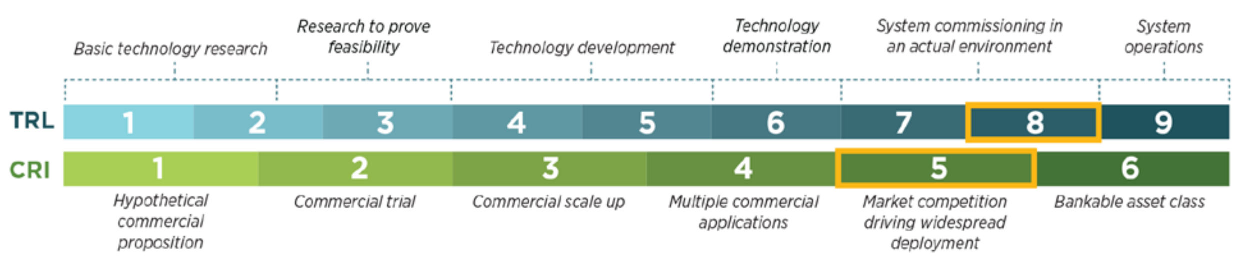
Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector Electric Space Conditioning Product Category Advanced Thermostat Products Last Updated 01/07/2019	 *Figure 1: Telkonet is one of many advanced thermostats on the market*

Product Category Overview

Smart and effective thermostat devices may provide opportunities for building occupants to improve thermal comfort conditions while simultaneously reducing space conditioning energy, responding to grid reliability signals, and reducing maintenance compared to legacy systems. Various technologies include occupancy sensing, advanced algorithms (e.g. learning occupant schedules and preferences, internal space load profiles), engaging user interfaces, and networked-systems (e.g. to the Internet or other systems, such as voice-activated gateways (Alexa, Echo), sensors, ceiling fans, or building management systems).

Characterization at a Glance



Product Category Characterization

Energy Benefits

Advanced thermostats lower energy consumption by reducing the runtime of heating, cooling, and fan equipment while maintaining safe and comfortable indoor environments. Thermostats adapt the target temperatures or set points of HVAC systems in response to occupancy, a programmed or learned schedule, or reliability signals from the utility grid. Advanced algorithms include "learning" house heat transfer profile, occupant schedules, and occupant temperature preferences to improve energy performance and/or reduce input required by user.

Non-Energy Benefits

Non-Energy Benefits include improved comfort, added convenience, and lower costs due to reduced energy consumption. Networked systems allow a single manager to access and change settings in multiple zones or buildings. Thermostats may also promote grid reliance by responding to reliability or price signals.

Product Category Differentiation

An advanced thermostat belongs to the categories (1) networked devices (e.g. Internet of things), (2) embedded devices (e.g. microcomputer capable of logging data, performing analytics, and conducting machine learning), and (3) controllers for HVAC. An advanced thermostat is all three: a controller and smart networked embedded device.

Technology Readiness Assessment and Projection

- Current Technology Readiness Level assessment:
  Rapid improvement in usability and function of advanced thermostats has evolved in the past 8 years (e.g. Nest). Yet the assertion that these devices will in fact save energy has only seen any rigor in the past three years, with the development of the Environmental Protection Agency (EPA)'s Climate Control program.[1] This program requires the collection of energy use data to ascertain savings, and is still evolving. The usability of these thermostats so that occupants and building managers can actually achieve savings has not yet been determined. Electrification of heating systems (e.g., replacement of gas wall heaters and furnaces) with heat pumps creates a new problem as not many advanced thermostats can control heat pumps and electric backup. In addition, ensuring that these devices reconnect to the Internet or hub after a power outage or disruption in network is still an ongoing problem.
- Short-term TRL projection:
  The TRL level of these thermostats is projected to advance to 9 over the period of this project.

Installation Pathway and Dependencies

The installation pathways are new construction, major renovation, and retrofit. Currently installation dependencies are compatible with the following HVAC equipment: Roof Top Units (RTUs), conventional compressor-based Air Conditioning, and Forced Air Units with low voltage (24V AC) wiring to the thermostat (the vast majority of these thermostats require a "C" or common wire). In many cases, one can use a special kit to (1) bring 24V AC power to the thermostat from the existing equipment or (2) power the thermostat with 120V AC with a wall receptacle. The devices require network support to remain connected to the Internet or hub/gateway.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Nest	T3007ES, T3008US	Learning Thermostat	Learning occupant schedule and thermostat set point preferences, occupancy sensing.
EcoBee	EcoBee 4	Smart Thermostat	Optimization.
Honeywell	many	Smart Thermostat	Optimization.
Telkonet	EcoInsight™	Smart Thermostat	Occupancy sensing, Smart recovery.
EPRI LIT	Low Income Thermostat	CEC-funded research	Low cost, smart thermostat; Bluetooth to phone for interface.

[1]https://www.energystar.gov/sites/default/files/specs/private/Final_ENERGY_STAR_Residential_Climate_Controls_Remote_Interface_Discussion_Document.pdf

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
New York, New York, USA	Field study Telkonet, Inc. occupancy sensing thermostats were installed in a total of 4629 dormitory rooms in 11 buildings. When the room was “unoccupied”, the set point temperature was set back to an energy saving level, typically 2-4°F above or below the “occupied” set point. Energy consumption (per room) was calculated based on heating and cooling equipment runtime for the building divided by the number of rooms. Energy savings were calculated in comparison to previously measured energy consumption for the original thermostat configuration.	Overall annual energy savings per room was estimated to be between 25-32%. Measured annual cooling electricity savings ranged between 200-800 kWh per room.	[1]
N/A	Energy simulation study Heating and cooling set points were varied parametrically in seven ASHRAE climate zones and in six distinct medium-sized office buildings.	Without reducing satisfaction levels, by increasing the cooling set point of 22.2 °C (72 °F) to 25 °C (77 °F), an average of 29% of cooling energy and 27% total HVAC energy savings are achieved. Reducing the heating set point of 21.1 °C (70 °F) to 20 °C (68 °F) saves an average of 34% of the energy needed to heat a typical room.	[2]
N/A	Field study Retrofit of a 20,500 square foot, medium-sized commercial building with a system of communicating thermostats, wireless monitoring sensors, and network control infrastructure. Using the electricity interval data, energy use between the pre- and post-upgrade periods was compared and savings estimated.	The annual energy savings was estimated to be 22%.	[3]

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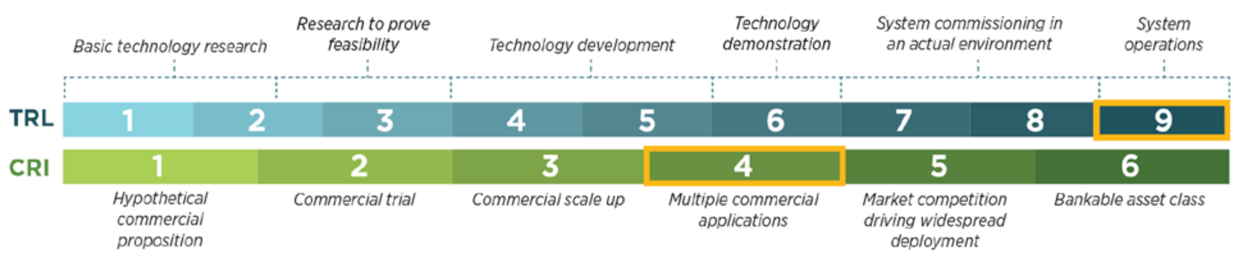
Technology Sector Electric Space Conditioning Product Category Aerosol Sealing for Ducts and Building Envelopes Last Updated 12/20/2018	 *Figure 1: Nozzle injecting sealant into building envelope during construction.*

Product Category Overview

Aerosol-applied sealants are used to seal small holes and gaps up to half an inch in size. The aerosol sealing process is a commercially available technology for sealing building envelopes and HVAC duct systems. The process involves briefly pressurizing the space to be sealed while injecting an atomized liquid sealant. As air escapes through leaks in the building envelope or duct system, the sealant "fog" is transported to the leaks by the escaping air where the particles stick to the leak. The process (excluding equipment setup and removal) typically lasts 60 to 120 minutes and seals up to 80% of leaks in the space.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Sealing ductwork reduces the fan power required to circulate air through ductwork as well as prevents losing conditioned air to unconditioned spaces. Sealing exhaust ventilation systems can also reduce fan power by reducing excess airflow pulled through leaks that does not contribute to the ventilation requirement. Similarly, sealing building envelopes reduces the amount of uncontrolled infiltration. Controlling airflows through the building envelope reduces thermal.

Non-Energy Benefits

Sealing leaks in the ductwork and building can also improve indoor air quality. Sealing ductwork and building envelopes greatly reduces entry points for outdoor pollution and particulate matter. This allows better control of outdoor air entering a building for ventilation purposes and provides an opportunity to filter that air.

Product Category Differentiation

Traditionally, building envelopes are sealed using gasket material during the construction phase, followed by manually applying insulating foam sealant to remaining gaps. Similarly, ducts are manually sealed by covering gaps and holes with metal tape or mastic sealant. Currently, there are no other products on the market similar to what AeroSeal offers for building and duct sealing. The sealing process automates finding and sealing leaks, reducing the chance of missing leaks as well as the amount of time required to do so. There is also potential for replacing various building materials currently used to create air barriers at the building envelope, but this approach would require training contractors on new installation approaches. Additionally, ductwork that is often inaccessible during or after construction can be sealed remotely using aerosol sealants.

Installation Pathway and Dependencies

Aerosols are best suited for use sealing building envelopes during the rough-in stage of construction or after drywall has been installed. During rough-in, seals form directly at the exterior wall, which requires a complete building shell (e.g. windows, doors) in order to pressurize the space during the process. Sealing can also be performed after drywall is installed. While still effective at creating a tightly sealed conditioned space, leaks behind walls and above ceilings will still be present, and seals may be susceptible to damage while finishing construction (such as in electrical boxes). Ventilation must also be considered when sealing building envelopes. Passive infiltration is greatly reduced so ventilation systems should be designed, installed, commissioned and operated appropriately for sealed buildings.

Duct sealing can be applied at any point after installation, including as a retrofit. Fan speeds may need to be adjusted and systems balanced after sealing due to the reduced losses in the system.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
AeroSeal	AeroSeal	Aerosol duct sealing system	Automates sealing of ductwork and allows for inaccessible leaks to be sealed.
AeroSeal	AeroBarrier	Aerosol building sealing system	Automates sealing building envelopes, with potential to replace building materials used to create air barriers.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Virginia, North Carolina, Pennsylvania, USA	Field test of building envelope sealing. Retrofit of nine existing buildings of various sizes and functions on three military bases with aerosol sealant to test performance. Building leakage was measured and labor requirements and materials used were tracked.	Less than 0.25 cfm of leakage per sq. ft at a pressure of 75 Pa observed. Buildings 1,500 sq. ft or smaller required less than 16 person hours per 1,000 sq. ft.	[1]
California, USA	Lab simulation of building envelope sealing. EnergyPlus modeling of pre-1980 small commercial office building in four different climate zones performed to estimate energy savings.	30-40% reduction in energy required for heating, <10% reduction for cooling and fans. Source energy consumption reduced between 21-150 GJ annually.	[1]
California, Nevada, Massachusetts, Ohio, New Jersey, New York, USA; France; UAE	Field test of duct sealing and envelope sealing. Exhaust duct systems sealed at multiple buildings, including hotels, apartment style buildings, a large office building, and a laboratory. Envelope sealing performed during new construction of single family detached and multifamily homes after drywall.	Aerosol based duct sealing was able to seal approximately 90% of leakage found in building exhaust systems. Aerosol sealing in new construction and existing homes showed at least 50% reduction in leakage after two hours.	[2]
Minnesota, USA	Field test of envelope sealing. 18 new construction multifamily units along with 9 existing multifamily units were sealed with aerosols.	Results for new construction homes showed 67-94% reduction in leakage, and existing homes showed 39-89% reduction in leakage.	[3]

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Technology Sector Electric Space Conditioning Product Category Air Source Heat Pumps Last Updated 12/07/2018	 *Figure 1: Air to water heat pump with outdoor unit on left and indoor unit with tank on right (Daikin), https://www.daikin.com/products/ac/lineup/heat_pump/index.html*

Product Category Overview

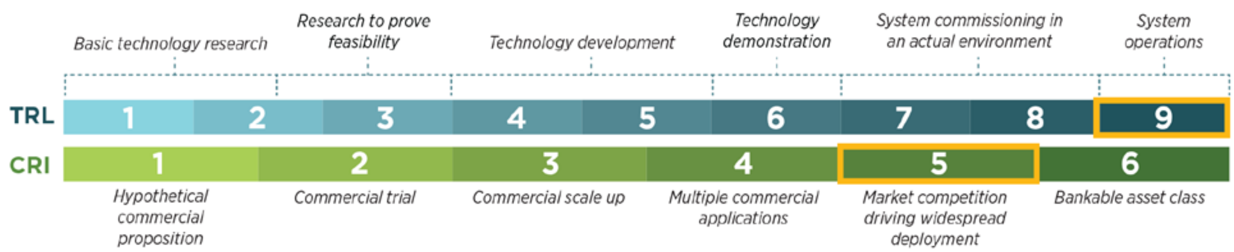
Air source heat pumps (ASHP) are an all-electric heating and cooling solution that can achieve high efficiency. Air source heat pumps transfer heat to and from the outdoor air and are well-suited for climates with mild winters. Air source heat pumps are slightly less efficient than ground source heat pumps, which transfer heat to and from the ground, but are significantly less costly to install. Heat pumps use electrical energy and move thermal energy from a lower temperature source to higher temperature sink in order to heat or cool a building and/or heat domestic hot water. Coefficient of performance (COP), one metric to assess heat pump performance, is defined as the amount of heat added or removed from a space divided by the amount of energy input to the heat pump. Heat pumps have a COP greater than one which means they can move more thermal energy than the electrical energy that they require. Heat pumps can reduce energy usage at the site by replacing fossil fuel combustion boilers or electric resistance heating that can only provide 80% to 100% of the input fuel energy as heat delivered [1, 2]. High efficiency heat pumps use one or more variable speed components including compressors, fans, and pumps to achieve a higher COP.

Air-to-air heat pumps (ATAHP) heat or cool air moving through an air handler and ducts to heat or cool spaces in a building. ATAHPs have a COP range of 1.2 to 5. A variation of ATAHPs pump refrigerant through pipes to fan coils distributed through a building; when they serve one zone they are called mini-splits, when they serve multiple zones they are called multi-splits, and the larger systems are called variable refrigerant flow (VRF) systems. VRF systems are covered in a separate characterization report.
Air-to-water heat pumps (ATWHP) heat or cool water or a water/glycol mix that is then pumped through a distribution loop to heat or cool spaces in a building or to heat domestic hot water. The thermal energy can be transferred from the water loop to or from the spaces using hydronic or radiant systems and/or conditioning supply air using air handler units. ATWHPs have a COP range of 2 to 5. Using water to distribute thermal energy also makes it simpler to use other technologies like thermal storage to reduce energy costs.

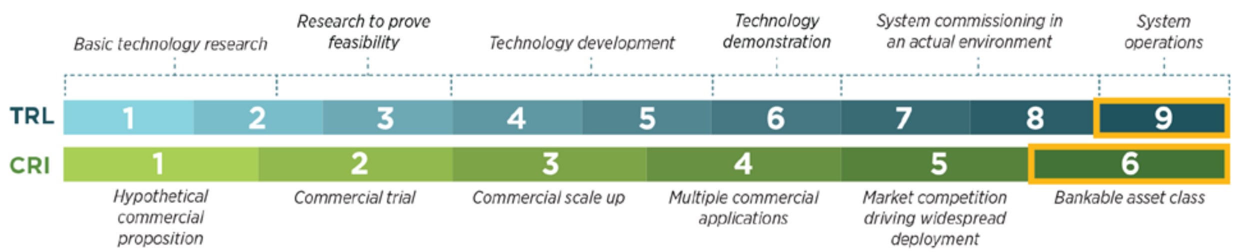
Whether air source heat pumps will reduce energy costs depends on the cost per unit of energy for electricity compared to the fuel(s) that would have been used by boilers, local climate outdoor air temperatures, system design, and opportunities to increase efficiency by using the same equipment to deliver heating and cooling simultaneously.

Characterization at a Glance

Air-to-water heat pumps:



Air-to-air heat pumps:



Product Category Characterization

Energy Benefits

The primary application for ATAHPs is to replace fossil fuel combustion furnaces and electric resistance systems for space heating. The primary application for ATWHPs is to replace fossil fuel combustion boilers and electric resistance water heaters that are used for space heating and optionally also used for domestic hot water supply. Many heat pumps include a simple flow reversing valve that allows them to also supply cooling using the same components, which eliminates the need for an additional air conditioning system. Fossil fuel combustion boilers and furnaces range in average fuel utilization efficiency (AFUE) from 80% - 97%, where the highest efficiencies are achieved in condensing types of equipment that condense liquid water from the combustion exhaust [1, 2, 3, 4]. Electric resistance space heating systems achieve near 100% efficiency converting electrical energy into thermal energy in the space or in hot water [5]. ATAHPs can move thermal energy from outside to inside to achieve a typical COP averaged over the heating season in the range of 1.6 up to 5.2 [6]. ATWHPs can achieve a COP averaged over the heating season in the range of 2 up to 4.8 with peak COP of around 5 [7, 8, 9].

Actual energy savings for heat pumps depend on the temperature difference between the indoor and outdoor temperatures. For ATWHPs, thermal energy distribution methods designed to operate with supply water temperatures closer to the desired indoor temperature (e.g. larger radiant/hydronic/fan coil heat transfer surfaces) allow the heat pump to be more efficient. Extreme outdoor temperatures reduce the efficiency of all heat pumps and will reduce energy savings. Cold climate air-source heat pump technology improvements over the past decade have increased the COP of air to water heat pumps in cold climates (and reduced the efficiency advantage of ground source heat pumps) [10].

Energy cost savings when a fossil fuel combustion furnace or boiler is replaced with an air source heat pump are highly dependent on electricity cost compared to fossil fuel cost and can be impacted by electric rate schedules such as tiered or time-of-use. Regions where the cost of electrical energy is more than four times higher than the cost of combustion fuel energy are likely to not have significant energy cost savings from ASHPs.

Non-Energy Benefits

Replacing combustion heating with high efficiency electrically driven heating eliminates combustion and associated exhaust toxicity risks such as carbon monoxide. If the electricity used by the heat pump is renewably produced, then large reductions in greenhouse gas emissions are possible. Most air source heat pumps are reversible, meaning that they can also provide space cooling, avoiding the need for a separate air conditioner. Many air to water heat pumps are used in combination with hydronic heating and radiant heating distribution systems that may increase thermal comfort due to more stable and more even space temperatures (reduce stratification, drafts, building pressurization) [10].

Product Category Differentiation

Compared to combustion heating systems, air source heat pumps offer all electric heating and cooling with option for using renewably produced electricity, improved efficiency, and no direct emissions from combustion. There are several types of air source heat pumps for different applications.

Air-to-air heat pumps include:

- Packaged unit (roof top unit (RTU), wall mount, packed terminal heat pump (PTHP)). Packaged units heat or cool air moving through an air handler and distributed it to spaces through ducts.
- Split system, mini-split and multi-split. These systems pump refrigerant through pipes to fan coils distributed through a building.

Air-to-water heat pumps include:

- Split systems (outdoor compressor with indoor water tank)
- Mono-block (compressor and tank in one unit)

In ATWHPs, the water can be used to heat/cool individual spaces by pumping it to air handlers, radiant floors, radiant panels, differnet types of radiators, and/or hydronic baseboards. ATWHPs can provide domestic hot water for the building, enable hydronic and radiant heating and cooling, and can be used for charging themal storage water tanks.

These different types of systems can have a number of different performance levels and features including:

- Energy Star and Energy Star Most Efficient rated models

- Low-ambient / cold climate models
- Very high efficiency low temperature supply water (<130 °F)
- High efficiency high temperature supply water (> 130°F) often for domestic hot water
- Units with single speed, multi speed, and variable speed components
- Controls with automatic water supply temperatures resets based on outdoor air temeprature to maximize efficiency
- Demand-defrost control to avoid running outdoor coil defrost heaters unnecessarily
- Desuperheater or refrigeration heat reclaimer to use waste heat from cooling to heat hot water

Installation Pathway and Dependencies

The primary installation pathways are in new construction, major renovation, and in some cases retrofit. Where ASHPs replace existing furnaces they can often be retrofit to use the existing ducts if the ducts are well sealed. Where ASHPs replace existing boilers they can sometimes be retrofit to use the existing indoor heat transfer devices (fan coils, hydronic, radiant) if the existing devices are compatible with the often lower water supply temperatures from ASHPs compared to boilers.

Installation Dependencies:

- Sufficient electrical power utility service and distribution wiring or ability to upgrade
- Either space for the exterior compressor and heat exchanger unit on the ground surrounding the building or both roof space and sufficient roof structure strength to hold the weight of the exterior unit (for smaller systems the exterior units can be relatively light since water tanks are typically in the indoor unit, but are often heavier than fossil fuel furnaces)
- Very cold climates require special ASHP designs, often require a backup heat source such as fossil fuel combustion or electric resistance heating, and depending on the fraction of heat supplied by the backup heat source may not save as much energy compared to milder climates

List of Products

Hundreds of manufacturers produce over 20 million ASHPs per year worldwide with major suppliers including brands from the USA: American Standard and Carrier, Japanese multinationals: Daikin, Mitsubishi, Panasonic and Sanyo, and the largest suppliers by volume now being from China including Gree and Haier [6]. Table 1 summarizes a sample of ATAHP product lines of interest to commercial buildings with small to medium heating and cooling loads. ATWHPs have fewer manufacturers and less diverse product offerings, with a representative sample listed in Table 2.

Table 1: Summary of manufacturers and products for air-to-air heat pumps.

Manufacturer	Model	Type	Differentiating Feature
American Standard	Commercial packaged unit product lines: Voyager, Precedent Commercial split system product line: Odyssey	ATAHP roof top packaged heat pump	EER 10.5 to 13.35 IEER 12.0 to 15.5 Compact size makes the odyssey system a good candidate for retrofits in tight spaces.
Carrier	Commercial packaged unit product lines: Performance, Weathermaster, Weathermaker Commercial split system product line: Gemini	ATAHP rooftop packaged heat pump	EER 10.3 to 16.0 IEER 13.0 to 21.0 Performance model uses Puron refrigerant which does not contribute to ozone depletion of atmosphere.
Daikin	Commercial packaged unit product line: Rebel	ATAHP rooftop packaged units 3-15 ton	EER 11.0 to 13.5 IEER 16.9 to 20.6 Up to 43% savings from ASHRAE 90.1 Variable speed: Inverter driven scroll compressor, direct drive ECM motor for fans
Mitsubishi	Commercial split system product line: P-Series brochure	ATAHP split system	Hyper-heating inverter delivers 100% capacity at 5°F outdoor ambient and 80% capacity at -13°F outdoor ambient
Panasonic	Mini-split system product line: Exterios, Pro	ATAHP mini-split	
Gree	Multi-split (outdoor units: Freematch, indoor units: Hyper Range, Hansol, Cozy), VRF	ATAHP multi-split	Largest manufacturers Low frequency inverter technology
Haier	Ductless From single zone to multi to many (min-split, multi-split, VRF) Outdoor (FlexFit)	ATAHP mini-split and multi-split	Largest manufacturers

Table 2: Summary of manufacturers and products for air-to-water heat pumps.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Daikin	Altherma 3 (4,6,8 kW outdoor, with indoor 180, 230, 300, 500 L indoor tank) [7]	ATWHP, split system with outdoor and indoor units	Variable speed inverter driven compressor, Efficient COP 5 (at 7ºC outdoor and 35ºC water supply (A7/W35)), Water supply up to 65ºC, outdoor temperature down to -25ºC Smart grid ready, connections for solar thermal auxiliary system, can be connected with other heating systems (electric or NG back up), R32 refrigerant, 25W standing loss 180L tank
Daikin	Altherma High Temperature [11]	ATWHP, split system with outdoor and indoor units	Up to 80ºC water supply for both space heating (using existing radiators) and domestic hot water (two stage vapor compression for larger temperature lift.
Fujitsu	Watersage [12]	ATWHP, split system with outdoor and indoor units	Higher temperature supply (60ºC) even at -20ºC outdoor air temperature, Efficiency COP 4.3 at 7ºC outdoor, 2.4 at -7ºC outdoor, and 35ºC supply water, two zone control, automatic temperature reset
Maritime Geothermal Ltd.	Nordic ATW 45 to 75 [13]	ATWHP, split system with outdoor and indoor units	Low ambient temperature performance (oversized outdoor heat exchanger slanted to reduce icing, intelligent defrost logic, compressor in indoor unit avoids crankcase heater. Outdoor temperature reset, potable water heat exchanger)
Chiltrix	CX34 [14]	ATWHP, split system with outdoor and indoor units	Variable speed compressor, pump, condenser fan, CX34 2 Tons Cooling/ 3 Tons Heating. Self-contained R410a chiller heat pump. Options DC inverter indoor fan coil units
Multiaqua	MHRC2 [15]	ATWHP, split system with outdoor and indoor units	Simultaneous heating and cooling, 5 ton
Panasonic	Aquarea T CAP [9]	ATWHP, split system with outdoor and indoor units	Danish Technological Institute lab testing found the industry's highest SCOP rating of 4.84 (SCOP European rating standard seasonal average COP). Output 9.29 kW at 10°C.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Tables 3 and 4. Performance of air-to-water heat pumps are dependent on the thermal distribution system design and set points. Therefore most case studies do not separate out air-to-water heat pump energy performance from overall heating system performance so that proper design of the thermal distribution system is a prerequisite for good overall performance.

Table 3: Summary of results from literature review *for Air to Air Heat Pumps*

Location	Application	Results	Reference
Europe	Field tests: Residential Baseline Technology: Condensing boiler or furnace Measured: Heat Pump (HP) energy consumption, heating and cooling provided by HP, energy consumed by balance of system	COP averaged over the heating season in the range of 1.6 up to 5.2 across a range of models and hundreds of installations COP strongly dependent on temperature lift so dependent on how thermal energy is distributed in the buildings and local climate	[6]
Alaska, USA	Field tests: Residential (Cold Climate Housing Research Center) Measured: HP energy consumption, heating and cooling provided by HP	COP varies widely depending on model and local climate. Very cold climates with outdoor temperature regularly below 17^{o}C often require alternative backup sources of heat.	[16]
Connecticut, USA	Field Tests: Residential 124 single family homes, 2 ton ATAHP ductless Baseline: Electric resistance space heating Measured: Utility bills during heating season	2,700 kWh/y average savings. 26 homes had no savings or increase in electrical usage.	[17, 18]
Northeast USA	Field Tests: Residential 93single family homes, ATAHP ductless Baseline: Electric resistance space heating Measured: Utility bills during heating season	3,049 kWh/y average savings, standard deviation in savings 2,424 kWh/y	[17, 19]

Table 4: Summary of results from literature review *for Air to Water Heat Pumps*

Location	**Application**	**Results**	**Reference**
Chico, California and Tucson, Arizona, USA	Field test: Residential single family low load distribution radiant and fan coil Baseline Technology: standard air-to-air heat pump with tight ducts in attic or conditioned space Measured: Overall HVAC energy consumption	Annual HVAC energy savings of 31% vs baseline with ducts in attic or 28% vs baseline with ducts in conditioned space	[20]
Geneva, Switzerland	Field test: Multifamily residential Baseline: NG or fuel oil fired boilers	Total heating costs increased approximately 6% to 9% CO_2 emissions decreased by 74% to 98% Seasonal COP (SCOP) 2.8, 3.0, and 3.0	[8]
Vancouver, Canada	Field test: City hall building, air source heat pump (ATWHP) Aermec NRP multipurpose ASHP Baseline: NG fired boilers and chiller with cooling tower for cooling Measured: Predicted savings, measurements in progress	Combined simultaneous heating and cooling COP 6.3 maximum at 10^{o}C outdoor temperature Predicted 45% NG savings, 34% GHG savings, -6% electricity savings Backup natural gas boilers required when below freezing	[21]
Eltham and Victoria, Australia	Field test: Single family residential radiant heating and domestic hot water Baseline: LPG fired boiler Measured: Overall energy costs (assume heating only)	75% lower energy costs (assume heating only)	[22]
Modesto, California, USA	Field test: Single family residential	GTI demonstration house in Modesto report will be available mid 2019	[23]
Juneau, Alaska, USA	Field Test: Residential	COP 2.5, reduced diesel generator consumption by 858 gallons per year	[16]

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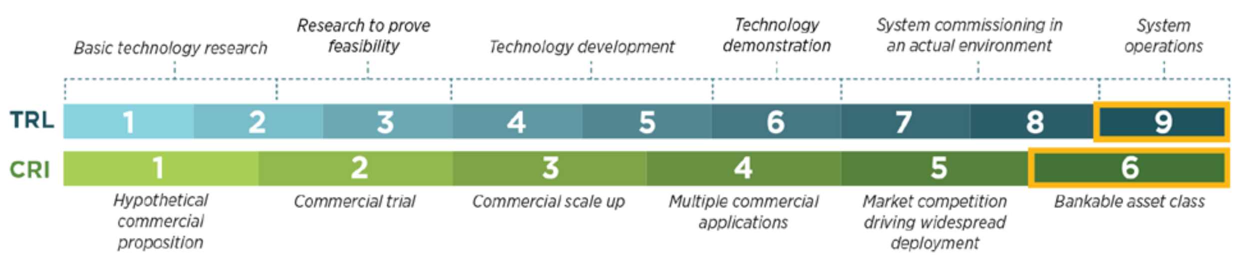
Technology Sector Electric Space Conditioning Product Category Ceiling Fans Last Updated 12/27/2018	 Figure 1: Ceiling fan [Source: Big Ass Fans]

Product Category Overview

Ceiling fans are a type of personal comfort system that uses air motion to provide occupant cooling, but they are typically under the control of (or impacting) more than one individual. While small-sized ceiling fans are common in residential buildings, recently larger diameter ceiling fans are becoming available for use in larger and high-ceiling spaces (e.g. open plan offices, classrooms, warehouses, etc.).

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings can be achieved through intelligent control and integration with relatively energy-intensive centralized space conditioning equipment. Air movement created by ceiling fans can cool a person indoors in a similar manner as lowering the space temperature, but uses only a tiny fraction of the energy required by HVAC systems. New fans, using only 1 to 8 watts and producing 1.5 to 2 mph air movement near each of a building's occupants, can offset a 3°C increase in indoor air temperature. Allowing higher indoor temperatures reduces a building's total HVAC energy an average of 9% per °C.

When properly integrated and controlled, ceiling fans can serve as a first stage cooling system, allowing mechanical cooling equipment to remain off until higher temperatures are reached and to use less energy once switched on. Ceiling fans also have great comfort and energy benefits in sport facilities, where normally the spaces are controlled at quite low ambient temperatures (often around 20°C). With ceiling fans, the ambient temperature can be raised 6°C up to 26°C, while equivalent or better comfort is achieved.

Non-Energy Benefits

Ceiling fans are a particular type of personal comfort system that have the potential to satisfy individual comfort requirements under cooling conditions by allowing occupants to control their local thermal environment by increasing or decreasing the local air movement to match their comfort preferences.

The increased air motion will improve not only the occupants' comfort but also their perceived air quality. Interpersonal differences between building occupants are equivalent to 2-5°C (4-9°F) difference in ambient temperature. Occupant-controlled ceiling fans can help to mitigate those differences. Occupant controlled fans can also address transient thermal comfort needs in a way that centralized HVAC cannot. For example, addressing a short term (e.g. 10-15 minute) cooling need after an occupant commutes into work on a hot summer day. It also helps in transitional spaces like entrances/hall ways of an air-conditioned space.

Product Category Differentiation

Ceiling fans are differentiated from other personal comfort devices such as desk fans in that they may influence comfort conditions for more than one person at a time (e.g. in open plan office applications). Affected building occupants may need to use consensus to determine optimal control strategies. To achieve energy savings, the operation of ceiling fans under cooling conditions must be integrated with zone thermostats enabling the adjustment of (or reduction of on-time) centralized HVAC equipment.

Installation Pathway and Dependencies

A wide range of ceiling fan products are available and suitable for installation in new construction, major renovation, retrofit, and/or plug-in. Ceiling fans can be installed in commercial, education, residential, multi-family, warehouse, and other building types. As described above, to achieve energy savings, the operation of ceiling fans must be integrated with the control of the centralized space conditioning system in the building. This can be done manually, but the most effective approach is to install smart ceiling fans with communicating thermostats for intelligent building control. Smart fans integrated with smart thermostats represent the next generation of energy efficiency.

List of Products

Many ceiling fans are available on the market, including small (residential) and large-diameter (commercial and industrial) models. A preferred “smart ceiling fan” is included in the table below.

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Big Ass Fans	Haiku® with SenseME™ control	Smart ceiling fan	Smart fan is capable of learning occupant preferences and automatically adjusting fan rotational speed based on temperature, humidity and occupancy. Energy efficient DC motor.
Big Ass Fans	3025, 3600, 4900	Commercial/industrial ceiling fan	10 ft 6 in, 12 ft 6 in, 14 ft 6 in diameter ceiling fans
Aeratron	AE2, AE3	Ceiling fan	Energy efficient DC motor with multiple speeds.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
N/A	Energy simulation study Heating and cooling setpoints were varied parametrically in seven ASHRAE climate zones and in six distinct medium-sized office buildings.	Without reducing satisfaction levels, by increasing the cooling setpoint of 22.2 °C (72 °F) to 25 °C (77 °F), an average of 29% of cooling energy and 27% total HVAC energy savings are achieved.	[1]
Berkeley, California, USA	Human subject Laboratory study, in a climate chamber controlled at three temperatures (26°C, 28°C and 30°C) and two relative humidities (RH 60% and 80%) The effects of air movement from ceiling fans on subjective thermal comfort and perceived air quality (PAQ) were examined for warm-humid environments. 16 subjects (8 males and 8 females) dressed in summer clothing (0.5 clo) were exposed to 7 levels of air speeds ranging from 0.05 m/s to 1.8 m/s. Unit clo quantifies clothing insulation level, the higher the value, the better the insulation. 1 clo = 0.155 m2°C/Watt. 0.5 clo corresponds to an ensemble of short-sleeved shirt and long slacks. It has half the insulation value of a fairly warm business suit.	Air movement from ceiling fans significantly improves the subjects' thermal comfort, PAQ, and humidity sensation without causing dry eye discomfort. Without air movement, the 80% acceptable limit established by the ASHRAE standard 55 was reached at 26°C/60% RH, 26°C/80% RH, and 28°C/60% RH. With air movement, more than 80% of the subjects perceived the environments acceptable at 28°C/80% RH, 30°C/60% RH, and 30°C/80% RH.	[2]

Location	Application	Results	Reference
Berkeley, California, USA	Human subject laboratory study. Subjects were tested under a set of air speed setpoints as might be used in automated control of ceiling fans. 23 subjects in summer clothing experienced a matrix of four temperatures (24°C, 26°C, 28°C and 30°C), two levels of humidity (RH 40% and 60%), and two metabolic rates (1.0, 1.4 met).	The automated fan control strategy worked well, producing comfort for over 80% of the subject population throughout the test conditions. The air speeds personally chosen by test subjects in the 24°C and 26°C conditions differed little from the experiment's fixed air speeds. Subjects chose significantly greater air speeds in the 28°C and 30°C conditions. Ceiling fans were very effective for providing comfort in warm temperatures and high humidities, up to the 30°C/60% RH hottest environment tested in this experiment. Without air movement, the upper comfortable limit was 26°C/60% RH. The corrective power of the ceiling fans was therefore at least 4°C.	[3]
Singapore	Field study Performed in three environmental conditions (one with a set-point of 23 °C—a typical set-point used in Singapore—and two elevated (up to 28 °C) room temperature conditions). Occupants had shared control of ceiling fans.	The most comfortable thermal condition is achieved at a room temperature of 26 °C with operating fans. Increasing the temperature set-point from 23 °C to 26 °C resulted in a significant increase in thermal acceptability (from 59% to 91%) 44 kWh/m^2 annual savings in electrical energy used for comfort cooling. A room's set-point temperature can be increased up to 27 °C without creating a negative impact when controllable air movement is provided compared to an environment with a set-point of 23 °C. Occupant's self-reported ability to concentrate, be alert, and ability to be productive was comparably high in all conditions.	[4]

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Technology Sector
Electric Space Conditioning

Product Category
Condenser Air Evaporative Pre-Coolers

Last Updated
10/05/2018

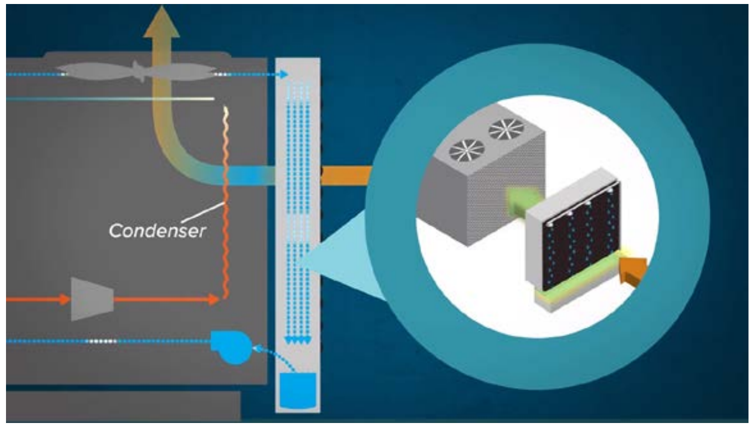
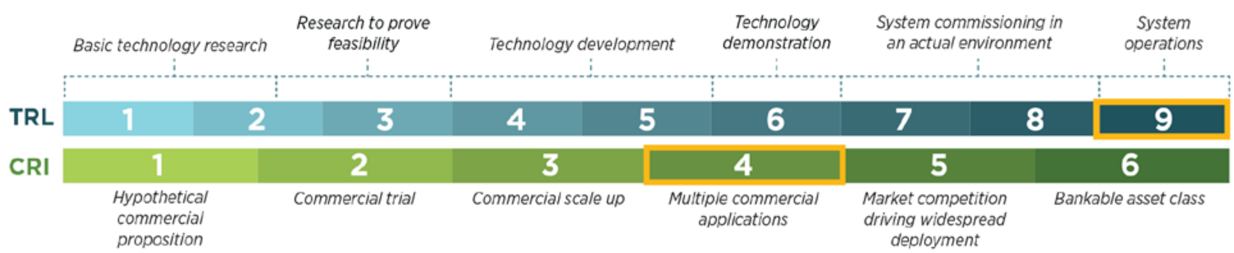


Figure 1: Diagram of an evaporative condenser-air pre-cooler installed on an RTU where the water passes through the evaporative media to pre-cool the condenser air [1].

Product Category Overview

Evaporative condenser-air pre-cooling is used to cool the air passing over the condenser coil of a traditional compressor-based air conditioning system, which increases the efficiency of the air conditioning process by lowering the heat rejection temperature. In evaporative pre-cooling, water is evaporated into the outdoor air which cools the air stream. The improvement in the air conditioner efficiency reduces energy consumption and peak demand for cooling.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Cooling for commercial buildings is provided predominantly by rooftop packaged air conditioning units (RTUs) and other unitary vapor-compression systems. In these cooling systems, condensing units reject heat from refrigerant directly into the outside airstream. As the outdoor air temperature rises, the efficiency of the air conditioning system drops and requires more energy to provide the same amount of cooling to the conditioned space. The decrease in both cooling capacity and energy efficiency with increasing ambient temperatures result in greater stress on California's electrical grid.

Evaporative pre-cooling is a technology used to cool the air passing over the condenser coil of a traditional compressor-based air conditioning system. Lowering the temperature of the airstream across the condenser coil decreases refrigerant pressure and the work that needs to be done by the compressor. In evaporative pre-cooling, water is evaporated to cool the airstream before reaching the condenser coil. The improvement in the air conditioner efficiency reduces energy consumption and peak demand for cooling. There are various designs for evaporative pre-coolers, particularly with regards to how the water is evaporated prior to the condenser coil. Products vary in nozzle type, spray pressure, water flow rate, and the type of evaporative media used.

Non-Energy Benefits

This technology may extend the life of the HVAC equipment due to the decrease in work of the cooling equipment's compressor. Pre-coolers also increase building occupant comfort by increasing compressor capacity during peak conditions, when it is needed most.

Product Category Differentiation

This evaporative pre-cooler technology is applied to the air that passes over the cooling system's condenser. This is unlike other evaporative cooling technologies, such as indierect and direct evaporative coolers, which use the evaporative cooling process to cool the air being delivered to the building.

Installation Pathway and Dependencies

This technology is most commonly installed as a retrofit for packaged air conditioning units with air-cooled condensers or for air cooled chillers, but it can also be installed during new construction or major renovation. Because this technology uses water to precool the condenser air, a water line must be available for system hook up, with a supply flow specified by the manufacturer. Some evaporative pre-cooler products come with a maintenance agreement to perform period checks of the equipment and remote monitoring systems for fault detection.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Evaporcool	Evaporcool	Roof top addition attached to the condenser coil opening	Smart controller, includes 3G wireless on Demand network services, a webserver, data logger and remotely programmable control and performance monitoring software applications.
Blue Energy Technologies	SMART PreCooling	Roof top addition, installed before the condenser	Fine water mist (fog) cools air passing through SMART PreCooling panels
Integrated Comfort Inc.	DualCool	Retrofit for roof top unit	System does both condenser-air pre-cooling and indirectly cools the incoming outdoor ventilation air.
Integrated Comfort Inc.	CoilCool	Retrofit for roof top unit	"Unibody" assembly design made to outlast rooftop unit.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Palmdale, California, USA	Field Test Big-box retail 13 RTUs, ranging 13- to 20-tons Pre-cooling applied to Condenser Air + Ventilation Air	Reduce peak electrical demand by more than 40%. Retrofitted RTUs ranged in 9% to 41% reduction in Energy Intensity Ratio for outdoor air temperatures 85°F to 95°F. 3.4 gal/kWh savings possible with appropriate bleed rate.	[1]
Marysville, California, USA	Field Test Air Force Base dining facility 50-ton chiller Pre-cooling applied to Condenser Air	20% peak savings, reduced peak power draw by 6 kW. 0.9 gal/day-ton water usage. 280 kWh/yr-ton energy reduction. 14,000 kWh/year energy savings.	[2]
Davis, California, USA	Lab Test WCEC lab facilities Five evaporative pre-cooler technologies 4-ton RTU Pre-cooling applied to Condenser air	Demonstrated 20% to 80% evaporative effectiveness. An analysis tool for CZ 10 demonstrated: - 70% effectiveness translates to ~20% peak demand savings and 10% total energy savings - 50% effectiveness translates to 15% peak demand savings and 8% total energy savings Water use effectiveness (amount of water evaporated that generated useful cooling) was 25-100%.	[3]
Davis, California, USA	Lab test WCEC lab facilities Pre-cooler packaged with an Indirect Evaporative Cooler 8 ½ ton RTU Pre-cooling applied to Condenser air	Packaged system can reduce peak demand energy use by 26% and energy consumption by nearly 60%. Condenser pre-cooler evaporates approximately 12 gal/hr, does not account for additional water use for maintenance or bleed rate specified by manufacturer.	[4]
Rancho Santa Margarita, California, USA	Field test Small data center 17.5 ton RTU Pre-cooling applied to Condenser Air	No energy savings were observed. 7.53 gal/hr water usage.	[5]

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Technology Sector
Electric Space Conditioning

Product Category
Dedicated Outdoor Air Systems

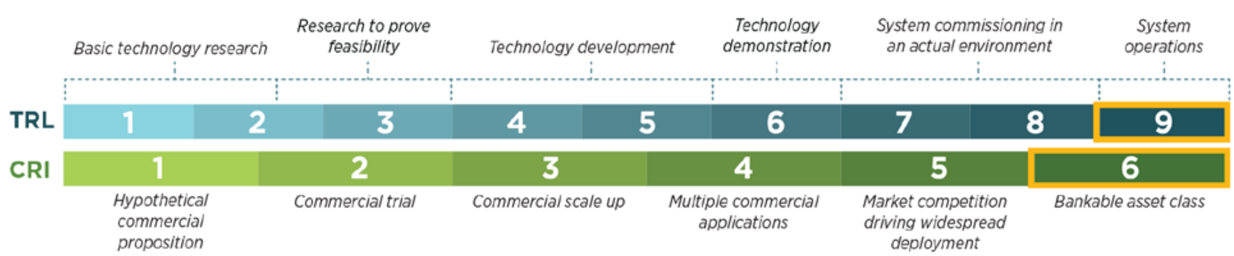
Last Updated
12/14/18

Figure 1: A Carrier brand Dedicated Outdoor Air System [1].

Product Category Overview

Dedicated outdoor air systems deliver 100% outdoor air for ventilation purposes. These systems are specifically designed to condition outdoor air prior to delivering it to the indoor space. Dedicated outdoor air systems decouple ventilation from heating and cooling of recirculated indoor building air, enabling significant fan energy savings and enabling use of emerging technologies. For example, evaporative cooling can be used to condition outdoor ventilation air, and variable refrigerant flow systems can be used for conditioning recirculated indoor air.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Dedicated Outdoor Air Systems (DOAS) save energy by providing ventilation with a dedicated system that is separate from equipment that cools and heats indoor air. A DOAS system can provide the precise amount of outdoor air needed to meet ventilation requirements. The DOAS system can be combined with demand control ventilation to reduce ventilation loads and meet the ventilation demand. High efficiency DOAS include components to improve the efficiency of conditioning outdoor air, such as evaporative cooling and/or energy recovery. Using a DOAS enables use of other energy efficient technologies for heating and cooling indoor air, including technologies that distribute thermal energy using refrigerant or water/glycol. Refrigerant and water/glycol distribution systems are more efficient than distributing thermal energy with air ducts, since ducts leak and are more difficult to insulate. Air distribution systems also require more fan power per unit of thermal energy to move air than an equivalent amount of water of refrigerant. With a DOAS, only the air needed for ventilation must be delivered with an air distribution system. Any additional fans used for the heating/cooling system can then be shut off when heating/cooling set points are met.

Non-Energy Benefits

DOAS may increase indoor air quality by ensuring the required amount of ventilation is provided. Thermal comfort may be improved with a DOAS system because the technology is designed to control the temperature of supplied ventilation air, which can reduce drafts and temperature swings.

Product Category Differentiation

Typical packaged HVAC systems combine outdoor ventilation air with recirculated air for conditioning and distributing to a space. The DOAS conditions only the outdoor air. A DOAS may contain demand control ventilation, energy recovery, and/or indirect evaporative cooling components, which are also specified as separate product categories (because they can be used in applications other than DOAS).

Installation Pathway and Dependencies

Dedicated outdoor air systems can be installed for new construction or equipment replacement. The DOAS can be installed either in series or in parallel with the building's heating and cooling system. If installed in series with existing ductwork, the ventilation air from the DOAS is connected and mixed with the return air to the cooling unit. If installed in parallel, the ventilation air from the DOAS requires its own duct system, as this configuration supplies the conditioned air from the DOAS directly to the zone. When installed in parallel, DOAS can be installed with a high efficiency heating/cooling system, such as variable refrigerant flow or radiant systems. In general, DOAS technology is more attractive for applications with high occupant densities and large outdoor air requirements such as gymnasiums, auditoriums, retail, conference rooms, etc.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Differentiating Feature
York	DOAS	Energy recovery wheel Modulating gas heat Up to 70 tons cooling capacity Up to 18,000 cfm
Carrier	62X	Up to 55 tons cooling capacity Up to 9,000 cfm
Desert Aire	Aura DOAS	Energy recovery wheel option Heat pump option Up to 12,000 cfm
Addison	DOAS	Demand control ventilation Variable speed compressor Up to 70 tons cooling capacity Up to 20,000 cfm
Munters	EPX	Indirect evaporative cooling Up to 77 tons cooling capacity Up to 15,000 cfm

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
San Ramon, California, USA	Field test at a grocery store. This study evaluated the performance of an indirect evaporative-vapor compression hybrid DOAS system. Each stage of the unit was evaluated for performance: indirect evaporative cooing, 2 stages of vapor compression cooling and ventilation only.	Reduces whole building electrical demand for cooling and ventilation during peak conditions by more than 20%. Since installation, project demonstrated 20% energy savings. Ratio of water use to electrical energy savings at peak conditions is 2.5-3.1 gal/kWh savings.	[2]
Pennsylvania, USA	Software modeling. Comparison of VAV systems with and air-side economizer to a DOAS and radiant panel cooling system. VAV system with a 14-ton air-cooled chiller. DOAS/radiant panel system with 2, 5-ton air cooled chillers.	57% peak cooling coil load reduced with DOAS+radiant panels vs the VAV system. 42% total energy consumption saved by using DOAS+radiant panels.	[3]
USA	Energy modelling tool. Modern 2-story office building in multiple U.S. climate types. Baseline system included water source heat pumps with a cooling tower and a boiler serving common loop. Retrofit system consisted of the water source heat pump augmented with a DOAS.	Energy cost analysis was performed and the DOAS resulted in annual HVAC energy cost savings from 21% to 38%. Assumes $.08 per kWh for electricity and $0.60 per therm for natural gas.	[4]
Dallas, Texas; St. Louis, Missouri; Washington District of Columbia; New Orleans, Louisiana, USA	Simulation model for large retail store for four different geographic locations. Compared typical single-path system to dual-path (ventilation and recirculated air conditioned separately).	Results showed that the dual-path system provided 14% to 27% annual energy savings.	[5]

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Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector
Electric Space Conditioning

Product Category
Demand Control Ventilation Products

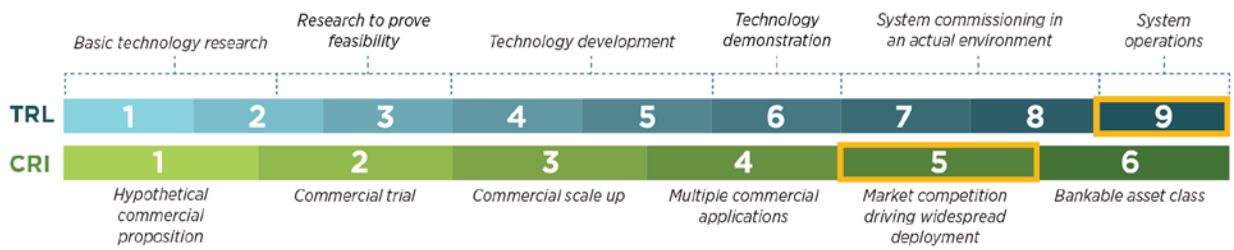
Last Updated
12/06/2018

Figure 1: Demand controlled ventilation delivers ventilation when and where it is needed to reduce loads on equipment, while maintaining compliant indoor air quality standards [1]. *CO_2 sensors, often integrated into thermostats, are used as occupancy feedback for the control system* [2].

Product Category Overview

Demand control ventilation (DCV) is an automated method of controlling ventilation equipment based on occupancy. DCV modulates the volume exchange of outside air into an enclosed space by ventilation equipment, which may be a stand-alone system or incorporated into a packaged heating, ventilation, and air conditioning (HVAC) system. DCV systems monitor either an occupancy metric or measured control variable to determine ventilation demand in a given space and use this metric over time to make adjustments to the ventilation intake and/or exhaust to meet the demand. For the purpose of this evaluation we will only consider systems that use carbon dioxide (CO_2) sensors as their occupancy sensing metric, as this is currently the most accurate and cost effective method in use. The indoor CO_2 concentration is increased when occupants exhale CO_2 and reduced when outdoor ventilation air is introduced into the space. A minimum ventilation rate is required even when CO_2 levels are low in order to remove building contaminants that are not a function of occupancy levels (e.g. off-gassing of building materials).

Characterization at a Glance



Product Category Characterization

Energy Benefits

There is significant energy saving potential in rigorous outdoor air control. By monitoring fresh air requirements in the space, supply air conditioning and heating loads are reduced as more energy is often needed to condition outdoor air. In some cases, when ventilation and conditioning demands are met or reduced fan energy can be saved as well. This leads to energy savings while delivering adequate ventilation air to maintaining a comfortable environment. Energy savings potential is the largest in spaces that have high occupant densities (i.e. high ventilation rates) but are intermittently occupied (e.g. conference rooms, auditoriums).

Non-Energy Benefits

DCV has the potential to improve Indoor Air Quality (IAQ) as well, as it controls ventilation levels to maintain code-compliant conditions. In addition, the CO_2 sensor provides continuous monitoring that can be used to detect ventilation system problems. There is significant evidence that adequate ventilation reduces absence rates and improves student performance in K-12 schools [3] and that lower CO_2 levels improve decision making performance in adults [4]. Finally, DCV can reduce exposure to outdoor pollutants by only bringing inside the amount of outdoor air required to control indoor pollutants. In addition to ventilation rate, filtration methods significantly affect the impact of outdoor pollution on indoor spaces.

Product Category Differentiation

DCV is a control strategy that can be implemented with a range of products. DCV combines sensors with existing control devices and existing infrastructure in an optimized way to achieve energy savings and desired indoor air quality. DCV is different from other strategies in that it modulates the amount of ventilation air to meet the demand in the space rather than providing a fixed rate. Fixed position ventilation dampers have two possible problems: they may over-ventilate, leading to energy expenditures to condition excess outdoor air, or under-ventilate, leading to reduced indoor air quality due to excess indoor pollutants. DCV mitigates these two problems by balancing IAQ and the energy needed to meet conditioning loads. Once the system is installed, it can be updated as needed to add additional sensors or changing programming logic.

Installation Pathway and Dependencies

DCV systems can be installed at any time in a building's life cycle but may be easier in some instances than others. For single zone conditioning systems, it could be as easy as installing a CO_2 sensing thermostat in the conditioned space, connecting the signal to operate the ventilation system, and programming the control logic. Systems that already have an economizer are ideal candidates as they have a modulating damper installed at the outdoor air intake, and in many cases economizer controllers already have an input for a CO_2 sensor signal. For more complex multi-zone buildings it may require use of a more versatile logic controller along with installation of modulating dampers or exhaust fans, which would be best to install during new construction, major renovations, or retrofits. If appropriate modulating equipment is already in place, the occupancy sensors and integrated control logic can be installed at any time.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Delta Controls	EZNS-T100	Programmable CO2 and humidity sensing thermostat	Back light, touch interface, fully programmable, extremely versatile. BACnet™ compatible
Pelican Wireless	TS250	Internet Programmable CO2 Sensing Thermostat	Easy to use Web control portal, Web API and usage history data. WiFi enabled

Manufacturer	Model	Type	Differentiating Feature
KMC Controls	BAC – 13,14xxxx FlexStat	Programmable CO2 Sensing Thermostat	BACnet™ compatible, models for continuous occupation or occupied/unoccupied applications. Flexible input output configurations
Honeywell Jade DCV economizer	W7220	Jade Economizer module	Commonly implemented economizer controller often found on existing equipment with economizers. BACnet™ and 2~10Vdc configurable DCV signal input.
Pelican Wireless	Pearl	Economizer and Demand Ventilation Controller	With real-time Online monitoring and automated email/text message of fault detection. WiFi enabled.
Delta Controls	DSC 606E	Native BACnet™ Building Controller	Fully programmable logic controller, could operate and control multiple zones, and/or pieces of equipment. General Versatility and BACnet™ compatibility.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
California, USA	Modeling evaluation DCV compared against fixed ventilation Estimated cost impacts on $/m^2 basis. Estimated break even points for DCV for various climate zones	Results show high potential for savings when evaluated in more extreme climates (i.e. CZ 14 and 16), compared against the higher fixed ventilation rates, and as occupancy loads increase. DCV becomes cost effective when the base case minimum ventilation rate is greater than 42.5, 43.0, 24.0, 19.0, and 18.0 L/s per person for climate zone 3, 6, 12, 14, and 16, respectively.	[5]
USA	State of the Art Review of CO_2 DCV technology	DCV systems can have varying outcomes depending on a number of building use factors. As expected, the energy savings are largest for high density spaces with generally variable occupancy, such as halls, theatres and cinemas. The lowest savings are seen in the office spaces, which generally have lower occupancy densities with less variation than the other spaces. While CO_2 DCV can control occupant-generated contaminants effectively, it may not control contaminants with non-occupant sources as well.	[6]

Location	Application	Results	Reference
N/A	Modern look into how to use environmental sensing metrics to detect occupancy. While DCV is already in a state to make huge impacts on the way we control ventilation rates in buildings, there are still evolving and more accurate ways that control algorithms can be implemented to further increase IAQ and reduce energy demand where possible.	As control methods improve, DCV systems can be updated with little trouble to further increase energy savings. For instance a method called "Sensing by Proxy" can potentially save 55% of total ventilation compared with the traditional fixed schedule ventilation strategy. It does this by developing more accurate occupancy estimates based on real time monitoring of occupancy metrics and environmental factors, such as CO_2 and temperature, to respond more quickly to actual occupancy demands. Current DCV methods tend to target a steady state ventilation flow that meets a code required level for $C0_2$ or other monitored variable, and for this reason tend to under or over ventilate during occupancy level transitions. Newer control methods have the potential to gain even more savings during these times.	[7]

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Product Characterization Report

California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector
Electric Space Conditioning

Product Category
Direct and Indirect Evaporative Cooling Products

Last Updated
12/20/2018

Figure 1: Indirect evaporative heat exchanger media

Product Category Overview

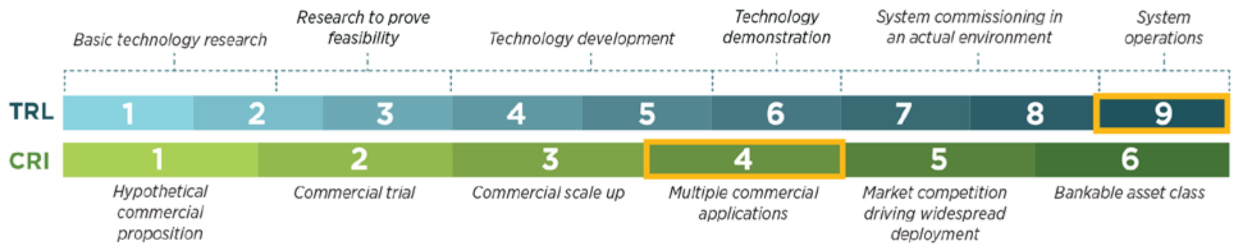
Evaporative coolers provide cooling by evaporating water and use much less energy than compresor-based cooling. There are three types: direct, indirect, and indirect-direct evaporative coolers. Each one consists of at least one fan, connection to a water source, internal water distribution system, and evaporative media. Higher efficiency evaporative coolers use high efficiency fans, pumps, and evaporative media.

Direct evaporative coolers are the simplest of the three types and provide sensible cooling by evaporating water directly into the air stream used for cooling. Applications are limited because moisture is added to the space and the performance depends on the wet-bulb temperature of the inlet air.

Indirect evaporative coolers use direct evaporative cooling combined with an air-to-air heat exchanger to produce cool air without adding moisture. The heat exchangers typically have wet and dry channels. Air flowing through the dry channels is cooled by conducting heat to the wet channels. Air flowing through the wet channels can be either: a fraction of the air that passed through the dry channels, outdoor air, or return air from the space being cooled. The hot, humid air from the wet channel is exhausted outside. Applications are more broad because indirect evaporative coolers can cool air below the wet-bulb temperature of the ambient air (the theoretical cooling limit is the outdoor air dewpoint. They can also be combined with compressor-based cooling to improve efficiency and increase comfort.

Indirect-direct evaporative coolers combine indirect with direct evaporative cooling in series to produce cool air. This all-in-one configuration produces air that is cooler than either techonology individually and and adds minimal mositure to the space. Indirect-direct evaporative cooling can be combined with compressor-based cooling to improve efficiency and increase comfort under a wide-range of climate conditions.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Evaporative coolers save energy by providing cooling without using compressors. In addition, the efficiency of an evaporative cooling system increases with increasing outdoor air temperatures, whereas the efficiency of compressor-based cooling decreases with increasing outdoor air temperature. When combined with compressor-based cooling, evaporative cooling equipment saves energy by increasing the efficiency of the overall system and by reducing the runtime of the compressor-based system. Evaporative cooling equipment has the greatest energy benefits for cooling the ventilation air required for the building. One effective strategy is to use evaporative cooling for the building ventilation air in combination with compressor-based systems to cool the recirculation air.

Non-Energy Benefits

Evaporative coolers do not use hydroflourocarbon (HFC) refrigerants like typical compressor-based systems. Therefore, the equipment has the additional benefit of reducing or eliminating HFC refrigerants that could leak into the atmosphere. Evaporative coolers may provide more outdoor air to a building than comperssor-based systems which can provide an indoor air quality benefit when combined with adequate filtration of outdoor particulates.

Product Category Differentiation

Evaporative coolers are classified by producing cool air that is used to condition a space. Evaporative cooling is also used in related technologies where the air cooled through an evaporative process is used to cool condenser coils (condenser air pre-coolers) or chill water (cooling towers and sub-wet-bulb evaporative chillers).

Installation Pathway and Dependencies

Evaporative coolers can be installed as part of new construction, major renovation, or as a retrofit. Installation of the equipment is dependent on access to building power, connection to the buildings domestic water line, and the roof being able to support the operating weight of the equipment. Depending on the installation location, evaporative coolers may require additional maintenance to maintain proper water quality, shorter intervals between air filter changes (because of increased outdoor air volumes), and winterization to prevent water pipes from freezing.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Air_2O	Standard Series	Indirect/Direct	Gas heating option available. Proprietary automated control system with BACnet compatibility
Coolerado	M50	Indirect	Designed to be modular with zero side clearance required.
Munters	Oasis® IEC	Direct, Indirect, or Indirect/Direct	Polymer tube, plate, or heat pipe indirect heat exchangers available.
Seeley International	Breezair	Direct	Direct drive fan motor Different evaporative media thicknesses available.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table *2*.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Cudahy, CA and Placentia, CA, USA	Field testing. Two indirect evaporative cooling technologies compared to existing mechanical system for cooling cellular sites. Measurements included: Measurements included: dry-bulb temperature and humidity of inlet and outlet air, electrical power consumption, water consumption, and airflow	The indirect evaporative cooler had the following coefficient of performance (COP) [$kW_{COOLING}/kW_{POWER}$] and water use efficiency [Gal/Ton-hr cooling] Cooler 1: COP 10.2-18.6, water use 3.4-4.4 Gal/Ton-hr Cooler 1: COP 10.2-18.6 Water use 3.4-4.4 Gal/Ton-hr	[1]
Australia	Field testing. Indirect evaporative cooling compared to existing mechanical system for cooling ventilation air for a commercial building. Measurements included: dry-bulb temperature and humidity of inlet and outlet air, electrical power consumption, and airflow.	The indirect evaporative cooler operated with coefficient of performance (COP) [$kW_{COOLING}/kW_{POWER}$] between 8 and 12, with an average of 11.5.	[2]

Location	Application	Results	Reference
Iran	Laboratory testing. Indirect evaporative coolers to pre-cool air for the conventional mechanical cooling system tested at 48 points relevant to the Iran climate. Measurements included: dry-bulb temperature and humidity of inlet and outlet air, electrical power consumption, and airflow.	The indirect evaporative cooler could reduce the cooling load on the mechanical system by 75% and reduce the power consumption of the mechanical system by 55%.	[3]
Saudi Arabia	Laboratory testing. 5-ton indirect evaporative cooler under controlled hot and dry climatic conditions. Measurements included: dry-bulb temperature and humidity of inlet and outlet air, electrical power consumption, airflow, fan speed, water consumption rate.	The COP of the indirect evaporative cooler varied from 7.1 to 55.1 depending on the airflow rate and climatic conditions. The power consumption varied between 68.3 to 746 watts Water consumption varied between 0.0160 m^3/h to 0.0598 m^3/h	[4]
Iran	Laboratory testing. Two-stage indirect/direct evaporative cooling system in various climate conditions relevant to Iran. Dry-bulb temperature and humidity of inlet and outlet air of indirect evaporative component Dry-bulb temperature and humidity of inlet and outlet air of direct evaporative component Airflow. Electrical power consumption. Water consumption.	The coefficient of performance [$kW_{SENSIBLE\ COOLING}$ / kW_{POWER}] of the two-stage system was between 8.2 and 9.1. The energy savings over a conventional vapor compression system was estimated to be 64% to 68%. The water consumption was quantified using the metric [$kg_{WATER}/kg_{PRIMARY\ AIR}$]. The two-stage system consumed 0.00875 to 0.0119 $kg_{WATER}/kg_{PRIMARY\ AIR}$ based on the tested climate conditions	[5]

References

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Technology Sector
Electric Space Conditioning

Product Category
Energy Recovery Ventilators

Last Updated
12/21/2018

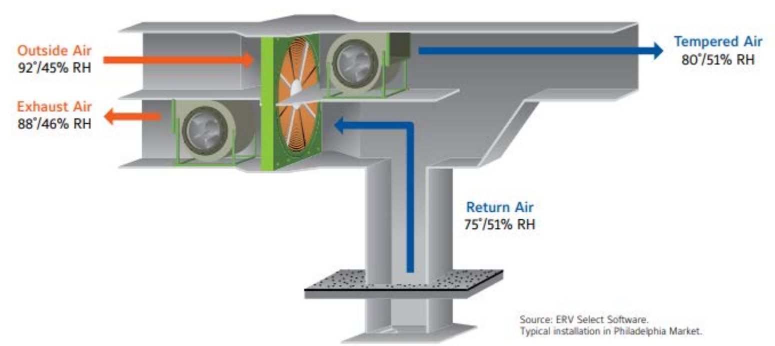
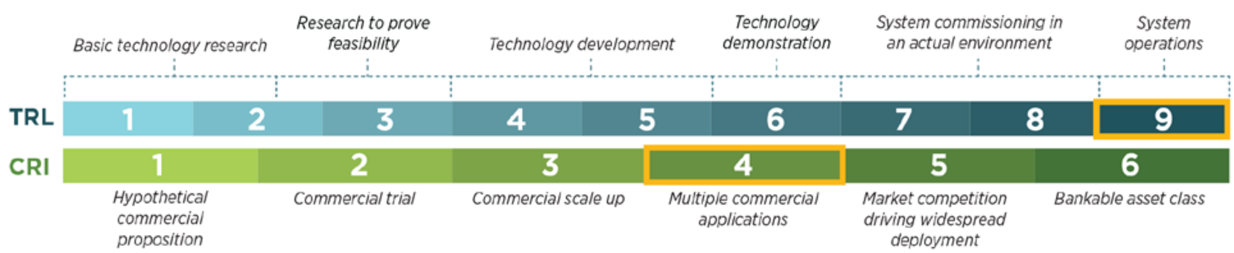


Figure 1: Example of a type of Energy Recovery Ventilator during summer operation [1].

Product Category Overview

Energy recovery ventilators (ERVs) exchange energy or heat between ventilation air entering and exhaust air exiting a building. In winter, the warm exhaust air exiting a building pre-heats the cool outdoor ventilation air being introduced into the building. Similarly in the summer, the cool exhaust air exiting a building pre-cools the hot incoming ventilation air. The energy transfer between the exhaust and ventilation air can either be sensible (heat recovery only) or sensible and latent (heat and moisture recovery). Types of configurations for energy recovery ventilators include plate heat exchangers and enthalpy wheels. Energy is saved by reducing the amount of thermal conditioning needed for ventilation air.

Characterization at a Glance



Product Category Characterization

Energy Benefits

ERVs use otherwise wasted heat from exhuast air leaving a building to precondition incoming outside air. In the winter, the warm return air from the building pre-conditions the incoming cooler outdoor air, reducing the energy required by HVAC equipment to condition the outdoor air. Similarly in the summer, the cooler return air from the building pre-conditions the incoming hot outdoor air.

There are two types of recovery ventilators, Heat Recovery Ventilators (HRV) and Energy Recovery Ventilators. Both designs offer energy savings by using the heating or cooling energy from the building exhaust air, but an HRV does so by transferring the sensible heat only while an ERV system tranfers both heat and humidity.

Non-Energy Benefits

Energy and Heat Recovery Ventilators ensure the proper amount of ventilation air to a space. These systems can increase and improve indoor air quality, increasing occupant health comfort. Additionally, energy recovery ventilators can provide better humidity control in the air being supplied to the space, which also increases occupant comfort.

Product Category Differentiation

Typical HVAC equipment provides ventilation by exhuasting indoor air returned from a space and replacing it with outdoor air. This outdoor air is conditioned before entering the space, especially when outdoor conditions diverge from thermostat setpoints, resulting in more energy use by the HVAC equipment. Instead of using the HVAC equipment to completely condition the outdoor air, ERVs and HRVs use the return exhaust air from the building to pre-condition the incoming outdoor air.

Installation Pathway and Dependencies

ERV and HRV systems can be installed during new construction or retrofit applications. When installed as a retrofit, it may be possible to combine the system with an existing HVAC system to use existing ductwork [2].

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
RenewAire	EV series (light commercial), HE series (commercial/packaged units), LE series (commercial/large capacity)	Indoor and rooftop installations available.	EV airflow ranges 200 to 540 cfm. HE airflow ranges 250 to 7,950 cfm. LE airflow range 1,500 to 11,000 cfm.
Fantech	SHR series, ECHO series, SER series	Models are for both HRV and ERVs.	SER airflow ranges 450 to 1,300 cfm. ECHO airflow up to 2,800 cfm. SHR airflow ranges 450 to 1,400 cfm.
Lifebreath	Various models	ERV	Airflow for various models range from 300 cfm up to 1,225 cfm.
Ventacity	VS1000 RT	HRV	Airflow up to 1060 cfm.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
N/A	Used results from an ERV installed in a laboratory at the University of British Columbia over 4 weeks. eQUEST energy simulation tool used to study impact of the ERV for a low rise multi story building. Single zone, packaged HVAC unit used for baseline in simulation software.	Simulation results show 10-50% less energy consumption than actual for the baseline building simulated. Gas consumption decreased with ERV while electric energy consumption increased. Electric consumption increase due to increase in space cooling and ventilation fans use. Simulation assumed no mechanism to bypass ERV in summer, likely increase in electrical consumption from baseline.	[3]
Miami, Florida, USA; Phoenix, Arizona, USA; Chicago, Illinois, USA; and Helena, Montana, USA	10-story office building modeled in TRNSYS. Four different climate zones used for simulations. Ventilation set at constant rate (by air changes per hour). Baseline hass no ERV in place while meeting building ventilation requirements.	Depending on climate and system effectiveness, ERV reduces annual heating energy consumption by 40% during heating season. Results or the cooling season show, using optimum control strategies, up to 20% annual cooling energy saved (depending on geographical location).	[4]

References

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Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector
Electric Space Conditioning

Product Category
Exhaust Fans and Turbine Ventilators

Last Updated
12/20/2018

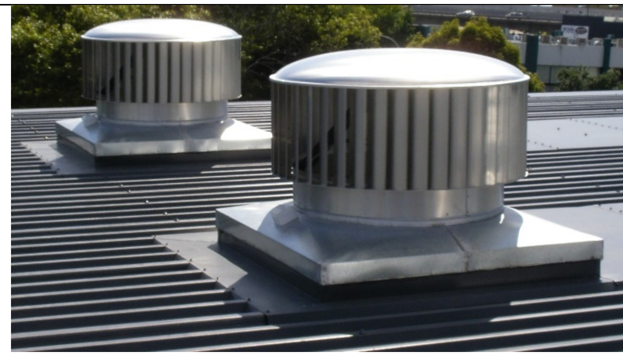
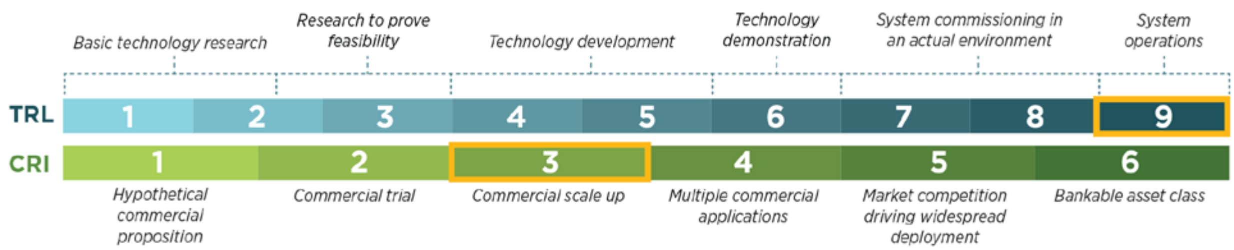


Figure 1: Example turbine ventilator fan installed on roof

Product Category Overview

Building exhaust systems can either be powered by fans or passively driven by wind (also known as turbine ventilators). At least one hybrid version is available that combines a high efficiency powered exhaust fan with a turbine ventilator to maximize overall operational efficiency and reduce energy consumption.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Exhaust systems are necessary to maintain acceptable air quality in buildings. Energy savings is possible from using higher efficiency motors (typically electrically commutated motors (ECMs)) to drive the fans or different fan designs that allow for the fan to be driven passively by the ambient wind.

Non-Energy Benefits

Non-energy benefits of exhaust fans include improved indoor air quality for occupants of the building. Indoor air quality is improved by the exhaust fans removing contaminated air generated from various sources inside the building.

Product Category Differentiation

These fans are different in that some have a hybrid operation allowing for the fan to either be driven by a motor or driven passively by the wind when possible. This allows for the energy consumption to be reduced by utilizing the passive wind power.

Installation Pathway and Dependencies

This technology can be installed during new construction, major renovation, and as a retrofit. In order to install this equipment the ventilation system would have to be temporarily disabled to remove the old fan and install the new technology. This technology also requires ducting for ventilation.

List of Products

Table 1: Summary of manufacturers and products for the product category

Manufacturer	Model	Type	Differentiating Feature
Edmonds	EcoPower	Hybrid turbine ventilator.	Has both an ECM and turbine configuration so it can operate actively with the motor or passively by using wind power.
Canarm	ALX-UD-EC-Upblast Direct Drive Spun Alum Exhauster, ALX-DD-EC Downblast Direct Drive Spun Alum Exhauster	Exhaust vent with ECM.	Traditional exhaust fan with ECM that is more efficient than traditional induction motor.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Caerphilly, UK	Performed laboratory test of motorized turbine exhaust ventilator. The baseline technology was a conventional direct current fan. The baseline fan was not tested but a common direct current fan performance was estimated. The flowrate through the turbine and power consumption were computed to assess the performance.	The flowrate through the turbine when powered with the direct current motor was found to be less than when it was driven by the wind at the same speed. It was believed to be lower because the wind driving the turbine creates a negative pressure that increases the flowrate. When compared the baseline direct current fan, it was found to move twice the air for the same power draw.	[1]

References

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Technology Sector
Electric Space Conditioning

Product Category
High Efficiency Air Filters

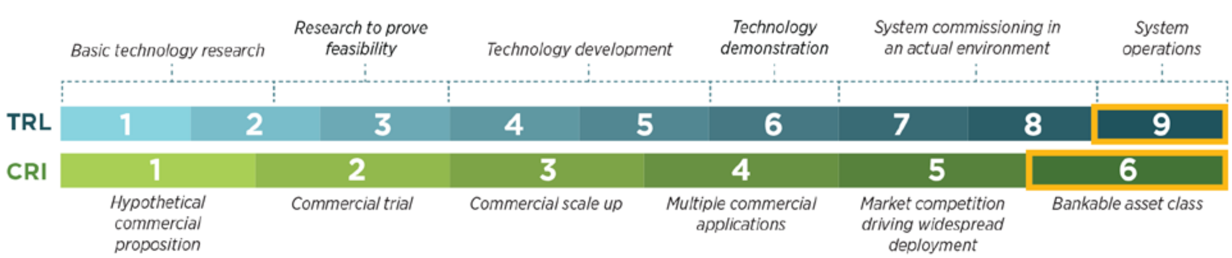
Last Updated
1-18-19

Figure 1: Air filter with minimum efficiency rating value of 13

Product Category Overview

Forced air heating, ventilation, and air conditioning (HVAC) systems require filtration of the air to remove particulates and maintain indoor air quality standards. This filtration is performed by passing the air across filters commonly located upstream of the evaporator coil, which physically traps and removes the debris from the airstream. There is a spectrum of filter performance reported as a minimum efficiency reporting value (MERV), which rates the filters ability to remove particles from the air. Depending on the MERV, a filter can be capable of removing large particles such as pollen and carpet fibers down to small particles such as bacteria and tobacco smoke. Filters use different methods for removing particulates including physical barriers to trap particulates and electrically charging surfaces so that small particles collect. Although the MERV filter performance rating is generally reported for each filter, the consumer generally has no information on the initial pressure drop of the filter and associated energy impacts. Manufacturers claim to produce higher efficiency designs and test data is needed to verify these claims. California's Appliance Standards (Title 24) will require air filters manufactured after April 1st, 2019, to be labeled with their MERV value, particle size efficiencies, and initial resistance at five airflow rates [1].

Characterization at a Glance



Product Category Characterization

Energy Benefits

Filters add resistance to airflow in an HVAC unit, and some filters have more resistance than others. A study completed by the University of Texas and University of Toronto demonstrated that there is a wide range of initial resistance (i.e. filter pressure drop) for filters with the same MERV rating. Maximizing the surface area of the filter reduces the total resistance to the airflow. This reduction in resistance can improve energy efficiency of the blower fan in the HVAC unit, and in some cases the heating and cooling efficiency if reduced resistance increases delivered airflow, which is the case for fixed speed blower fans.

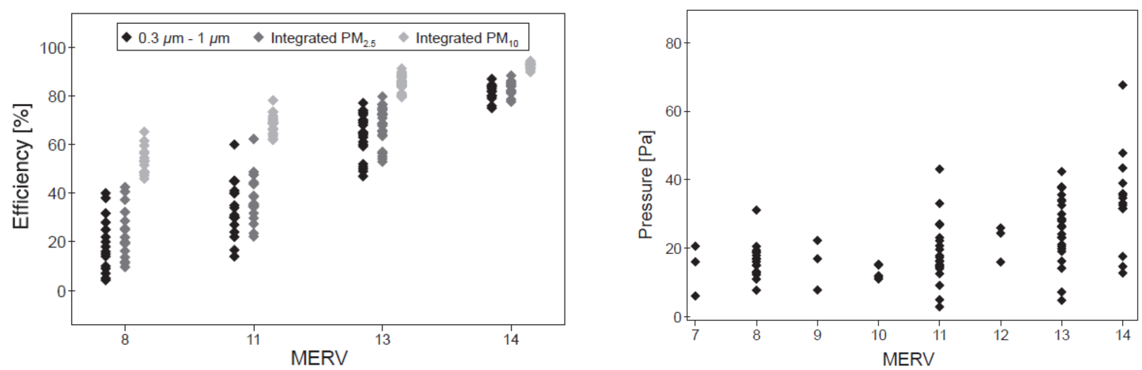
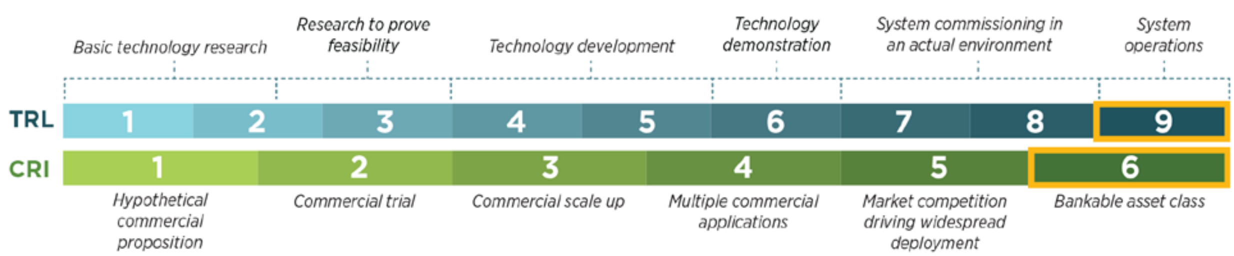


Figure 2: Particulate matter removal efficiency versus MERV rating (left) and initial filter pressure drop versus MERV rating (right) [2].

Non-Energy Benefits

The main non-energy benefits of HVAC air filters is that they improve indoor air quality by filtering out pollutants. This has been shown to improve work performance, reduce absence, and reduce health care needs [3].



Product Category Differentiation

Unlike ventilation, which improves indoor air quality by diluting the indoor air with fresh outdoor air, air filters improve air quality by removing pollutants from the air in the conditioned space. Ventilation allows for the reduction in CO2 concentration which cannot be improved by air filters. Air filters allow for the purification of the indoor air which cannot be performed by ventilation alone. Therefore, both ventilation and air filters are necessary to maintain a health indoor air quality.

Installation Pathway and Dependencies

Air filters are replaced at regular intervals and can be often installed with no tools or specialized knowledge. It is also important to implement a replacement schedule since the resistance of the filter increases as particles accumulate.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
3M	Filtrete	Pleated air filter	Rating up to MERV 14
Air Bear	Air Bear media filters	Pleated air filter	Available in efficiency ratings between MERV 8 to 13
Aprilaire	210, 213, 213CBN, 216, 410, 413, 413CBN, 416, 510, 513m 513CNBm 516, 310, 313, 110, 113	Pleated air filter	Comes in various sizes and MERV ratings. Offer odor reduction filters which use carbon to remove odors
Bryant	Preferred Series EZ Flex Cabinet Air Filter	Pleated air filter	Available in MERV 10 or 13
Carrier	Infinity	Pleated air filter	Available in MERV 6 to 15
Honeywell		Pleated air filter	Available in MERV 4 to 13
Lennox	Healthy Climate, Carbon Clean Healthy Climate, PureAir	Pleated air filter	Available in up to MERV 16 with carbon filtration available to reduce odors
IQ Air		Pleated air filter	MERV 16 filter available
Air Filters Incorporated	Lifetime Silver Series, EZ2000 Series, Quik-Kleen Perm-A-Foam	Electrostatic washable filter	Reusable filter which can be washed instead of being replaced

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Austin, TX	Field data collected on 14 roof top units at a big box retail store.	Results demonstrated a weak correlation between filter pressure drop and MERV rating. Pressure drops vary widely based on differences in filter design.	[2]
Davis, CA	Lab testing of 13 residential air filters with MERV ratings 8-13	There was a high variability in fan energy consumption for filters with a MERV 8 rating. The lowest resistance filters used 10% less fan power than the highest resistance filter.	[4]

References

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Technology Sector
Electric Space Conditioning

Product Category
High Efficiency Motors

Last Updated
12/20/2018

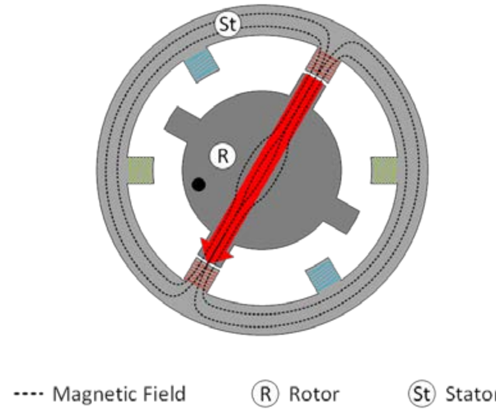
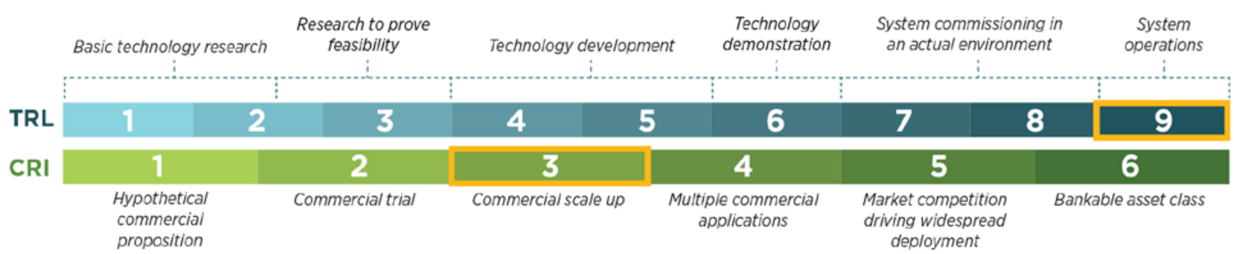


Figure 1: Schematic of the primary components of a switched reluctance motors

Product Category Overview

High efficiency motors, which include switched reluctance motors, operate at a higher efficiency compared to induction motors that meet federal minimum efficiency requirements. High efficiency motors are particularly advantageous in variable speed applications. Switched reluctance motors are more efficient when compared to induction motors because they are actively controlled systems. The speed is controlled by an inverter that operates at higher efficiency than a variable frequency drive used to control the speed of an induction motor. High efficiency motors save energy in HVAC applications by improving efficiency of fan systems.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Rooftop package air conditioning units use blowers consisting of a fan and motor to move conditioned air into buildings. Induction motors are one of the most common types of electric motors used for this application [1]. The primary components of an induction motor are the stator (ST) (stationary part), a rotor (R) (rotating part), and the wire windings in them that create the electromagnetic poles (Figure 1). Induction motors have windings on both the stator and rotor (Figure 1, left). Induction motors operate at a fixed shaft speed which is based on the frequency of the alternating current (AC) power supplied to the motor as well as the number of poles in the stator. The torque output of the motor depends on the difference between the rotational speed of the magnetic field generated in the stator and physical rotational speed of the rotor, called slip.

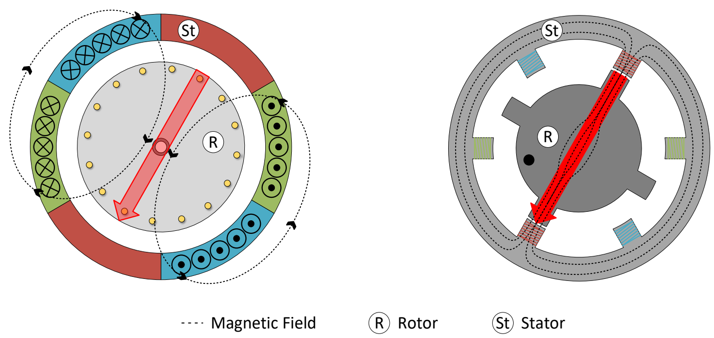


Figure 2: Schematic of traditional induction motor (left) and high rotor pole switched reluctance motor (tight). The stator is the stationary part of the motor (St) while the rotor (R) rotates inside the stator.

Switch reluctance motors (SRMs) are a variation of an electrical motor that has been used in industrial applications since the 1850s. However, it wasn't until more recent availability of cheap and reliable solid state switching devices that the technology's potential for wider use was able to be realized [2]. High rotor pole SRMs are a subset of SRMs that differ by having a non-traditional ratio of stator poles to rotor poles (i.e., 6/10 versus 6/4) [3]. The use of a non-traditional ratio reduces the rotational travel per excitation and increases the static torque that can be produced [3] [4].

SRMs, in general, have the following differences when compared to induction motors:

1. The rotor is made of a stack of ferrous laminate material and does not have windings (Figure 2, right)
2. The stator poles are driven with direct current (DC) power and require an inverter when powered by AC power
3. The current in the stator windings requires active control and cannot operate without an inverter/controller

High efficiency motors are more efficient than traditional motors at 100% speed but they are particularly advantageous in variable speed applications [5]. When an induction motor is operated at a variable speed using a variable frequency drive (VFD), the efficiency of the motor is reduced. At lower speeds SRM motors do not experience the same reduction in efficiency. This makes SRM motors the more efficienct option when operating motors at variable speeds [5].

Non-Energy Benefits

Switch reluctance motors are considered to be more rugged and reliable than traditional induction motors due to them having fewer fault modes. Due to the motors being more dependable, this could result in reduced maintenance cost over the lifetime of the motor.

Product Category Differentiation

The most similar product category is an induction motor paired with a variable frequency drive, which has a fundamentally different motor design. Unlike induction motors, which use coils of wire on the stator and rotor to create the electromagnetic poles, SRMs use solid state switching devices with ferrous laminate material to operate. The speed of an induction motor is controlled by the frequency of the AC current being used to power it while the torque output is dependent upon the rotation of the magnetic field in the stator and the rotation of the rotor. Unlike an induction motor, the speed of an SRM is controlled by the switching of the solid state switching devices and the torque can be controlled independently by the amount of current used to power the motor. These difference makes SRMs more efficient than traditional motors.

Installation Pathway and Dependencies

High efficiency motors can be used for any motor application and can be installed during new construction, major renovations, or as a retrofit. One limitation of SRMs is that they are currently only available in a limited horsepower range from 1-10 HP. Another limitation is necessary space for a retrofit installation. Installation space must include sufficient space to install both the replacement motor, which is typically the same approximate size as the original motor (but maybe be larger), as well as an inverter/controller.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
SMC	Vulcan	SRM	High efficiency motor which can independently control speed and torque. Their motors are connected devices and include controls to improve overall system operation efficiency.
Nidec Motors	U.S. Motors	SRM	High efficiency motor which can independently control speed and torque. US Motors are rare-earth free and are durable due to having no brushes, windings, motor bars, or end rings.
Rocky Mountain Technologies	SR130, SR165, SR210, SRB280	SRM	High efficiency motor which can independently control speed and torque. Also have a range of standard drives and custom drives to allow for an optimally matched system.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Davis, California, USA	Laboratory testing comparing efficiency of a baseline induction motor and VFD to a SRM in a 10 ton RTU. The performance was assessed by measuring torque, motor speed, power, airflow, motor/drive efficiency, and power factor. Field test comparing a baseline induction motor and VFD to a SRM motor in 10 ton RTU. The performance was assessed by measurign airflow and fan power intensity.	Laboratory testing demonstrated a fan power intensity [CFM/Watt] reduction between 16.9-21.3%. Field testing demonstrated a fan power draw reduction of 15% compared to the induction motor.	[5]
Kerala, India	Modeling study comparing the efficiency of a baseline single pole induction motor to a SRM. The performance was assessed by computing the input power and the output power to compute efficiency.	The results of the modeling found the SRM to be 26% more efficient when compared to the single pole induction motor.	[6]
Santa Rosa, California, USA	A retrofit of 7 RTU fan motors was completed for a 20,000 square foot building. The baseline technology consisted of seven 1 HP induction fan motors and they were replaced with seven 1 HP SMC switch reluctance motors. The savings were quantified with annualized energy savings.	The monthly energy savings was found to be 881 kWh after the retrofit which was a 53% total annualized fan energy savings.	[7]

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Technology Sector Electric Space Conditioning

Product Category High Temperature Heat Pumps

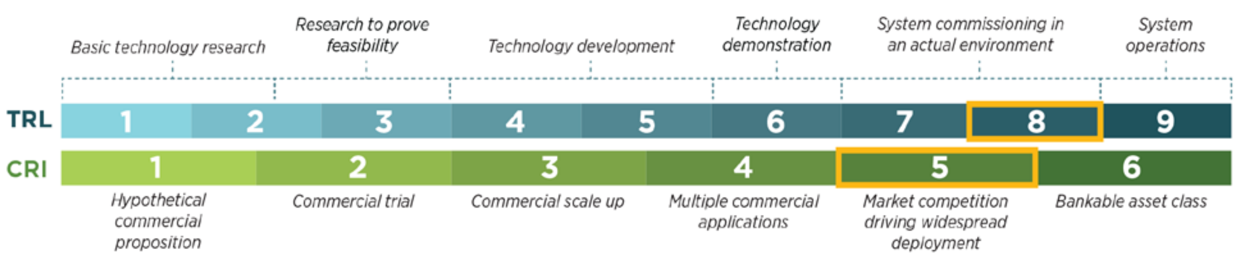
Last Updated 12/07/2018

Figure 1: Mayakawa CO_2 transcritical heat pump providing simultaneous heating of water to 194°F and cooling for refrigeration [1]

Product Category Overview

High temperature heat pumps are a classification of heat pumps that typically have heat sink temperatures between 80°C and 100°C. These heat pumps can be used in applications that, until recently, could only be achieved by burning fossil fuels or using electric resistance heaters. This new technology allows for electrification of processes that previously required the use of fossil fuel. These systems may reduce energy consumption when electric resistance heating is replaced and/or waste heat is recovered.

Characterization at a Glance



Product Category Characterization

Energy Benefits

High temperature heat pumps (HTHP) are defined as heat pumps with supply temperatures between 80°C and 100°C. HTHPs are used to generate industrial process heat for drying, sterilization, evaporation, papermaking, or food preparation. HTHPs can replace fossil fuel combustion in boilers and burners or replace electric resistance heaters [2]. The potential for recovery and upgrading of waste heat can significantly increase efficiency and lead to significant energy savings compared to the fossil fuel and electric resistance systems [2]. The energy benefits are highly dependent on the supply temperature required, the input fluid temperature, the temperature of waste heat available, and the capacity of the systems under consideration. COP values range between 2.4 and 5.8 with a temperature lift (difference between supply fluid temperature and input fluid temperature) of 95 to 40°C [2].The rate that high temperature heat pumps can supply thermal energy ranges from about 20 kW to 20 MW for commercially available systems.

Another application area for HTHP is in district heating loops where higher temperatures (80°C) are required for heating existing buildings with traditional low surface area steam radiators or older hydronic baseboards [3, 4]. Typical modern district heating loops have water supply temperatures of 80°C and future applications are targeting lower temperatures [5].

There are opportunities for even greater energy savings when both cooling and heating services can be provided simultaneously by the same piece of equipment. Simultaneous heating and cooling loads are common in food processing and a number of other industrial processes.

Non-Energy Benefits

Non-energy benefits of HTHPs include shifting to electric heating from fuel combustion heating thereby eliminating or reducing combustion emissions of greenhouse gases and carbon monoxide, utilization of renewably generated electrical energy, and potential for energy cost savings.

Product Category Differentiation

Heat pumps with supply temperatures in the range 80°C to 100°C have application in industrial processes including heat for drying, sterilization, evaporation, papermaking, or food preparation, as well as a small subset of space heating applications including district heating, and hydronic heating retrofits with prexisting low surface area radiators or baseboards [2, 3, 5, 4].

Selection of a HTHP will depend on the requried supply temperature, sources of waste heat, lift temperature required from fluid inlet to supply outlet, and the rate at which energy needs to be supplied (capacity of HTHP). Proper selection requires engineering skills and is necessary for achieving high efficiency operation.

Installation Pathway and Dependencies

HTHPs can be installed during new construction and major renovations. Conversion from fossil fuel combustion systems to high temperature heat pumps in industrial settings require significant changes in equipment and potentially changes to plant operations with a high degree of engineering work in order to select the right equipment and justify the large up front capital cost. HTHPs also require sufficient or upgraded electrical service and distribution wiring. Lastly, there are limitations on heat pump capacity and they sometimes require natural gas or electric resistance boosters to meet the total capacity needed.

Electrical energy typically costs more than fossil fuel energy so for high temperature heat pump systems to compete with fossil fuel combustion systems one or more of the following factors must be present: lower than typical cost for electrical energy, higher than typical cost for fossil energy (fuel oil or other liquid fuels), significant potential for waste heat recovery enabled by the heat pump and not practical for the combustion based system (relatively low temperature waste heat), economic cost for combustion emissions, and/or institutional value placed on reducing use of fossil fuels and combustion emissions.

List of Products

There are more than 20 HTHPs commercially available from 13 manufacturers which can provide supply water or air temperatures of at least 90 °C [2].

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Kobe Steel (Kobelco steam grow heat pump)	HEM-HR90,-90A	High Temperature Heat Pump	R134a/R245fa, 90 °C,70 to 230 kW
Ochsner	IWWHS ER3b	High Temperature Heat Pump	ÖKO (R245fa), 95 °C, 60 to 850 kW
Mayekawa	Eco Cute Unimo	High Temperature Heat Pump	R744 (CO_2), 90 °C, 45 to 110 kW
Combitherm	HWW R1234ze	High Temperature Heat Pump	R1234ze(E), 95 °C, 85 to 1301 kW
Friotherm	Unitop 22	High Temperature Heat Pump	R1234ze(E), 95 °C, 0.6 to 3.6 MW
Friotherm	Unitop 50	High Temperature Heat Pump	R134a, 90 °C, 9 to 20 MW
Star Refrigeration	Neatpump	High Temperature Heat Pump	R717 (NH_3),90 °C, 0.35 to 15 MW
GEA Refrigeration	GEA Grasso FX P 63 bar	High Temperature Heat Pump	R717 (NH_3), 90 °C, 2 to 4.5 MW
Johnson Controls	HeatPAC HPX	High Temperature Heat Pump	R717 (NH_3), 90 °C, 326 to 1‘324 kW
Johnson Controls	HeatPAC Screw	High Temperature Heat Pump	R717 (NH_3), 90 °C, 230 to 1315 kW
Johnson Controls	Titan OM	High Temperature Heat Pump	R134a, 90 °C, 5 to 20 MW
Mitsubishi	ETW-L	High Temperature Heat Pump	R134a, 90 °C, 340 to 600 kW
Viessmann	Vitocal 350-HT Pro	High Temperature Heat Pump	R1234ze(E), 90 °C, 148 to 390 kW

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2. Energy and economic performance are highly dependent on the specific application including the required supply temperature, sources of waste heat, lift temperature required from fluid inlet to supply outlet, and the rate at which energy needs to be supplied (capacity of HTHP), as well as opportunities for simultaneous heating and cooling.

Table 2: Summary of results from literature review

Location	**Application**	**Results**	**Reference**
Various	Laboratory testing in multiple labs. Review of test results from commercially available systems. Measured: energy consumption, heating and cooling rates provided, COP, etc.	COP values range between 2.4 and 5.8 with a temperature lift, supply fluid temperature minus input fluid temperature of 95 to 40°C. Heating rates range from about 20 kW to 20 MW.	[2]
Seward, Alaska, USA	Field: Industrial installation at Alaska Sea Life Center, sea water to water heat pump. Baseline: Fossil fuel boilers. Measured: Energy consumption, heating and cooling provided, COP.	Average COP>2.5, Transcritical CO_2 cycle, T out up to 90°C, simultaneous heating and cooling: Two 90-ton water-to-water heat pumps: $190,000; Corrosion-resistant heat exchangers: $36,000; Design: $100,000; Labor: $150,000. Total Project Cost: $476,000 with existing sea water intake.	[6]
Drammen, Norway	Field: District Heating, central heat pump plant (Neatpump) Baseline: fossil fuel boilers Measured: Energy consumption, operating costs	Heat source fjord water at 8°C, water loop T_{supply} 90°C $T_{return\ water}$ 60°C, Ammonia refrigerant, world's largest district-wide natural heat pump system. Supplies 85% of heat for district, with hydroelectric generation. Electric cost is low (1 pence per unit of electrical energy compared to 5 pence for natural gas), annual savings is around €2m a year and 1.5m tonnes of CO_2 emissions, payback time is less than 4 years.	[4, 3]
California, USA	Field: industrial winery Baseline: NG boilers and separate refrigeration Measured: Energy use to supply similar heating and cooling, COP	Mayekawa simultaneous heating and cooling, transcritical CO_2 (total 24 lbs.) first in a winery in USA. Supply water 194°F: 28% lower carbon emissions 25% installation cost premium over conventional new systems 22% energy savings. Cooling glycol loop and or water source chiller condenser water. Combined COP 3.6 to 4.	[1]

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Technology Sector Electrical Space Conditioning Product Category Hydronic System Controls Last Updated 12/21/18	 *Figure 1: Example small circulator pumps with automated controls*

Product Category Overview

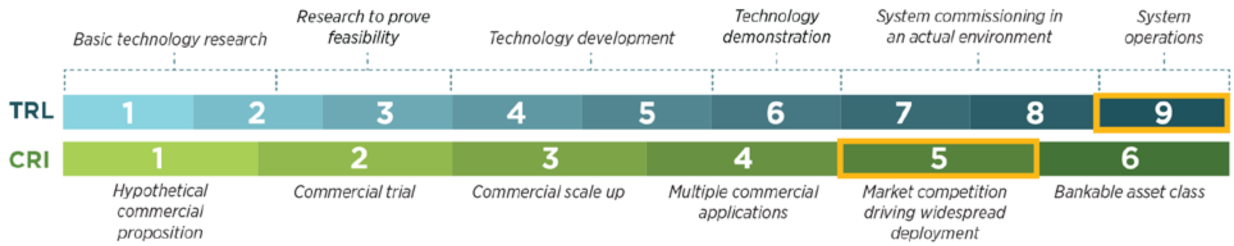
Water distribution systems are a commonly used method for providing heating and cooling to the spaces of a building. These systems circulate hot and/or chilled water through air handler units for building conditioning applications. Traditional water distribution systems use a combination of large and small single speed pumps combined with bypass and throttling valves to reduce water flow rate. The pumps are all operated at a single speed and use the throttling valves to reduce flow to specific coils when full system capacity is not required [1]. In addition to only operating at a single speed, traditional systems also only operate at a fixed temperature set point, independent of indoor and outdoor conditions, resulting in heating and cooling equipment consuming excess energy.

Variable speed pumps offer one solution to inefficient traditional systems. There are several different control methods for variable speed pumps that allow pump speed and power to be reduced when cooling and/or heating demand is reduced. A high efficiency option is a differential pressure reset strategy, where the system is integrated with a pressure sensor and modulating control valves. In this strategy, the required differential pressure (and pump speed) is reduced to save energy until at least one valve in the system is open 100%. In addition to variable speed pumps, water distribution systems can also be instrumented with temperature sensors so the set point of the hot or chilled water system can be adjusted to save energy depending on indoor and outdoor conditions.

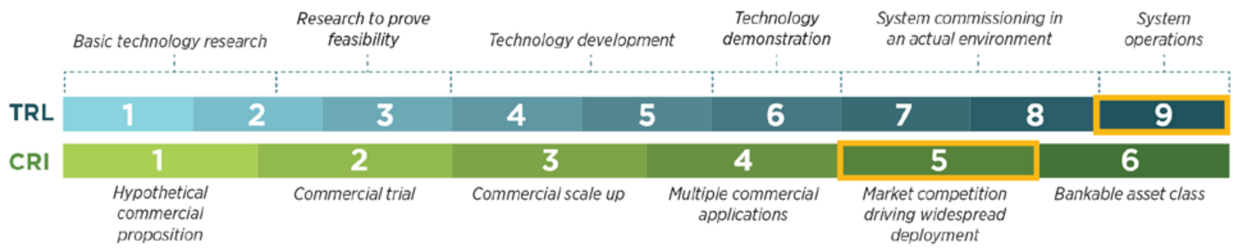
An alternative to a centralized pumping system (either single or variable speed) is to use many distributed small circulator pumps with automated controls. In traditional distributed systems, each zone would have a small single speed circulator pump to circulate the conditioned water. New small circulator pumps with automated controls offer two potential methods for improving efficiency over traditional distributed pumping systems. One method is to simply retrofit the single speed circulator pump with a new one with automated controls, which will save energy due to the new pump being more efficient. This method does not reduce the energy wasted due to limiting flow through the individual coils using throttling valves but does reduce the pumping power due to an increase in pump efficiency. Another emerging solution is to instead replace the central pumping system and throttling valve of each coil with a small circulator pump. These small circulator pumps save energy compared to the valves by reducing flowrate and pumping power during periods when heating and/cooling loads are reduced, as determined by pressure and/or temperature sensors integrated into the pump.

Characterization at a Glance

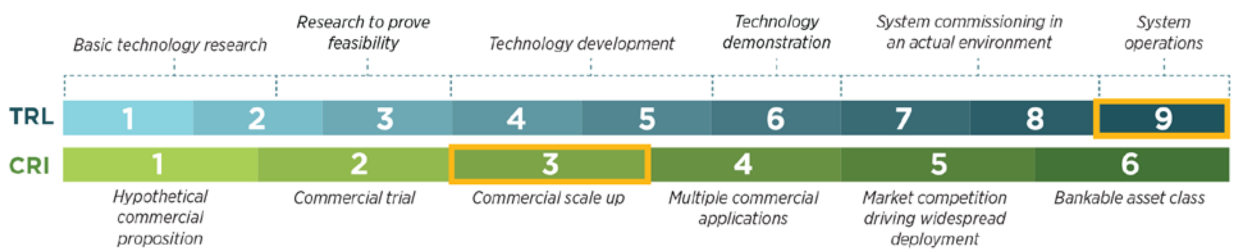
Control optimization for centralized pumping systems:



Small circulator pumps with automated controls:



Control optimization for distributed pumping systems:



Product Category Characterization

Energy Benefits

Energy benefits provided by water distribution control optimization include variable speed controls as well as setbacks based on cooling or heating loads. Traditional circulation pumps for water distribution systems run at a single speed circulating the hot or chilled water through the entire building and reduce demand by using a series of bypass and throttling valves. With variable speed technologies, the centralized circulation pumps can be ramped up and down depending on demand for water in specific zones. In a centralized system, demand is determined by a differential pressure sensor and the valve opening position for each coil or piece of equipment served by the system. This control method eliminates the need for bypass valves and reduces the overall pumping power required during non-peak times. By only circulating that amount of hot or chilled water needed, significant energy savings can be achieved. In a decentralized system with many small circulating pumps, each pump speed is controlled individually based on integrated sensors.

In addition to variable speed technologies, savings can also be achieved by incorporating setbacks in set point temperatures for the heated or chilled water. Incorporating the outside air temperature into the control algorithm allows for the set point to be lowered or raised for heating and cooling respectively on more mild days. The system is able to still meet the building loads while reducing the amount of energy expended to heat and cool the water. By implementing these control methods, reduction in excess energy commonly consumed by water distribution systems can be achieved.

Non-Energy Benefits

Non-energy benefits of this product category include improved thermal comfort provided by the system, reduced noise when pumps are running at lower speeds, and improved component lifespan due to reduced run times.

Product Category Differentiation

This product category covers only the water distribution system controls, which are only one component of a large centralized HVAC system. Heating and cooling of the water are accomplished with other mechanical equipment such as chillers, cooling towers, boilers, and/or heat pumps. Heating and cooling coils in a water distribution system integrated into air handlers may serve variable air volume systems, which are covered as a separate category.

Installation Pathway and Dependencies

Water distribution system controls can be installed in new construction, major renovation, and retrofits. Retrofits are most feasible when adding controls to an existing centralized single speed pumping system. In many cases, a centralized single speed pump can be retrofitted with a variable frequency drive to add speed control capabilities. The system also requires necessary sensors, zone control valves, and a control system to be installed. The retrofitting of the original equipment requires the water distribution system to be shut down temporarily during the instillation.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Grundfos	Alpha1, Alpha2, Alpha3, Magna 1, Magna 2, Magna 3	Decentralized small circulator pump	Variable speed ECM motor for water circulation. Implements advance controls to automatically adapt pumping speed based on changing demand
Taco Comfort Solutions	VR3452	Decentralized small circulator pump	ECM high-efficient circulators that uses pressure drop in circulation line to modulate speed
Armstrong	Design Envelope Compass H Circulators, Design Envelope Compass R Circulators	Decentralized small circulator pump	Variable speed ECM motor with eight operating modes
Wilo Stratos	Wilo Stratos ECO, Wilo Stratos, Wilo Stratos D, Wilo Stratos Z	Decentralized small circulator pump	EC motor with built in controller
Taco Comfort Solutions	Advanced hydronic systems	Centralized variable speed pump system control	Complete hydronic system created with Taco design tools and built with Taco components. Taco design tool is a proprietary software to reduce hydronic system design time
Siemens	Hydronic flow optimization	Centralized variable speed pump system control	System incorporates variable frequency drives for centralized pumping system and pressure-independent control valves which maintain proper flow throughout coils and heat exchangers regardless of pressure fluctuations
Grundfos	Packaged Pumping Systems	Centralized variable speed pump system control	Designed and manufactured packaged pumping systems are factory built and shipped to location
Johnson Controls	Central Plant Optimization	Centralized variable speed pump system control	Customized service to optimize central plant for building
Hartman Company	Hartman Loop	Centralized variable speed pump system control	A fully integrated chiller plant loop utilizing variable speeds for the chiller, and pumping. The system fully integrates all aspects instead of trying to just optimize each of the individual components of the chilled water system

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 1.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Denver, Colorado	A field test of a decentralized pumping system with a high-performance small circulator pump was performed at a federal building in Denver, Colorado. The small pump circulated heating hot water through an air handler unit. The baseline technology was a constant speed small circulation pump. The savings of the emerging technology were quantified with a reduction in power consumption compared to the baseline pump.	For the heating hot water application, the emerging technology was found to produce an overall savings of 26%. In addition to energy savings, it was predicted that the new pumps would also produce a maintenance cost savings due to the motor not requiring greasing of the bearings.	[2]
Dayton, Ohio	A field test of an optimized pressure control algorithm for a centralized pumping system. The system consisted of two variable speed pumps and chillers and multiple end uses. The baseline in the study was the original pressure setpoints to be maintained across the chillers and across the building. These pressure setpoints were then lowered in an attempt to optimize the system and reduce its overall power consumption. The savings were quantified with flow-normalized energy savings.	After lowering the pressure setpoints across the chillers and the building to more optimal values a 6% reduction in power draw was achieved.	[1]
Montgomery, Alabama	A field test was performed where a chiller plant with a centralized pumping system serving two buildings was retrofitted with VFDs on all pumps and fans and no VFDs were used for the chillers. Baseline data was not collected prior to the retrofit being performed so to collect baseline data, the system was run in manual mode for a period of time without the controller functioning. Savings were quantified with percent cooling energy savings.	The holistic chiller plant optimization approach saved 35% cooling energy savings. Based on these savings, the average payback was computed to be five years for the system.	[3]

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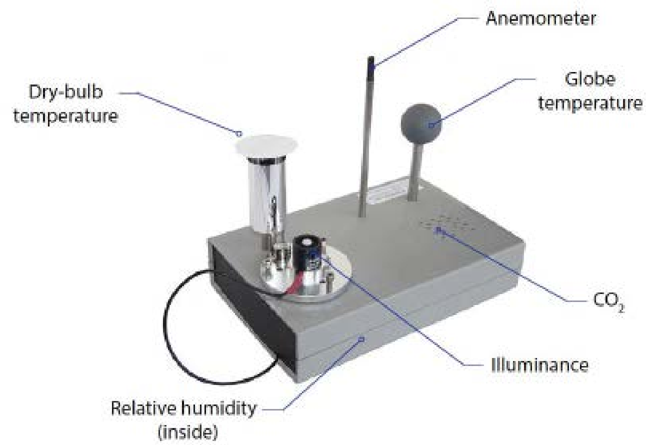
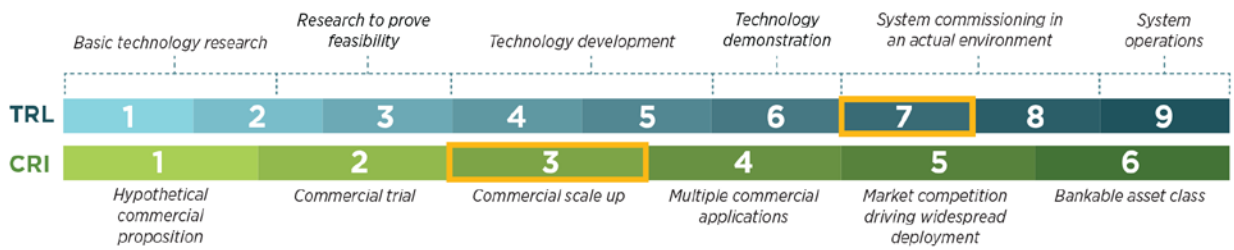
Technology Sector Electric Space Conditioning Product Category Indoor Environmental Quality (IEQ) Monitoring Products Last Updated 01/07/2018	 *Figure 1: Example of IEQ measurement multi-sensor monitoring device; data collection via mesh networking*

Product Category Overview

Indoor Environment Quality (IEQ) uses the accurate measurement and assessment of indoor conditions (temperature, humidity, indoor air quality, air movement, etc.) which can lead to informed data-driven decisions for improving the quality of indoor environments while also saving energy. Many new IEQ measurement devices, including IoT-based systems, are currently being developed and introduced to the market.

Characterization at a Glance



Product Category Characterization

Energy Benefits

New IEQ technologies enable monitoring of energy use and determining how many occupants are present in the space. This allows us to understand how buildings behave with partial occupancy, the level of pollution, and how air supply rates can be adjusted to respond in an energy responsible manner to the varying occupancy in the space. Measuring thermal comfort and IEQ parameters provides information that can be used to further modify system controls to reduce energy usage.

Non-Energy Benefits

Non-energy benefits include improvement occupants' health, well-being, and productivity. Ventilation affects occupant's health by reducing exposure to TVOC, PM2.5, CO, NOx, SOx, O_3. Results from previous studies showed that improved ventilation (reducing CO_2 and other environmental pollutants) and improved lighting (especially daylighting), lead to the better productivity of building occupants. Studies also showed that indoor noise may cause a large productivity detriment.

Product Category Differentiation

IEQ environmental sensing is being made possible with new IoT technology that enables real-time monitoring of conditions inside the building. The sensing grid can provide large granularity of information about the environment that was not available before IoT technology. This enables all the stakeholders to better understand the relationship between building operation, occupancy, energy consumption, and environmental parameters. The only comparable technology is sensing used for BMS purposes. BMS sensing has a much lower resolution of sensing points, much less environmental information, and is centered around system operation and not the occupant experience.

Technology Readiness Assessment and Projection

Current Technology Readiness Level assessment:

> The readiness of continuous IEQ sensing at scale is currently unclear due to the rate of technological advances, availability of robust products and systems and data analytics capabilities. These considerations will be made during more detailed evaluation of candidate products to be tested.

Short-term TRL projection:

> We anticipate that this project will certainly help advance this technology but the level attained over the project time frame is uncertain since it depends on the how advanced the selected technology is in terms of its commercial development.

Installation Pathway and Dependencies

Testing of IEQ systems requires a combination of laboratory work (e.g. testing sensor properties and the effects of indoor location environmental differences) as well as full-scale building level deployments to investigate sensor configurations over large spaces and to verify communications and data reliability. Further analysis is required for the data analytics capabilities. Building level deployments requires selection based on "willing partners" to minimize disruption of occupants and help from supportive building operators.

List of Products

There is a variety of products becoming available for high resolution continuous monitoring for both indoors and outdoors. The use of these (and other) products will be better defined once the project scope is clarified. The list below focuses on indoor (IEQ) products and systems.

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Senseware	various [1]	Configurable multi- sensor measurement platform of networked devices with data visualization software and focus on indoor measurements.	Variety of sensor options for each device, easily configured. (Potential for using CBE advanced analytics software as data collection and analysis vehicle).
Clarity	Clarity Outdoor Node, Clarity Indoor Node	Nodes configured to monitor with potential for high granularity over varying options of IAQ measurements including particles, temperature, VOCs, RH, CO_2 and other targeted gases.	Uses cloud data collection and offers wide area deployments along with visualization software.
Aclima	various	Specialization for outdoor pollution monitoring with potential for high granularity over varying options of IAQ measurements including particles, temperature, VOCs, RH, CO_2 and other targeted gases.	Uses cloud data collection and offers wide area deployments along with visualization software. Aclima intends to introduce more sensors on the market in 2019.
Purple Air	PA-II, PA-II-SD, PA-I-Indoor	Specialization for outdoor pollution monitoring with potential for high granularity over varying options of IAQ measurements including particles, temperature, VOCs, RH, CO_2 and other targeted gases.	Uses cloud data collection and offers wide area deployments along with visualization software.
Arbnco	Arbnwell	Building modelling and simulation software company. Via partnerships with leading research bodies, develop scalable, global and disruptive software solutions for managing energy and environmental performance in the built environment.	Global indoor IEQ ‘Sensor as a Service’ software. Provides real-time monitoring, analysis of human feedback and integration with measurements.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
United Kingdom	Overview article. Presents fundamental drivers behind rise of IEQ technology for the management of energy and indoor air quality. Highlights research gaps that should be closed by future investigations.	Conventional monitoring for building management system control are general only capable of providing average energy levels per building zone and are unable to capture variations over time and space that are important for conserving energy. In addition, as advanced design solutions and control strategies are implemented, such as lowering ventilation rates, thet may cause unintended problems with IEQ. Advanced IEQ sensing technology can address these and other challenges related to simultaneously achieving energy efficiency savings while maintaining acceptable IEQ.	[1]
Singapore	Simulation study. The study implements a multi-agent comfort and energy system (MACES) to model alternative management and control of building systems and occupants. Real-world building data on thermal zones, temperatures, occupant preferences, and occupant schedules were used to set up the simulation of building operations under three different control strategies. These strategies used measured data from HVAC, lighting, and appliance devices to turn off lighting and appliances when occupants leave the room. The third strategy included relocating meetings to more energy and comfort conscious rooms. Predicted energy and comfort results are compared for these control strategies versus the baseline condition.	A 12% reduction in energy consumption and a 5% improvement in occupant comfort were realized compared to the baseline control.	[2]

Location	Application	Results	Reference
Pittsburgh, Pennsylvania, USA	Energy simulation study. The study is based on the installation of a complex environmental sensor network (acoustics, lighting, CO_2 and motion detection) at the Robert L. Preger Intelligent Workplace (IW) at Carnegie Mellon University. To estimate energy savings based on the occupant behavior detection (i.e., number and duration of occupancy) in the space, an EnergyPlus model of the IW with a standard variable air volume (VAV) system was used. Energy use is compared between a predicted dynamic occupancy schedule versus the baseline condition using a conventional temperature set-point schedule.	Results showed energy savings of 18.5% while maintaining acceptable indoor thermal comfort.	[3]

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Technology Sector
Electric Space Conditioning

Product Category
Low Global Warming Potential Refrigerants

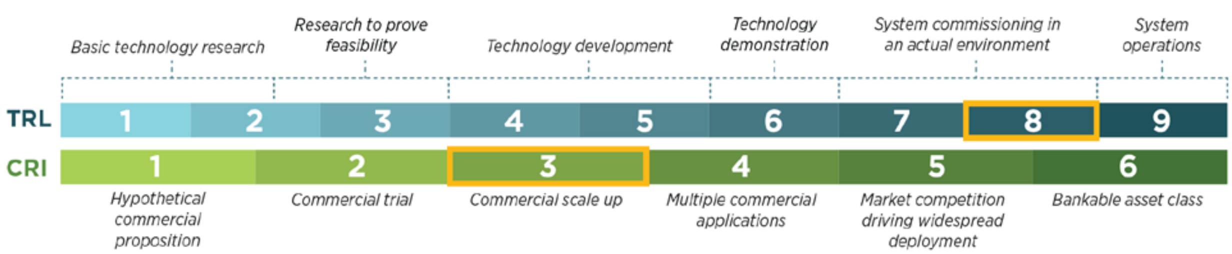
Last Updated
12/6/2018

Figure 1: Technician charging a system with refrigerant

Product Category Overview

Alternative refrigerants are being developed to reduce the effects of climate change due to refrigerants used in air conditioners, heat pumps, and refrigeration systems. Early developments in refrigerants attempted to find compounds that were non-toxic and non-flammable. More recently, the Montreal Protocol resulted in phasing out of refrigerants with ozone depleting substances. Current efforts are focused on finding refrigerants that have low global warming potential (GWP). There are two primary ways that refrigerant selection impacts the GWP of refrigeration systems: 1) directly - through leakage of the refrigerant to the environment, and 2) indirectly - through the electricity consumption of the refrigeration system (refrigerant selection impacts system efficiency).

Characterization at a Glance



Product Category Characterization

Energy Benefits

Alternative refrigerants can achieve energy savings by improving the efficiency of the refrigeration cycle. A refrigeration cycle is used to move heat from a cold reservoir to a hot reservoir, and the maximum efficiency of a refrigeration cycle is a function of the temperature difference between the two reservoirs (e.g. between a house and outside). Refrigerant selection impacts how closely the system can achieve maximum thermodynamic efficiency. According to the US EPA, 95-98% of the global warming impact of refrigerants is caused by the energy consumption of the systems that use the refrigerant rather than direct losses of refrigerant to the environment; therefore, alternative refrigerants need to have equal or higher efficiency than current refrigerants.

Non-Energy Benefits

Alternative refrigerants are being developed specifically to reduce the GWP of systems that use refrigerants. Much of the focus has been on finding refrigerants with a lower GWP than current refrigerants while also achieving similar or better efficiency. Past developments have removed ozone depleting substances and reduced the toxicity of refrigerants. Reducing the effect of global warming has a significant non-energy benefit as climate change impacts people throughout the world.

Product Category Differentiation

There is no similar product category that relates to refrigerant substances or mixtures.

Installation Pathway and Dependencies

Alternative refrigerants have many installation pathways since the category includes design-compatible products, as well as new products that would require different equipment. Design-compatible refrigerants are being developed to replace existing refrigerants as a retrofit. These products are suitable for use with existing equipment but have other benefits including better efficiency and/or lower GWP. Other refrigerants may require a complete redesign of components including compressors, evaporators, condensers and expansion valves. These refrigerants may have a larger potential impact, but will be slower to penetrate the market due to the need for new equipment.

One barrier to installation of alternative refrigerants is related to safety. Many advancements in refrigerant technology have resulted in substances that are flammable. For example, propane is an excellent refrigerant in terms of both efficiency potential and GWP; however, propane is highly flammable and there are concerns about the use of propane as a refrigerant in buildings. Other refrigerants are considered mildly flammable but still run into regulatory restrictions for their use in the US. The regulations will need to evolve before many refrigerants can be approved for use in California buildings.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type (flammability rating)	Differentiating Feature
Chemours	R-452B	A2L	Low GWP refrigerant that is design compatible with R-410A equipment. Product is mildly flammable.
Honeywell	R-466A	A1	Low GWP refrigerant that is design compatible with R-410A equipment. Product is not flammable.
Daikin	R-32	A2L	Low GWP refrigerant that is design compatible with R-410A equipment. Product is mildly flammable.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
California, USA	Lab test. R-452B replacement in standard R-410A rooftop unit. Efficiency relative to R-410A was measured.	5% higher efficiency at 95°F ambient. Lower charge weight of refrigerant. Similar capacity at slightly lower power.	[1]
Indiana, USA	Lab test. Compares efficiency of R-32 versus R-410A. Efficiency relative to R-410A was measured.	3% higher efficiency at 95°F ambient. Lower charge weight of refrigerant. Higher capacity.	[2]

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[2] C. Harrington, "Performance Testing of DR-55 as a Replacement for R-410A Refrigerant," *UC Davis Western Cooling Efficiency Center Research Brief,* 2015.

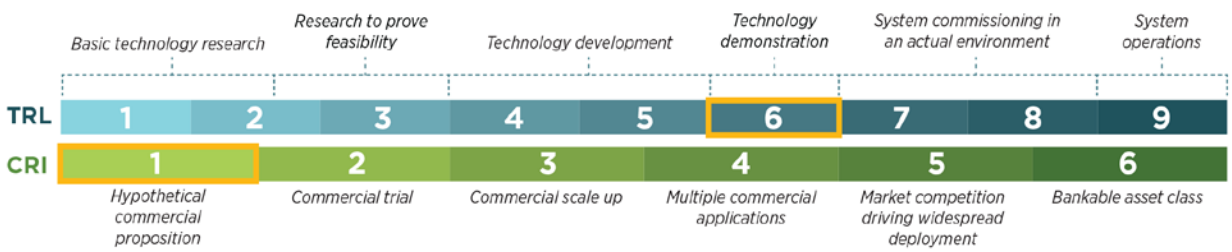
Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector Electric Space Conditioning Product Category Personal Comfort Systems (PCS) Last Updated 12/04/2018	 Figure 1: Heated and cooled (PCS) chair

Product Category Overview

Personal Comfort Systems (PCS) are electrical equipment that individuals can use to provide the thermal environment they prefer at any particular moment, right where they are. Currently, PCS components consist of chairs that provide both heating and cooling, small desk fans, other small personal heaters, foot warming devices, and leg warming devices.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings can be achieved through intelligent control and integration with relatively energy-intensive centralized space conditioning equipment. The use of PCS can reduce and in some cases eliminate the need for centralized space conditioning by allowing a wider temperature deadband, meaning occupants with access to PCS will accept and be comfortable at a wider range of temperatures. Energy simulation studies have shown that if it is possible to relax the temperature range in either the hot or cold direction (widen the deadband), total HVAC energy is reduced at a rate of 10% per degree Celsius. Savings of this magnitude exceed those of virtually any energy-conserving technology available in the industry, and they can be obtained through reprogramming controls sequences without changing the building's HVAC hardware.

Non-Energy Benefits

PCS have the potential to satisfy individual comfort requirements by allowing occupants to control their local thermal environment to match their comfort preferences. Interpersonal differences between building occupants are equivalent to 2-5°C (4-9°F) difference in ambient temperature. In jointly occupied spaces it is therefore impossible for everyone's individual requirements to be met by any uniformly distributed temperature, as is typically done with conventional HVAC system controls. Field demonstration studies have shown that when PCS devices are provided to building occupants, a higher percentage will express satisfaction with their thermal environment than is commonly achieved in buildings (often well below the 80% specified by ASHRAE thermal comfort Standard 55) [1].

Product Category Differentiation

PCS represent a class of local heating and cooling products that provide individual control of the thermal environment surrounding occupants. They cover a wide range of components, including chairs that provide both heating and cooling, small desk fans and heated/cooled desktop surfaces, radiant and conductive heaters for feet, legs, hands, and arms. These components can provide warm and cool comfort to occupants many times more efficiently than using the building's HVAC. They can be simple retrofit products or designs integrated into office furniture. They preferably should include occupant sensing for automatic on/off. They may include communications allowing their operation to be coordinated with the building's HVAC control, but this is not a requirement. There are certain forms of personal devices (~1000W convective heaters) that are excluded from PCS under ASHRAE's comfort control classification system, because they are very inefficient at warming the person, no better than the HVAC system itself. PCS systems should be capable of providing adequate temperature corrective power using less than 30W per occupant averaged over time.

Technology Readiness Assessment and Projection

- Current Technology Readiness Level assessment:
  The PCS technology represented by heated and cooled chairs was part of a recent prototype system field demonstration in a CEC/PIER research project [2].
- Short-term TRL projection:
  To advance to TRL 8, newly available commercial PCS chairs should be manufactured and tested in a field demonstration that features fully integrated energy-saving building control strategies.

Installation Pathway and Dependencies

PCS are most commonly unitary plug-in electrical devices that can be installed in both existing and new buildings. An installation strategy will sometimes involve providing PCS as a solution in areas of the building where temperature control is difficult or to individual occupants who are experiencing thermal comfort challenges. While installing PCS alone will improve occupant comfort and satisfaction, to achieve energy savings, the installation must be coordinated with an adjustment to the controls of the centralized HVAC system.

List of Products

Beyond a large variety of desk and ceiling fans, there are not many formal PCS commercially available in the marketplace.

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Com4tek LLC	See www.com4tek.com	Heated and cooled office chair	Only product of its kind currently under development for manufacturing.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Berkeley, California, USA	Literature review and analysis. 41 lab studies with different PCS devices were reviewed. The comfort-producing effectiveness of PCS was quantified in terms of a temperature difference, coining the index 'corrective power' (CP). CP is defined as the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use.	Cooling corrective power (CP) ranges from -1 to -6K (-2 to 11°F, and heating CP from 2K to 10K (4 to 18°F).	[3]
N/A	Energy simulation study Heating and cooling setpoints were varied parametrically in seven ASHRAE climate zones and in six distinct medium-sized office buildings.	Without reducing satisfaction levels, by increasing the cooling setpoint of 22.2 °C (72 °F) to 25 °C (77 °F), an average of 29% of cooling energy and 27% total HVAC energy savings are achieved. Reducing the heating setpoint of 21.1 °C (70 °F) to 20 °C (68 °F) saves an average of 34% of the energy needed to heat a typical room.	[4]
Berkeley, California, USA	Human subject laboratory study Twenty-three college students participated in 69, 2.25-hour tests. Four heated/cooled chairs were placed in an environmental chamber resembling an office environment. The chamber temperatures were 16°C, 18°C and 29°C. During the tests the subjects had full control of the chair power.	The chair provided comfortable conditions for 92% of the subjects in a range of temperatures from 18°C to 29°C. The results show that the heated/cooled chair strongly influences the subjects' thermal sensation and improves thermal comfort and perceived air quality.	[5]
Redwood City, California, USA	Field demonstration study In summer 2016, the Center for the Built Environment, UC Berkeley carried out a study with PCS chairs involving 37 occupants in an office building in California. >5 million chair usage data-points collected and 4500 occupant survey responses, as well as continuous measurements of environmental and HVAC system conditions.	The results showed that (1) PCS chairs produce much higher comfort satisfaction (96%) than typically achieved in buildings; (2) local temperatures experienced by individual occupants vary quite widely across different parts of the building, even within the same thermal zone; and (3) occupants often have different thermal preferences even under the same thermal conditions.	[2]

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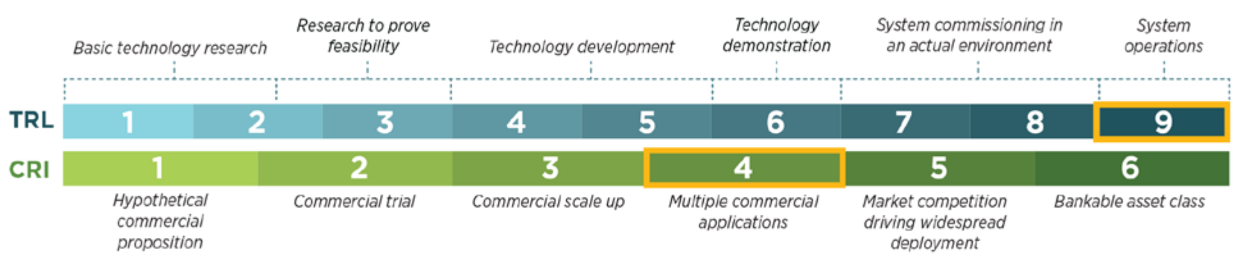
Technology Sector Electric Space Conditioning Product Category Thermal Energy Storage Products Last Updated 11/29/2018	 *Figure 1: Thermal Energy Storage Tank*

Product Category Overview

Thermal Energy Storage (TES) systems use the vapor-compression cycle to cool a thermal mass, such as stratified chilled water, or cause a phase change in a material such as ice, wax or salt. The thermal energy stored in the cooled material can then be used at a later time to cool the building. TES decouples the demand for cooling and the demand for electricity necessary to meet that cooling demand. Using TES, the electric demand from cooling can be shifted to off-peak hours. Additionally, at times when there is a large amount of solar or wind energy available on the grid but the cooling demand is low, TES systems can be used to absorb excess grid capacity, allowing the utility grid operators to avoid costly abatement.

Characterization at a Glance



Product Category Characterization

Energy Benefits

When TES is deployed to offset a cooling load, the grid impact is the difference between the electric demand that would have been required by the primary cooling system to meet the offset load, and the electricity demand associated with operating the TES system. Since most building cooling systems use vapor-compression cycles, the reduced electric demand achieved by TES systems is attributed to de-energizing the vapor-compression cycle (compressor and condenser fan or cooling tower). The system efficiency of vapor-compression equipment decreases as outdoor the air temperature increases, resulting in an elevated electrical demand to meet a given thermal load at hotter ambient air temperatures. Thus, as the outdoor air temperature increases, the value of stored thermal energy increases.

The charge-discharge process of all energy storage systems is less than 100% efficient. Modern TES systems have round-trip thermal efficiencies between 97.5% and 99% [1]. The inefficiency of the charge-discharge process usually means that the use of energy storage for peak shifting results in a net increase in energy consumption. This is not always the case for TES systems, due to the temperature dependency of the vapor-compression cycle efficiency. Depending on ambient temperatures, the energy lost to the charge-discharge process can be less than the electric energy saved by charging the TES system during off-peak, lower-ambient-temperature hours instead of using the vapor-compression cycle during peak hours to directly meet the cooling load, resulting in a reduced net electricity consumption [2].

Non-Energy Benefits

A charged TES system can continue to provide cooling in the event of power loss or a mechanical failure in the vapor compression equipment. In critical applications, where a loss in cooling would result in property damage, the resiliency offered by TES can reduce the need for redundancy and minimize downtime for repairs. TES systems themselves have no moving parts, are low maintenance and can even be buried, taking up minimal space.

Product Category Differentiation

An alternative to TES is electrochemical energy storage (batteries). Although individual electrochemical battery cells have a very high energy density, when they are assembled into a pack they require a container, air gaps, cooling system, battery management system, and an inverter. A battery pack built into a 40-foot shipping container typically has a capacity of up to 1 MWh, resulting in an energy density by volume of approximately 50 kJ/L. Similarly, ice storage tanks require insulation and a glycol loop resulting in an energy density by volume for the TES system of approximately 200 kJ/L.

Although TES cannot be efficiently used for electric round trip storage (grid to storage back to grid) it directly addresses the cooling load, which is often the largest contributor to the peak demand of buildings. Additionally, when compared to batteries, TES is significantly cheaper, is built with abundant recyclable materials, is not prone to cycling-induced degradation, and has a long usable lifetime [3].

Installation Pathway and Dependencies

TES systems are installed alongside hydronic systems in commercial buildings. A chiller is used to charge a TES tank and the stored thermal energy is discharged through one or more water coils. Valves are used to control when the TES system is being charged, discharged or bypassed to allow normal operation of the hydronic loop.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
CALMAC	IceBank Energy Storage Tank	Ice Tank	Seamless one-piece tank. Counter-flow polyethylene heat exchanger. Modular with an internalized main header.
Phase Change Energy Solutions	PhaseStor	Phase Change Material (PCM) Container	Can be used with standard chillers. No expansion or contraction during phase change. Tunable operating temperature.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Texas, USA	Case study. Estimates changes in grid-wide, energy consumption caused by load shifting via cold thermal energy storage in the building sector.	Using TES to shift daytime cooling load to nighttime cooling storage can reduce annual, system-wide, primary fuel consumption by 17.6MWh for each MWh of installed TES capacity.	[1]
California, New York, Maine, and Massachusetts, USA	Analysis of Field Installations. Analyzes small TES projects across the country and describe how small TES systems can improve grid efficiency, decrease peak load growth, defer distribution grid upgrades, integrate renewables, and reduce greenhouse gas and criteria air pollutant emissions.	Small TES systems can operate at greater than 100% round-trip efficiency, offsetting more peak energy than the energy they require to charge.	[2]

References

[1] T. A. Deetjen, A. S. Reimers and M. Webber, "Can storage reduce electricity consumption?," *Environmental Research Letters,* 2018.

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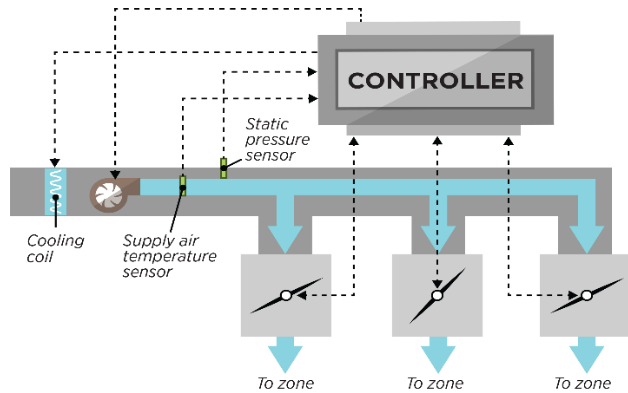
[4] G. Alva, Y. Lin and G. Fang, "An overview of thermal energy storage systems," *Energy,* no. C, pp. 341-378, 2018.

Technology Sector Electrical Space Conditioning Product Category Variable Air Volume (VAV) System Controls Last Updated 01/03/2018	 *Figure 1: VAV system.*

Product Category Overview

Variable air volume (VAV) systems are a type of ducted heating, ventilation, and cooling (HVAC) technology that consist of a central variable speed fan, cooling and heating coils, zone level terminal units, and a controller. VAV systems are more efficient than constant air volume (CAV) systems, which do not adjust airflow. Each VAV terminal unit has a damper that increases or decreases air flow to its zone, based on the zone cooling and heating loads. The dampers have a minimum position that allows them to always meet ventilation requirements. The VAV system requires a control strategy to match the supply fan flow to the sum of the demand side flows, and the control strategy can significantly impact energy consumption of the system. The control methods that are typically used are:

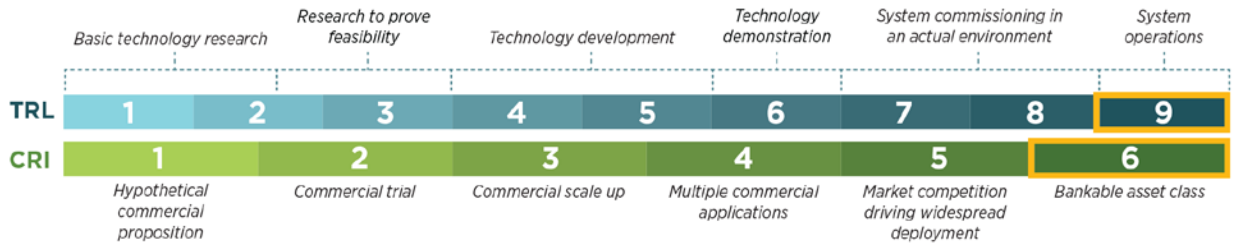
1) Constant pressure set point strategy
2) Static pressure reset strategy
3) Supply air temperature reset strategy based on damper position

The constant pressure setpoint strategy is the simplest VAV control strategy. A pressure sensor is placed in the supply duct. As the zone level dampers open and close based on the air flow demand in the zone, the supply duct pressure changes. The controller monitors the duct pressure, and changes the fan speed to keep the duct pressure constant. The result is lower airflow compared CAV systems.

The static pressure reset strategy is similar to the constant pressure setpoint strategy, in that the fan speed is changed to meet a supply duct pressure setpoint. However, with the reset strategy, the controller reduces the supply duct pressure setpoint when every terminal unit is operating under a part load. When the strategy is implemented, the controller opens the terminal unit dampers as it decreases the fan speed. This results in the same air flow to each zone, at a lower supply duct pressure, enabling energy savings through reduced fan power and reduced duct leakage.

The supply air temperature reset strategy based on damper position is implemented to increase the VAV supply air temperature when less cooling is needed. When this strategy is used, the controller first uses the static pressure reset strategy until the static pressure setpoint cannot be further reduced. If the cooling demand continues to fall, the controller will then reset the supply air temperature set point higher by raising the cooling coil temperature, while maintaining the supply duct pressure [1]. When this strategy is used, it reduces compressor energy and reheat coil energy. The controller will continue to raise the supply air setpoint until the cooling loads stop decreasing, or the supply air setpoint reaches its upper limit.

Characterization at a Glance



Product Category Characterization

Energy Benefits

The constant pressure setpoint strategy provides the least benefit of the listed control strategies, and is the minimum control strategy required for VAV implementation. The strategy allows the VAV to save energy compared to CAV systems by enabling variable speed fan operation.

The static pressure reset strategy reduces fan energy use compared to the constant pressure setpoint strategy, because it allows the supply duct static pressure to be lowered when all the zones of the VAV are in part load operation. Most zones in a building are under part load operation for significant periods of time, which means that the strategy has a high potential to reduce fan energy and reduce duct leakage (because the duct is at a lower pressure).

The supply air temperature reset strategy based on damper position reduces energy consumed by cooling equipment. The strategy also reduces reheat energy, since the supply air is warmer than it would otherwise be if the strategy were not implemented. The strategy does not further decrease fan energy use.

Non-Energy Benefits

Compared to CAV systems, a VAV system using the constant pressure setpoint strategy will have reduced fan wear. The leads to reduced maintenance costs, and longer equipment life.

The static pressure reset strategy allows the fan to operate against a lower static pressure, which further reduces fan wear and maintenance costs. The strategy is less sensitive to the placement of the supply duct pressure sensor, which may reduce sensor installation costs. Because the strategy reduces the static pressure in the supply duct, it results in less duct leakage. The static pressure reset strategy also allows the fan to operate over a larger range without encountering the fan surge instability. The strategy also improves occupant comfort by reducing noise levels.

The supply air temperature reset strategy based on damper position has all the benefits of the static pressure reset strategy, and also reduces compressor wear.

Product Category Differentiation

VAV systems rely on a control algorithm to vary the fan and compressor speed based on changes in the terminal unit damper positions. Each of the control strategies presented in this paper can be implemented as this primary control algorithm, and to the authors knowledge these are the common primary control methods. The primary control method may be supplemented with additional control features such as ventilation optimization strategies, optimized start/stop techniques, or temperature reset based on outdoor air temperature. These additional strategies can be used to further reduce VAV system energy use.

Installation Pathway and Dependencies

The constant pressure setpoint strategy is the simplest control strategy, and can be operated without direct digital controls (DDC) at the zone level. DDC at zone level means that the controller for the VAV system has control of each zone, including damper position setting. The static pressure reset strategy can be implemented in any system with DDC at the zone level. At least one retrofit system exists that does not require DDC at the zone level [2], [3]. This retrofit system uses air flow measurements at the air handler and duct static pressure measurements [3]. The system uses an algorithm to determine the appropriate static pressure setpoint, based on empirical data [4].The prescriptive compliance method of the 2016 edition of California Title 24 requires new VAV systems with DDC at the zone level, installed in commercial buildings, to use the static pressure reset strategy. The supply air temperature reset strategy based on damper position requires DDC at the zone level. The strategy is more costly to implement than the static pressure reset strategy. In many cases, the static pressure reset strategy and the supply air temperature reset strategy based on damper position can be implemented by reprogramming an existing controller.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Trane	Many	Any	Large manufacturer of HVAC systems
Belimo	Many	Any	The manufacturer produces a range of products that can be used to implement the strategies, from controllers to actuators.
Federspiel Controls LLC	SAV with InCITe™	Static pressure reset strategy	Can be used without DDC to zone level. Control is based on retrofit flow measurements
All VAV manufacturers	Many	Any	At least one of the control strategies is used for each VAV installation. Many VAV installations can support multiple strategies using the existing controller or building management system.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Stanislaus, California, USA and Oakland, California, USA	Field test and data extrapolation. The VAV systems were retrofitted to operate using the static pressure reset strategy. The observed savings were extrapolated to estimate annual savings	$6,300 savings, equal to 0.8 year payback period at Stanislaus site. $9,800 savings, equal to 1 year payback period at UCOP building	[2]
Berkeley, California, USA	Feasibility Study. The costs of a retrofit were estimated, and the savings were estimated, to determine the feasibility of retrofitting several VAV systems to use the static pressure reset strategy	The simple payback was estimated to be 0.4 years for four of the VAV systems. The simple payback period for a fifth VAV system was estimated to be 3.4 years.	[3]
California, USA	Field implementation of supply air temperature reset and static pressure reset strategies. The supply air temperature was reset using a trim and respond algorithm, as opposed to a PID algorithm	The cost of implementation was cut in half by utility incentives. Simple payback period of 0.08 years (about 1 month), after incentives.	[5]

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[3] University of California Office of the President, "UC Strategic Energy Plan," University of California, Berkeley, July 2008.

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[5] P. Arik Cohen, *Supply Air Temperature Reset,* 2012.

Technology Sector
Electric Space Conditioning

Product Category
Variable Refrigerant Flow (VRF) Systems

Last Updated
12/14/2018

Figure 1: Variable Refrigerant Flow

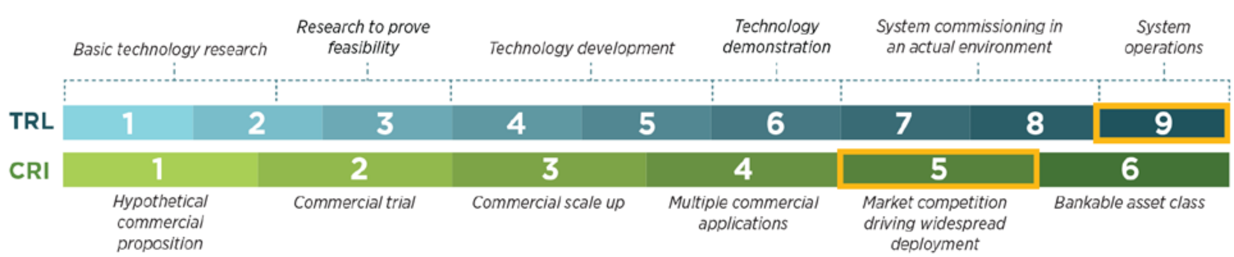
Product Category Overview

Variable refrigerant flow (VRF) is a heating, ventilation, and cooling (HVAC) technology that provides space heating and cooling. Some key features of a VRF system are:

- The system delivers refrigerant to multiple indoor units from a single outdoor unit
- The indoor units are zoned, which means each indoor unit can be controlled independently
- The outdoor unit has a variable-speed compressor, which allows the compressor to run at low speeds when the building heating or cooling loads are low
- They are designed without a centralized air-delivery system, which reduces fan energy use and allows for use of a dedicated ventilation system or a dedicated outdoor air system (DOAS)

There are several variants of VRF technology with the most advanced systems capable of providing simultaneous heating and cooling to different zones, with heat recovery between zones in cooling and zones in heating. The simplest systems perform cooling only, while others can provide heating and cooling, but not at the same time. Most VRF systems are air-cooled, but water-cooled systems do exist.

Characterization at a Glance



Product Category Characterization

Energy Benefits

VRF systems can save energy in several ways. When cooling and heating loads are low, the compressor runs at a lower speed which reduces compressor energy use and improves efficiency. VRF systems can also save fan energy in two ways compared to other HVAC systems:

1) Air flow through the indoor units can be decoupled from the ventilation needs, and can be minimized to only meet the loads in the zone
2) With a dedicated ventilation system, the ventilation fan is sized and operated to only provide the minimum flow required to meet the ventilation needs

The overall effect of minimizing zone level airflows and having a dedicated ventilation system is lower fan energy use than other HVAC systems, which often run the central fan continuously to provide ventilation with only a fraction of the flow coming from outside. VRF systems also reduce fan energy because they pump refrigerant to multiple indoor units, which reduces the amount of ductwork and associated friction losses that the fans must overcome. Lastly, the zoning capabilities of VRF systems limit the amount of overheating and overcooling that occurs in buildings without zoning, which results in reduced energy use and improved comfort.

Non-Energy Benefits

VRF systems also have many non-energy benefits. VRF systems can increase occupant comfort by allowing zone level temperature control. They are generally smaller than traditional ducted systems which saves space inside a building and can add significant value to the owner [1]. It is generally assumed that not all indoor units will run in the same mode at the same time, so outdoor condensing unit sizing can also be reduced. Some consider VRF systems more visually appealing since they don't rely on ductwork. They also reduce noise levels compared to traditional ducted systems because they operate at a lower fan pressure.

Product Category Differentiation

Many HVAC system types share common features with VRF. For instance, split systems pump refrigerant between the indoor and outdoor units, and variable air volume (VAV) systems allow for zone level control. Mini-split HVAC systems use multiple indoor units but do not share an outdoor unit. Several defining features are shared by all variants of VRF technology:

1) VRF systems have a variable speed compressor
2) Multiple indoor units can be served by a single outdoor unit
3) VRF systems need a supplementary system to provide ventilation

Installation Pathways and Dependencies

VRF systems are commonly installed in commercial buildings and in multi-family residential buildings. The technology is installed in new buildings, and as a retrofit system in existing buildings. The initial cost of the technology has been documented to be the same as or up to 20% more expensive than other HVAC technology [2]. The initial cost is highly dependent on the application. VRF technology is best suited for buildings with multiple zones and diverse heating and cooling requirements. Although VRF systems have not fully infiltrated the North American market, they have been installed in international markets since the 1980s. In Japan, about 50% of medium-sized commercial buildings use VRF technology as of 2007 [2]. The technology is also common in Europe and South America. The North American market has recently begun to adopt VRF at an increasing pace, as contractors and designers become more familiar with the technology. Based on the international success of the technology, this trend is likely to continue.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Outdoor Unit Model	Type	Differentiating Feature
Daikin	VRV IV Heat Recovery	Simultaneous heating and cooling with heat recovery	3-pipe system. Incorporates variable refrigerant temperature technology
Mitsubishi	R2 Series	Simultaneous heating and cooling with heat recovery	2-pipe system. The manufacturer claims installation and maintenance cost savings due to less piping.
Manufacturer	**Outdoor Unit Model**	**Type**	**Differentiating Features**
Carrier	Heat Recovery 38VMR	Simultaneous heating and cooling with heat recovery.	2-pipe system. The manufacturer claims that the outdoor unit is the industry's most compact 20 ton VRF system.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Minnesota, USA	Field tests of VRF performance, coupled with baseline energy use estimation.	The annual savings ranged from 10% to 82%. The authors estimated a payback period of 5.1 to 19.1 years depending on the baseline system assumptions.	[3]
Oak Ridge, Tennessee, USA	Controlled test at a test building. The performance results are based on observations and a correction for weather factors. The baseline system is a VAV with electric heating.	The VRF had slightly better thermal control in cooling, and saved 30%, 37%, and 47% at 100%, 75%, and 50% load conditions. The VAV with electric heating had better thermal control in heating, but the VRF saved 51%, 47%, and 27% at 100%, 75%, and 50% load conditions.	[4]

References

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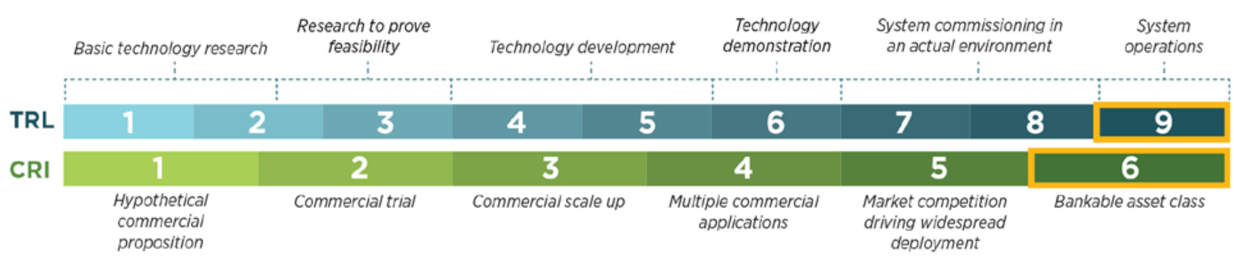
Technology Sector Electric Space Conditioning Product Category Variable Speed & Variable Frequency Drives Last Updated 12/20/2018	 *Figure 1: Supply air fan variable frequency drive*

Product Category Overview

Variable Frequency Drives (VFDs) and Variable Speed Drives (VSDs) are equipment that control the output of alternating current (AC) and direct current (DC) electric motors, respectively. VFDs control AC motors by increasing or decreasing the frequency of the waveform supplied to the AC motor. VSDs control the frequency, current or voltage of the electrical pulses sent to the DC motor.

Characterization at a Glance



Product Category Characterization

Energy Benefits

VFDs and VSDs can save energy by operating motors driving HVAC fans at lower speeds when appropriate. Significant electricity savings are theoretically possible because the motor power required for a fan system is proportional to the cubic of the motor speed. For example, a 50% reduction in fan speed could, ideally, result in an 87.5% reduction in power. VFDs and VSDs also typically have analog or digital inputs which allows the VFD/VSD to be controlled remotely. This can allow the fan speed to be controlled by the HVAC unit's operating mode, occupancy sensors, etc. However, using a VFD to achieve variable speed control may lower the indoor motor/fan efficiency, making it harder to achieve the full savings potential. The lower system efficiency is a result of operating the induction motor below its design point, as well as additional losses from adding a VFD to the indoor fan system.

Non-Energy Benefits

VFDs and VSDs can also control startup power demand, reducing voltage sag in the power supply system, which can protect sensitive equipment. Starting and stopping acceleration can also be controlled which reduces jerk in the fan system, increasing component longevity. Control of fan speeds can help with air balancing of HVAC systems that are made up of multiple HVAC units of different sizes and/or configurations, potentially impoving thermal comfort and indoor air quality.

Product Category Differentiation

VFDs are an improvement on traditional on/off control and dual speed systems because they allow high resolution control over the fan. Frequency ranges vary by model but most fall into the range of 0-100% power with resolutions down to 0.01 Hz. VFDs are used in applications other than for HVAC system fans, which are not covered here (e.g., in pumping applications).

Installation Pathway and Dependencies

VFD and VSD installation requires a compatible AC or DC motor as well as space for the drive to be mounted and protected from harsh environments. VFDs and VSDs can be installed on their own as an incremental energy saving measure or as a part of a larger energy saving plan.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Toshiba	Q9 Plus HVAC	Adjustable Speed Drive	Virtual Linear Pump Technology – Linearizes traditional non-linear fan curve providing stable and precise control to HVAC systems
Honeywell	SmartVFD HVAC	Variable Frequency Drive	SmartVFD Bypass Option – a variety of bypass types are available for critical applications that require the VFD to be bypassed
Allen-Bradley	PowerFlex DC Drive	Direct Current Drive	Can be programmed with Studio 5000 Logix program, allows for coordination of multiple VFDs before deployment

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	**Application**	**Results**	**Reference**
Kuwait	Field Test Cooling tower fans that were VFD controlled compared to 2-speed controller Water consumption Chiller power Cooling tower fan power	Reduction in water consumption over 13%. Reduction in combined cooling tower and chiller power of 5.8% for same output.	[1]
Israel	Field Test Greenhouse Fans with on/off controller and VFD	Reduction in average energy consumption of 36% measured over a 1 month period.	[2]
Europe	Report	Decrease in fan energy by 25-50%.	[3]

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