Handling Humidity

Part 3 – Methods for Managing Moisture

A Report on Moisture Control in Homes

Ty Newell, PhD, PE
Vice President; Build Equinox, Inc
Emeritus Professor of Mechanical Engineering; University of Illinois
Urbana, Illinois
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BUILD EQUINOX
www.buildequinox.com

FOREWORD

At Build Equinox, we have always included moisture management as a primary aspect of CERV2 smart ventilation design. Our free-to-use ZEROs (Zero Energy Residential Optimization software) model is one of the few residential programs that can predict dehumidification and humidification in residences. Health, comfort and energy impacts of humidity are important!

Moisture is complex and has many facets, however it is an old, old problem that experienced HVACR engineers know how to address. This report discusses sources of moisture in homes, and how to manage moisture. We look around North America to learn how climate zones impact moisture management in homes. More and more regions around the world are experiencing increased temperature and humidity and the need for active comfort conditioning is expanding.

Build Equinox conducts residential research encompassing health, well-being, comfort, sustainable living, and energy efficiency topics. We hope sharing our knowledge will be a benefit to our growing CERV community. It is time to move beyond energy, designing homes with exceptional indoor environments that improve our health, comfort and well-being!

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Part 3 Introduction – Methods for Managing Moisture

Most homes require active management of moisture to maintain comfortable conditions using human devised systems that add or subtract water from indoor air. Maintaining a comfortable indoor environment is not just a nice thing to do. Human productivity is directly related to comfort as is human health and longevity. Poor humidity control stresses humans, with elderly, infirm and youth especially harmed by uncomfortable conditions.

Moisture management is almost always ignored in home design, while exhaustive effort is expended on thermal bridge and insulation design details. Although moisture physics are perhaps more complex than heating and cooling analyses, the fundamentals of moisture modeling are well known. In fact, as discussed in Part 1, Willis Carrier's very first building air conditioning system more than 100 years ago was for dehumidification, not cooling!

Moisture removal, that is, dehumidification, is our primary emphasis. We have broader tolerance to low humidity levels. Humans are natural humidifiers, and many of our activities add moisture to the indoor environment. We will discuss humidification processes, however, most properly constructed homes (ie, well-sealed) do not require humidification, but most homes do require dehumidification.

Our Part 3 Handling Humidity report focuses on the performance and energy requirements of common household moisture management systems. We discuss 5 topics:

- Air conditioning (vapor compression process)
- Smart ventilation with heat pump energy exchange
- Heat pump (aka, "hybrid") water heaters
- Ducted and unitary dehumidifiers
- Humidification (steam and evaporative types)

The first three systems form the foundation of sustainable (renewable energy powered), comfortable, healthy, and clean homes. A technology revolution has occurred over the past 2 decades with the creation of 3 disruptive technologies:

- Comfort conditioning heat pumps (eg, low temperature minisplit heat pumps and ground source or "geothermal" heat pumps)
- Smart, heat pump-based ventilation systems (CERV2)
- Heat pump water heaters (HPWH, also commonly referred to as "hybrid" water heaters)

The synergistic interaction of these three technologies in today's homes result in energy efficient homes that can be powered with today's renewable energy technologies. All three can contribute to a home's dehumidification needs.

Dehumidifiers, our fourth topic, have been with us for many decades. When latent (moisture) conditioning requirements exceed the moisture management capabilities of the first three systems in a home, dehumidifiers provide an additional means for moisture removal.

Most well-insulated and highly sealed homes should not need winter humidification, but occupant activities and preferences, climate, and home construction characteristics impact a home's winter humidity. For those homes in which some moisture addition is desirable, energy is required for vaporizing water. We will discuss the two most common methods of home humidification; steam injection and droplet vaporization.

We end our Part 3 report with real data. Part 1 and Part 2 of our Handling Humidity series presented real data showing moisture collection and indoor humidity data from Equinox House, our home and a test bed for Build Equinox research. For Part 3, we present data from the minisplit air conditioner, CERV smart ventilation system, and a heat pump water heater during humid, summertime conditions to demonstrate each component's contribution to moisture management.

Air Conditioning

The most common method for removing moisture from a building is condensation of water on cold surfaces. Willis Carrier used cold water droplets to condense water vapor. Today's "vapor compression" air conditioners remove water by condensing it on a cold heat exchanger called an "evaporator".

A "heat pump" is an air conditioner that can be "reversed" in winter to heat a home by absorbing heat from the cold outdoors, and "pumping" it up in temperature to provide heat to a home. Over the past two decades, manufacturers have developed low temperature, "air-source" heat pumps that provide nameplate heating capacity at their low temperature operation limit (-5F, -13F, and -22F are common low temperature operation limits for today's heat pumps). Geothermal heat pumps are connected to earth temperatures with either horizontal or vertical (well) pipe loops that exchange energy with the earth. Heating air in a heat pump does not impact moisture level (humidity ratio) although relative humidity level does change as air is heated.

Figures 1 and 2 show indoor heat exchanger units for "ductless" (Figure 1) and "ducted" (Figure 2) minisplit heat pumps. The outdoor unit, consisting of a heat exchanger, compressor and fan, is identical for both ducted and ductless heat pumps and is shown in Figure 3. We use a 1 ton minisplit as the basis for our discussion on moisture management because these heat pumps are rapidly moving into the high performance home market. Architects, designers, builders, and homeowners are finding minisplit heat pump capacity and zoning flexibility to be an excellent match for today's highly insulated and sealed homes. Other types of air conditioners (geothermal, central AC) have similar dehumidification characteristics.

Figure 4 is a plot of the daily dehumidification capacity for one manufacturer's 1 ton ducted minisplit heat pump. Dehumidification capacity is related to the indoor humidity ratio, which in turn, is related to water's vapor pressure in the air. The temperature of the refrigerant in the cooling coils must be at a temperature lower than the "dew point" temperature of the water vapor to condense some of the water vapor. Low indoor humidity ratio air has a low water vapor pressure (and therefore, low dew point temperature).

The difference in vapor pressure between water vapor in the air and the vapor pressure of the cooling coil surface temperature drives the dehumidification process. For example, air at 70F and 100% relative humidity has a vapor pressure of 2.4kPa. A refrigerant cooling coil only needs to be less than 70F in order to have a vapor pressure less than 2.4kPa. Air at 70F and 50% relative humidity has a water vapor pressure of 1.2kPa, which requires a cooling coil temperature of 50F or less in order to have a low enough vapor pressure for water condensation. Therefore, as the humidity in air decreases, the dehumidification capacity of a cooling coil decreases.

Figure 4 shows that the 1 ton minisplit heat pump unit removes nearly 40kg/day of moisture when outdoor temperatures are 87F or less. As outdoor temperature increases to 95F, dehumidification capacity is reduced to 35kg per day. From our previous example, Contractor Loose's home in Miami requires 92kg of daily moisture removal, while Contractor Tight's Miami home requires 44kg per day of moisture removal. Loose's home clearly requires additional moisture removal capacity, most likely from a dehumidifier, which unfortunately decreases the home's energy inefficiency and adds equipment cost as we'll discuss later.

Tight's home is on the edge, and for sure will have days when outdoor humidity is much higher than the average summer humidity used for the example (see Miami weather plot in Part 2, Appendix C). Contractor Smart's home can be moisture managed with the 1 ton minisplit unit with characteristics shown in Figure 4. Extreme outdoor humidity conditions can double the average summer dehumidification capacity. And, if someone is having a party with a lot of people and cooking spaghetti, dehumidification capacity increases further.

Many of today's heat pumps and air conditioners have variable speed compressor and fans. Controlling an air conditioner's fan and compressor speeds is an efficient way to modulate capacity. Unlike yesterday's "bang-bang" on/off controls, today's units stay on at the capacity needed. Bang-bang control often results in poor humidity management because sensible (temperature) conditioning might be met before cooling coils reach a low enough temperature for dehumidification. The variable speed control of today's units keep them running very efficiently at partial speeds. In fact, heat pumps with variable speed control are more efficient at lower speeds and partial capacity (see our Minisplit Mania report to learn why).

Figures 5 and 6 show our example minisplit heat pump's total cooling capacity and the "SHR" (Sensible Heat Ratio). At nominal room temperature conditions (68F to 76F), the 1 ton minisplit has a total cooling capacity of 12,000Btu/hour, or 1 ton of cooling capacity. The SHR indicates the fraction of the total cooling capacity that is sensible (temperature cooling), with an average SHR of 0.7 to 0.75. Therefore, approximately 25% to 30% of the mini-split's 1 ton cooling capacity is latent (moisture) dehumidification. A latent capacity of 3000 to 3600Btu.hr is equivalent to 30 to 40 kg of moisture removal per day, in agreement with Figure 4 data.

Figure 7 is a plot of the 1 ton heat pump's COP (Coefficient of Performance), a dimensionless ratio of the total cooling capacity to the electrical power required for operating the unit. The unit operates with a COP of 3 to 3.5 during typical summer conditions and indoor comfort conditions.

Figure 8 determines the 1 ton mini-split heat pump's dehumidification performance by calculating it "Energy Factor" (EF), a ratio of the water condensed (kg) per electrical energy (kWh) required. Energy Star ratings require a minimum EF of 2.0 for dehumidifiers. Although much of the data in Figure 8 has an EF less than 2, we will find that an adjusted EF for Energy Star qualified dehumidifiers tends to be lower than the mini-split heat pump's dehumidification efficiency. Also, the mini-split heat pump contributes sensible cooling to the home while a dehumidifier adds heat that must be removed by additional cooling. We will address these considerations more directly in the section on dehumidification.

Two more factors also contribute to a smart-ventilated, well-sealed home's moisture management capabilities. First, today's minisplit heat pumps and air conditioners often have a "dehum" or "dry" operation mode in which latent (dehumidification) conditioning is emphasized. Dehum mode is characterized by a slow fan speed that reduces air flow through the cooling coils, which causes the cooling coils to become colder. The colder the cooling surface, the lower its water vapor pressure, which increases the water vapor pressure difference that drives the dehumidification rate.

The second factor we will discuss in more detail are CERV2 smart ventilation dehumidification of fresh ventilation air and heat pump water heater dehumidification. These two new technologies synergistically augment moisture management in a beneficial manner in warm and humid climates, further relieving the need for additional moisture management systems.

Figure 1 Indoor heat exchanger for a "ductless" minisplit heat pump. During summer operation as an air conditioner, the heat exchanger is cold and condenses water vapor. The white insulation clad tube on the left is the condensate drain tubing.

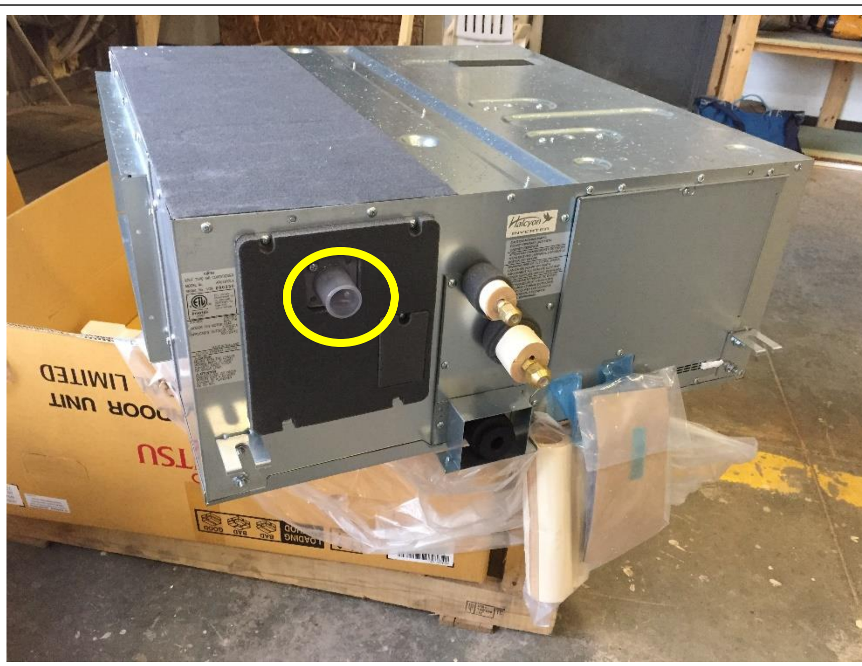

Figure 2 A "ducted" minisplit air conditioner indoor "head" can be concealed and connected to ductwork for air distribution. A circle is drawn around the condensate drain tube.

Figure 3 Equinox House has two ductless minisplit heat pump units. The outside units with compressor and outdoor heat exchanger are identical for ducted and ductless heat pumps. Read our “Minisplit Mania” news article and related report to learn why two heat pumps are more efficient than one!

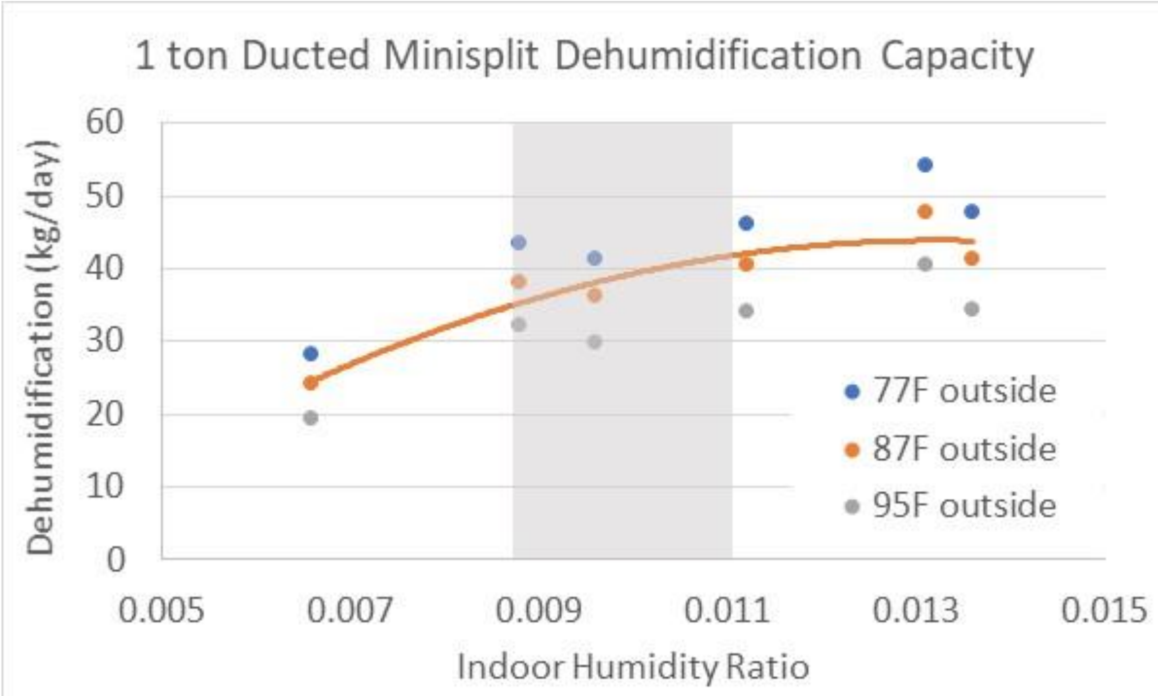

Figure 4 Daily dehumidification capacity for a 1 ton ducted minisplit heat pump versus the indoor humidity ratio. A humidity ratio of 0.009 to 0.010 at 70F represent 55 to 60% relative humidity, typical of indoor summer conditions. Note that 1 kg is 1 liter of liquid water.

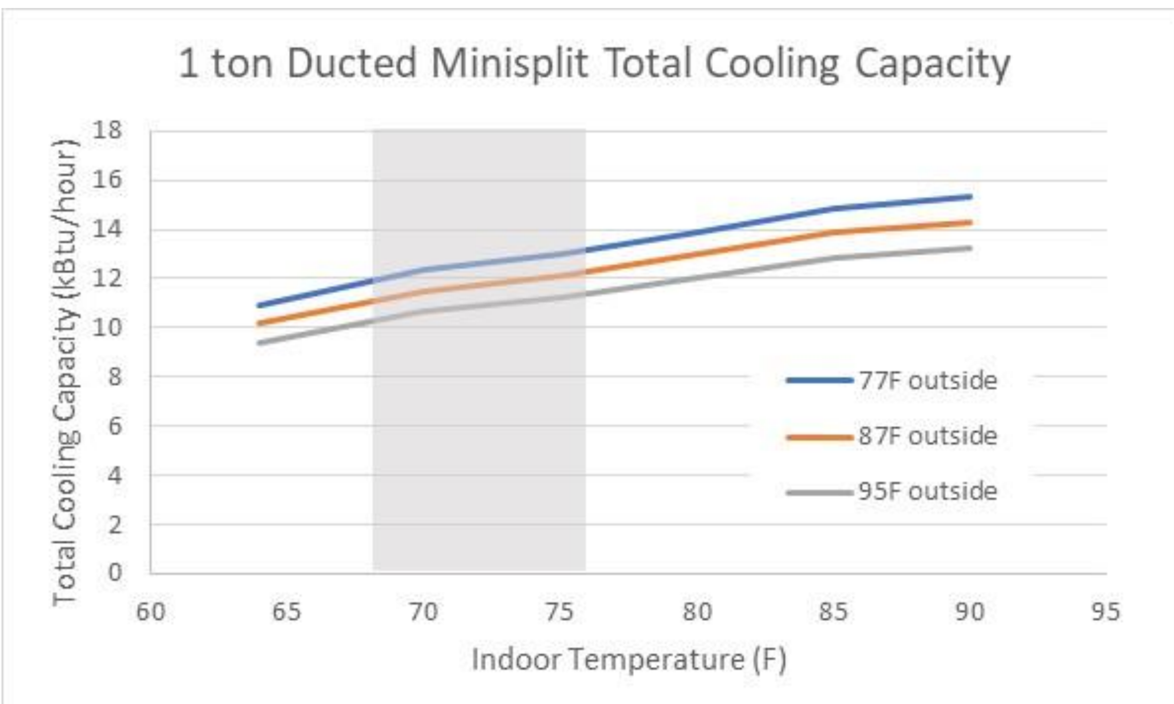

Figure 5 Total cooling capacity for a 1 ton ducted minisplit heat pump versus the indoor temperature (drybulb).

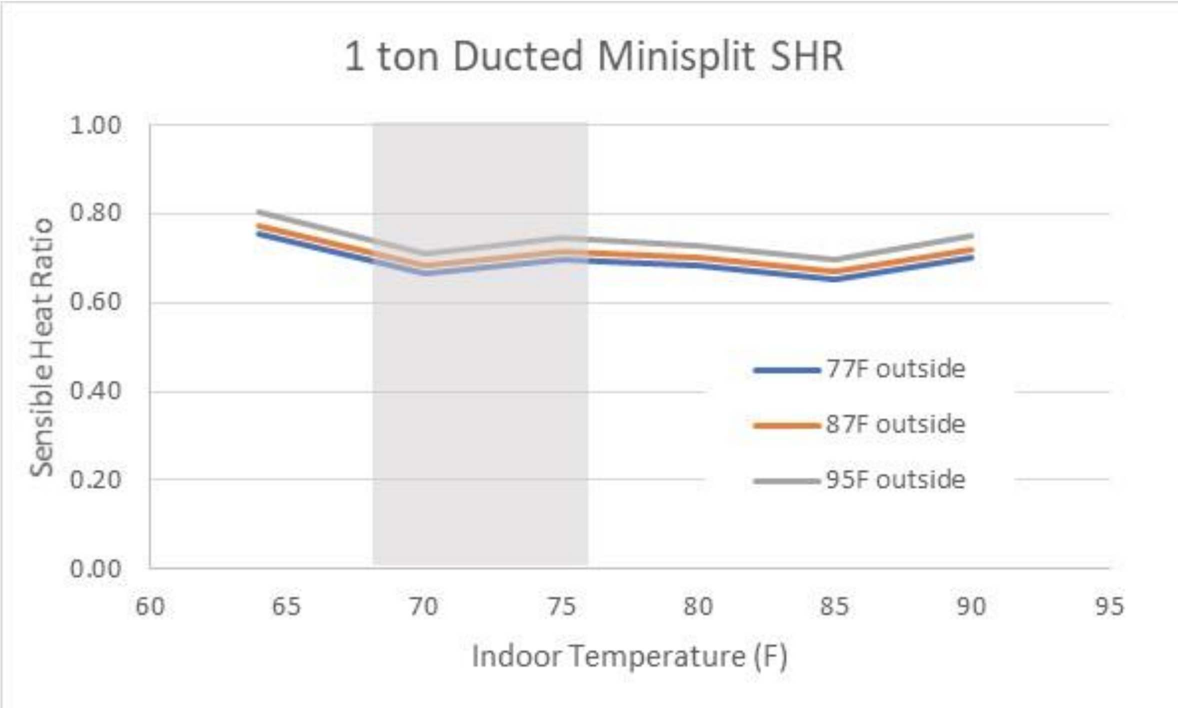

Figure 6 Sensible Heat Ratio (SHR) for a 1 ton ducted minisplit heat pump versus the indoor temperature (drybulb).

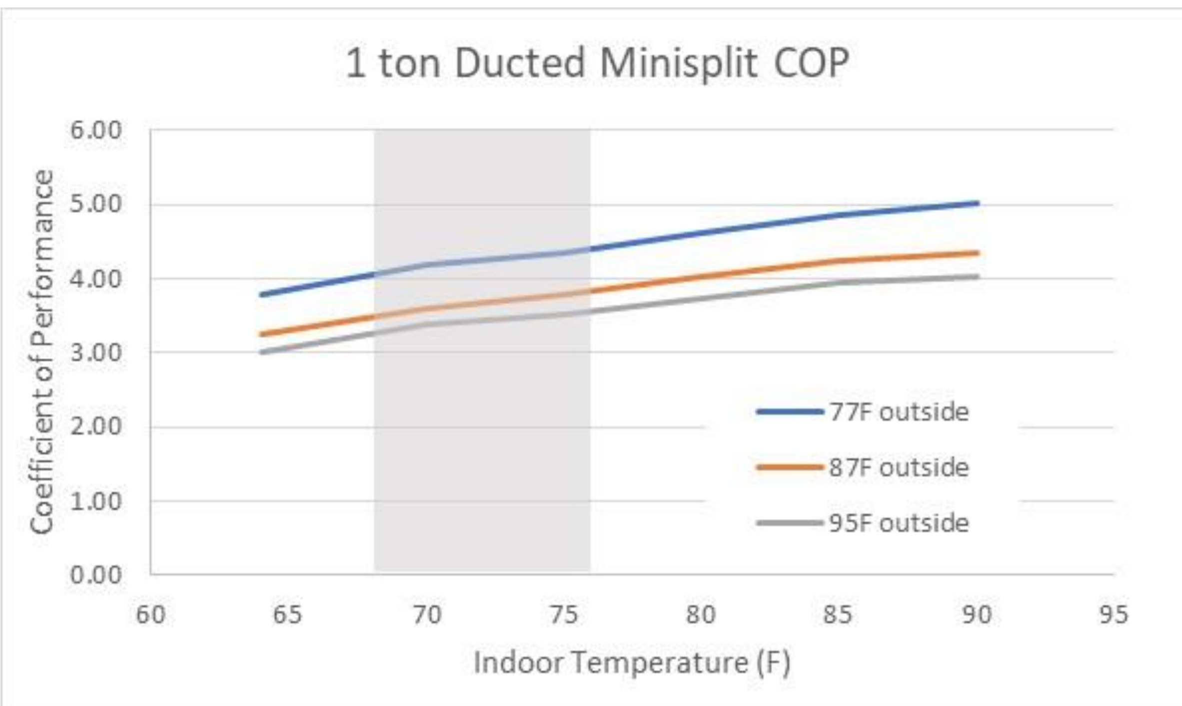

Figure 7 Coefficient of Performance (COP) for a 1 ton ducted minisplit heat pump versus the indoor temperature (drybulb).

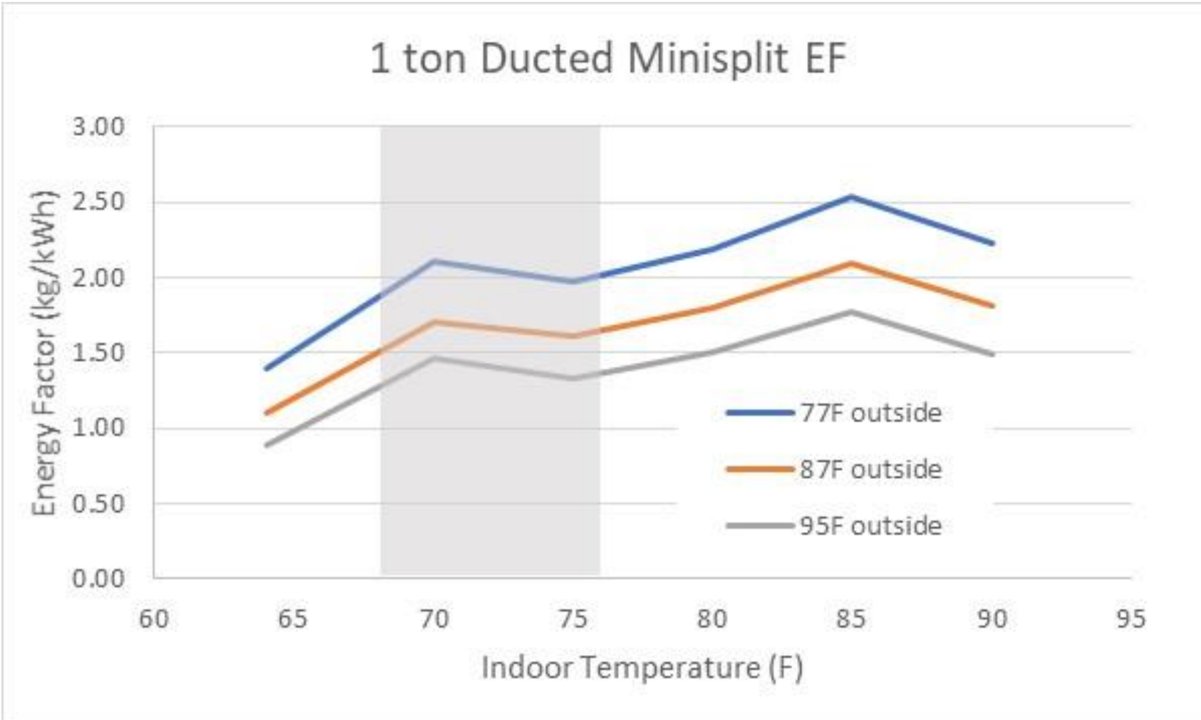

Figure 8 Energy Factor (EF) characteristics of a 1 ton minisplit heat pump.

CERV2 Smart Ventilation Moisture Management

A CERV2 smart ventilation system cools and dehumidifies warm, outdoor air before it mixes with indoor air. Dehumidifying humid outside air before it mixes with indoor air increases cooling efficiency and dehumidification capacity. As previously mentioned, a 50F cooling coil cannot condense water from 70F and 50% relative humidity air, however, it can condense water from 70F and 100% relative humidity air. When humid, outside ventilation air mixes with indoor air, the large indoor air volume reduces the outside air humidity which reduces dehumidification capacity.

Figure 9 shows external and internal views of a CERV2 and its heat pump energy exchange system. During ventilation mode, fresh filtered outside air is dehumidified during cooling. Indoor air is cooled and dehumidified during the CERV2's recirculation mode. Recirculation of a home's air is essential for reducing house particulates and for utilizing fresh air stored in unoccupied regions of a home.

The CERV2's heat pump is designed to efficiently operate over a broad range of indoor and outdoor temperature and humidity conditions. A conventional air conditioner is designed for operation within a narrow band of indoor conditions. For example, the 1 ton heat pump discussed in the previous section will not operate in cooling mode with indoor temperatures below 64F, and operates with limited capacity when indoor temperatures are reduced below 68F. Similar operation restrictions apply to a conventional heat pump unit in heating mode as indoor temperature exceeds 76F.

The CERV2 operates without restriction in any combination of indoor temperature and outdoor temperature conditions. In addition, the robust and rugged CERV2 heat pump can switch indoor and outdoor conditions instantly as it changes from ventilation mode to recirculation mode (ie, indoor temperature air and outdoor temperature air streams regularly move between the hot and cold sides of the heat pump). Additionally, the CERV2 does not need to prevent or avoid frosting conditions. In fact, during winter operation, the CERV2 wrings energy out of indoor moisture being exhausted from a house, temporarily freezing moisture on its cooling coils. Our smart ("adaptive") defrost algorithm removes frost as needed. HRVs and ERVs are unable to benefit from this latent to sensible energy recovery because of the need to avoid frost in their heat exchangers.

Figure 10 shows CERV2 dehumidification characteristics in a similar manner to Figure 4 for the 1 ton mini split heat pump. The CERV2 is a nominal 1/3 ton capacity heat pump, and its dehumidification characteristics roughly correspond to 1/3 of the dehumidification capacity of the 1 ton mini split unit. During recirculation, with typical indoor summer conditions of 74-76F and 60% relative humidity, which is a humidity ratio of 0.010 to 0.011, the CERV2 removes 5-6 kg (liters) of water per day. During outdoor conditions with higher humidity ratios, the CERV2 approaches 20kg of water removal per day. As previously described, if humid outdoor air is mixed with indoor air before passing through an air conditioning or dehumidification unit, dehumidification capacity and dehumidification efficiency are reduced.

The CERV2 dehumidification capacity increases as humidity increases. Figure 10 shows increasing dehumidification capacity as humidity ratio increases above 0.09. Below 0.09 humidity ratio, which corresponds to 50% relative humidity and 76F, all of the CERV2's cooling capacity is sensible cooling. A 0.09 humidity ratio corresponds to a dew point temperature of 55F, which is approximately the temperature we operate the CERV2's heat pump cooling coils.

Figure 11 shows the CERV2's total cooling capacity during recirculation and fresh air ventilation modes. During recirculation mode operation when the CERV2 is cooling and dehumidifying indoor air, the CERV2's total cooling capacity trends are similar to that of other heat pumps (eg, see Figure 5 for the 1 ton minisplit heat pump). As indoor temperature is increased, relative to a fixed outdoor temperature, cooling capacity increases. During ventilation mode operation, the CERV2 has the opposite characteristic in which increasing indoor temperature decreases the CERV2's cooling capacity. Indoor air absorbs heat removed from the outdoor air during fresh air ventilation, and as indoor air temperature increases, it is unable to absorb as much heat from the outside air. Notice how fresh air ventilation mode cooling capacities are much greater than recirculation cooling capacities in the 68 to 76F indoor comfort temperature range when energy is being "recovered".

Figure 12 shows the CERV2's Sensible Heat Ratio (SHR) trends during recirculation and fresh air ventilation modes. The SHR is 1 as temperatures decrease below 60F as previously mentioned because the CERV2's cooling coil temperature operates at a dew point of approximately 55F. The SHR during recirculation tends to be greater than the ventilation SHR, which is a desirable trend because outdoor conditions are more likely to have higher humidity ratios, and therefore more dehumidification capacity needs (when the associated humidity ratio is high).

Figure 13 shows the CERV2's Coefficient of Performance (COP) during recirculation and ventilation modes. The CERV2's COP is very high (5-6) during fresh air ventilation when exchanging energy between the incoming fresh air stream and the outgoing exhaust air stream. The CERV2's COP is lower (2-4) during recirculation mode for typical summer indoor temperatures (74-76F).

The CERV2's purpose in life is automated, energy efficient management of indoor air quality, with the added feature of beneficially contributing to moisture control needs. Figure 14 shows the CERV2's performance as a dehumidifier, similar to Figure 8 for the mini-split heat pump. As mentioned, the CERV2 automatically reduces its dehumidification capacity as air temperature to its cooling coils decreases, in parallel with a reduced need for dehumidification capacity. The EF for lower temperatures is low in this range as the CERV2 shifts its energy exchange and cooling capacity to sensible energy.

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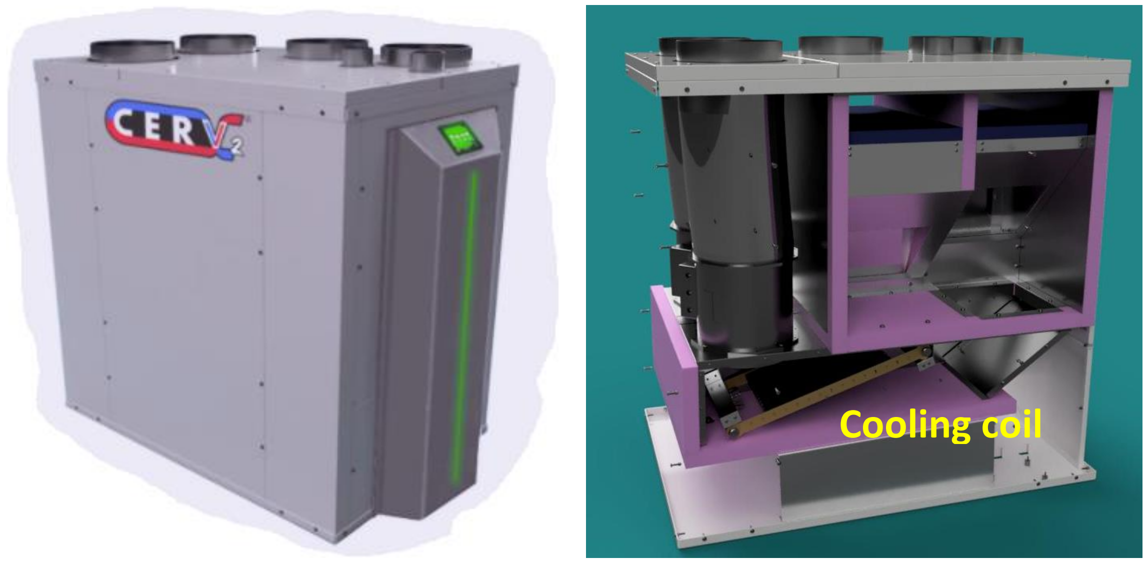

Figure 9 CERV2 external and internal views. Condensate collects under cooling coil.

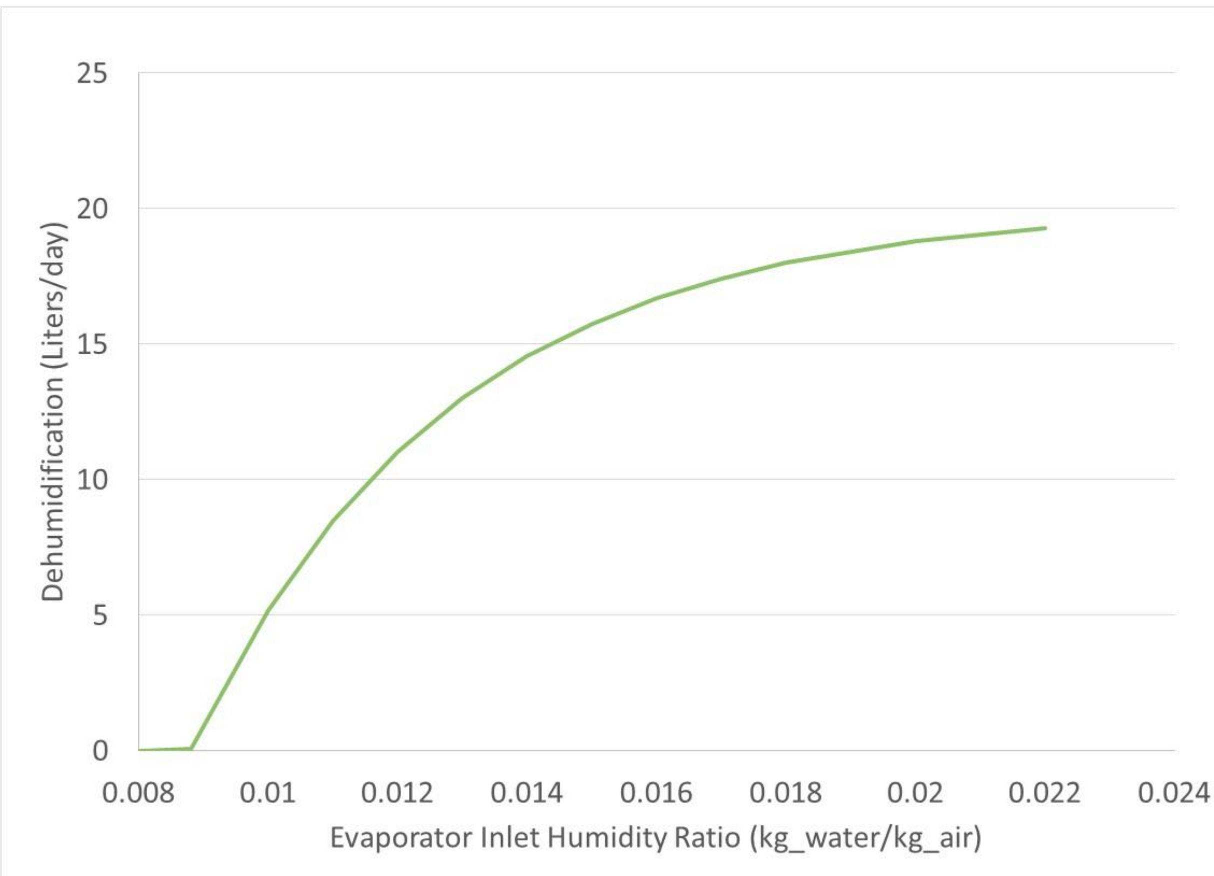

Figure 10 CERV2 dehumidification capacity in relation to humidity ratio.

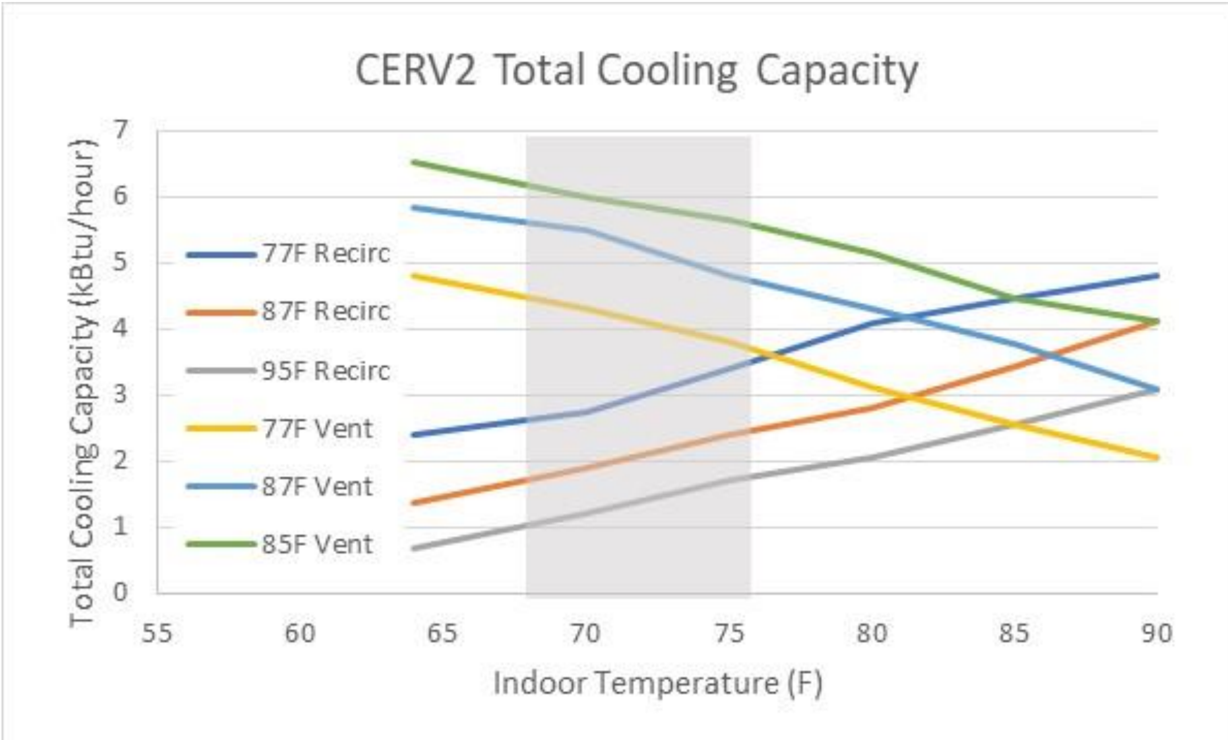

Figure 11 Total cooling capacity for CERV2 recirculation and ventilation operation. Note: outdoor air is cooled and dehumidified during ventilation mode.

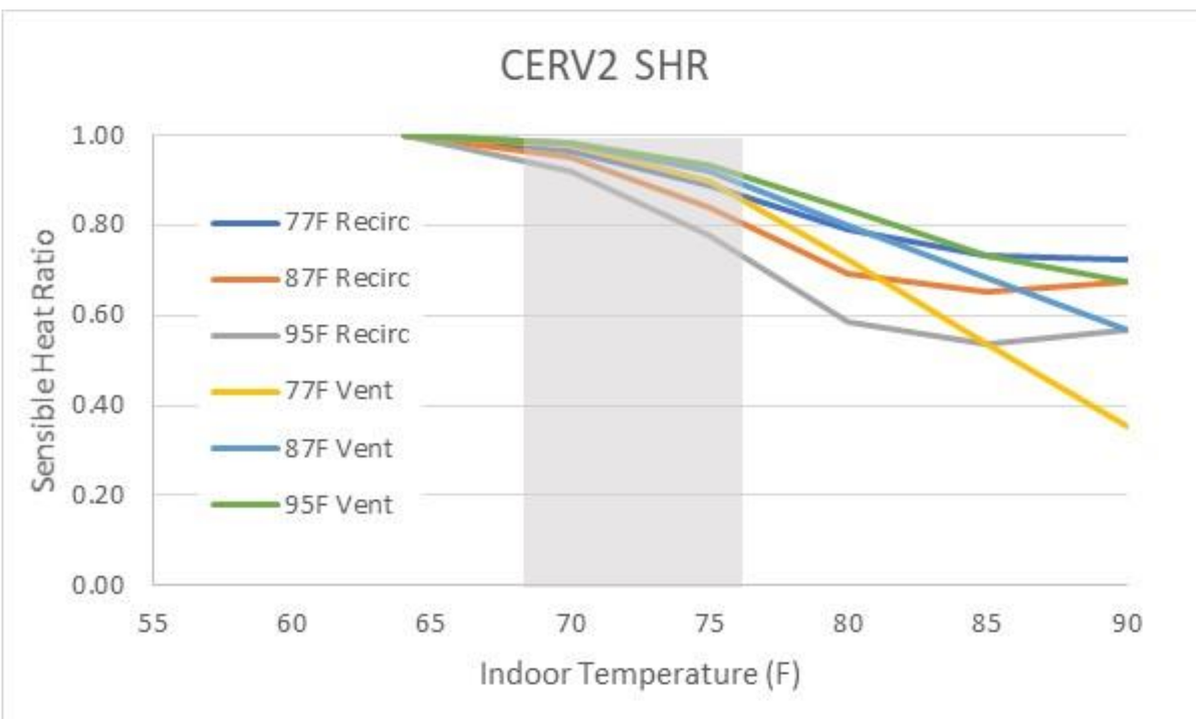

Figure 12 Sensible Heat Ratio for CERV2 during recirculation and ventilation modes.

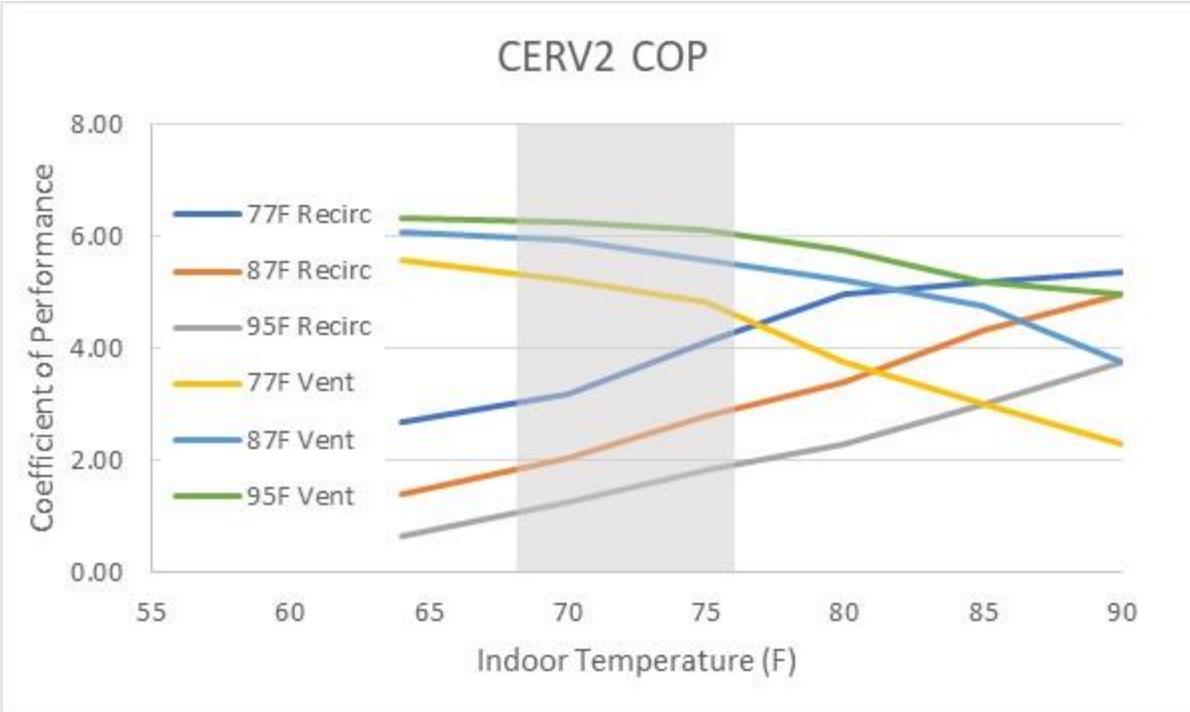

Figure 13 Coefficient of Performance (COP) for CERV2 during recirculation and ventilation mode operation.

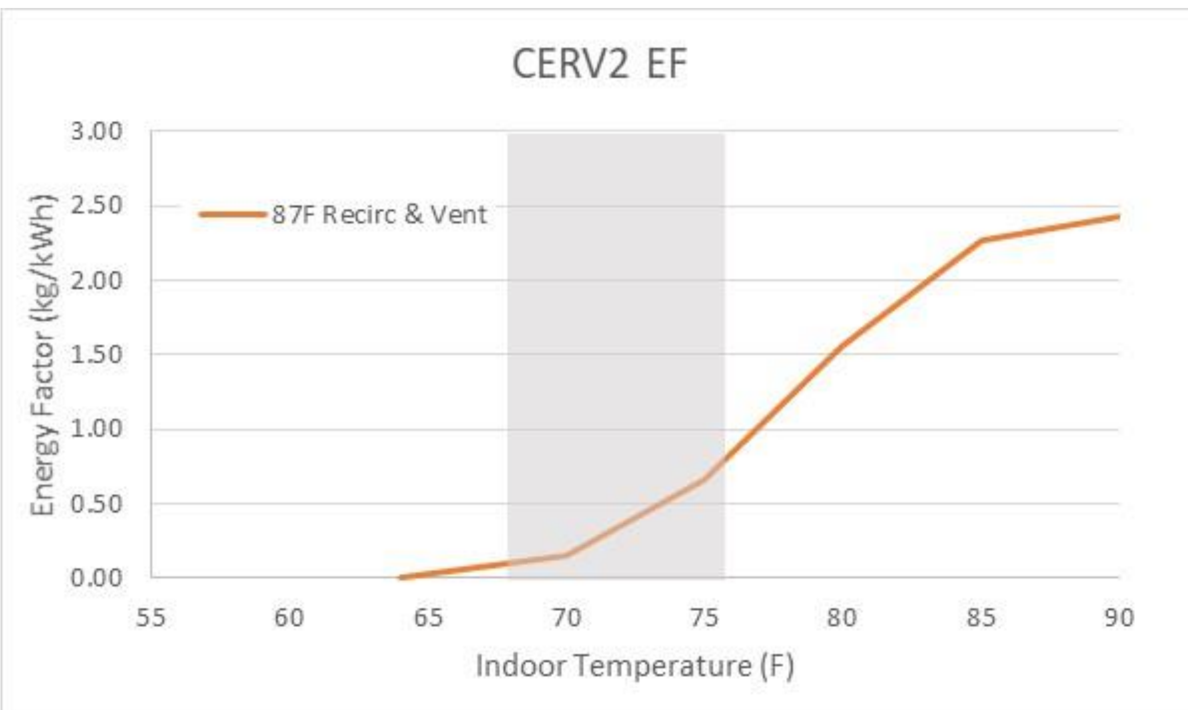

Figure 14 CERV2 dehumidification Energy Factor (EF) trends.

Heat Pump Water Heater (HPWH) Dehumidification

The purpose of a HPWH is to provide a home with hot. An added bonus of a HPWH is moisture condensation from indoor air when humidity increases. HPWH manufacturers do not provide condensation performance in their operation literature. We can estimate moisture performance based on generalized characteristics of heat pumps as discussed for air conditioners and CERV2 heat pumps.

HPWHs remove transfer heat from their surroundings into the hot water tank. Most HPWHs in North America are located indoors, but a few operate outdoors. Indoor operation is preferred in North America because heat removal from the indoor ambient is a benefit in the summer. Heat removal from indoors in the winter is also efficient when a home is heated by a heat pump.

Figure 15 shows a HPWH located in a cramped mechanical closet. Adjacent to the HPWH is a CERV2 ventilation unit. HPWH manufacturers recommend locating HPWHs in large rooms because a smaller room's temperature can be lowered, which reduces HPWH efficiency. A CERV2 unit moves air through all spaces in a home, including mechanical closets, which allows a HPWH to be located in restricted spaces.

HPWH energy usage and moisture condensation from indoor air is related to the number of people in a home. When no one is home, no hot water is used, and HPWH energy usage is very low. As occupancy increases, hot water usage increases, increasing heat removal and water condensation from indoor air.

Average hot water usage in North America is 18 gallons (~65 liters) of hot water per person per day. Assuming water is heated from 50F (10C) to 120F (50C), the heat added to water is an energy change of 3kWh per person per day (~10,400Btu/person-day). Typical HPWH COP (Coefficient of Performance, also called Energy Factor) is 3, which means 1kWh per person per day of hot water energy is electrical energy operating the heat pump, and 2kWh per person per day of energy is from the surrounding ambient air. Interestingly, 2kWh of heat removed from indoor ambient air is nearly equivalent to the amount of heat that each occupant's metabolism adds to the indoor environment. That is, a HPWH transfers your body's heat to your hot water tank for washing and showering.

A HPWH condensation characteristics are similar to the CERV2's heat pump, and an SHR (Sensible Heat Ratio) of 0.80 would be expected. At an SHR of 0.80, 0.4kWh of latent conditioning occurs, which would be 0.6kg per person per day of water condensation. In our "Making It Real" section, we will present data showing this is a realistic value for HPWH moisture removal.

Figure 15 HPWH installed in a small mechanical closet adjacent to a CERV2 (left) smart ventilation unit. The CERV2 allows the HPWH to be placed in a small, enclosed space.

Dehumidifiers

Homes with low Sensible Heat Ratios have high latent (moisture) conditioning in relation to their sensible cooling needs. Increasing an air conditioner's cooling capacity will not increase its moisture management capacity because it is tied to the unit's sensible cooling capacity as previously discussed. In fact, over-sizing an air conditioner in the hope to increasing moisture management capacity is the opposite of what is needed. Reaching an air conditioner's full moisture condensation capacity requires a unit to operate continuously. Oversized air conditioners that briefly operate to satisfy sensible cooling are unable to reach stable, cold coil temperatures needed for dehumidification.

We discussed climatic effects on a home's dehumidification needs, and for sealed homes with smart ventilation and typical occupant moisture generation, the foundational triad of a high performance comfort conditioning heat pump, CERV2 smart ventilation system, and a HPWH will manage moisture nicely throughout most of North America. Homes that are not well-sealed, do not have smart ventilation, and/or have high levels of internal moisture generation (large number of plants, several aquariums, indoor exercise rooms, greater than average cooking, etc) may need a separate dehumidifier to manage moisture with SHR levels below 0.7.

Dehumidifers are available as self-contained "basement dehum" units or inline dehums that are connected to a home's ventilation system. Dehumidifiers have been around for several decades, as noted by Figure 16 with a photo and advertisement of an Oasis dehum from the 1950's. Figure 17 shows three modern, self-contained dehums. The cost for these units is low, however, their failure rates are very high in contrast the Figure 16 unit that still operates after many years of operation in multiple basements. Figure 18 is a high quality, inline, ducted dehumidifier.

An Energy Star rated dehumidifier requires an Energy Factor (EF) ratio greater than 2kg per kWh. Dehumidifiers reject waste heat into the indoor space, often causing rooms to overheat when low or no heating is desired. The heat transferred to an indoor space is the combined energy of the electrical energy used for powering the dehumidifier and the "phase-change" energy that must be removed from water vapor to condense it into liquid water.

Figure 19 shows EF performance for two high EF rated, ducted dehumidifier units. Dehumidifiers are rated at 80F and 60% relative humidity, which shows EF ratings of 2.4 and 2.9 for the two units in Figure 19. Dehumidifiers operating a more typical comfort conditions have EF levels that are 15 to 20% lower as shown in Figure 19 for indoor temperature and relative humidity of 70F and 60%.

The dehumidifier's heat exhausted to an indoor space must be air conditioned out of the building. In effect, the dehumidifier is able to reduce the SHR of a home's conditioning system by removing moisture, and increasing the sensible heat of the air conditioner. Accounting for the air conditioner's increase cooling load, an "actual" EF for a dehumidifier can be determined. In Figure 19, the COP of the 1 ton high performance minisplit heat pump previously discussed is

3.3 at 70F and 3.8 at 80F. The actual EFs for the two dehumidifiers is lowered by a significant amount. In fact, Figure 19 shows the minisplit heat pump to have a better EF than either dehumidifier with the added cooling load included. Additionally, the minisplit heat pump EF does not include the beneficial sensible cooling that is twice the latent energy capacity.

Obtaining as much dehumidification with an air conditioner, augmented by a CERV2 and HPWH dehumidification contributions is more energy efficient than today's high performance dehumidifiers. When conditions occur that lower the SHR below the capability of the air conditioning unit, a dehumidifier provides a method for removing additional moisture.

Figure 16 A 1950s era Oasis dehumidifier in our "historic" corner of Build Equinox facility. The unit still runs with a capacity of 3 gallons per day using Freon 12 refrigerant.

Figure 17 "Basement dehums" come in a variety of capacity levels with EFs at Energy Star minimum levels (2.0). The 30 pint per day (ppd, or, 14 kg/day) unit costs $157, the 50ppd (24 kg/day) costs $199, and the 70ppd (33 kg/day) unit costs $219.

Figure 18 Duct mounted dehumidifier with 95ppd (45 kg per day) capacity operates with an airflow of 200 to 250cfm. This unit can be incorporated into the ductwork between a CERV2 smart ventilator and 1 ton ducted minisplit heat pump, with the CERV2 controlling all three units. Ducted dehumidifiers cost $1000 to $2000 depending on capacity and quality.

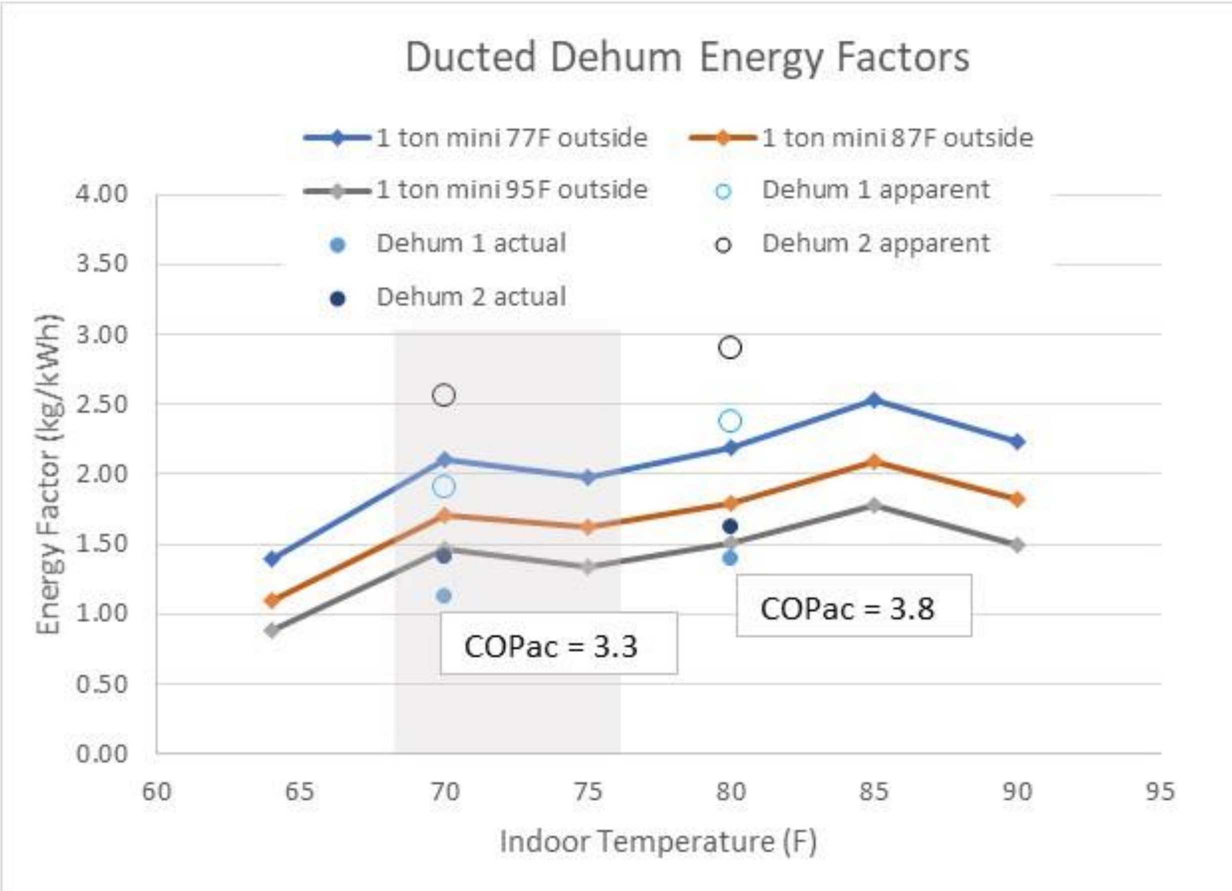

Figure 19 Comparison of Energy Factors (kg/kWh) for two Energy Star ducted dehumidifier units in comparison to a 1 ton ducted minisplit heat pump's EF. Apparent (Energy Star rating) and actual (accounts for indoor heating) dehumidifier EF values are shown.

Humidifiers

Humidifiers should rarely be required in a well-sealed and insulated home, however, some situations such as respiratory sensitivities may need elevated humidity levels. Parts 1 and 2 discussed the humidification needs of leaky and over-ventilated homes. For a home in Urbana, as much as 10 to 20 liters of water must be added to a home's indoor air per day in order to keep indoor relative humidity at 30%. Part 2 presented data from Equinox House demonstrating its ability to maintain indoor relative humidity between 40 to 50% in the winter due to low infiltration, CERV smart ventilation, and a large number of plants.

Vaporizing one liter (kg) of liquid water requires 2400kJ (0.67kWh) of energy. Steam vaporizers, such as shown in Figure 20, electrically heat water until is vaporizes, similar to a teapot on a stove. The hot vapor mixes with indoor air, and causes very little change of air temperature. Ducted steam vaporizers are also available that are connected to a home's ventilation ducts. Because the generation of water vapor is a 1-to-1 conversion of electrical energy to vaporized water, a home requiring 20 liters of water vaporization per day is using 13.5kWh of electricity per day, or about 400kWh per month! Steam vaporizers much be periodically clean of scale that forms on its heating surfaces, similar to those in a teapot and coffee pot.

A second method for increasing humidity is evaporation of water. Water evaporation implies that energy required for vaporizing water comes from the surrounding air, which can cause a room to be noticeably cooled. Figures 21, 22, and 23 shows a portable evaporator humidifier. Water reservoirs add water to a paper evaporator that wicks water into its passageways. A fan blows air through the paper evaporator, which increases the humidity of the air stream.

Similar to the cooling effect of air blowing over wet skin, evaporative cooling and vaporization of water requires the home's heating system to increase capacity to make up for the vaporization energy. Therefore, efficiency of evaporation humidification is related to the home's heating system efficiency. A home with heat pump heating will vaporize water with the heat pump's efficiency (COP). A heat pump COP of 3 requires 1/3 of the electrical energy that a steam vaporizer requires.

Although the energy efficiency of an evaporative humidifier can be much greater than a steam vaporizer, maintenance is essential with evaporative humidifiers to ensure it is clean without mold, endotoxins or similar biological growths that the cooler temperature vaporization allows. Evaporation humidifiers have been identified as major generators of endotoxins, which cause severe fevers, fatigue and septic shock.

Plants are perhaps the best of all worlds. The plant-root-dirt matrix is known to self-sanitize water, and the water vapor produced is an evaporative (transpiration) process that occurs at the efficiency level of a home's heat pump conditioning system. Plants also contribute to VOC reductions (as well as add some of their own). In Equinox House, our 50 plants add 5 (summer) to 7 (winter) liters of water per week.

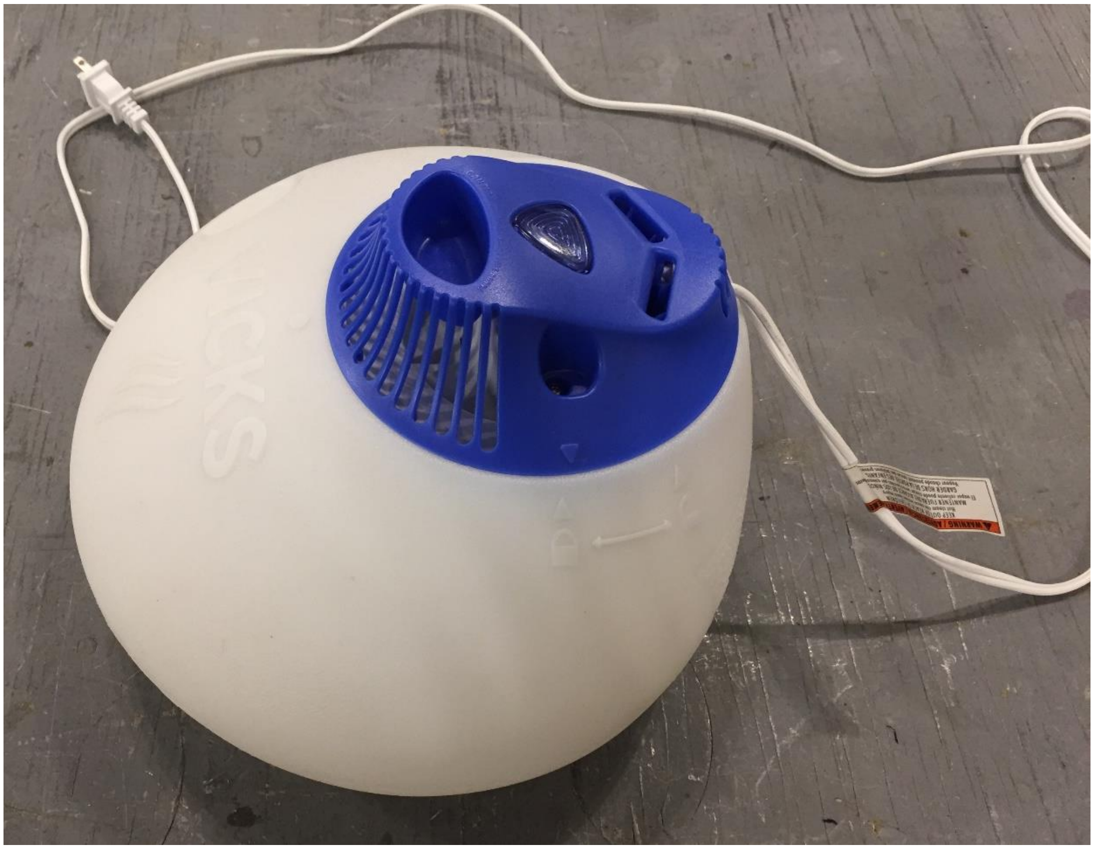

Figure 20 Typical room “steam” vaporizer for humidifying.

Figure 21 Cool mist, evaporative humidifier for whole house humidification.

Figure 22 Two water tanks (~2 gallons each) supply water to a paper evaporator.

Figure 23 A fan blows air through a paper evaporator soaked in water.

Making It Real

The preceding sections describe methods and energy requirements for removing and adding moisture to a home using today's moisture management technologies. Three disruptive technologies; high performance heat pumps, CERV2 smart ventilation, and HPWH form the foundation for sustainable living powered by renewable energy. Figure 24 is a schematic of these synergistic systems. Many of our readers are part of the revolution that is underway, demonstrating that a sustainable lifestyle is possible and economical in any climate!

How do these three technologies interact with each other? Does one prevent the other two from contributing their potential? Are the levels of moisture management in agreement with the performance characteristics previously discussed? We demonstrate in this section that comfort conditioning heat pumps, CERV2 smart ventilators and HPWHs do indeed work very well together.

Figure 25 shows a CERV2 and a HPWH sharing a small mechanical room in a high performance Vermod home. Until recently, Vermod homes used ductless minisplit heat pumps for comfort conditioning. Vermod has recently transitioned to CERV2 smart ventilation systems coupled with a ducted minisplit heat pump. Figure 26 shows a CERV2 directly connected to the indoor unit of a 1 ton, ducted minisplit heat pump. The CERV2's advanced, online controller manages the ducted minisplit heat pump operation in addition to automatically managing air quality, providing seamless and synergistic operation of a home's comfort and air quality. The CERV2 also filters air delivered to the minisplit, providing effective control of indoor particulates.

Water condensation data is very sparse. Like most building collection data activities, buildings are relatively slow moving entities that require more than a year of continuous monitoring in order to better understand their operation. And, data collection and analyses are tedious and boring!

Although water collection can be automated, over 40 years of building monitoring experience has shown that manual collection of condensate is one of the best ways to understand system performance. Writing a daily log is important in order to include seemingly innocuous events that would otherwise be unknown with automated monitoring. Figure 27 shows a collection bucket at the Build Equinox test facility with 24 hours of condensate from a CERV2 during warm and humid outdoor and indoor conditions. Four years of daily condensate collection from 3 different heat pumps (ductless minisplit, CERV, and HPWH) represents 4000 buckets of condensate!

Figures 28, 29, 30 and 31 show summer daily-accumulated condensate data for Equinox House for the 2011, 2012, 2013, and 2014 summer seasons. Condensate was separately collected from a ductless minisplit heat pump (1 ton Mitsubishi Hyper Heat), a CERV (1st generation CERV smart ventilator) unit, and a 40 gallon HPWH. During Equinox House 1st year of operation, calibrations were conducted to better understand house thermal and moisture performance. A stand-alone dehumidifier was used prior to installing a minisplit heat pump for the 2011 summer in order to better understand moisture management needs of the house. All data after 2011 is from a 1 ton minisplit heat pump.

The 2011 and 2012 summers were relatively warm and humid, and required 700 to 800 kg of water removal from mid-May to mid-September, or 6 to 7kg of water removal per day, in good agreement with our house moisture management requirements determined in Handling Humidity report Parts 1 and 2. The summers of 2013 and 2014 were noticeably drier, with only 400 to 500kg of moisture removal required.

The HPWH removed approximately 100 kg of water per summer season for all 4 years, indicating that its operation is independent of climatic variations with a relatively constant 1kg per day of moisture removal over the 90 to 120 day summer season. Equinox House has 2 occupants, and the 0.5kg per day per person of HPWH moisture removal is in good agreement with our calculated estimate of 0.6kg per day per person.

The comfort conditioning minisplit heat pump and the CERV heat pump system dehumidification performance are directly related to climatic conditions. The CERV's dehumidification is 200 to 250 kg of moisture removal during the humid 2011 and 2012 summers. The CERV's dehumidification is reduced to 50 to 100 kg per summer during the dry 2013 and 2014 seasons. As previously discussed, lower humidity conditions reduce the CERV's dehumidification capacity. Additionally, as in more arid regions, cool nighttime temperatures are detected by the CERV, which switches into a "free cooling" mode that reduces energy consumption, and fills a home with fresh air the reduces the need to deliver fresh air during the daytime.

The dehumidifier used during 2011 and the 1 ton minisplit heat pump used for 2012, 2013, and 2014 provided up to 400 kg of dehumidification capacity. As discussed, these units are capable of removing up to 40 kg per day of condensate. During very humid periods when indoor relative humidity reach 65%, the minisplit heat pump is switched to its "dehum" or "dry" mode for 8 hours. The house relative humidity will be reduced to 60%. Additional dehum periods are added if outdoor weather conditions continue increasing indoor relative humidity to 65%. Note that 65% relative humidity is a level at which a human's evaporative cooling by perspiration is reduced, increasing one's discomfort with slight increases of metabolic activity.

Figure 32 shows the 2012/2013 winter season. The minisplit heat pump removes water in its outdoor unit during the winter, and therefore does not impact indoor moisture balances. The CERV removes moisture from both outdoor air during recirculation mode, and from the indoor air during fresh air ventilation periods. During winter, the CERV removes 400 to 500 kg of water per year from either indoor air or outdoor air. The CERV's condensing of water during winter does not impact the indoor moisture balance of the house, but is a very significant energy benefit that is unavailable to conventional HRV and ERV energy recovery units. The CERV converts the "latent" heat of the condensed water into sensible heat input to the house. In the case of Equinox House, 450kg of water condensation is 1,000,000 kJ (300kWh) of heat input to the house.

The HPWH continues removing water from the indoor environment during the winter at a rate of approximately 1 kg per day as it did during the summer, for a total of 100 kg over the 3 to 4 month winter season. The kg per day of water removal by the HPWH, balances with Equinox House moisture generation from occupant metabolism, cooking, washing, plants, etc that results in a very comfortable 40 to 50% indoor relative humidity during the winter as discussed in our Part 2 report. Because Equinox House is heated with a high performance minisplit heat pump, the HPWH heat and moisture removal are countered by the comfort conditioning system's capacity for an overall high house performance efficiency. Our August 2016 newsletter article ("Understanding the House as a System") provides analyses and discussion for understanding why a HPWH's cooling effect in the winter is a benefit.

Figure 33 shows dehumidification and humidification data from a 1920's era home located in Urbana Illinois. The data is from the 1990's with summer condensate collected from the home's central air conditioning unit. The home's humidity was increased during the winter with the humidifier shown in Figure 21, which barely kept relative humidity above 20% during bitter cold, windy weather conditions. During summer, up to 40 kg of water was removed per day, similar to what we estimated for a home built by Contractor Loose in Part 1 and Part 2 reports. Winter humidification reached 20 kg of water addition per day, which was limited by the humidification capacity of the humidifier.

Water condensation and evaporation data, as shown in Figure 33, can be used similar to other "tracer gas" methods for estimating a home's infiltration levels. The summertime dehumidification data in Figure 33 indicates an average infiltration level of 115cfm while the wintertime humidification data indicates an average infiltration rate of 170cfm. Winter infiltration is greater than summer infiltration because wind and indoor/outdoor temperature differentials are greater, and because the gas furnace in the house used indoor sourced combustion air. With indoor combustion air, every time the furnace operated, combustion air exhausted from the house is replaced by infiltrated air.

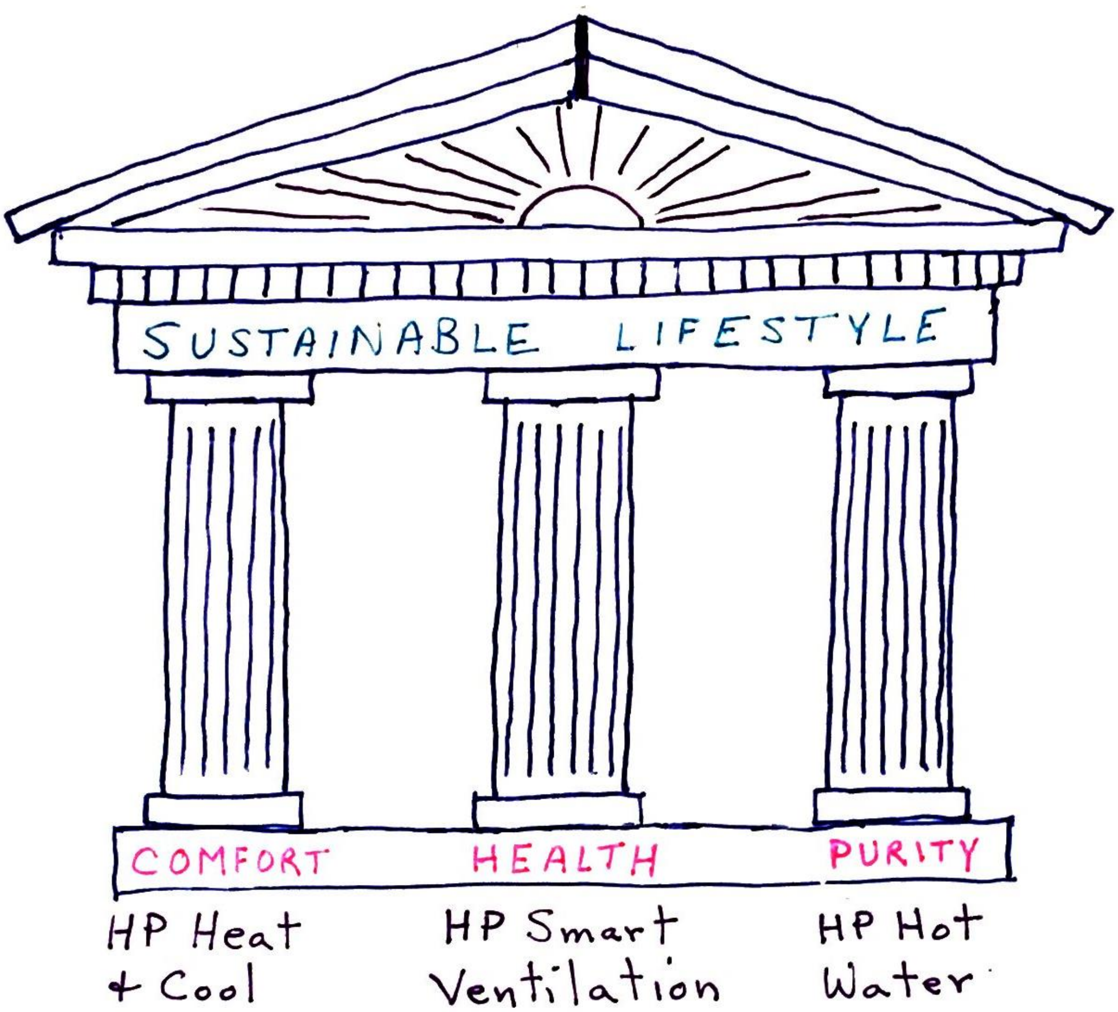

Figure 24 Triad of disruptive technologies revolutionizing comfort conditioning, indoor air quality and cleanliness of homes that provide an important path toward sustainable living.

Figure 25 A second generation CERV2 in a small mechanical room shared with a HPWH in a high performance Vermod home. The HPWH and CERV2 share a condensate drain (white plastic pipe between the units).

Figure 26 A CERV2 and high performance ducted minisplit heat pump are connected inline with an 8 inch diameter insulated duct at our Build Equinox laboratory. The CERV2 provides the brains for controlling the minisplit heat pump, seamlessly providing online control of automated air quality and comfort management.

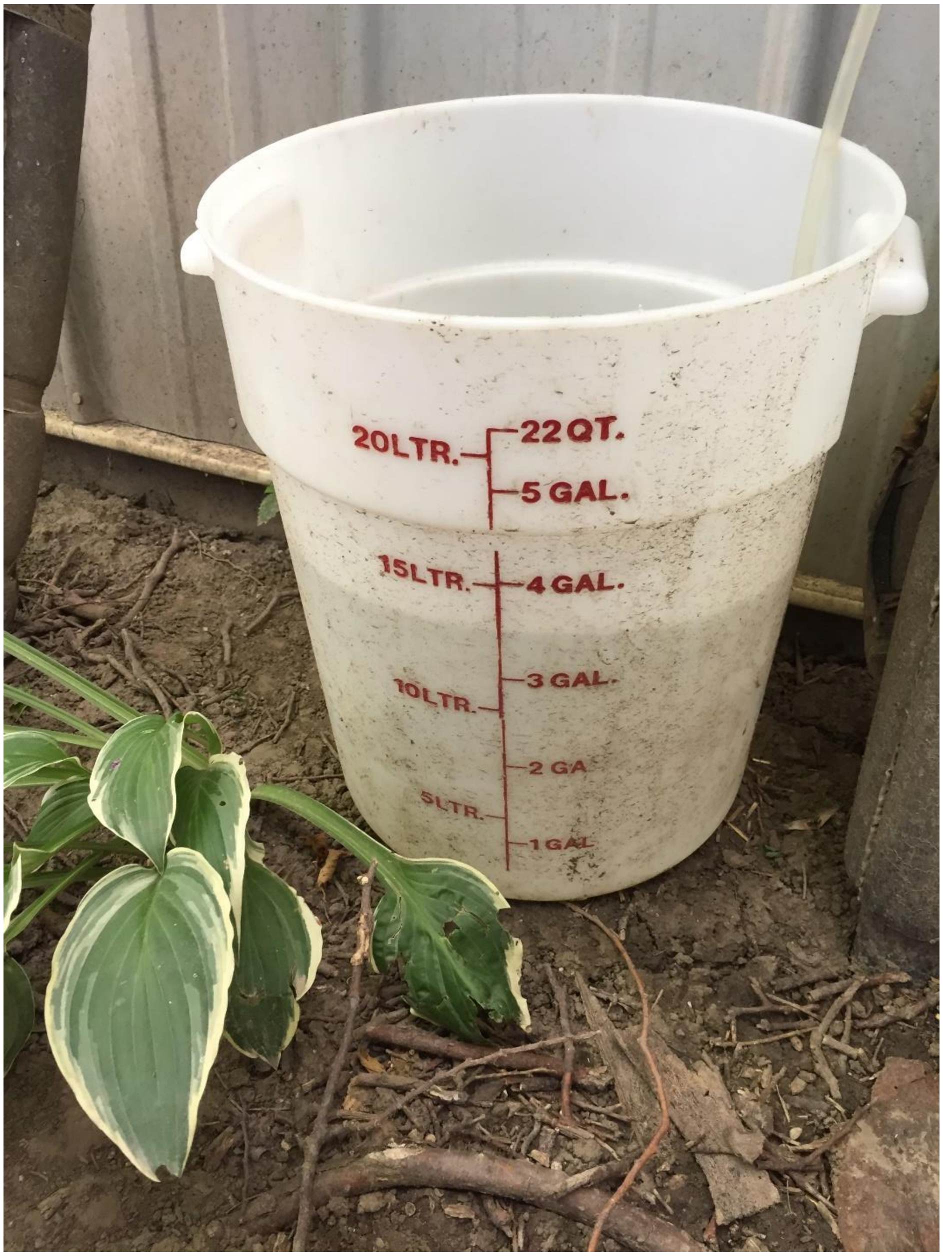

Figure 27 Condensation data is best collected manually coupled with daily logs of associated activities (cooking, showering, occupancy, weather extremes, etc). More than four years of collecting daily condensation data from Equinox House's heat pump, CERV, and HPWH required emptying 4000 containers of water!

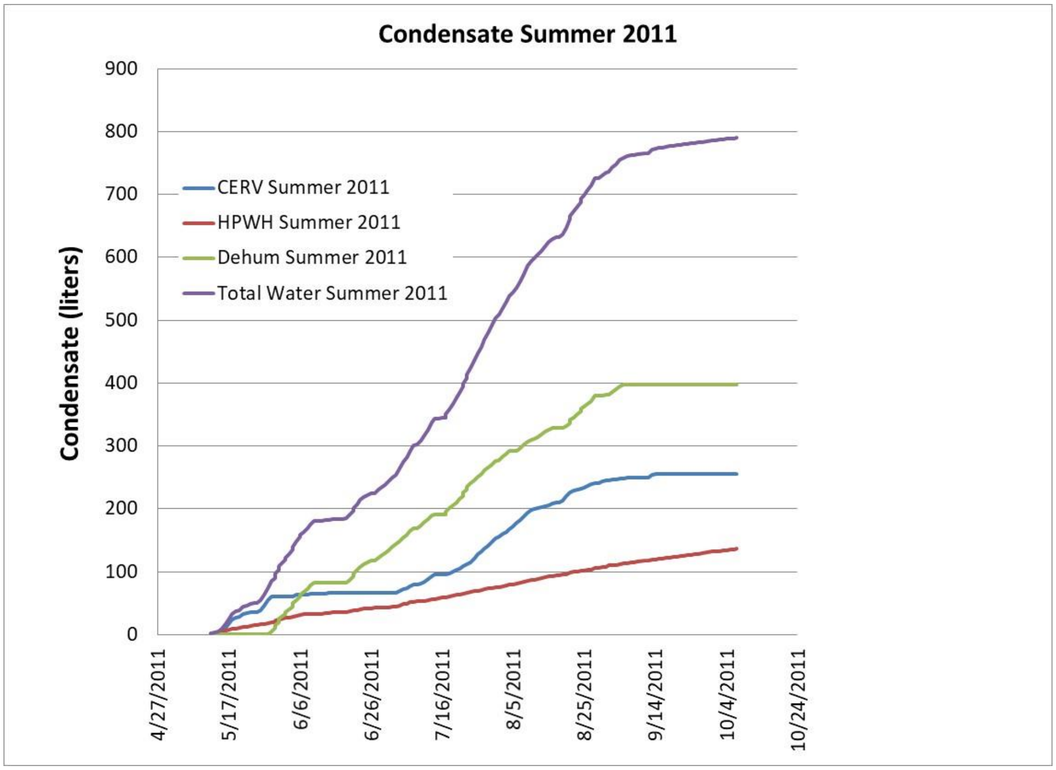

Figure 28 Equinox House (Urbana IL) accumulated daily condensate for 2011 summer. Note that a dehumidifier was used for our first "calibration" year.

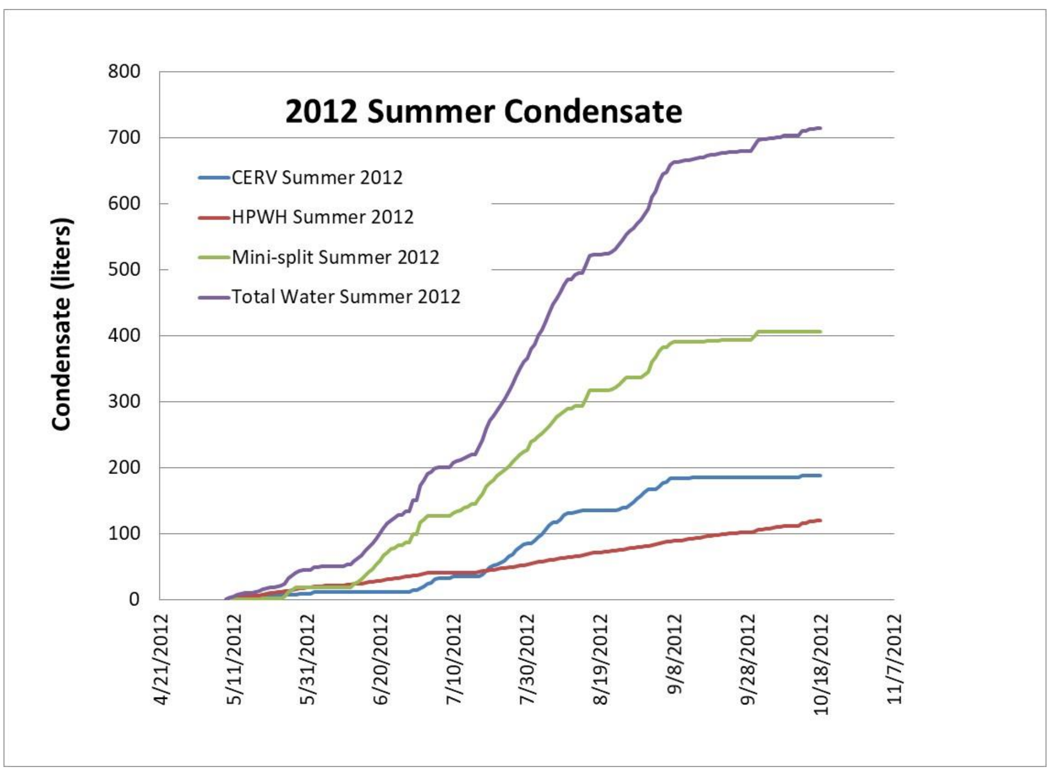

Figure 29 Equinox House (Urbana IL) accumulated daily condensate for 2012 summer.

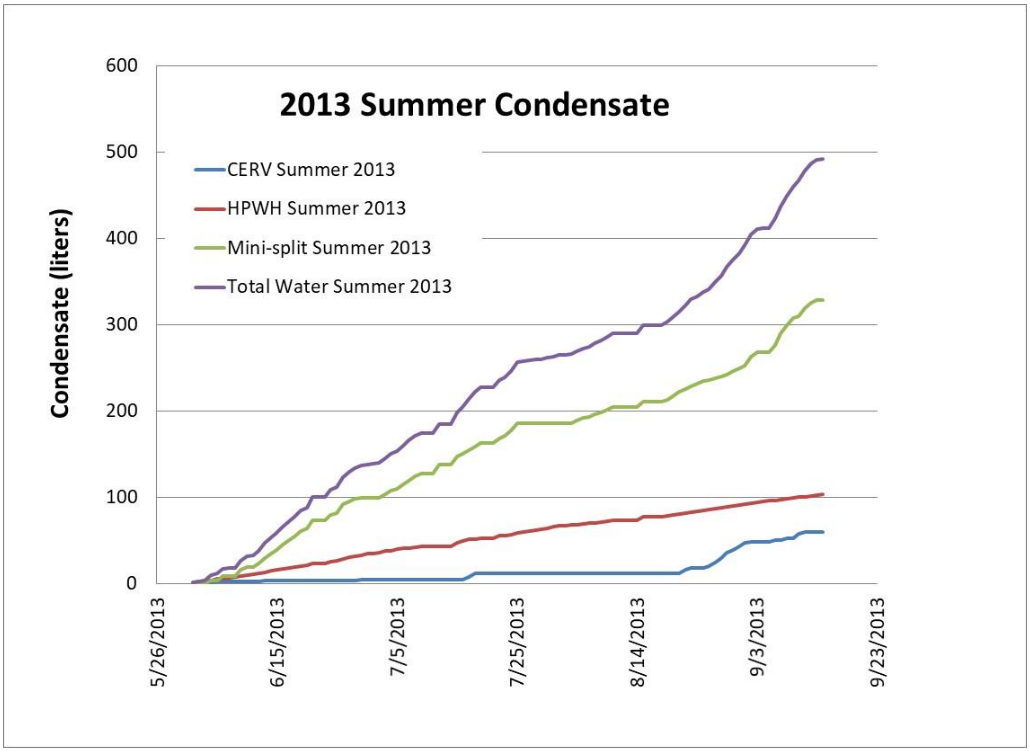

Figure 30 Equinox House (Urbana IL) accumulated daily condensate for 2013 summer.

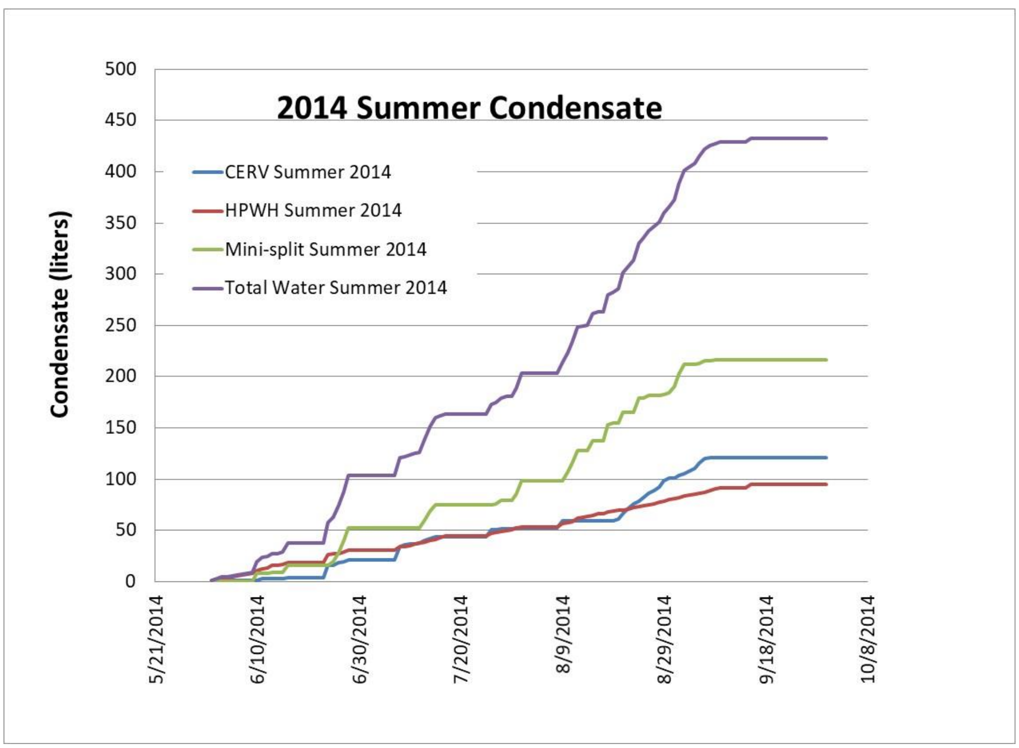

Figure 31 Equinox House (Urbana IL) accumulated daily condensate for 2014 summer.

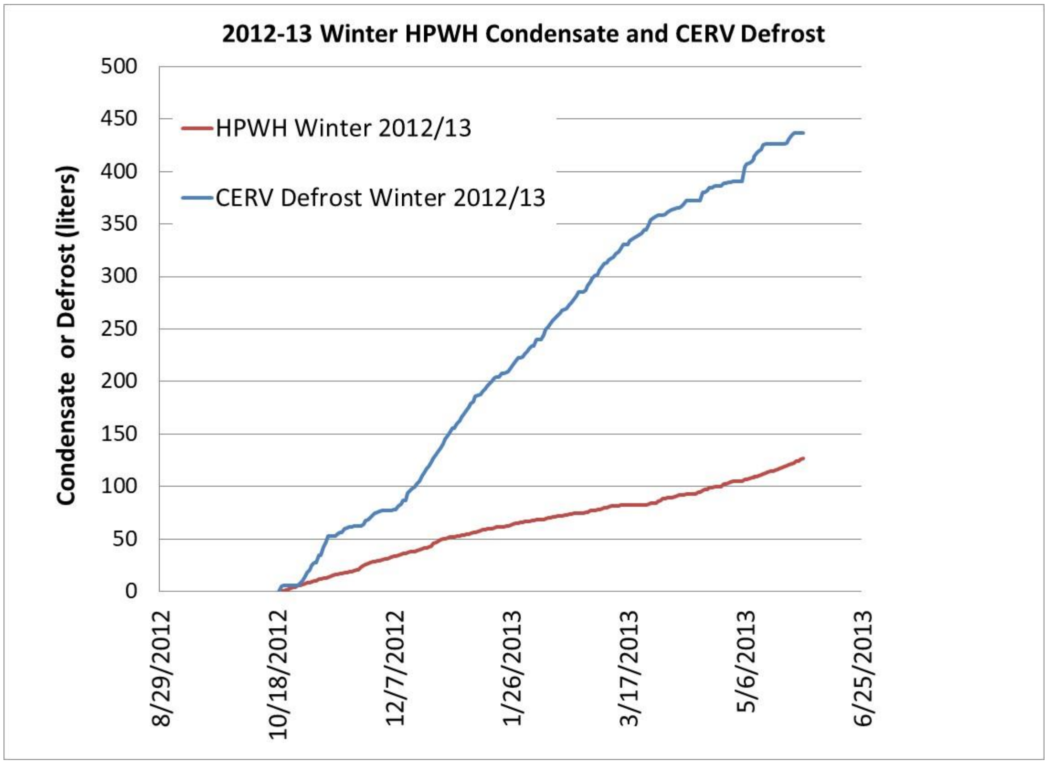

Figure 32 Equinox House (Urbana IL) accumulated daily condensate for 2012/13 winter.

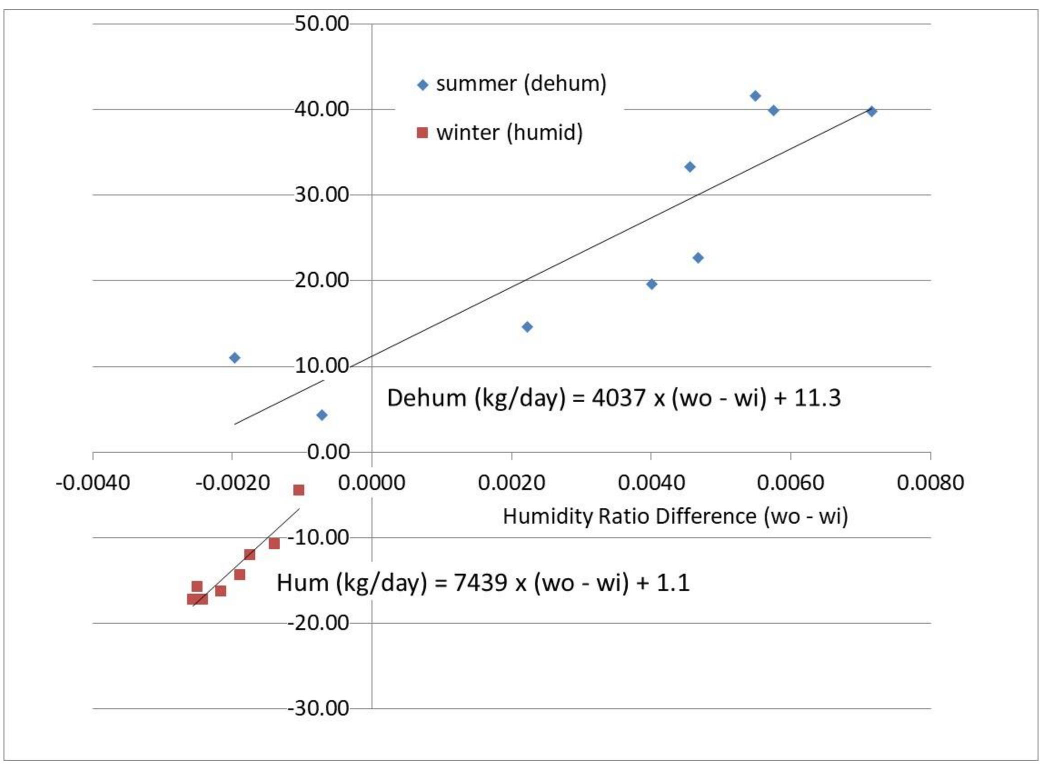

Figure 33 Dehumidification (summer) and humidification (winter) data a 1920's era, 3000sqft home in Urbana IL.

Summary

We summarize Part 3 as follows: SEAL TIGHT and VENTILATE SMART! Sealing a house coupled with smart ventilation reduces moisture management to levels that a home's comfort conditioning system augmented by a CERV2 smart ventilation and a HPWH units are sufficient in most North American climates. When additional moisture management capacity is required, dehumidifier and humidifier can be added.

Our Part 4 report puts everything together: house construction and occupant activities, climate, and moisture management systems. Our ZEROs (Zero Energy Residence Optimization software) allows us to understand how energy related to moisture management compares to a home's other energy uses. We return to our example in which we compare Contractor Loose, Contractor Tight, and Contractor Smart constructed homes.