inside the Blueprint 2021). For example, New Zealand taxes the amount and GWP of HVAC refrigerant under a net GHG impact scheme that is cited as a motivator to reduce charge and use lower GWP refrigerant in HVRF literature (Mitsubishi 2019). The New Zealand Emissions Trading Scheme (ETS) has put a price on GHG emissions and provides an incentive to reduce emissions and promote strategies to absorb CO2. “This is known as the SGG (Synthetic Greenhouse Gas) Levy. Due to the increasing cost of refrigerant associated with the ETS Synthetic Greenhouse Gas Levy (NZ), building capital and maintenance costs will continue to climb using traditional heating and cooling systems that utilize higher GWP refrigerants such as R410A” (Mitsubishi 2019).

Daikin developed its VRV approach in 1982, and it sometimes referred to the system as a “multi air conditioner” (initially, it was cooling only) because the managed direct flow of refrigerant to and among distributed inside terminal units was the key innovation that made the approach workable (Daikin 2008). Traditional VRF systems deliver and return refrigerant to each “terminal” FCU and normally have at least one such FCU either within an occupied space or connected via relatively short ductwork. Bringing refrigerant into or very close to occupied space meets the ASHRAE Standard 15 definition to be considered “high probability” systems. Notably, this can be true of packaged RTUs, split DX units, and through-wall “all in one” units as well as VRF and HVRF, all to different degrees. As a result, HVAC system designers must apply further calculations to determine how much refrigerant could be introduced to what volume of occupied space to establish a room concentration limit and apply that to each room served by the system. Volume 37-1 of Trane’s Engineers Newsletter reviews application of ASHRAE Standard 15 to various system types by example: “Switching to a VRF system generally changes both the refrigerant charge and the volume available for dilution. In a typical VRF system, each room is served by a terminal unit located in the room. All of the terminal units are connected to the condensing unit and each other using either a loop of refrigerant lines or a header system. The refrigerant contained in all the lines must be included when determining the total system refrigerant charge (Trane 2008). A Mitsubishi

VRF trainer clarified: “if a circuit leaks, the circuit controller does not know to shut down that circuit, so maintenance is required to detect and repair leaks” (Korman 2022). HVRF limits the refrigerant present to a much shorter trunk circuit between the inside controller and outside heat exchange units. By using only hydronic distribution beyond the Hybrid Circuit Controller most of the building’s occupied spaces do not suffer any risk of exposing occupants to refrigerant and the total refrigerant required is reduced by ”15-20 percent” according to HVRF Product Manager, Matthew Blocker (Blocker 2023). A further contrast is made in this report to packaged RTUs and packaged through-wall unit ventilators located within the room: in respect to ASHRAE Standard 15, these systems have lower charge sizes per ton of capacity by definition because the refrigerant circuit is entirely within the unit itself and therefore shorter than either VRF or HVRF but must meet the same ultimate concentration limit standard for occupant safety.” VRF systems are always going to have more (refrigerant) charge per ton than other system types,” Mr. Blocker noted.

The project team interviewed commercial installers of VRF, a Daikin equipment distribution and training provider, and Trane and Mitsubishi representatives and product managers to ask a series of market and technology questions regarding VRF, HVRF, and other competing hydronic heat pump approaches. We also interviewed independent specifying engineers, all of whom have extensive measurement and verification experience. Further information on the application of these technologies came from METUS’s VRF/HVRF design software training certification and online training webinars by Carrier, Trane, and Mitsubishi as well as marketing materials, data sheets, and installation guides by these and other major manufacturers including Johnson Controls, Inc./Hitachi, LG, Samsung, and Gree. Approximately two dozen manufacturers produce some range of VRF equipment globally.

We also completed a review of system features common to traditional VRF and HVRF, as well as those features HVRF improves upon, which corroborated the refrigerant leaks risk traditional VRF poses and given potential further CARB action and unknown availability of reclaimed R-410A, the viability of VRF as an appropriate technology for decarbonization of buildings or energy efficiency incentives. The VRF approach has features that can simultaneously be considered advantages in some respects such as design and purchasing convenience and disadvantages in others such as relative value to reducing total embodied and operating carbon equivalent emissions.

DOAS REQUIRED TO UTILIZE VRF / HVRF—DUCTWORK IS NOT ELIMINATED

Tom Dowling, Vice President of Mitsubishi Electric Trane US noted: “VRF technology around the world has been very popular. It’s become more popular in the United States over the past 20 years or so and the reason is the efficiencies are very high, the installations are simpler because you’re running refrigerant lines rather than a lot of duct work in the building, and it actually gives the building owner more space to operate” (Inside the Blueprint 2021). While it is true that ductwork is more voluminous than either refrigerant or water piping, building HVAC systems with primary space conditioning from either VRF or HVRF nearly always include some ductwork to distribute air downstream from air local air handling units and many also must include additional ductwork as part of either a separate or VRF-integrated DOAS system to meet ventilation requirements. Importantly, a VRF + DOAS approach can allow HVAC designers to avoid the largest “trunk” ductwork lines required by other systems and potentially some amount of ductwork fire dampers. Without large trunk ductwork, floor-to-floor heights due to ductwork can sometimes be reduced, allowing more floors in a tall building’s total height limit. VRF marketing typically does not recognize the fact that HVRF makes evident: hydronic and refrigerant lines both avoid increasing floor-to-floor height and a hydronic HVAC system can similarly reduce total building volume versus ductwork-only space conditioning distribution approaches.

MARKETS FOR VRF, HYBRID VRF, AND COMPETITIVE TECHNOLOGIES

This section of the report describes the markets for VRF/HVRF relative to established and emerging competitive technologies at an introductory level. Traditional VRV/VRF was developed as a commercial market offering requiring three-phase electrical power. More recently, manufacturers have introduced a version of "mini-VRF" with three-to-five-ton outdoor unit capacity powered by single-phase AC electrical supplies used in small commercial and residential properties. The project team intentionally grouped multifamily residential buildings of more than four units with larger commercial properties because these often have three-phase electrical available and are viewed by VRF manufacturers as a commercial segment. For the 1-4 family residential / small commercial market segment, single-phase VRF systems compete with all other single-phase systems, primarily:

- Gas and petroleum-fuel boilers and furnaces (oil and Liquid Petroleum Gas, LPG) ○ coupled with or without:
    - Cooling-only heat pumps, or
    - Cooling-dominant heat pumps capable of mild temperature heating, or
    - Window A/C units providing cooling only.
- Split DX systems:
    - 1:1 (outdoor coil to indoor coil) "mini-splits," either
        - singly or
        - in multiples, often one per room / connected rooms area.
    - "Multi-splits" which circulate refrigerant to two-to-five indoor FCUs through fully separate "line sets" (liquid and vapor lines as a set), each connecting directly to an indoor FCU and returning to the single outdoor unit. Of note, this "multi-split" approach is distinct from the unit-to-unit branching pipe layout or indoor circuit controller "branch box" connection of VRF systems.

Notable emerging technology competitors in the residential/small commercial market include:

- Air-to-water heat pumps and ground-source heat pumps, both of which are able to circulate low-to-medium temperature water for heating and chilled water for cooling through multiple indoor emitters including AHU's and radiant floor as well as most FCU styles utilized by VRF systems.
- "Through Window" configuration heat pumps, such as Gradient, capable of being semi-permanently mounted in part of an existing window.
- The through-wall inverter-driven compressor with variable speed fan packaged heat pump systems could be applied to this segment but are so far being marketed to larger multifamily and commercial projects with a focus on hospitality but are able to operate on split-phase 240V AC.

The commercial market for VRF spans an application range across most all building types, with the exception of Warehouse and Data Center segments. Interviewed market participants consistently mentioned Hospitality/Hotels, Multifamily, Office, Schools, and Higher Education as “vertical” market segments where VRF enjoys the most success. As a modular technology, VRF system capacity in commercial applications ranges from six tons up to well over 1,000-ton systems. For VRF and competitive technologies, very large systems in aggregate can be designed using multiple separate large systems if needed. However, the large system technology mentioned by interviewees as being incumbent is hydronic distribution to hydronic interior FCU’s and AHU’s with cooling from large chillers of 200–2,000 tons and with cooling towers to reject heat and gas boilers providing heating and dehumidification via “re-heat” coils (where air passing through an air handler is cooled to remove moisture, reheated, then cooled again for further moisture removal and final temperature conditioning). Every interviewee mentioned the term “chiller killer” to refer to a shift of market share from such hydronic systems to VRF. The primary competitive technologies in this segment include:

- Packaged single-zone air conditioning with gas furnace heating with distribution ductwork, commonly known as RTU. These typically range in size from small two to five-ton units up to 150-200 tons.
- Packaged variable air volume.
- Hydronic four-pipe distribution of heating from boilers and cooling via chillers and cooling towers.
- PTAC/PTHP through wall units, typically found in hotels with no inherent ventilation function.

Notable emerging technology competitors in commercial segments include:

- Distributed Small Unit Design Approach:
    - Small (7,000 Btu/h to 36,000 Btu/h) “through wall” configuration heat pumps such as the Ephoca duct-through-wall (Ephoca 2022) configuration and the Friedrich “VRP” rectangular duct-through-wall configuration (Friedrich 2023) intended for single rooms up to small apartments. Both of these examples inherently provide fresh air ventilation and have optional energy recovery ventilators (ERVs) for additional efficiency and capacity.
    - Heat pump only versions within several manufacturer’s RTU lines of small (two-to six-tons) packaged RTUs capable of drop-in replacement of AC with gas furnace versions (Trane 2022a).
- Centralized System Approach:
    - Smaller modular cold climate inverter air-to-water heat pumps of eight- to 20-tons cooling capacity designed to work with hydronic distribution to FCUs and AHUs and replace or supplement boilers (ATH 2023).
    - Larger (30- to 80-tons) air-cooled modular chillers with heat recovery and air-to-water heat pumps designed to work with hydronic distribution to FCUs and AHUs and replace or supplement boilers—up to ten modular roof/ground mounted units can be combined to create medium- to large-sized systems, similar to VRF (Trane 2023a).
    - Large (140- to 230-tons) single unit air-to-water heat pumps capable of replacing boilers and supplementing or replacing existing chillers in large hydronic systems of approximately 300 to over 1,000 tons (Trane 2022b and 2023b).

APPLICATION CONCEPTS DIRECTLY COMPETE FOR MARKET SHARE: DISTRIBUTED VS. CENTRALIZED

Similar to METUS executives who are citing refrigerant safety and reduced refrigerant amount used and lesser leak potential as advantages of HVRF over traditional VRF, competing emerging technologies also cite these same advantages. Fully hydronic distribution systems including four-pipe heat recovery capable systems have existed for many years. They are very common in the largest buildings, using boilers to provide heating and chillers to remove heat from "chilled water" loops providing cooling at terminal fan coils and air handler units of all the same styles used by VRF. In the centralized hydronic distribution approach to decarbonization, the piping can remain but heat recovery chillers that cool water by removing heat and putting it into hot water for heating or domestic hot water are being marketed as a solution to eliminating fuel burning boilers. A new generation of hydronic (air-to-water) heat pumps can either reject heat to the air to displace maintenance-intensive cooling towers or can pull heat from the air-to-heat water and supplement or replace boilers, sitting on a roof top or ground mechanical area as VRF outdoor units do. These competitors now offer modular small and medium capacity outdoor units that can be configured to meet many incremental capacity totals similar to VRF outdoor units. With this "heat pump on the roof" approach, an existing hydronic system and its terminal units can be preserved, and the heating decarbonized with less cooling maintenance—a direct challenge to VRF as the "chiller killer."

Similarly, VRF is the marketing target for both of the small, through-wall heat pump example competitors cited that utilize variable speed compressors and fans to offer "…single package simplicity with the combined performance of VRF and complex make up air systems, all at a lower total installed cost" per Friedrich describing their "variable refrigerant package heat pumps" (Friedrich 2022). As shown below, both Friedrich and Ephoca provide similar graphics comparing their distributed approach versus VRF.

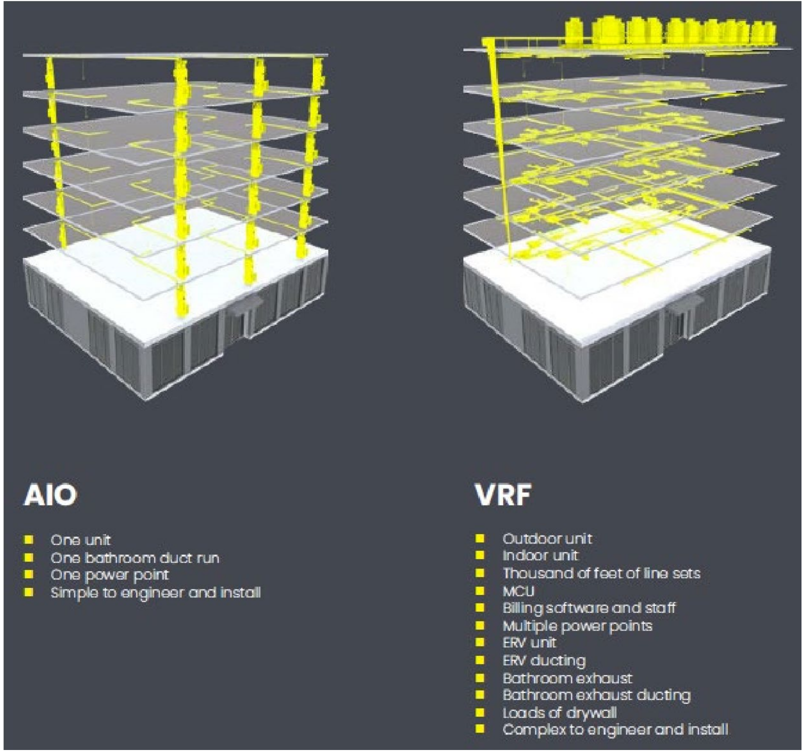


Figure 11: Comparison drawing between Ephoca all-in-one (AOI and VRF).

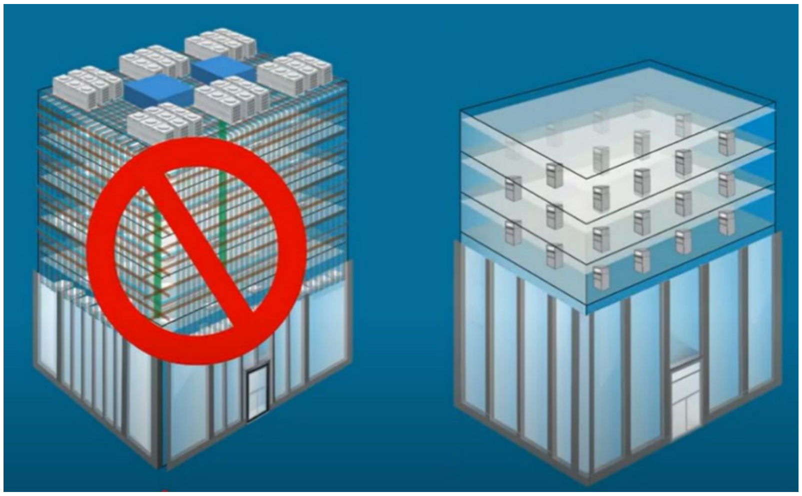


Figure 12: VRF vs. Friedrich VRP packaged units.

When significant diversity of heating and cooling needs exists within a building, VRF with correctly designed indoor zones may be able to provide incremental energy efficiency. However, it is not an inherent feature of all traditional VRF systems. With HVRF, the heat recovery capability is an inherent feature of the standard hybrid branch controller. compares the possible application of same-capacity VRF, Hybrid VRF and Distributed Through-wall system approaches to eliminating fuel combustion for heating at an example Primary School in order to illustrate topics addressed in Objectives 6, 7, and 8.

Recommendations

The California utilities should explicitly exclude R-410A-based VRF systems from their custom and prescriptive measures. Utilities should wait until after 2026 to reassess the likely lifetime of this technology once there is market experience with new VRF equipment using mid-GWP refrigerants.

Hybrid VRF represents a meaningful but small reduction in the use of refrigerant in the VRF approach, however, the reduction in system points of failure and leak potential is more significant. It remains unclear whether Hybrid VRF will prove an ultimately more durable system due to the same requirement for matched components that traditional VRF has. Until Hybrid VRF is available using mid-GWP A2L refrigerants that can be expected to be available throughout its assumed measure life, utilities incur unnecessary risk by incentivizing the R-410A version of the technology currently available.

Rationale - the energy efficiency of VRF technology as commonly installed in the field is unknown: it is not sufficiently documented and no consensus methodology for accurately verifying operating efficiency is identifiable at this time. Should the HVAC industry develop or provide such methodology and data on operating buildings in the future and the information represents a meaningful sample of the range of capacities and designs of as-installed systems, that information can be evaluated through the technical resource manual process at that time. A compounding unknown and identifiable risk to measure lifetime being shorter than normally expected is that R-410A-based VRF systems will:

- Need the most refrigerant per ton of any alternative heat pump system,
- Have the most points of failure and potential for leaks with the least ability to minimize leaks economically through leak detection, and
- Will be relying on the thus far unsuccessful attempts to increase the recovery and reclamation of a discontinued refrigerant.
- In competition for available reclaimed supply with the world's largest manufacturer of HVAC who are publicly committed to continued use of R-32 which they have publicly stated they can provide for their US customers through the reclaim of R-32 by removing R-410A from the market at the necessary ratio of 2x R-410A = 1x R-32 as component part.

The total refrigerant efficiency of alternative HVAC systems through detailed design comparisons as applied to common building types is worthy of investigation. The potential to eliminate the GHG impacts of HVAC while maintaining operating energy efficiency through the use of emerging HVAC systems able to safely use R-290 in particular would position California utilities to leverage market trends in the EU, UK, China, India and other major world markets. Recommended additional research on related markets:

- Engage RTU market leaders to understand technology roadmap for more efficient heat pump only drop-in replacement units that employ inverter-driven variable speed compressors specifically and ultimate prospect for R-290.
- Focused market study comparing costs and operating efficiency of heat pump technology and market options for replacing fuel burning HVAC systems, particularly RTUs.

A comparative analysis of the performance and refrigerant leak potential of 36,000 Btu/h to 60,000 Btu/h capacity range, single-phase multi-head split unit vs mini-VRF vs. Air-to-water heat pumps. At this capacity range, a laboratory side-by-side comparison of performance should be feasible.

Appendix 1: ASHRAE Standards 15 and 34

This Appendix provides additional insight into VRF application considerations and their applicability in California, particularly as they relate to ASHRAE Standards 15 and 34, which govern how refrigerant is classified and risk is assessed when refrigerant circuits through occupied space. Standards 15 and 34 provide essential guidance to manufacturers, design engineers, and operators who need to stay current with new AC and refrigerating requirements. Standard 34 describes a shorthand way of naming refrigerants and assigns safety classifications based on toxicity and flammability data, while Standard 15 establishes procedures for operating equipment and systems when using those refrigerants. Combined, these safety standards are used as guidance for HVAC system designers and incorporated into state and local codes. The assessment procedure they describe focuses on leaks relative to safety, however, leaked refrigerant continues on to become a SLCP emission. Determining which requirements apply to a given system is accomplished using the following three basic sorting classifications:

1) System. System classification divides refrigeration system types according to the potential of the refrigeration equipment to expose the occupants to refrigerant. By this definition, any refrigeration system with a refrigerant containing component in the occupied space, or the airstream serving an occupied space, is considered a high probability system" (Trane 2008).

2) Occupancy. Six classes of "occupancy" are defined to classify the risk of exposure to refrigerant leaking from an HVAC system which directs designers to consider hotels or hospital rooms differently from public lobbies for example.

3) Refrigerant. The third basic system sorting classification based on the refrigerant itself comes from Standard 34 which is functionally incorporated into and referenced by Standard 15.

Designers must consider the building occupancy, system type, and the refrigerant used by the system equipment—whether it is more or less toxic and more or less flammable—in order to assess whether risk to occupants has been addressed properly.

California's policy (per CARB regulation) to greatly reduce the emissions of high-GWP HFC refrigerants has changed the near-term refrigerant options for VRF and other HVAC equipment sold in the state with a mandated transition over 2023-2026 (CARB 2020). Carbon dioxide excepted, the lower-GWP refrigerants meeting the new CARB standards are either slightly more flammable or much more flammable than the high-GWP HFC refrigerants they replace. For example, the lowest GWP refrigerant that can be used in medium pressure equipment such as VRF or RTU's is R-290, a high-purity propane, with a GWP of less than 0.2 carbon dioxide equivalent (CO2e) (Stausholm 2021), but R-290 has higher flammability. Therefore, the application of ASHRAE 15 and 34 limits the amount of refrigerant that could be potentially introduced into a given air volume of an occupied room. Additionally, the change to lower-GWP with increased refrigerant flammability directly affects how and whether a given system type can be used. The net result is that the future technology roadmap for all system types is greatly affected by California's requirements to use refrigerants with lower GWP than 750.

Table 3: ASHRAE Classification of Toxic Refrigerants

Table 3: ASHRAE Standard 34 Classification of Selected Less Toxic Category A Refrigerants

ASHRAE Standard 34 (2019) Classification of Selected Less Toxic Category A Refrigerants	Refrigerant Material	GWP – IPCC 4 Currently Referenced by CARB (2023)
A3 – Flammable	R-290 High Purity Propane	3 (IPCC AR4) <0.2 (IPCC AR6)
A2L – Mildly Flammable	R-454B	466 (IPCC AR4)
A2L – Mildly Flammable	R-32	675 (IPCC AR4) 771 (IPCC AR6)
A1 – No Flame Propagation	R-410A	2,088
A1 – No Flame Propagation	R-744 (Carbon Dioxide)	1 – CO2 is GWP reference

"The current inventory uses 100-year global warming potential (GWP) values from the IPCC Fourth Assessment Report, consistent with current international and national GHG inventory practices. …
Calculation methodologies are consistent with the 2006 IPCC Guidelines" (CARB, 2023).

As noted above in this report, traditional VRF systems deliver and return refrigerant to each "terminal" FCU and normally have at least one such FCU either within an occupied space or connected via relatively short ductwork. Bringing refrigerant into or very close to occupied space meets the Standard 15 definition to be considered "high probability" systems. Notably, this can be true of packaged RTUs, split DX units, and through-wall "all in one" units, as well as VRF and HVRF, all to different degrees. As a result, HVAC system designers must apply further calculations to determine how much refrigerant could be introduced to what volume of occupied space to establish a room concentration limit and apply that to each room served by the system.

Volume 37-1 of Trane's Engineers Newsletter reviews application of Standard 15 to various system types by example: "Switching to a VRF system generally changes both the refrigerant charge and the volume available for dilution. In a typical VRF system, each room is served by a terminal unit located in the room. All terminal units are connected to the condensing unit and each other using either a loop of refrigerant lines or a header system. The refrigerant contained in all the lines must be included when determining the total system refrigerant charge (Trane 2008).” A Mitsubishi VRF trainer clarified: “if a circuit leaks, the circuit controller does not know to shut down that circuit, so maintenance is required to detect and repair leaks” (Korman 2022). HVRF limits the refrigerant present to a much shorter trunk circuit between the inside controller and outside heat exchange units. By using only hydronic distribution beyond the Branch Circuit Controller most of the building’s occupied spaces do not suffer any risk of exposing occupants to refrigerant and the total refrigerant required is reduced by ”15 to 20 percent,” according to HVRF Product Manager, Matthew Blocker (2023). A further contrast is made in this report to packaged roof top units and packaged throughwall all-in-one units located within the room: in respect to Standard 15, these systems have lower charge sizes per ton of capacity by definition because the refrigerant circuit is entirely within the unit itself and therefore shorter than either VRF or HVRF but must meet the same ultimate concentration limit standard for occupant safety. “VRF systems are always going to have more (refrigerant) charge per ton than other system types,” Mr. Blocker noted.

Appendix 2: HVAC System Comparison Exercise

Objective 8 of this report asked, “Do we need VRF to electrify California buildings?” When a new building is built or a new HVAC system is retrofitted to an existing building, the building owner, owner’s representatives (often engineers), and general and trade contractors and their vendors have a variety of options for meeting the California policy and regulatory requirements including the directive to reduce GHG emissions and building codes among other considerations. This appendix describes an exercise comparing the application of three alternative HVAC systems at a conceptual level to examine for a specific example building site what changes and what does not change if a VRF system or alternative of equal capacity is installed to serve ventilation and space conditioning needs or “loads.” In particular, the project team developed an application scenario for the compared types of HVAC systems capable of providing 100 percent of heating, cooling, and ventilation for the example Wadsworth Avenue Elementary school in Los Angeles, California. As part of this exercise, the project team:

- Calculated heating and cooling loads for varied climate zones, including Fresno, San Francisco, Sacramento, and Los Angeles.
- Described and compared the following applied systems:
  - Traditional VRF systems for each building ○ Hybrid VRF system alternative ○ Heat pump-only RTU (upper story or 1-story) and through-wall VRP packaged units (lower story)
- Compared relative total of each system’s high-GWP refrigerant.
- Estimated the points of failure and ability to have automatic leak detection applied in support of a leak-detection and repair program.

As noted earlier in this report, the project team’s review of California commercial building data suggested that among the market segments where VRF systems had higher penetration were Primary Schools and Medium Offices. The data showed 6,754 Primary Schools in California, the largest category of commercial building for which VRF retrofit would be considered likely. For this reason, Primary School was chosen as the building type for further examination. Building stock data and a visual review using Google Earth confirmed that most of the Primary Schools are either one or a mix of one and two-story buildings, usually set in a small campus arrangement with some amount of hallway or covered walkway connection between buildings.

The Wadsworth Avenue Elementary school is comprised of 11 major buildings or building segments (where a building was a mix of one-story and two-story sections) with a total of approximately 102,975 square feet.

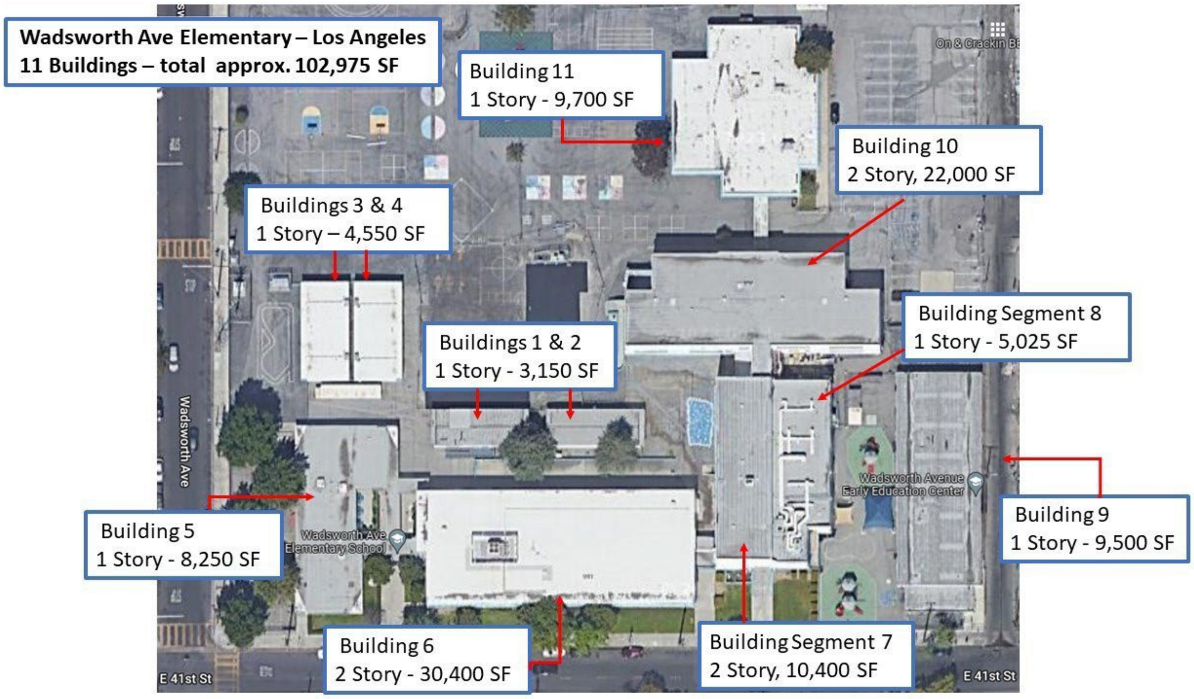


Figure 13: Wadsworth Avenue Elementary, Los Angeles. Building identification, height, and size description.

OpenStudio energy modeling was used to estimate the heating and cooling loads for the average Primary School size of 92,000 square feet and loads were calculated for four different climate zones. The modeled building heating and cooling requirements were adjusted from the average size to the actual size of Wadsworth Avenue Elementary.

Table 4: Heating and Cooling Loads for Wadsworth Avenue Elementary by Climate Zone

Climate Zone	Cooling Tons	Cooling Tons + 15%	Heating Total (Btu/hr)	Heating Total + 20% (Btu/hr)
Fresno	131	151	242,850	291,400
Sacramento	121	139	319,530	383,450
Los Angeles	108	124	90,100	108,130
San Francisco	97	112	277,760	333,310

Because the actual floor plans were not known and the number of spaces into which the building footprint was apportioned need only be kept constant across compared systems, a rough estimate of size for either a classroom or other use of equal size for a given building was applied. These individual spaces ranged from 788 to 1,733 square feet each depending on the building size. In the example shown below, a logical division of buildings Three and Four into four areas of approximately 1,137 square feet is visually confirmed by the presence of four RTUs.

Figure 14: Wadsworth Avenue Elementary space apportioning for HVAC in buildings Three and Four.

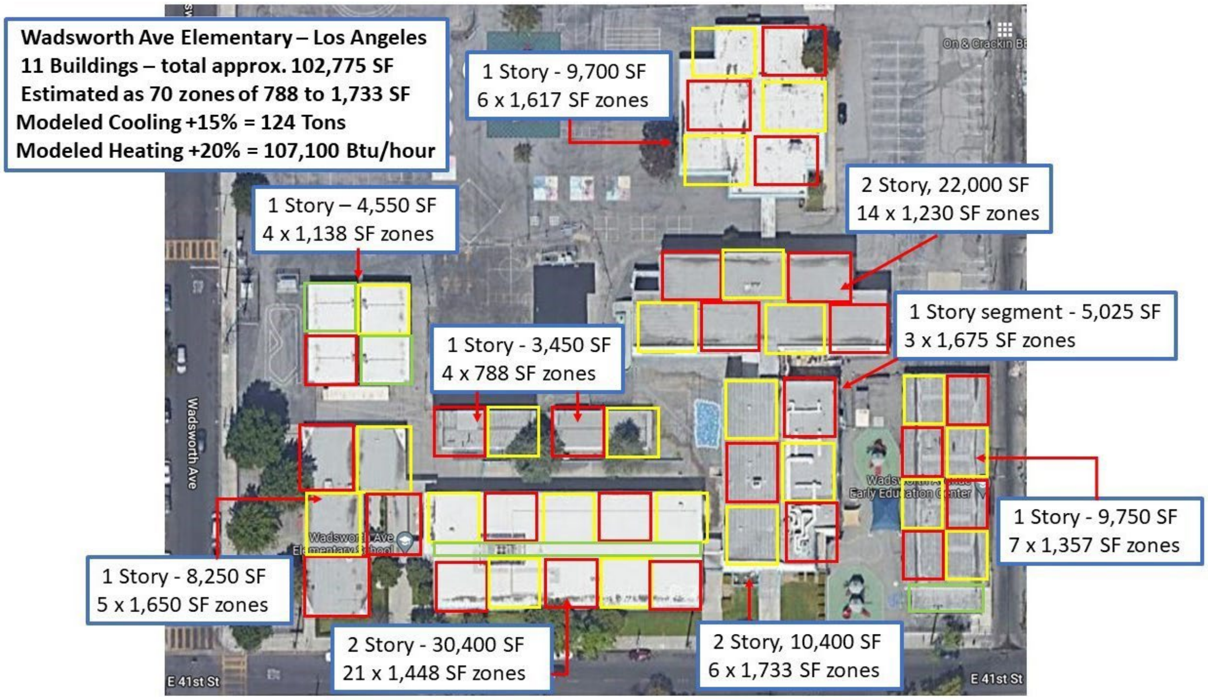


Figure 15: Wadsworth Avenue Elementary modeled heating and cooling load, space apportionment.

When both one-story and two-story buildings and building segments are accounted for the total number of interior space zones needing ventilation, heating, and cooling was estimated at 70 as detailed in Figure 15 above. In this example, there are only two purely interior zones, all 68 other zones have a primary exterior exposure that is east, west, north, or south. This implies some hours where some amount of “load diversity” among zones would require HVAC systems to provide varied amounts of cooling in the later afternoon, for example. A per square foot calculation to allocate the total modeled heating and cooling loads was applied to each space resulting in per space loads ranging from 0.93 to 2.06 tons. As a result, the alternative system scenario was based on 1-ton and 2-ton units. In the case where a zone might have two spaces that could not share ductwork and air distribution, the exercise presumes that two or three smaller Ephoca through-wall units with variable capacity rated at nominal 8,500 Btu cooling could be substituted for a single 2-ton unit shown in the system overview.

The alternative system applied in this exercise provided each zone with an individual packaged unit capable of providing fresh air ventilation, heating, and cooling using heat pump only:

- For larger interior first-floor spaces, a 2-ton RTU connected to a short ductwork run to circulate air through the space via distributed supply and centralized return to the RTU.
- For smaller first-floor spaces or north-exposure-only spaces, a 1-ton Friedrich VRP unit was used.
- For larger and south-facing first-floor spaces, a 2-ton Friedrich VRP unit was used.

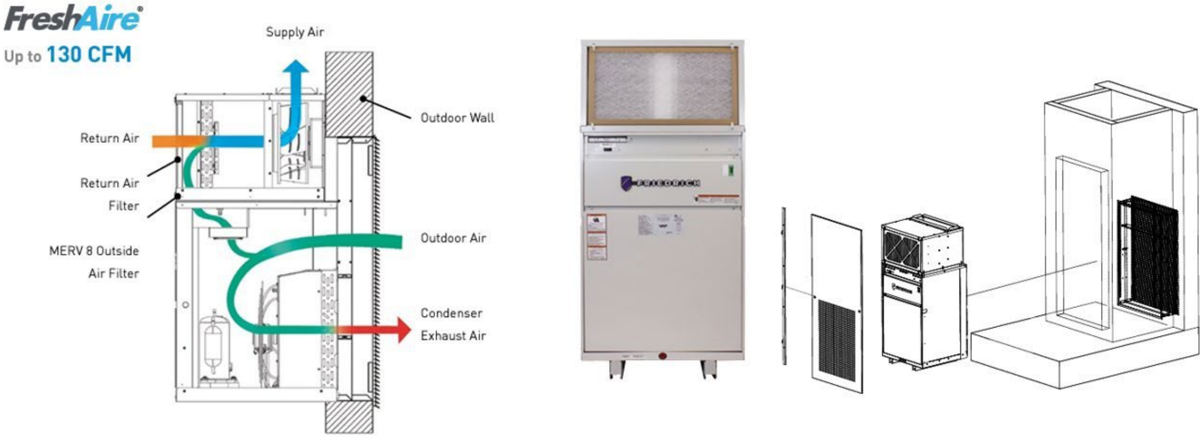


Figure 16: (left to right) Schematic of air flows and components of Friedrich VRP, the image of the unit front, installation diagram showing louvered door, VRP unit, concealment closet, and through-wall ventilation connection.

As noted by Daikin’s Rusty Tharp and Nathan Walker, the use of variable-speed compressors is common globally outside the US and can create more refrigerant efficiency in a heat pump design versus single- or two-stage compressors coupled with larger refrigerant-bearing coils (Daikin, 2023). The alternative system uses inverter-driven variable speed compressors wherever possible and RTUs elsewhere. There is a significant market gap in that commercial buildings needing a “drop-in” replacement of RTUs with heat pump-only models that provide low-ambient heating do not have ready options comparable to residential heat pumps, meaning full capacity heating to 5 degrees Fahrenheit and efficiency in refrigerant use and operating electricity use via variable speed compressors. Traditional and Hybrid VRF systems use variable speed compressors and more refrigerant-efficient coils. However, the nature of VRF is to have fewer compressors in fewer outdoor units connected over much longer refrigerant-bearing piping systems to a given number of indoor coils, resulting in a net loss of refrigerant efficiency.

Alternative system features include:

- No separate DOAS is required, which means no additional refrigerant or heat pump capacity to meet code ventilation requirements.
- Friedrich VRP unit:
    - No impact to building exterior or roof beyond opening for outside air similar size to a small window (W x H = 13.5” x 25”)
    - R-410A, factory sealed charge, no field installed piping or refrigerant for 0.6-ton = 1.94 lbs.; 1-ton = 3.12 lbs.; 2-ton = 4.25 lbs.; 3-ton = 7.8 lbs.
    - Minimal ductwork can be fitted as needed to distribute airflow supplied to the room(s) served, and can be fitted in a small closet
    - Inverter-driven variable speed compressors operate from 40 percent to 120 percent of rated capacity to match output to space demands
    - Low-ambient heat pump operation down to 0 degrees F
    - Humidity control via on-board sensors and humidistats and re-heat coil
- Ephoca “All-In-One" AIO through-wall packaged unit:
- No impact to the building exterior beyond two 8” round louvered openings for supply and exhaust airflow
    - R-32 or R-410A currently available, for 0.75-ton unit refrigerant charge (R-410A) =
    - 1.375 lbs.
    - Near-zero GHG R-290-based units in testing in the EU; small charge size meets IEC standard currently.
    - Inverter variable speed compressor
    - Cooling range 3,400 – 15,000 Btu per hour, 8,500 nominal (excluding optional ERV)
    - SEER 15 ○ Heating to 5 degrees F with COP of 1.83; at 13 F, COP is 2.09 (heat pump only, excluding ERV)
    - Optional ERV adds Btu capacity ○ Minimal ductwork can be fitted as needed to distribute airflow supplied to the room(s) served
    - Per image below right, right to left: can be fitted in a small closet, on a wall in a vertical or horizontal console, or on the ceiling as ducted/enclosed or on-ceiling package to eliminate floor space demand

Figure 17: Ephoca AIO through-wall unitary packaged HVAC unit shown with ERV.

One of the purposes of the system comparison exercise was to determine whether the example Primary School heating and cooling loads could be equally served using a distributed packaged unit HVAC approach. A visual review of several dozen primary schools in San Francisco, Fresno, and Los Angeles confirms that school floor plate dimensions are consistently narrow enough to provide exterior walls to most indoor spaces. The visual review also identified that RTUs seem to be one of the most common existing HVAC approaches, implying that ductwork and roof curbs are available for reuse in many HVAC retrofit projects, unlike the example Wadsworth Avenue Elementary school. This means a large market need for low-GWP or R-290-based variable speed compressor “drop-in” replacement RTUs to provide a non-fuel combustion alternative when existing gas furnace/air conditioning R-22 and R-410A RTUs reach end-of-life or early replacement.

Figure 18: Example of RTU HVAC visible on many California schools, including River Bluff Elementary and Rio Vista Middle School, Fresno, California

Like most California climate zones, the example school's modeled design load is cooling-dominated, and the exercise used a "cooling + 15 percent" load estimate to account for increasingly hot ambient conditions due to climate heating. Wadsworth Avenue Elementary's targeted capacity was 123 tons or 1.19 tons per 1,000 square feet. As visualized below in Figure 19, the alternative HVAC approach shows a total of 125 tons capacity or 101.6 percent of the targeted capacity. One 2-ton RTU is included to address a presumed center hallway space on each floor of the two-story building 30,000 square-foot largest building. Otherwise, a presumed logical distribution of 2-ton Friedrich VRP units is supplemented by 1-ton VRP units in the smallest buildings and some north and east-facing first-floor spaces with presumed lower solar gain.

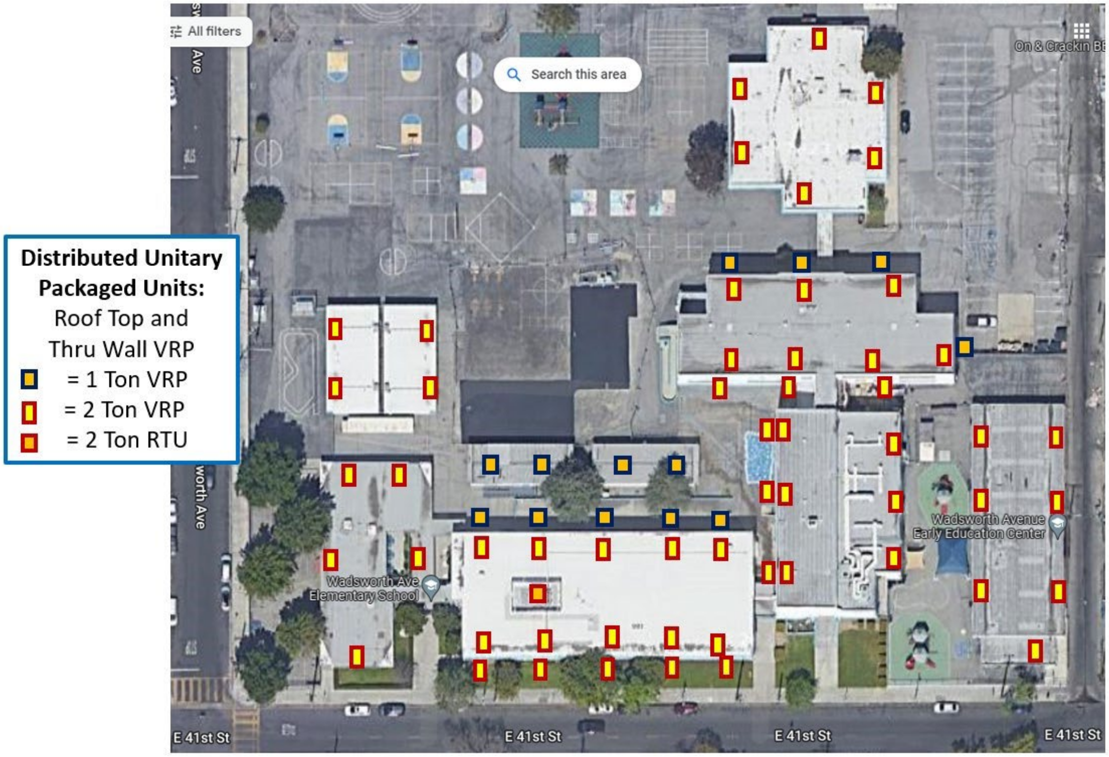


Figure 19: Wadsworth Avenue Elementary distributed unitary packaged units.

For the traditional VRF and Hybrid VRF systems, capacity is driven by the outdoor units' total capacity, which would be the same in both cases. Hybrid VRF uses the same outdoor units as Mitsubishi or Trane's other VRF systems and would require the same capacity of Hybrid Branch Controllers providing distribution via water loops as Circuit Branch Controllers providing distribution via refrigerant piping. Figure 20 shows a comparable capacity VRF scenario applied to the same buildings with as close a match to modeled loads for each building as the available VRF outdoor unit sizes allow. The total shown is 126 tons capacity for the VRF systems or 102 percent of the targeted capacity. The smallest buildings are too small for commercial 3-phase VRF, necessitating the use of single-phase units available in a 3-ton capacity. This campus overview does not show the indoor distribution piping and indoor terminal FCU.

One of the advantages of the VRF approach at this conceptual application stage is that it is valid to assume that each separated space can be supplied with a terminal FCU appropriate to the heating and cooling loads in that space within the constraints of life-safety requirements imposed by ASHRAE Standards 15 and 34 (see Appendix 1), which can limit the ability to apply VRF to small occupied rooms in some situations because of the potential for larger amounts of refrigerant to be leaked into that space. The alternative distributed HVAC approach must also conform to the requirements of these standards. Still, the potential to asphyxiate occupants is limited because the charge size available to any given room is limited to that within the relatively small individual unit within the room—no refrigerant piping and larger volume from elsewhere in the building must be accounted for in a distributed unit approach.

A significant disadvantage of both VRF and Hybrid VRF systems that is acknowledged but not detailed in this exercise is that a separate DOAS that requires additional refrigerant, additional outdoor unit capacity, additional indoor DOAS units, substantial amounts of ductwork, and some wall /roof penetrations must be accounted for. Therefore, the as-shown VRF and Hybrid VRF capacity is understated, but the alternative HVAC system's ventilation needs are presumed to be addressed because ventilation is inherent in the equipment.

In a retrofit conversion from an existing RTU-based HVAC system, because the VRF system does not have inherent ventilation, it is reasonable to presume existing ductwork would need rework or abandonment for a DOAS system with new ductwork to provide the code-required ventilation. Despite the treatment in VRF marketing literature, VRF systems either require new ductwork for DOAS or rely on existing DOAS ductwork for ventilation. For a retrofit from RTUs using primarily through-wall heat pump units as presented above, existing RTU ductwork could be removed or abandoned, and some new ductwork to extend ventilation to interior spaces can be presumed. Alternatively, some interior spaces might require small-area DOAS. In any case, it is reasonable to assume the through-wall units serve the bulk of ventilation needs. If a new generation of heat pump only low-ambient heating capable RTUs become available, many commercial buildings would be able to essentially reuse existing ductwork and decarbonize with similar efficiency to the alternative through-wall-based HVAC system presented here.

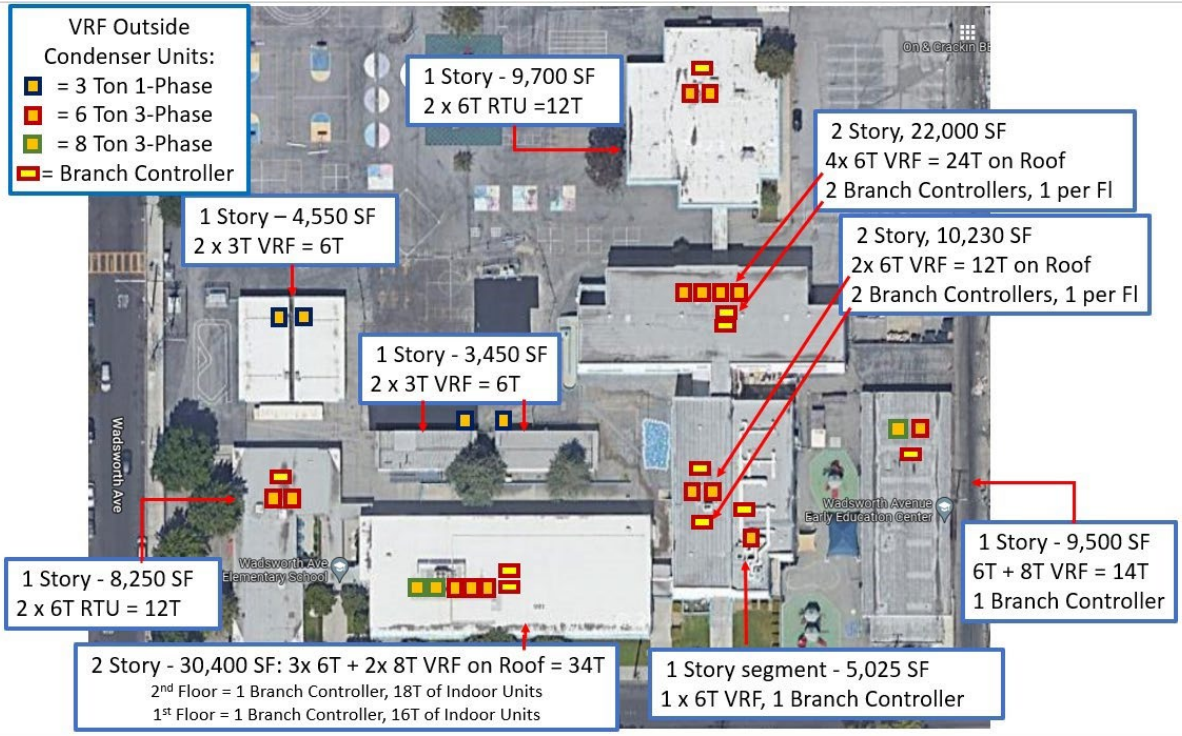


Figure 20: Wadsworth Avenue Elementary VRF outside condenser unit capacity by building/segment.

Even without a detailed design, the large differences among these compared systems allow the relative number of points of failure and required distribution of refrigerant-bearing piping across a building to be readily evident. Figure 21shows the location of a single-story building of less than 10,000 square feet used in the following comparison showing the interior features of each system. In all cases, the bulk of the thermal demand is at the perimeter of the building.

Figure 21: Wadsworth Avenue Elementary location of comparison building.

The VRF and Hybrid VRF systems shown in Figures 24 and 25, respectively, similarly employ a centralized location for the two 6-ton roof-mounted outdoor units and a Branch Circuit Controller or Hybrid Circuit Controller respectively located above a hallway ceiling or in a mechanical closet relatively close to the outdoor units. In the traditional VRF system, the bulk of the total refrigerant charge is contained primarily in the outdoor units, the inside Circuit Controller, and the larger diameter piping connecting them, while generally 20 percent or less of the total charge is contained in the smaller diameter refrigerant piping to the indoor terminal units.

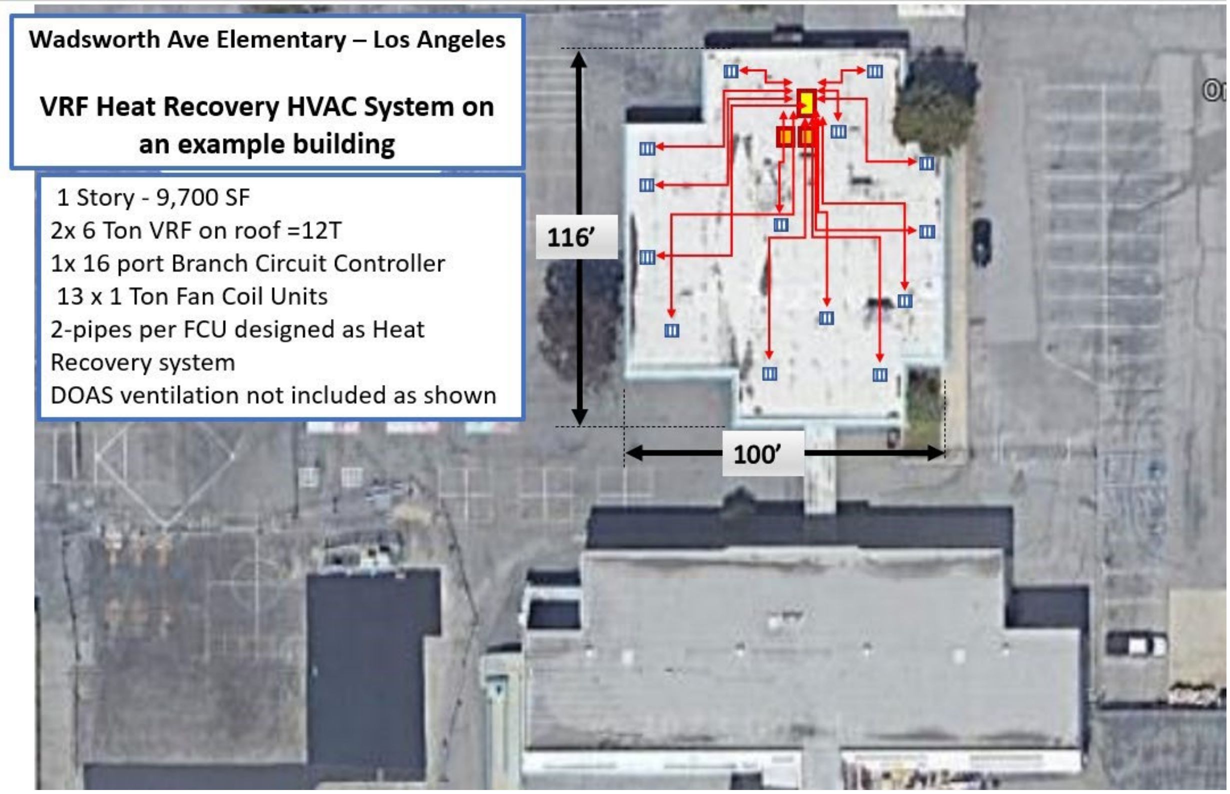


Figure 22: Wadsworth Avenue Elementary VRF heat recovery HVAC system on example building.

In the Hybrid VRF system, the piping connections between the Circuit Controller and indoor terminal units and the coils in the terminal units are all hydronic, which would be expected to eliminate refrigerant leak potential from all this piping length regardless of the relative number of joints in any design. However, the total refrigerant charge is reduced by no more than 20 percent, and the total refrigerant charge per ton would be expected to be more than the through-wall packaged units. (Blocker, M. 2023). The hydronic distribution piping in Figure 23 is shown in blue (versus red in Figure 22) to denote this distinction between the traditional VRF and Hybrid VRF, while the large diameter main circulation refrigerant lines between the inside Circuit Controller and outdoor units are not shown.

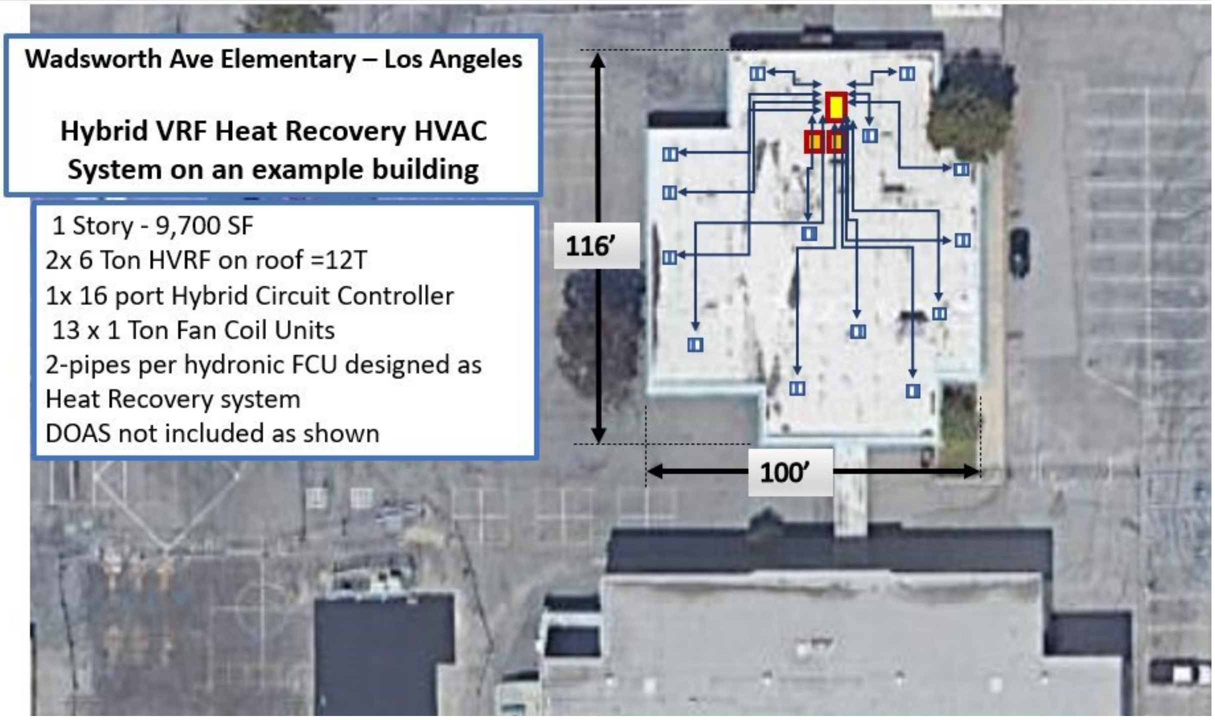


Figure 23: Wadsworth Ave Elementary Hybrid VRF heat recovery HVAC system.

In traditional VRF, the application of leak detection is problematic due to the expense and limited lead detection sensitivity as well the very large piping footprint that would have to be covered. If, at some point the various VRF manufacturers introduced something like the Daikin OnSite leak detection software in the US market, that would be an improvement even though that offering seems to be unable to detect leaks of less than 33 percent meaning before at least a significant percentage of total charge has already leaked (Daikin 2022). By contrast, the much-reduced refrigerant line length and building footprint occupied by refrigerant lines necessary for Hybrid VRF raises the prospect of relatively less expensive application of physical sensing automatic leak detection. To date, Mitsubishi has yet to indicate a software-based solution to leak detection is forthcoming.

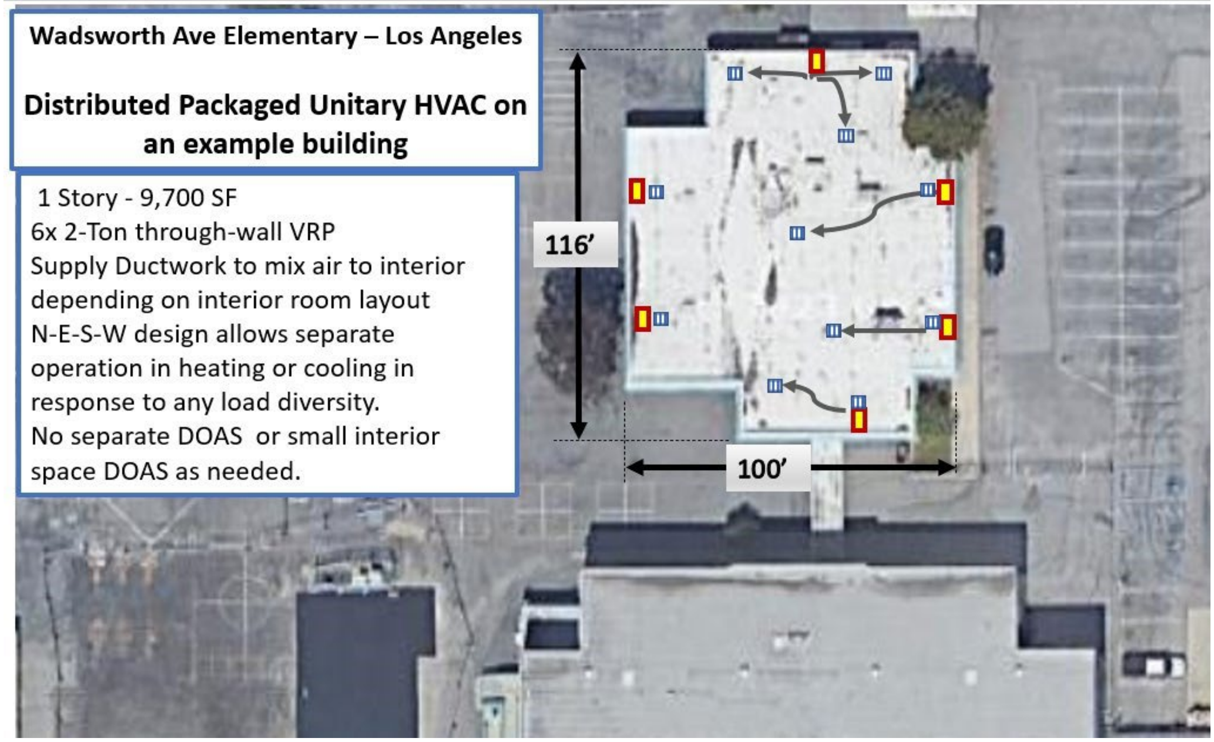


Figure 24: Wadsworth Ave Elementary distributed packaged unitary HVAC.

In the alternative HVAC design, all refrigerant is sealed inside the piping at the factory, and no fieldmade piping or piping joints need to be constructed within the building, and no refrigerant needs to be added. Onsite work is limited to the electrical connection, relatively little ductwork, and outdoor airpath connections. As A2L or, ultimately A3 versions of this through-wall equipment becomes available, manufacturers are likely to install interlocking sensors that valve off refrigerant if it begins to leak and prohibit the unit from operating. No other leak detection should be required.

Finally, VRF marketing literature presents the option of heat recovery capability in traditional VRF as important, but the actual value in energy efficiency is not evaluated anywhere our market review could find. The subject building must have significant load diversity that might require simultaneous heating and cooling at least for some hours of the year for heat recovery to have any value, and this is unlikely to be the case often in the strongly cooling-dominated climate zones with the bulk of California’s population. In any case, the alternative distributed packaged HVAC approach illustrated here is fully capable of serving diverse loads and the same degree of load matching as either VRF or Hybrid VRF. No data exists to support industry claims that heat recovery as built in the field would be relatively more efficient than the distributed unit approach despite its elegant engineering and the need to involve a large system that is refrigerant inefficient along with the limited applicability in many buildings means we do not need VRF to serve load diversity and cannot establish that it does so in a preferable way.

Appendix 3: Notable VRF System Evaluations and Issues

Objective three of this report asked, “What evidence of measured third-party verified efficient heating and cooling using VRF is readily available? How feasible is it to verify VRF operating efficiency as installed? What is the efficiency in low demand conditions and how is it achieved?”

In summary, it is quite difficult to measure the energy efficiency of VRF systems, we do not have a national standard for making such measurements or manufacturer-led efforts to create studies or standards. Finally, manufacturer claims that VRF should be expected to be more efficient than competitive heat-pump options are called into doubt by the information we do have. These issues have been communicated to manufacturers in detail over the last decade and remain unaddressed and unresolved. The question of VRF efficiency at low demand conditions remains important. One report on “residential VRF” identified reviews how the systems behave at high and low load concluding that VRF “does not necessarily” have “superior performance compared to a conventional system; particularly higher SEER conventional systems (ET06SCE1020).”

Two notable third-party energy efficiency studies of in-field operating VRF systems in occupied buildings resort to estimates of various kinds due to the understandable difficulties in directly measuring energy consumption versus delivered energy in complex, multi-indoor unit refrigerant-based VRF systems. While other hydronic or unitary split systems can be measured using direct changes in temperature in water or delivered air, the analogous accurate means to measure energy flows within a VRF system would require dozens or hundreds of measurement points of refrigerant flows sampled very frequently. To date, we have not been able to identify any manufacturer sponsored monitoring of energy across refrigerant flows in a VRF system available for public review. Retrofitting such refrigerant monitoring points typically voids the installation warranty, so this accurate technique is avoided. A manufacturer-led effort to persuade a system owner to allow refrigerant energy flows measurement at all points to establish inlet and outlet heat flows across outdoor units in particular (because outdoor airflows measurements are more difficult) would allow for a third-party to accurately establish energy efficiency. Measuring airflows across any system larger than a mini-VRF or more than one outdoor unit is extremely difficult, though one study did attempt this for such a small system. The two notable studies are substantial and sophisticated, but they ultimately use estimates and assumptions to make the task reasonable. Further, they document the need for and difficulty of utilities and third parties to verify the energy efficiency claims of manufacturers in the absence of manufacturer-supported measurement and verification projects.

VRF Energy Efficiency and Greenhouse Gas Issues

In 2018, the National Resources Defense Council (NRDC) requested VEIC provide a whitepaper to support their advocacy for increased heat pump adoption generally. In discussing the opportunity to deploy VRF, the authors noted that advancing the market for the technology should include “Evaluating and supporting accelerated transition of heat pumps to the use of lower GWP refrigerants” (VEIC 2018, 3). A very complete statement of issues with VRF comes from the list of market transformation strategies in the 2019 NEEP “Variable Refrigerant Flow (VRF) Market Strategies” report. The authors note in detail the outstanding GHG and energy efficiency issues needing to be addressed for establishing the benefits of

VRF, including:

1) “Increase reporting of VRF performance and costs to improve models for predicting cost-effectiveness, energy and GHG savings.

    a) Regional energy efficiency program administrators should introduce reporting requirements to capture project specific details on system design, upfront and operational costs and estimated or modeled savings. Additionally longer-term supplemental field evaluations, verification and pre/post monitoring studies are of critical importance for documentation of field VRF performance including changes in energy use, ongoing operational performance in relation to changing building loads, supplemental systems, and weather conditions.
    b) Regional VRF working group and manufacturers collaborate to assess the opportunity for leveraging existing or additional on-board metering of VRF systems to inform field-verified performance. Identify best practices for metering/monitoring VRF to identify the optimal balance of cost-effectiveness vs. Accuracy.
    c) Regional stakeholders collaborate to develop best practices for VRF building energy modeling and share updates to VRF performance curves (e.g. cold-climate models), field verified building models and system costs.

2) Support improved test procedures and performance criteria/standards to enable the promotion of climate-appropriate VRF.

    d) NEEP VRF working group should monitor and support development of national test procedures, standards and advanced specifications that improve the correlation and accuracy to real-world and climate-specific applications. The working group should evaluate the benefits of developing regional climate-specific performance reporting requirements and advanced criteria for VRF.

3) Develop a comprehensive regional strategy for addressing the climate and safety risks of refrigerants in VRF systems.

    e) NEEP VRF working group should initiate and collaborate in research aimed at identifying current VRF leakage rates, as well establishing data-informed best practices for VRF installations and servicing.
    f) NEEP VRF working group should invest in early support for industry evaluation of new refrigerants for VRF installations and encourage early market adoption. As new low-GWP refrigerants will potentially require re-piping for proper safety or performance, early planning and incentives may be required for avoiding barriers to market growth of VRF.
    g) Efficiency program administrators, state building code officials and industry can collaborate to support training on best practices for VRF design to mitigate safety, as well as reduce refrigerant charge to address leak risks. Similarly, site inspections prior to commissioning and code official enforcement of proper installations will support broader adoption among HVAC contractors.

4) Increase state policy support and program valuation of all energy savings and non-energy benefits of VRF.

    h) Regional state policy and efficiency programs should address policy barriers to the full valuation of VRF in reducing fossil fuel use through beneficial electrification and peak demand reduction. Additionally, the development of VRF case studies installations in a diverse set of building types, as well as increased field performance monitoring, will increase the confidence in VRF as a solution for building owners, and role in state GHG mitigation strategies.

5) Increase HVAC workforce development and training on proper VRF design, installation, and maintenance.

    i) Regional stakeholders, including manufacturers and program administrators, should increase the level of investment in HVAC workforce development and training to ensure that a sufficient number of "clean energy contractors" are trained in design, installation and maintenance best practices of new electrification technologies like VRF.
    j) In tandem to workforce development and training, program administrators should require manufacturer certification in the installation of VRF to increase confidence in system performance and reduce risk of refrigerant leaks. The NEEP workgroup can assess existing manufacturer training and value of developing regional best practice guides and standardized certifications for VRF contractors in critical areas (e.g. proper design, system sizing and start-up procedures)."

ET12SCE1090: "Testing of Commercial Variable Capacity Heat Pump for Small Commercial Office Buildings", December 2017, was conducted by the Electric Power Research Institute (EPRI) for Southern California Edison's Emerging Technologies Program.
A 5,710 square foot office building with two floors in Mission Viejo, California (Climate Zone 8) with two small data centers and offices had a 24-ton Mitsubishi City Multi VRF heat recovery system installed as two separate refrigerant circuits, one per floor and 12 tons each, connected to a total of 17 indoor units. Data was collected for 12 months from April 2014 to March 2015. "The electrical characteristics were used to determine the energy used, load profile and demand imposed by the system on the grid." The total VRF system energy use was determined to be 7.6 kWh/sq. foot/year.
The measurement of the electrical use is well designed and well documented. Understandably, refrigerant energy flows were not directly measured to determine delivered energy. "Capacity delivered (cooling or heating) by each indoor unit is estimated using the air enthalpy method" (EPRI 2017, 4). "Once the system was set up properly, the capacity delivered to the first floor and the second floor showed correlation with the outdoor temperature. Knowing the estimated capacity delivered and energy consumed, the estimated energy efficiency ratio (EER) of the system can be calculated"(EPRI 2017, 4).
The authors helpfully describe the background of the ANSI/AHRI Standard 1230 VRF rating standard as a method intended to "allow comparison of VRF equipment performance with that of unitary equipment at similar operating conditions. …Comparison of VRF to traditional unitary equipment in this similar manner represents a partial change in approach since two different classes of HVAC equipment are being compared. The crafters of the 1230 rating standard attempted to address this by making the testing conditions and methodology as similar to the unitary standards…as possible by allowing for VRF systems to be operated at

manufacturer-determined fixed operating conditions … . This leaves a rating standard which test equipment at fixed operation, while the same equipment in the field will vary its operation in accordance with changing load. This creates questions as to the direct applicability of the rating test as an accurate representation of actual field performance relative to other unitary equipment" (EPRI 2017, 9).

The report explains the need for field testing and developing operational data sets to validate estimations made by building modeling software: "Currently, energy savings derived from VRF use are generally considered difficult to characterize via any deem-able method and are thus typically modeled…. There is a need for detailed measurement of field performance of VRF heat recovery systems …to both help characterize actual yearly energy savings potential, and to provide quality data for use in energy modeling verification" (EPRI 2017, 10).

The several most notable conclusions regarding the VRF system operating efficiency:

- In comparison to the RTUs replaced by the VRF system, during two months that the new system was not optimized, energy use increased over prior years.
- When it was optimized during 10 of the 12 months studied, energy use was 41% lower.
- Coefficient of performance was not calculated.
- Summer EER ranged around 10-11.
- The number of hours when the system was in "mixed" mode indicating heat recovery operation were different by floor and overall quite limited, even with a small data center on each floor.

"MECA Air Source Variable Refrigerant Flow Field Study," Slipstream, December 31, 2021.

This report is the most recent and most comprehensive effort to monitor recently installed VRF systems at two hotels in Michigan. Each was monitored for 12 months, including energy usage, space temperatures and VRF supply temperatures. At one site, additional temperature and airflow rate data was captured to calculate the system's coefficient of performance (COP). "Monitoring the COP on VRF systems is difficult. Measuring the input power to the system … is straightforward. Measuring the energy delivered or removed is not straightforward. There are two possible strategies to accomplish this. The first is a refrigerant-side approach where refrigerant temperature and refrigerant flow rate are measured. One barrier to this approach is that measuring flow rate can be difficult, as the refrigerant is frequently in a mixed phase state. Furthermore, this method is intrusive, requiring cutting into the system to install measurement equipment. This would be a significant risk for an owner/operator as it would likely void manufacturer warranty.

The second strategy is an airside approach, where the temperature and flow rate of the air are measured. The primary drawback with this approach is that measuring the flow rate and temperature of air can be challenging, especially in circumstances where minimal or no ductwork is present (common with VRF system installations). However, this method is minimally intrusive, a major benefit when compared to the refrigerant side approach. Our research relied on airside measurements…" (Slipstream 2021, 19). The study notes the difficulty in outdoor airside measurement and that such approach cannot measure heat recovery at all.

While the conclusion is that "VRF has the potential to increase energy savings for efficiency programs as well as energy and cost savings for certain market segments," this is based on the heating baseline of a system that is ~90% efficient. We note that even a poor performing VRF or other heat pump system will provide heat slightly more efficient than this. The study used energy modeling to compare the performance of the VRF to a model PTAC and Water-

Source Heat Pump (WSHP) system, but also took the step to calibrate the model's starting values to the observed sub-metered data which forced the original model value (3.49) down to the observed 2.2 COP value (Slipstream 2021, 8). We note that this value is in the mainstream of other cold climate inverter heat pumps and is not superior.

The study also interviewed manufacturers' representatives who all "noted there is little to no independent field studies on the performance of the latest VRF technology." Despite this, all projected "double digit increases in units sold over the next 5 to 10 years" (Slipstream 2021, 36). Interviews with installers were also summarized: "VRF systems are complex and require error-free installation to be successful." Also, "VRF systems can be challenging to diagnose and trouble shoot. These systems are "black box" by nature, making traditional diagnosing and troubleshooting procedures less effective." The report expands on these interviewee comments on page 81: "While refrigerant leakage can be a problem for many different HVAC systems, it is particularly relevant for VRF systems because the refrigerant is not contained in a single appliance (e.g. chiller or air conditioner), rather it is piped around the building to various spaces, many of which are occupied. The possibility of a refrigerant leakage is therefore not just a climate change consideration but also must be a human safety concern." They continue: "Generally, refrigerant leaks in VRF systems are difficult to detect and locate due to the sheer size of most systems and the fact that piping is usually difficult to access. When a leak has occurred, replacement of the refrigerant in the system is often done inadequately because it is challenging to determine exactly how much refrigerant was lost" (Sabeer 2016).

It is notable that this Slipstream report aligns with the NEEP Market Strategies Report cited above in that the authors seek to understand how to promote adoption of VRF in the upper Midwest region by identifying and seeking answers to the refrigerant charge and leakage and operating efficiency unknowns identified by NEEP and this CalNEXT market analysis. From page 66: "Lastly, as more entities set emission reduction targets, which ultimately necessitate the shift to electric heating, a thorough investigation of refrigerant leakage is required. No data set currently exists which quantifies the scale of leakage. As we scale up the number and capacity of refrigerant based system in the market, it will be critical to understand the offsetting nature these systems may have on emissions savings. Any study of this nature should also consider the future refrigerants expected to be used in these systems." The authors expand on the topic in their Appendix B: Refrigerant Review where they note the impacts of currently used R-410A: "As more HVAC systems transition from fossil fuel-based heating to electric based heating (VRF and heat pumps – refrigerant based), the impact of refrigerants on the climate could increase. This increase can be mitigated by selecting refrigerants with lower GWP, and by managing refrigerant to ensure it does not leak into the atmosphere" (Slipstream 2021, 80). and note that "Most VRF systems contain between four and six pounds of refrigerant per ton of cooling …" Slipstream note the EPA HFC phase down incorrectly and hypothesize that even though VRF systems using R-410A will need to be replaced there will be reclaim available to avoid replacement until end of system life and not before: "…this phase-out may have cost impacts on VRF systems, as R-32 is not a drop in refrigerant for R-410A systems, meaning the piping, outdoor units, and fan coils would eventually need to be replaced (EPA 2018; Xylem Inc. 2018). The phase-out approach would allow this to happen at the convenience of most owners – owners would not be required to switch out equipment that is still operational" (Slipstream 2021, 80) We disagree with presenting this scenario as a certainty and identify the current regulation in California as instead representing a risk to measure life, in addition to representing a costly departure from large HVAC system historic norms where a distribution system survives the replacement of a boiler or chiller and instead, the entire VRF system must be replaced.

References

ASHRAE. 2020. "ASHRAE Handbook." In *Chapter 18*, 18.1.
ASHRAE. 2019. "Designation and Safety Classification of Refrigerants." https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/34_2019_f_20191213.pdf.
ATH. 2023. *Inverter Air-to-Water Heat Pump.* Advanced Thermal Hydronics. Accessed April 26, 2023.
https://www.knseries.com/commercial-heat-pumps.
Blocker, M. 2023. *Personal communication with VEIC* (January 20).
CARB. 2022. "California releases final proposal for world-leading climate action plan that drastically reduces fossil fuel dependence, slashes pollution." California Air Resources Board. https://ww2.arb.ca.gov/news/california-releases-final-2022-climate-scoping-plan-proposal.
—. 2023. "Current California GHG Emission Inventory Data." California Air Resources Board. https://ww2.arb.ca.gov/ghg-inventory-data .
CARB. 2020a. Final Statement of Reasons for Rulemaking, Including Summary of Comments and Agency Response. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/ctr/fsor.pdf.
CARB. 2020b. Prohibitions on Use of Certain Hydrofluorocarbons in Stationary Refrigeration, Chillers, Aerosols-Propellants, and Foam End-Uses Regulation. Proceeding, California Air Resources Board. https://ww2.arb.ca.gov/rulemaking/2020/hfc2020.
—. n.d. *Short-Lived Climate Pollutants.* Accessed June 1, 2023. https://ww2.arb.ca.gov/ourwork/programs/slcp/about.
CEC. 2023. *Core Responsibilities Fact Sheet.* California Energy Commission. Accessed April 25, 2023. https://www.energy.ca.gov/about/core-responsibility-fact-sheets.
Daikin. 2022. *Advanced Leak Detection with Daikin Remote Monitoring.* April 19. Accessed June 1, 2023. https://www.daikinapplied.uk/news-center/advanced-leak-detection-with-daikinremote-monitoring/.
Daikin. 2020. "Daikin's Policy and Comprehensive Actions on the Environmental Impact of Refrigerants." https://www.daikin.com/-/media/Project/Daikin/daikin_com/csr/information/influence/daikin_policy-en-pdf.pdf.
Daikin. 2008. "Shaping Air to Your Need - VRV 25 Years." p. 6. https://www.mclima.com/images/produkti/25_Years_of_VRV.pdf.
Devotta, S, R Sicars, J Agarwal, D Anderson, D Bivens, D Colbourne, G Hundy, et al. 2005. *IPCC/TEAP*
Special Report: Safeguarding the Ozone Layer and the Global Climate System. The Intergovernmental Panel on Climate Change.
https://archive.ipcc.ch/pdf/specialreports/sroc/sroc04.pdf.
EPA. 2023. Final Rule - Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the AIM Act. May 30. Accessed June 1, 2023. https://www.epa.gov/climate-hfcs-reduction/final-rule-phasedown-hydrofluorocarbonsestablishing-allowanceallocation#:~:text=The%20AIM%20Act%2C%20which%20was%20included%20in

%20the,to% 200.5%C2%B0%20Celsius%20of%20global%20warming%20by%202100.
EPA. 2023. *Greenhouse Gas Equivalencies Calculator.* Environmental Protection Agency. Accessed April 25, 2023. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
Ephoca. 2022. *Introducing AIO.* https://ephoca.com/wp-content/uploads/2022/01/Introducingaio.mp4.
Friedrich. 2023. "Variable Refrigerant Package Air Conditioner (VRP)." Product brochure. Accessed April 25, 2023. https://www.friedrich.com/professional/products/variable.
Friedrich. 2022. "Variable Refrigerant Packaged Heat Pumps." Product brochure. https://www.hts.com/wp-content/uploads/2022/05/HTS-Friedrich-Model-VRPBrochure_2022.pdf.
Gallagher, G., B. Deshpande, P. Gupta, A. Huang. 2016. *California's High Global Warming Potential*
Gases Emission Inventory. Emission Inventory Methodology and Technical Support Document, Air Quality Planning and Science Division, Air Resources Board, State of California.
Helbing, A. 2022. "Interview, Commercial Sales Air-tro." *Pasadena, CA installation contactor.*
ICF. 2005. Revised Draft Analysis of U.S. Commercial Supermarket Refrigeration Systems. Stratospheric Protection Division, U.S. EPA. https://www.epa.gov/sites/default/files/documents/EPASupermarketReport_PUBLIC_30Nov05.pdf.
Inside the Blueprint. 2021. World Class Heating and Cooling – Why Mitsubishi Electric VRF is the Future of HVAC. https://youtu.be/ZtGpWVPokqQ.
Johnson Controls. 2021. "Johnson Controls Commits to R-454B as Future Environmentally Sustainable Refrigerant Solution in North America." https://www.johnsoncontrols.com/media-center/news/pressreleases/2021/05/27/johnson-controls-commits-to-r454b-as-future-environmentallysustainable-refrigerant-solution-in-nort.
Kohli, A and P. Gupta (CARB staff), interview by J.T. Coneybeer VEIC. 2023. (February 21).
Korman, K. (Commercial Area Manager and VRF Trainer, Mitsubishi Electric Trane HVAC US LLC).
2022. Response to question during METUS Diamond System Builder training Lara, S. 2016. California Senate Bill 1383. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB1383.
Mitsubishi. 2019. *HVRF Now with R32 Refrigerant.* Product brochure, Mitsubishi Electric. https://mitsubishi-electric.co.nz/hvrf/r32-hvrf-low-environmental-impact.aspx.
NREL. 2023. *Buildings Data and Tools.* National Renewable Energy Laboratory. Accessed April 25, 2023. https://www.nrel.gov/buildings/data-tools.html.
Rajendran, R. 2022. *Refrigerant Changes Coming & The Helix w/ Emerson.* podcast 41:55. HVAC School. https://hvacrschool.com/podcasts/refrigerant-changes-coming-the-helix-wemerson/.
Sabine, S, and R. Slim, and L. Palandre, and D. Clodic. 2009. Inventory of direct and indirect GHG emissions from stationary air conditioning and refrigeration sources, with special emphasis on retail food refrigeration and unitary air conditioning. Research Division, Air Resources Board, State of California. https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/06-325.pdf.

Stausholm. 2021. *IPCC Includes GWPs for Hydrocarbons in New Report.* Hydrocarbons21. https://hydrocarbons21.com/ipcc-includes-gwps-for-hydrocarbons-in-new-report/.

Trane. 2022b. "ACX Comprehensive Chiller-Heater System application guide." Application Guide. https://www.trane.com/content/dam/Trane/Commercial/global/productssystems/equipment/chillers/air-cooled/ascend/SYS-APG003A-EN_04252022.pdf.

Trane. 2008. "ASHRAE Standard 15 Applied to Packaged, Split and VRE VRF Systems." *Engineers Newsletter* 37 (1). https://www.trane.com/content/dam/Trane/Commercial/global/productssystems/equipment/unitary/rooftop-systems/packaged-systems-1-1-2-to-5-tons/22-19721A-EN_10192022.pdf.

Trane. 2022. "Product Data: Single Packaged Heat Pump, 15 SEER2 Two Stage, Convertible, 2-5 Ton, R-410A."

Trane. 2023a. Thermafit™ Modular Air-to-Water Heat Pump Model AXM. Accessed April 25, 2023. https://www.trane.com/commercial/north-america/us/en/productssystems/chillers/modular-chillers/thermafit-air-to-water-heat-pump-axm.html.

Trane. 2023b. Ascend® Air-to-Water Heat Pump Model ACX. Accessed April 25, 2023. https://www.trane.com/commercial/north-america/us/en/products-systems/chillers/aircooled-chillers/ascend-air-to-water-heat-pump.html.

Turpin, J. 2022. "California Bans Sale of Bulk R-410A and Other HFC's." *Air Conditioning Heating Refrigeration News*, October 5. https://www.achrnews.com/articles/147115-california-banssale-of-bulk-r-410a-and-other-hfcs.

U.K. 2019. Environmental Reporting Guidelines: Including streamlined energy and carbon reporting guidance. Government of the United Kingdom. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_ data/file/850130/Env-reporting-guidance_inc_SECR31March.pdf.

Wilson, E, A Parker, A Fontanini, E Present, J Reyna, R Adhikari, C Bianchiand, et al. 2022. *End-Use Load Profiles for the U.S. Building Stock.* U.S. Department of Energy. https://www.nrel.gov/docs/fy22osti/80889.pdf.

Electric Power Research Institute. 2017. Testing of Commercial Vriable Capacity Heat Pump for Small Commercial Office Buildings - ET12SCE1090. Southern California Edison.

NEEP. 2019. "Vairable Refrigerant Flow (VRF) Market Strategies Report."

Slipstream. 2021. "MECA Air Source Variable Refrigerant Flow Field Study."

Southern California Edison. 2010. "Performance of Residential Variable Refrigerant Flow Systems - ET06SCE1020 Report."

VEIC. 2018. "Market and Technical Analysis of Variable Refrigerant Flow Heat Pump Technology"

VEIC. 2018. "Ramping Up Heat Pump Adoption in New York State: Targets and Programs to Accelerate Savings".