Lifecycle Refrigerant Management

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ABSTRACT

Refrigerant venting damages the ozone layer and produces approximately one ton of equivalent carbon dioxide (CO_2) emissions per pound of hydrochlorofluorocarbon (HCFC) refrigerant R-22 and hydrofluorocarbon (HFC) R-410a. Reducing refrigerant venting will help reduce global warming by 20% from 0.5°C to 0.04°C by year 2100. Refrigerant venting reduction goals are required by the United Nations 2016 Kigali Amendment to the Montreal Protocol on substances that deplete the ozone layer. The residential sector accounts for 32% of the Global Warming Potential (GWP) impact. Decarbonization requires greater focus on lifecycle refrigerant management (LRM) to detect, repair, and prevent refrigerant leaks, especially in the residential sector. Electronic leak detection and repair and locking Schrader caps (LSCs) help prevent leaks. Non-invasive temperature diagnostic (NTD) methods to evaluate air conditioning (AC) and heat pump (HP) faults avoid connecting refrigerant pressure gauges which causes about 50% of refrigerant venting. NTD software uses return, supply, and outdoor air temperatures and liquid and suction line temperatures to evaluate performance without connecting refrigerant pressure gauges. LRM NTD software provides accurate recommendations regarding refrigerant undercharge and other faults. For heat pump decarbonization programs, LRM offers positive net benefits of $770 per unit from refrigerant recovery and leak prevention, $363 from energy savings, and benefit cost ratio of 3.1. With 2.6 average benefit cost ratio, LRM is one of the most cost effective decarbonization measures in California.

Introduction

There are about 2 billion AC and HP systems in the world or approximately 1 system for every 4 people. Total refrigerant in cooling equipment worldwide ("installed refrigerant bank") is 24 billion $MTCO_2e$ – equivalent to annual emissions of 5 billion gas-powered cars (CCL 2022). Refrigerant venting damages the ozone layer and produces approximately one ton of equivalent carbon dioxide (CO_2) emissions per pound of hydrochlorofluorocarbon (HCFC) refrigerant R-22 and hydrofluorocarbon (HFC) R-410a. Reducing refrigerant venting will help reduce global warming from 0.5°C to 0.04°C by year 2100 (DNV GL. 2021). Refrigerant venting reduction goals are required by the United Nations 2016 Kigali Amendment to the Montreal Protocol on substances that deplete the ozone layer (UN 2016). The residential sector accounts for 32% of the Global Warming Potential (GWP) impact (CARB 2016).

Decarbonization requires greater focus on LRM to detect, repair, and prevent refrigerant leaks, especially in the residential sector (Theodoridi et al. 2022, Verified 2024). Non-invasive temperature diagnostic (NTD) tools, training, and software ensure proper refrigerant recovery, evacuation and installation of heat pumps and proper system evaluation to avoid connecting refrigerant pressure gauges which cause 50% of refrigerant venting or 5% of factory charge per year according to California Air Resources Board (CARB 2016). LRM has been approved by the California Public Utilities Commission (CPUC) as a statewide service (SWSV014) measure to improve AC and HP energy efficiency and reduce refrigerant venting (CAETEM 2024). For heat pump decarbonization measures, LRM provides net positive refrigerant benefits instead of net negative benefits (CAETRM 2024, CAETRM 2024b). This paper provides information about LRM, NTD methods, training, energy savings, and lifecycle refrigerant benefits to reduce venting which is responsible for 20% of global warming.

Code Requirements

LRM is not governed by federal or state appliance or building standards. The California Energy Commission (CEC) Building Energy Efficiency Standards (Title 24) require refrigerant charge (RC) verification of subcooling (SC) for systems with thermostatic expansion valves (TXV) or superheat (SH) for fixed-orifice or piston metering devices (non-TXV) (CEC 2012). Known CEC RC methods require connecting refrigerant pressure gauges to evaluate SC or SH which causes refrigerant venting. A Purdue University study reported CEC RC methods are only 58% accurate diagnosing -10 to -40% undercharge with no recommendations regarding amount of undercharge (Yuill 2012, CEC 2012). The Purdue study reported temperature split (TS) methods were less than 60% accurate when diagnosing airflow from -10 to -30% (Ibid). Based on Intertek tests, RC and TS methods provide 63% accuracy based on 57 correct tests out of 90 (Mowris et al. 2012, 2015). Intertek tests indicate TS methods provide 17% accuracy based on 15 correct tests out of 90 (Ibid). Furthermore, RC methods do not evaluate restrictions, non-condensables, or evaporator and condenser heat exchanger faults (Ibid).

The International Mechanical Code (IMC) (section 1101.10) mentions locking Schrader caps (LSCs), but they are not required by federal or state appliance or building standards for new or existing AC or HP units (ICC 2017). Building codes do not require tightening Schrader core valves to 5 inch-pounds (in-lbs) (0.56 N-m) torque to stop leaks or Nylog Blue sealant to prevent Schrader valve leaks (Schrader 2022). Therefore, the baseline comprises AC or HP units without leak detection, repairs, Nylog Blue sealant, or LSCs to prevent refrigerant leaks of 5.3% per year (CARB 2016, DNV GL 2021).

Non-locking Schrader caps provide no deterrence to prevent technicians from connecting refrigerant pressure gauges which cause venting. LRM requires HVAC contractors licensed by the Contractors State Licensing Board (CSLB) and technicians certified by the U.S. Environmental Protection Agency (EPA) under Section 608 of the Clean Air Act (CFR. 1992).

Lifecycle Refrigerant Management

Lifecycle refrigerant management (LRM) helps technicians achieve six goals (Theodoridi et al. 2022). (1) Enhance refrigerant responsibility and stewardship. (2) Increase refrigerant recovery, reclamation, and reuse. (3) Detect, repair, prevent, and reduce refrigerant leaks with locking Schrader caps. (4) Improve reporting and enforcement with LRM database. (5) Training and workforce development. (6) Improve installation and service procedures including verification of refrigerant recovery, low/high pressure leak testing, and evacuation.

Non-invasive temperature diagnostics (NTD) helps technicians achieve these goals by reducing refrigerant venting by 50% or more. NTD software uses return, supply, and outdoor air temperatures and liquid and suction line temperatures to evaluate system performance without connecting refrigerant pressure gauges (Verified 2023). NTD software accurately determines low airflow, low cooling capacity, and the amount of refrigerant under charge. NTD software also evaluates evaporator and condenser heat exchanger faults, refrigerant restrictions, non-condensables, and refrigerant over charge. Intertek NTD verification data indicate 99% accuracy with correct fault detection including undercharge for 107 out of 108 tests (CAETRM 2024).

Technicians performing LRM detect and repair refrigerant leaks and install Nylog Blue sealant and LSCs to prevent leaks. Technicians install new air filters, clean condenser coils, clean evaporator coils (if accessible), and measure evaporator airflow in cubic feet per minute (cfm). All supply registers must be open with clean air filters prior to airflow and NTD measurements. Airflow is measured using a digital hotwire anemometer, fan-powered flow hood (Duct Blaster®), pressure grid (Trueflow®), or balometer.[1] Final NTD test-out data are allowed when airflow is greater than or equal to (≥) 300 cfm per ton of cooling capacity.[2] Low airflow reduces efficiency and produces high temperature split, low superheat, or high subcooling and false alarm diagnostics. Low airflow is caused by dirty air filters, blocked evaporators, faulty blower fans, closed supply registers, crushed ducts, or improperly sized ducts. Technicians use NTD software to evaluate faults and determine how much refrigerant to add, if any. NTD software only recommends adding 7.5% or more of factory charge to avoid making small charge adjustments. If at least 7.5% undercharge and no other faults are detected, then weigh-in methods are used to add refrigerant to improve capacity and efficiency.

LRM requires refrigerant leak detection and repair before and after system is turned on and pressurized and before NTD evaluation. Leak detection is performed with electronic leak detectors at Schrader valves and other locations (Verified 2023). Leak detectors emit an audible alarm and bright flashing light if refrigerant leaks are detected. Most refrigerant leaks are from Schrader core valves under-tightened to less than 3 inch-pounds (0.34 Nm). To prevent refrigerant leaks, Schrader valves must be tightened to 5 in-lbs (0.56 N-m) with a torque tool per manufacturer specifications (Schrader 2022). Leaking over-tightened core valves are replaced with new valves properly torqued. High pressure liquid Schrader valves leak 40 times more refrigerant than low-pressure suction Schrader valves. Major leaks require refrigerant recovery and leak repair. After leak repair, Nylog Blue sealant is applied to valves, and all-metal dual wall LSCs with secondary "O" ring seals are installed. LSCs prevent refrigerant venting at Schrader valves and provide a barrier to prevent subsequent technicians from removing LSCs and randomly connecting refrigerant gauges which causes refrigerant venting.

Electronic leak detection, repair, and LSCs reduce refrigerant leakage by 80% (e.g., 20% leakage multiplier). The 80% reduction is based on a 20-year retention study of LSCs installed in 2004-2005 with a median effective useful life (EUL) of 29.4 years (Verified 2024). The 20-year retention study found 81.6% of LSCs were still installed in 2024 and 85.7% had proper refrigerant charge with an average leakage rate of 0.19% per year (Verified 2024). Furthermore, 70% of AC tune-up records (or 21,459 out of 30,831) in a low-income program with no LSCs installed were undercharged by an average 7.5% of factory charge (CAETRM 2024). Therefore, the baseline comprises AC or HP units leaking 5.3% per year without LSCs based on evidence that leaking Schrader valves are the main source of annual leakage (CARB 2016, Verified 2024).

Laboratory Tests

AC tests were performed at Intertek, an ISO-certified laboratory used by manufacturers and USDOE to test HVAC equipment for compliance with Federal energy efficiency standards (GAO 1975, Mowris et al. 2012, 2015). HP tests were performed at Purdue University (Kim and

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[1] Duct Blaster® and TrueFlow® are registered trademarks of The Energy Conservatory
https://store.energyconservatory.com/minneapolis-duct-blasterr-system-with-dg-1000.html
https://store.energyconservatory.com/digital-trueflow-kit.html
[2] One ton of cooling equals 12,000 British thermal units per hour (Btu/hr)

Braun 2010). The Intertek test facility consists of climate-controlled indoor and outdoor chambers where HVAC systems and measurement equipment are assembled and installed by laboratory technicians. Cooling verification tests were performed according to Air Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 210/240 2017 (AHRI 2017). Airflow tests were performed according to standard methods for laboratory airflow measurement per American National Standards Institute (ANSI) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ANSI/ASHRAE 1987). Laboratory test equipment was calibrated per International Organization for Standardization (ISO) 17025 by an accredited provider per the International Laboratory Accreditation Cooperation (ILAC) (ISO 2017).

Laboratory Test Results and Analysis

Laboratory and field tests were performed under steady-state conditions to measure AC cooling and HP heating capacity and efficiency for a range of RC conditions. Intertek laboratory measurements of airflow for a split-system air conditioner are provided in **Table 1**. Low airflow from -12% to -38% impacts the sensible energy efficiency ratio (EER*) by -7% to -21%.

Table 1: Airflow (cfm) and Sensible EER* Impact. *Source: Mowris et al. 2012, 2015*

Airflow cfm/ton	Sensible EER*	EER* Impact	Airflow % of Baseline
391	7.02	NA	NA
351	6.56	-7%	-12%
302	6.26	-11%	-25%
250	5.54	-21%	-38%

Cooling energy savings are based on the sensible EER* impacts versus refrigerant undercharge shown in **Figure 1** and **Table 2** (Mowris et. al. 2012, 2015). Cooling savings are also based on detecting, repairing, and preventing 5.3% per year base case refrigerant leakage without LSCs that causes undercharge (CARB 2016).

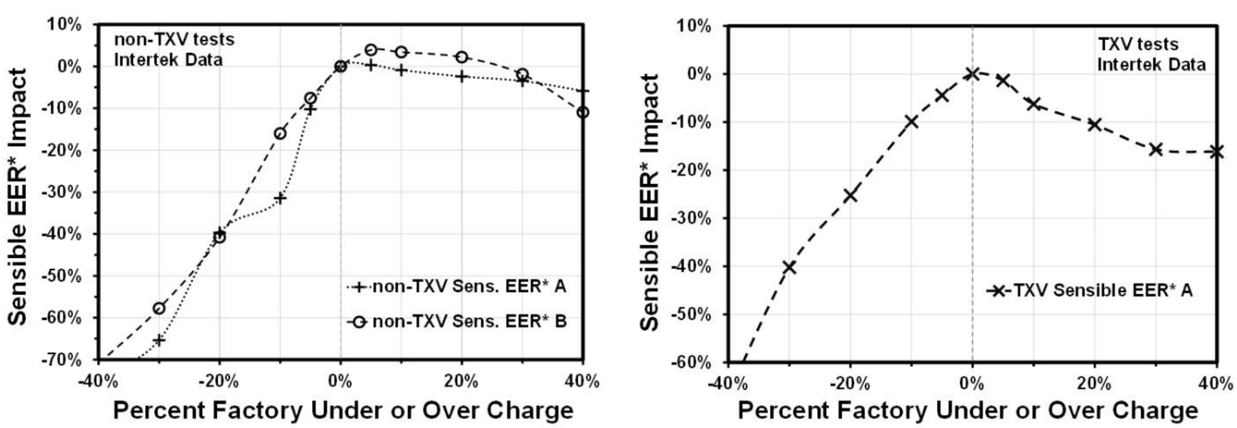

Figure 1: Sensible EER Impact vs. under or over charge for non-TXV and TXV. *Source Mowris et al. 2012, 2015.*

Table 2: Sensible EER* Impact vs. Factory Undercharge. Source: *Mowris 2012, 201, Intertek.*

% factory under charge	3-ton non-TXV EER* impact	3-ton TXV EER* Impact	Under charge ave. impact	% factory over charge	3-ton non-TXV EER* Impact	3-ton TXV EER* Impact	Over charge ave. impact
0%	0%	0%	0%	0%	0%	0%	0%
-5%	-10.8%	-4.4%	-8%	5%	-0.9%	-1.3%	-1%
-10%	-31.9%	-9.9%	-21%	10%	-1.5%	-6.2%	-4%
-20%	-40.1%	-25.2%	-33%	20%	-3.0%	-10.5%	-7%
-30%	-65.6%	-40.2%	-53%	30%	-4.1%	-15.7%	-10%
-40%	-74.2%	-66.5%	-70%	40%	-6.4%	-16.2%	-11%

The regression equation shown in **Figure 2** is based on Intertek laboratory test data for sensible EER* averaged over 82°F and 95°F outdoor air temperatures (OAT) and provides the same results as modeling impacts using cooling efficiency adjustments based on test data.

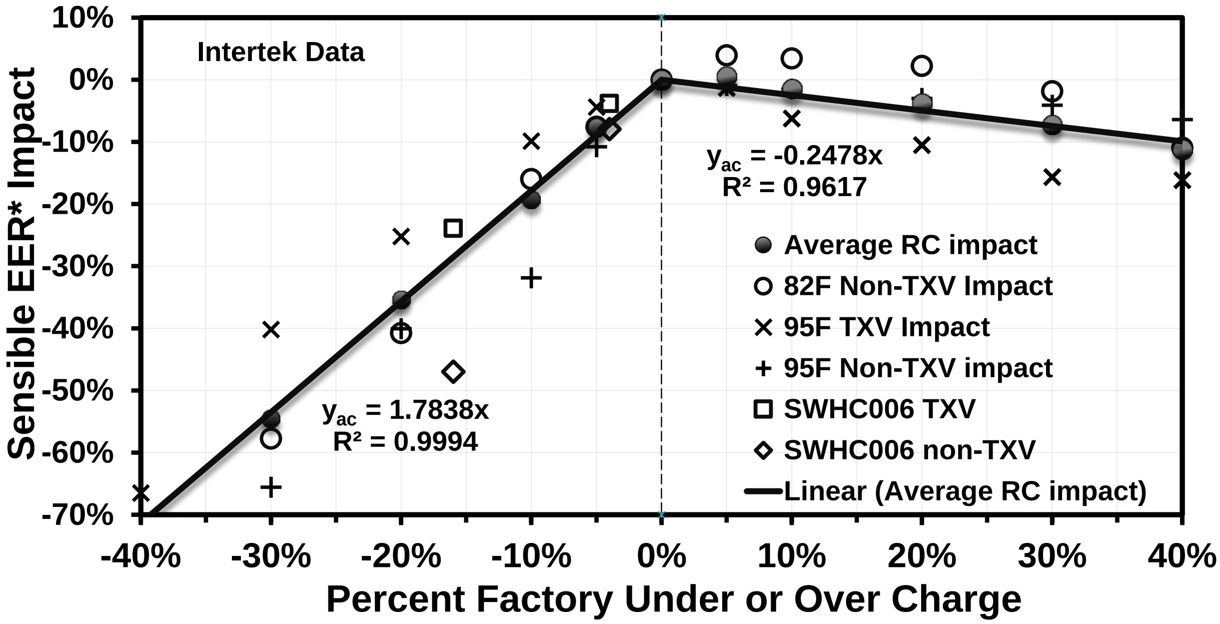

Figure 2: Sensible EER* Impact vs. Factory Under and Overcharge. *Source Mowris et al. 2012, 2015, SCE 2018.*

Reducing sensible EER* impacts AC operation based on sensible thermostat temperatures which are satisfied based on sensible capacity delivered to conditioned space. The following figure provides TXV and non-TXV percent savings from the statewide RC Adjustment measure package (SWSV006) for 4% undercharge and 16% undercharge (CAETRM 2024, SCE 2018). The regression equation curve fit for AC refrigerant undercharge is as follows.

Equation 1 $y_{ac} = 1.73838\ x$

Where, y_{ac} = sensible EER impact (dimensionless), and x = percent factory undercharge (UC).
Weighted average cooling savings (%): $y_{ac} = 19\% = 1.7838 * [0.053 * 0.3 + 0.128 * 0.7]$

Figure 3 and **Figure 4** provide RC impacts for heat pumps based on the coefficient of performance (COP) versus undercharge and OAT from 47°F (8°C) and 61°F (16°C) for TXV systems based on laboratory tests in the Purdue study for HP cooling (left figure) and HP heating (right figure) (Kim and Braun 2010). Impacts are similar to the Intertek test data for AC cooling shown above.

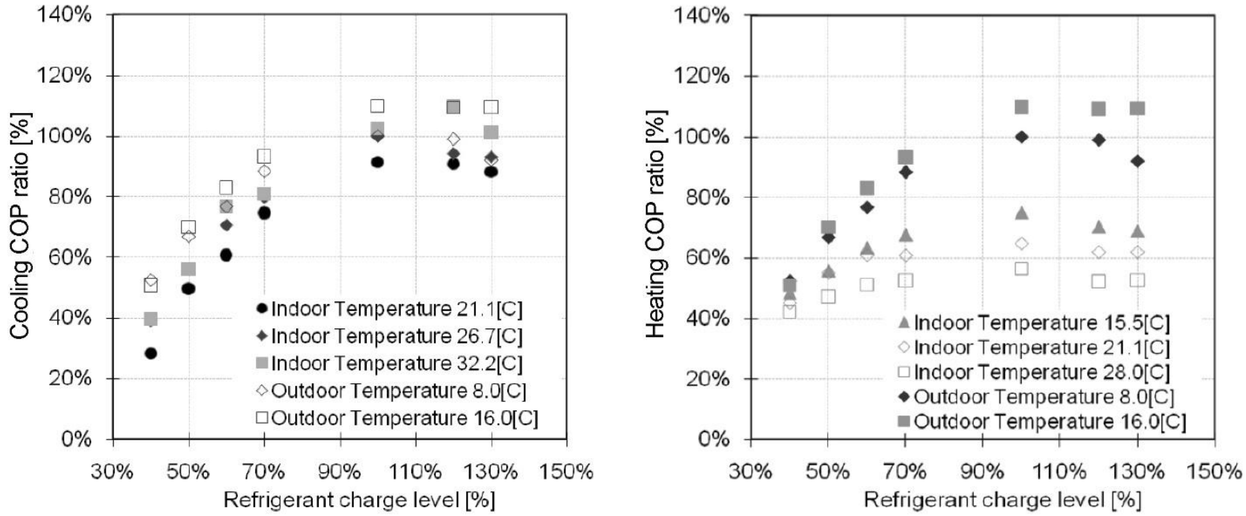

Figure 3: Heat Pump Cooling and Heating COP Impact versus Charge and OAT for TXV Systems (Purdue data)

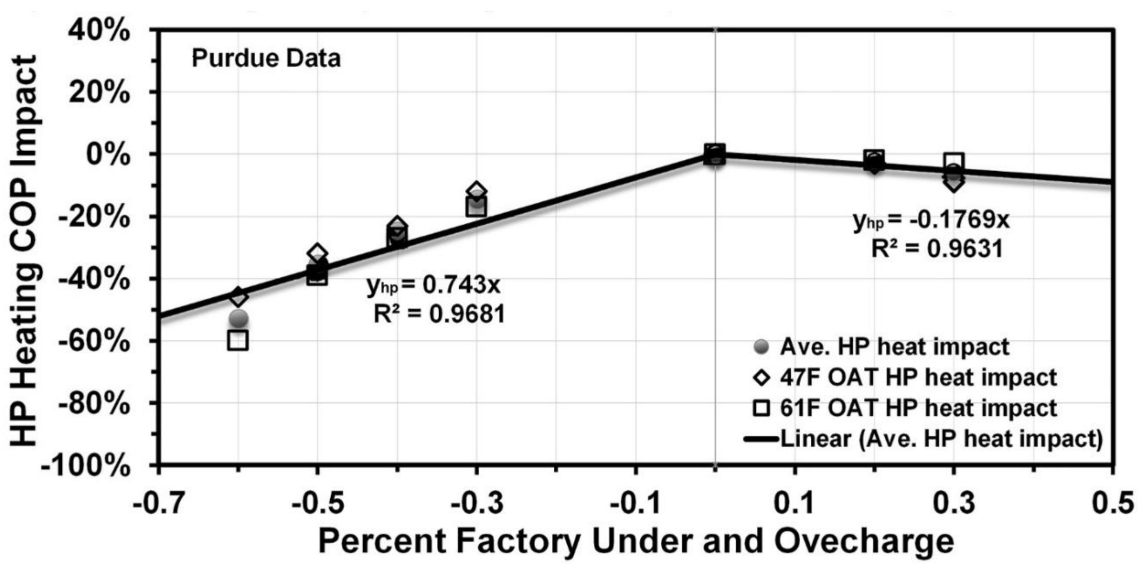

Figure 4: Heat Pump Heating COP Impact vs Factory Under and Overcharge (Purdue Data)

HP heating electric savings are based on correcting at least 7.5% refrigerant undercharge for 70% of units and preventing 5.3% undercharge on all units based on preventing 5.3% per year refrigerant venting due to leaks. HP heating energy savings for RC adjustments are 5.8% based on Purdue data and regression equation from above figure regarding `HP heating COP impact.

Equation 2 $y_{hp} = 0.743\ x$

Where, y_{hp} = HP COP impact (dimensionless), and x = percent factory undercharge (UC). Weighted average heat pump heating savings (%): y_{hp} = 8% = 0.743 * [0.053 * 0.3 + 0.128 * 0.7].

Annual electric unit energy consumption (UEC) data are used to calculate unit energy savings (UES) for AC cooling and HP heating based on Intertek and Purdue data. Based on average UEC data, the average LRM savings for homes in California are about 425 +/- 89 kWh/yr.

The peak demand reduction for correcting refrigerant undercharge on residential AC units is based on Intertek laboratory tests shown in **Figure 5** (Mowris 2012, Mowris 2015).

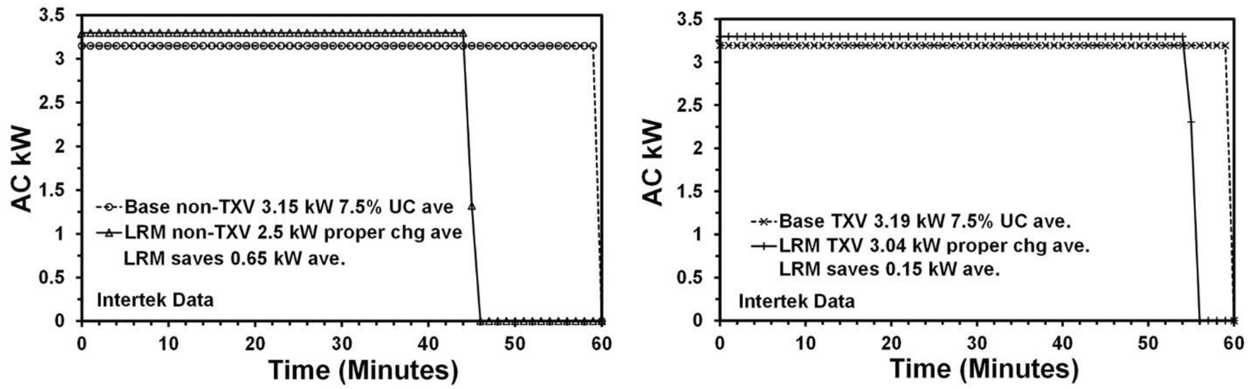

Figure 5: Peak Electric Demand (kW) reduction for proper charge vs 7.5% undercharge for non-TXV and TXV. Source: Mowris et al. 2012, 2015, Intertek.

Figure 5 (left) for a 3-ton non-TXV unit shows a peak day AC cycle from 4 PM to 9 PM where LRM reduces average peak demand by 0.72 kW compared to 7.5% undercharge. **Figure 5** (right) for 3-ton TXV unit shows a peak AC cycle from 4 PM to 9 PM where LRM reduces average peak demand by 0.22 kW compared to 7.5% undercharge. The LRM average peak demand reduction is based on proper charge requiring less AC operating time to provide same sensible cooling capacity for peak hour. LRM provides an average 0.72 kW reduction for the non-TXV unit and an average 0.22 kW reduction for the TXV unit based on Intertek tests and total average power over a peak hour normalized for sensible capacity. Data from 30,881 AC tune-up records indicate 79.1% are non-TXV and 20.9% are TXV (CAETRM 2024). Therefore, the weighted average peak demand reduction is 0.62 kW based on Intertek data (0.62 = 0.791 * 0.72 kW + 0.209 * 0.22). Average LRM peak demand savings for homes in California are 0.37 +/- 0.04 kW.

Non-Energy Refrigerant Benefits and Energy Savings Benefits

California uses the total resource cost (TRC) test to value climate and grid impacts of energy efficiency measures (CPUC 2022). The TRC is quantified in dollars using the Avoided Cost Calculator (ACC) to model avoided costs of demand side resources with respect to avoided energy generation and distribution. The ACC includes the Refrigerant Avoided Cost Calculator (RACC) to model carbon dioxide (CO2) equivalent impacts of refrigerant emissions and lifecycle avoided energy and emissions costs of energy efficiency and fuel-substitution measures (CPUC 2014). The RACC models refrigerant type and other parameters using CARB emission estimates by application type (CARB 2016). The RACC provides non-energy refrigerant benefits and energy savings benefits and avoided costs in dollars over the lifetime of a measure.

The LRM net present value (NPV in dollars) of non-energy refrigerant benefits based on RACC, present value (PV) of leak prevention benefits, and energy savings benefits are shown in **Table 3** (CPUC 2024). Total RACC and leak prevention benefits are $558 per unit for LRM for add on equipment (AOE), $770 per unit for normal replacement (NR), and $673 per unit for new construction (NC). Energy savings benefits range from $112 to $270 per unit based on CPUC ACC and energy savings based on laboratory tests by Intertek and Purdue University and calibrated EnergyPlus building energy simulations (Kim and Bruan 2010, Mowris 2012, DNV 2022, CPUC 2022). LRM measure costs range from $250 to $386 per unit based on 2024 construction cost data (RS Means 2024). RACC benefits are 74% of total for AOE, 76% for NR, and 80% for NC. For heat pump decarbonization programs,

LRM offers positive net benefits of $770 from refrigerant recovery and leak prevention and $270 from energy savings. Without LRM, heat pump fuel substitution decarbonization measures in California have a net negative refrigerant cost of -$509 per unit (CPUC 2024, CAETRM 2024b). With LRM, heat pump fuel substitution measures have a net positive refrigerant benefit of $770 (CAETRM 2024b). Greatest benefits are from preventing refrigerant venting and recovering refrigerant. With average benefit cost ratio of 2.6, LRM is one of the most cost effective decarbonization measures in California (CAETRM 2024).

Table 3: LRM Non-Energy Refrigerant Benefits and Energy Savings Benefits (NPV $)

LRM Measure	**HVAC**	**Refrigerant Type**	**Measure Type**	**RACC and Leak Prevention Benefits ($/unit)**	**Energy Saving Benefits ($/unit)**	**LRM Measure Costs ($/unit)**	**Total Resource Cost (TRC)**
LRM +7.5% RC LSC	AC/HP	R22, R410a	AOE	$558	$270	$355	2.3
LRM LSC	AC/HP	R22, R410a	AOE	$558	$112	$250	2.7
LRM LSC NR	AC	R410a	NC	$770	$249	$363	3.1
LRM LSC NC	HP	R410a	NR	$673	$170	$386	2.2
Average				$607	$200	$321	2.6

Conclusions

Refrigerant venting damages the ozone layer and produces approximately one ton of equivalent CO2 emissions per pound of HCFC refrigerant R-22 and HFC R-410a. Reducing refrigerant venting will help reduce global warming from 0.5°C to 0.04°C by year 2100. The worldwide shift towards electrification requires greater focus on LRM to detect, repair, and prevent refrigerant leaks, especially in the residential sector. Electronic leak detection and repair and LSCs help prevent leaks. NTD tools, training, and software are needed to evaluate air conditioning and heat pump system faults to avoid connecting refrigerant pressure gauges which causes about 50% of refrigerant venting. NTD methods combined with workforce training on refrigerant recovery of existing systems and evacuation and leak prevention of new systems will improve space cooling and heating efficiency and reduce refrigerant venting and carbon dioxide emissions. LRM can save about 19% on cooling and 8% on heat pump heating energy or 425 +/- 89 kWh/yr for an average home in California. Peak demand savings are about 0.37 +/- 0.4 kW per HVAC system. Average refrigerant benefits from leak prevention and recovery are $607 per unit or 75% of total net benefits compared to energy savings benefits of $200 per unit. For heat pump decarbonization programs, LRM NR offers positive net benefits of $770 per unit from refrigerant recovery and leak prevention, $363 from energy savings, and benefit cost ratio of 3.1. With 2.6 average benefit cost ratio, LRM is one of the most cost effective decarbonization measures in California.

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