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Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning

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Technical Report
NREL/TP-5500-49722
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Prepared under Task No. ARRB2206

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Executive Summary

NREL has developed the novel concept of a desiccant enhanced evaporative air conditioner (DEVap) with the objective of combining the benefits of liquid desiccant and evaporative cooling technologies into an innovative "cooling core." Liquid desiccant technologies have extraordinary dehumidification potential, but require an efficient cooling sink. Today's advanced indirect evaporative coolers provide powerful and efficient cooling sinks, but are fundamentally limited by the moisture content in the air. Alone, these coolers can achieve temperatures that approach the dew point of the ambient air without adding humidity; however, they cannot dehumidify. Use of stand-alone indirect evaporative coolers is thus relegated to arid or semiarid geographical areas.

Simply combining desiccant-based dehumidification and indirect evaporative cooling technologies is feasible, but has not shown promise because the equipment is too large and complex. Attempts have been made to apply liquid desiccant cooling to an indirect evaporative cooler core, but no viable design has been introduced to the market. DEVap attempts to clear this hurdle and combine, in a single cooling core, evaporative and desiccant cooling. DEVap's crucial advantage is the intimate thermal contact between the dehumidification and the cooling heat sink, which makes dehumidification many times more potent. This leads to distinct optimization advantages, including cheaper desiccant materials and a small cooling core. The novel design uses membrane technology to contain liquid desiccant and water. When used to contain liquid desiccant, it eliminates desiccant entrainment into the airstream. When used to contain water, it eliminates wet surfaces, prevents bacterial growth and mineral buildup, and avoids cooling core degradation.

DEVap's thermodynamic potential overcomes many shortcomings of standard refrigeration-based direct expansion cooling. DEVap decouples cooling and dehumidification performance, which results in independent temperature and humidity control. The energy input is largely switched away from electricity to low-grade thermal energy that can be sourced from fuels such as natural gas, waste heat, solar, or biofuels. Thermal energy consumption correlates directly to the humidity level in the operating environment. Modeling at NREL has shown that the yearly combined source energy for the thermal and electrical energy required to operate DEVap is expected to be 30%–90% less than state-of-the-art direct expansion cooling (depending on whether it is applied in a humid or a dry climate). Furthermore, desiccant technology is a new science with unpracticed technology improvements that can reduce energy consumption an additional 50%. And unlike most heating, ventilation, and air-conditioning systems, DEVap uses no environmentally harmful fluids, hydrofluorocarbons, or chlorofluorocarbons; instead, it uses water and concentrated salt water.

DEVap is novel and disruptive, so bringing it into the entrenched conventional air conditioner market will create some market risk. Designing and installing a new DEVap system requires retraining. DEVap has unknown longevity and reliability compared to standard A/C. The availability of natural gas or other thermal energy sources may be an issue in certain places. However, DEVap does not require a large outdoor condenser, but instead uses a much smaller desiccant regenerator that can be placed inside or outside, and can be integrated with solar and waste heat. If these risks can be properly addressed, the DEVap air conditioner concept has

strong potential to significantly reduce U.S. energy consumption and provide value to energy companies by reducing summertime electric power demand and resulting grid strain.

NREL has applied for international patent protection for the DEVap concept (see www.wipo.int/pctdb/en/wo.jsp?WO=2009094032).

Acronyms and Abbreviations

AAHX	air-to-air heat exchanger
AILR	AIL Research
A/C	air-conditioning
CHP	combined heat and power
COP	coefficient of performance
DEVap	desiccant-enhanced evaporative air conditioner
DOE	U.S. Department of Energy
DX	direct expansion air conditioner
HMX	heat and mass exchanger
HVAC	heating, ventilation, and air-conditioning
IRR	internal rate of return
LCC	life cycle cost
LDAC	liquid desiccant air conditioner
NREL	National Renewable Energy Laboratory
RH	relative humidity
RTU	rooftop unit
SEER	seasonal energy efficiency ratio
SHR	sensible heat ratio

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1.0 Introduction

1.1 Intention

Our intent is to describe the desiccant enhanced evaporative air conditioner (DEVap A/C) concept. To do this, we must give background in A/C design and liquid desiccant technology. After which, we can describe the concept which consists of a novel A/C geometry and a resulting process. We do this by:

- Discussing the goals of an air conditioner in comparison to expectations
- Discussing the benefits of combining desiccant technology and indirect evaporative cooling
- Describing the DEVap A/C process
- Providing a physical description of the DEVap device
- Discussing the energy savings potential
- Assessing the risks of introducing this novel concept to the marketplace
- Discussing future work to bring this concept to the marketplace.

This information is intended for an audience with technical knowledge of heating, ventilating, and air-conditioning (HVAC) technologies and analysis.

1.2 Background

Today's A/C is primarily based on the direct expansion (DX) or refrigeration process, which was invented by Willis Carrier more than 100 years ago. It is now so prevalent and entrenched in many societies that it is considered a necessity for maintaining efficient working and living environments. DX A/C has also had more than 100 years to be optimized for cost and thermodynamic efficiency, both of which are nearing their practical limits. However, the positive impact of improved comfort and productivity does not come without consequences. Each year, A/C uses approximately 4 out of 41 quadrillion Btu (quads) of the source energy used for electricity production in the United States alone, which results in the release of about 380 MMT of carbon dioxide into the atmosphere (DOE 2009).

R-22 (also known as Freon) as a refrigerant for A/C is quickly being phased out because of its deleterious effects on the ozone layer. The most common remaining refrigerants used today (R-410A and R-134A) are strong contributors to global warming. Their global warming potentials are 2000 and 1300, respectively (ASHRAE 2006). Finding data on air conditioner release rates is nearly impossible, as they are generally serviced only when broken and refrigerant recharge is not accurately accounted for. A typical residential size A/C unit may have as much as 13 pounds of R-410A, and a 10-ton commercial A/C has as much as 22 pounds.

Water is not commonly considered to be a refrigerant, but the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2009) recognizes it as the refrigerant R-718. Evaporative cooling uses the refrigerant properties of water to remove heat the same way DX systems use the refrigeration cycle. Water evaporates and drives heat from a first heat reservoir, and then the vapor is condensed into a second reservoir. Evaporative cooling is so efficient because atmospheric processes in nature, rather than a compressor and condenser heat exchanger, perform the energy-intensive process of recondensing the refrigerant. Water is delivered to the building as a liquid via the domestic water supply.

NREL's thermally activated technology program has been developing, primarily with AIL Research (AILR) as our industry partner, liquid-desiccant-based A/C (LDAC) for more than 15 years. The technology uses liquid desiccants to enable water as the refrigerant in lieu of chlorofluorocarbon-based refrigerants to drive the cooling process. The desiccants are strong salt water solutions. In high concentrations, desiccants can absorb water from air and drive dehumidification processes; thus, evaporative cooling devices can be used in novel ways in all climates. Thermal energy dries the desiccant solutions once the water is absorbed. LDACs substitute most electricity use with thermal energy, which can be powered by many types of energy sources, including natural gas, solar thermal, biofuels, and waste heat. The benefits include generally lower source energy use, much lower peak electricity demand, and lower carbon emissions, especially when a renewable fuel is used.

2.0 Research Goals

2.1 Air-Conditioning Functional Goals

In developing a novel air conditioner based on principles that are inherently different than traditional A/C, we must consider the design goals for a new conditioner to be successful. We first define what an air conditioning system does in building spaces only.

Today's A/C systems:

- Maintain a healthy building environment.
    - In commercial and new residential, A/C provides ventilation air to maintain indoor air quality.
    - A/C maintains humidity to prevent mold growth, sick building syndrome, etc.
- Maintain human comfort by providing
    - Temperature control (heat removal)
    - Humidity control (water removal)
    - Some air filtering (particulate removal).
- Distribute air throughout the space to encourage thermal uniformity.
- In commercial applications, provide make-up air to accommodate exhaust air (EA) flows.

Today's A/C systems have:

- Reasonable operations and maintenance (O&M) costs:
    - Cost of energy to operate
    - Ease of maintenance (for which the expectation is maintain at failure)
- Reasonable size and first cost
    - Must fit in an acceptable space
    - Must be cost effective compared to minimum efficiency A/C equipment.

At a minimum, a new air conditioner must be capable of meeting or surpassing these expectations when designed into an A/C system.

For human comfort and building health, A/C is commonly expected to maintain a humidity level of less than 60% and inside the ASHRAE comfort zone (ASHRAE Standard 55-2004) seen in Figure 2-1. The comfort zone is only a general requirement and may be strongly influenced by occupant activity and clothing level. The summer zone is primarily for sedentary activity with a t-shirt and trousers. Often, temperatures are set to lower set points because activity generally increases. The winter zone is for significantly heavier clothing, but still sedentary activity. The 60% relative humidity (RH) line does intersect the comfort zones, and thus influences how the A/C must react to provide proper building indoor air quality despite human comfort concerns.

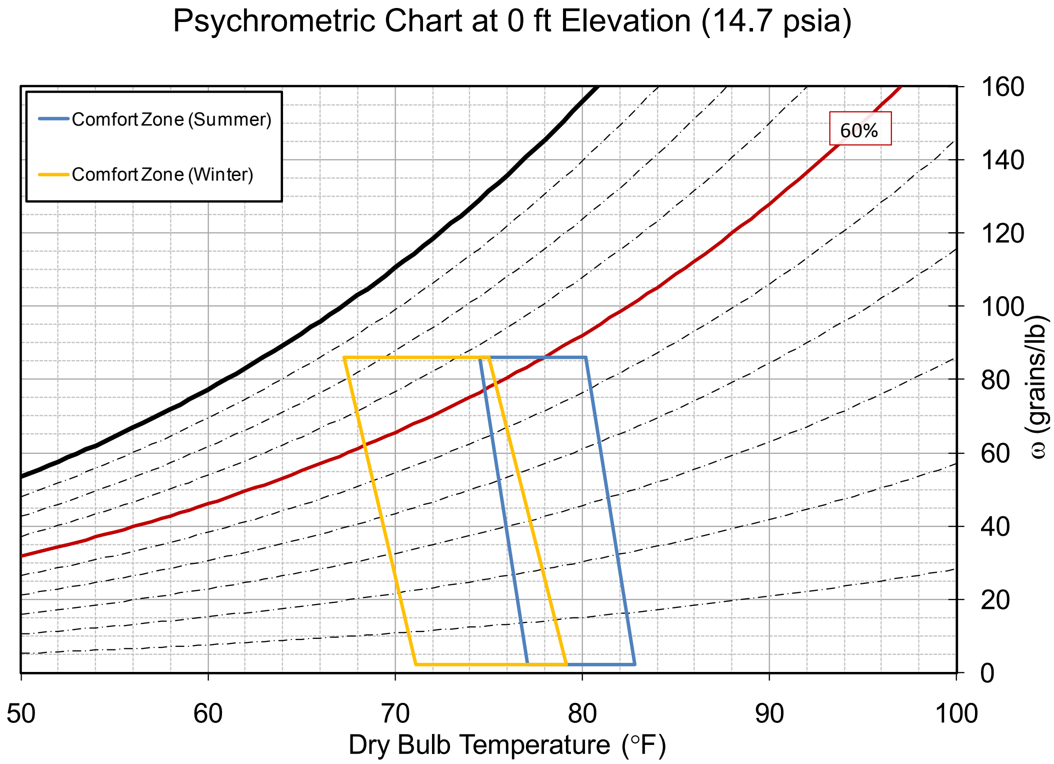


Figure 2-1 ASHRAE comfort zone and 60% RH limit for indoor air quality

Two types of space loads affect building humidity and temperature:

- **Sensible load.** This is the addition of heat to the building space and comes from a variety of sources (e.g., sunlight, envelope, people, lights, and equipment).
- **Latent load.** This is the addition of moisture to the building space and comes from multiple sources (e.g., infiltration, mechanical ventilation, and occupant activities).

Sensible and latent loads combined form the total load. The sensible load divided by the total load is the sensible heat ratio (SHR). A line of constant SHR is a straight line on a psychrometric chart, indicating simultaneous reduction in temperature and humidity. The building loads determine the SHR and an air conditioner must react to it accordingly to maintain temperature and humidity. To match the space load, an A/C system must provide air along a constant SHR originating from the space condition (76°F and varying RH). To meet an SHR of 0.7, one must follow the SHR line of 0.7 to a delivery condition that is lower in temperature and humidity. Figure 2-2 and Figure 2–3 show the implications of space SHR on an A/C system by illustrating how 60% and 50% RH levels influence A/C performance. Humidity is typically removed by cooling the air below the room air dew point. Thus, the saturation condition (black line at 100% RH) is the potential to dehumidify. The intersection of the SHR lines and the saturation line gives the "apparatus dew point" at which the cooling coil will operate. Reducing RH from 60% to 50% requires that the apparatus dew point change from 56°F to 47°F at a constant SHR of 0.7. When the SHR drops below 0.6 (which is typical of summer nights and swing seasons when sensible gains are low), the humidity cannot be maintained below 60% RH with standard DX cooling alone.

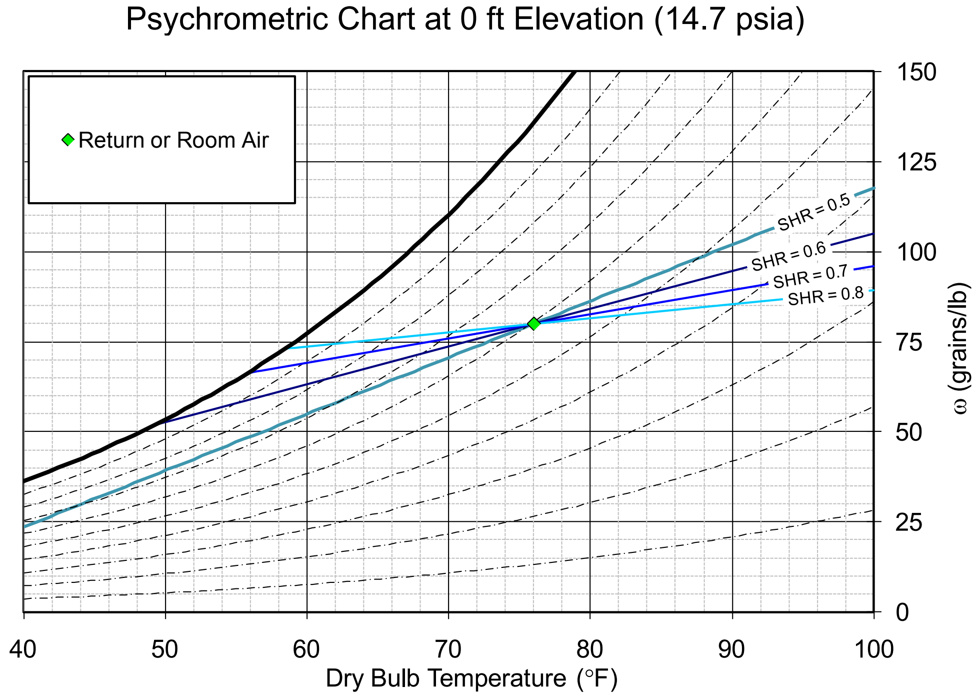


Figure 2-2 SHR lines plotted on a psychrometric chart with room air at 76°F and 60% RH

2.2 How Direct Expansion Air-Conditioning Achieves Performance Goals

For most of the A/C market, refrigeration-based (DX) cooling is the standard, and provides a point of comparison for new technologies. To describe the benefits and improvements of DEVap A/C technology, we must discuss standard A/C.

Standard A/C reacts to SHR by cooling the air sensibly and, if dehumidification is required, by cooling the air below the dew point. This removes water at a particular SHR. Maintaining a space at 76°F and 60% RH (see Figure 2-2) requires the A/C to deliver air along the relevant SHR line. If the SHR line does not intersect the saturation line (as in the case of SHR = 0.5), standard DX A/C cannot meet latent load, and the RH will increase. If humidity is maintained at 50% RH (Figure 2–3), standard DX A/C cannot maintain RH when the space SHR reaches below about 0.7.

Building simulation results provide insight into typical SHRs in residential and commercial buildings. Table 2–1 shows typical SHR ranges in a few U.S. climates. Humidity control with standard DX A/C becomes an issue in climate zones 1A–5A and 4C. Thus, humidity control must be added. Western climates in the hot/dry or hot/monsoon climates have sufficiently high SHR and generally do not require additional humidity control.

Table 2-1 SHRs of Typical Climate Zones (ASHRAE Zones Noted)

Climate	Typical SHR Range
1A–3A. Hot/Humid (e.g., Houston)	0.0–0.9
4A–5A. Hot/Humid/Cold (e.g., Chicago)	0.0–1.0
2B. Hot/Monsoon (e.g., Phoenix)	0.7–1.0
3B–5B: Hot/Dry (e.g., Las Vegas)	0.8–1.0
4C. Marine (e.g., San Francisco)	0.5–1.0

In the A/C industry, common technologies for meeting lower SHRs are:

1. DX + wrap-around heat exchanger or latent wheel
   - Trane CDQ (wrap-around active/desiccant wheel) (see Trane 2008)
   - Munters Wringer (wrap-around sensible wheel) (see Munters Web site www.munters.us/en/us/)
2. DX + active wheel
   - Munters DryCool system using condenser reheat to reactivate an active desiccant wheel (see Munters Web site www.munters.us/en/us/)
3. DX + reheat
   - Lennox Humiditrol with condenser reheat (see Figure 2-3)
4. DX + ice or apparatus dewpoint < 45°F
   - Four Seasons
   - Ice Energy Ice Bear energy storage module (see Ice Energy 2010)
5. DX + space dehumidifier

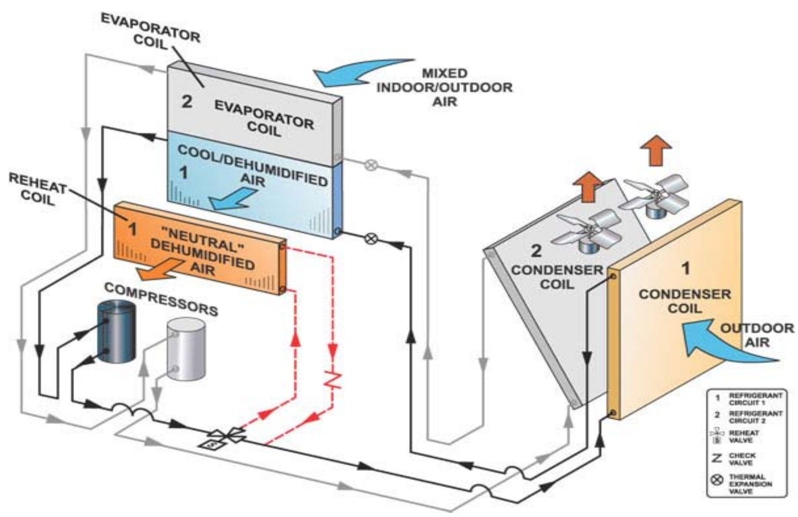


Figure 2-3 Lennox DX A/C with Humiditrol condenser reheat coil (Lennox Commercial 2010)

Humidity control options for various building types are shown in Table 2-2.

Table 2-2 Technology Options for Residential and Commercial Buildings

Building Type	New and Retrofit
Residential	3. DX + reheat 5. DX + space dehumidifier
Commercial	1. DX + wrap-around heat exchanger 2. DX + active wheel 3. DX + reheat 4. DX + ice or apparatus dew point < 45°F 5. DX + space dehumidifier

Commercial buildings can, in most cases, use all technology options. Residential systems align with options 3 and 5. These technologies do not come without penalties, which are always increased energy use and added upfront costs. With options 1 and 2, the primary energy use comes from significant increase in fan power to blow air through the various wheel types. Option 3, DX + reheat, is the most common, but essentially erases the cooling done by the DX circuit without significant DX cycle efficiency change. This creates an air conditioner rated at 3 tons that delivers 30% less cooling (or about 2 tons) with the same energy use as the original 3-ton system. DX + apparatus dew point < 45°F has reduced cycle efficiency because deep cooling is provided. DX + dehumidifier is much like DX + reheat, but the dehumidifier is a specialized DX system used to deeply dry the air before reheating.

Options 1, 2, and 4 are usually chosen to pretreat outdoor air (OA) in a dedicated outdoor air system, which in all but a few special cases (commercial kitchens and supermarkets with large exhaust flows) will not control indoor humidity. However, these technologies do meet large load profiles and can reduce the latent load requirements on the smaller DX systems serving the same spaces. For space humidity control, most people choose DX + reheat for commercial spaces and DX + reheat or dehumidifier for residential spaces. In all cases, latent cooling follows sensible cooling. Thus, sensible cooling is often too high and must either be reheated or combined with a desiccant to lower the SHR.

Table 2-3 Source Energy Efficiency Comparison for Commercial Equipment
(Kozubal 2010)

Humidity Level (dry bulb/wet bulb)	DX With Sensible Gas Reheat (200 cfm/ton)	DX With Desiccant Rotor and Condenser Heat Regeneration	DX With Wrap-Around Desiccant Rotor
High humidity (87°/77.3°F)	65%	75%	N/A
Medium humidity (80°/71°F)	55%	65%	85%
Modest humidity (80°/68°F)	48%	46%	83%

2.3 The DEVap Process

2.3.1 Commercial-Grade Liquid Desiccant Air Conditioner Technology

Desiccants reverse the paradigm of standard DX A/C by first dehumidifying, and then sensibly cooling to the necessary level. Desiccant at any given temperature has a water vapor pressure equilibrium that is roughly in line with constant RH lines on a psychrometric chart (Figure 2-4). The green lines show the potential for two common types of liquid desiccants, lithium chloride (LiCl) and calcium chloride ($CaCl_2$). If the free surface of the desiccant is kept at a constant temperature, the air will be driven to that condition. If used with an evaporative heat sink at 55°–85°F, the air can be significantly dehumidified and dew points < 32°F are easily achieved. The blue arrow shows the ambient air being driven to equilibrium with LiCl with an evaporative heat sink. At this point, the air can be sensibly cooled to the proper temperature. This type of desiccant A/C system decouples the sensible and latent cooling, and controls each independently.

During the dehumidification process, the liquid desiccant (about 43% concentration by weight salt in water solution) absorbs the water vapor and releases heat. The heat is carried away by a heat sink, usually chilled water from a cooling tower. As water vapor is absorbed from the ambient air, it dilutes the liquid desiccant and decreases its vapor pressure and its ability to absorb water vapor. Lower concentrations of desiccant come into equilibrium at higher ambient air RH levels. Dehumidification can be controlled by the desiccant concentration that is supplied to the device. The outlet humidity level can be controlled by controlling the supplied desiccant concentration or decreasing the flow of highly concentrated desiccant. The latter allows the highly concentrated desiccant to quickly be diluted and thus "act" as a weaker desiccant solution in the device.

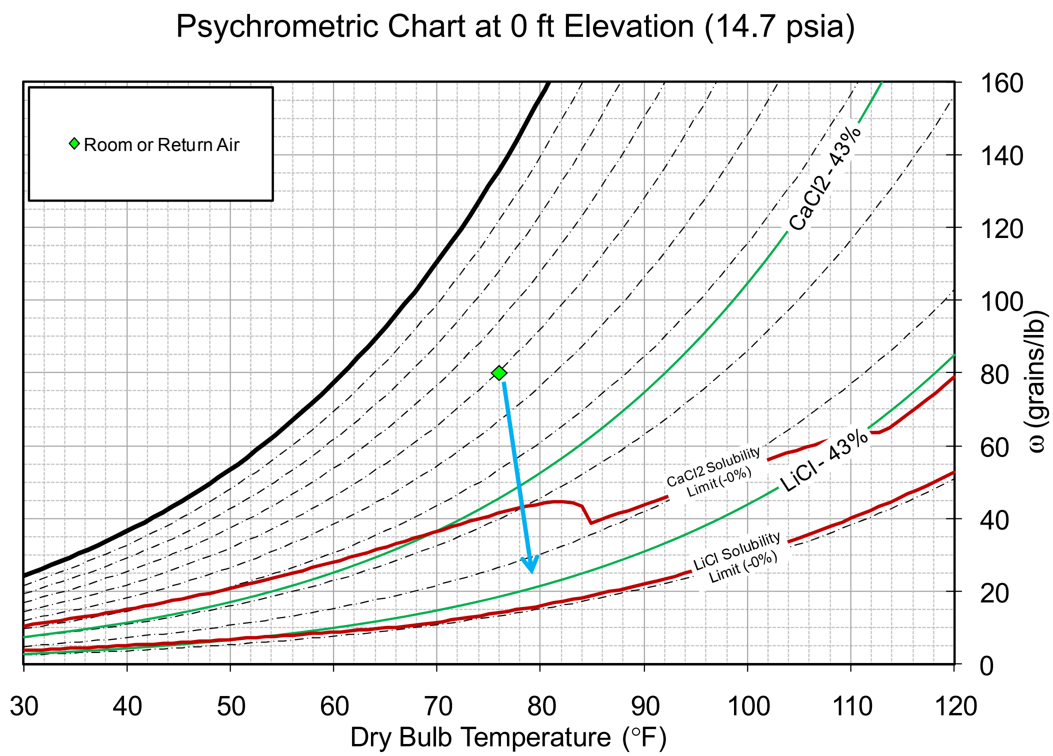


Figure 2-4 Psychrometric chart showing the dehumidification process using desiccants

Absorption will eventually weaken the desiccant solution and reduce its dehumidifying potential; the desiccant must then be regenerated to drive off the absorbed water. Thermal regeneration is the reverse: In this process, the desiccant is heated to a temperature at which the equilibrium vapor pressure is above ambient. The vapor desorbs from the desiccant and is carried away by an air stream (see Figure 2-5). Sensible heat is recovered by first preheating the ambient air using an air-to-air heat exchanger (AAHX). The air comes into heat and mass exchange with the hot desiccant (in this example at 190°F) and carries the desorbed water vapor away from the desiccant. Sensible heat is recovered by taking the hot humid air to preheat the incoming air through the AAHX. The change in enthalpy of the air stream represents the majority of the thermal input. Small heat loss mechanisms are not represented in the psychrometric process. The process uses hot water or steam to achieve a latent coefficient of performance (COP) of 0.8–0.94 depending on ultimate desiccant concentration. Latent COP is defined as:

$$COP_{Latent} = \frac{(Moisture\ Removal\ Rate) * (Heat\ of\ Vaporization)}{Heat\ Rate\ (Higher\ Heating\ Value)}$$

COP is maximized by maximizing the regeneration temperature and change in concentration while minimizing the ultimate desiccant concentration. Including the COP of the water heater (about 0.82), a typical combined latent COP is 0.82 × 0.85 = 0.7.

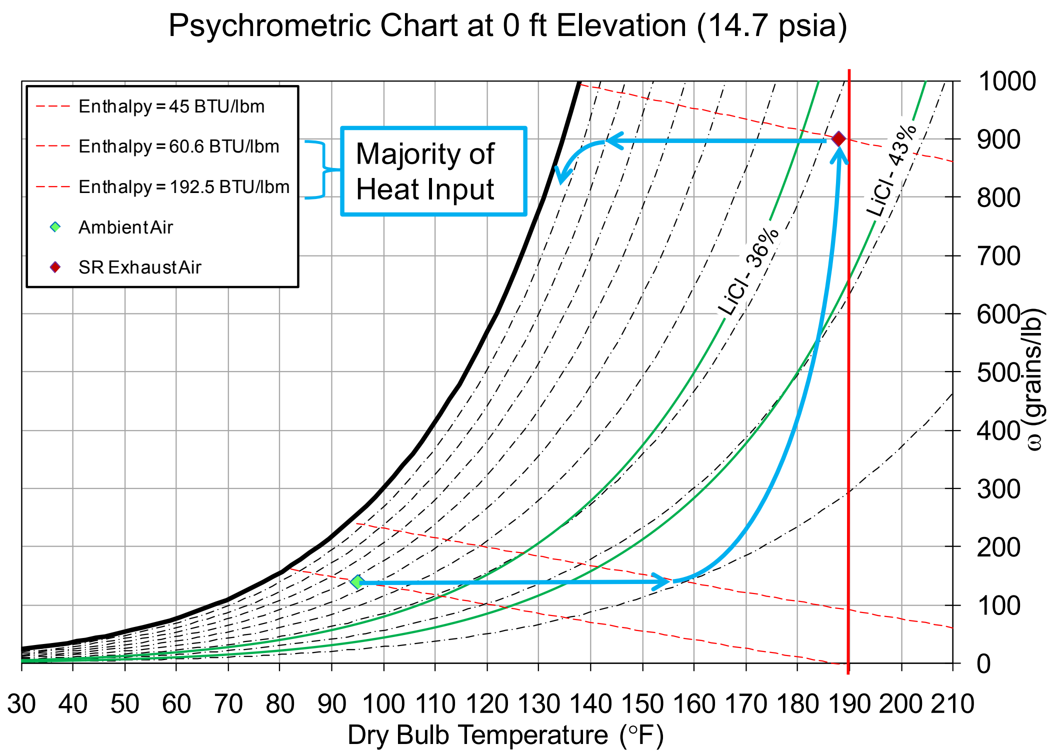


Figure 2-5 Desiccant reactivation using single-effect scavenging air regenerator

The AILR LDAC technology uses novel heat and mass exchangers (HMXs) to perform these two processes (see Figure 2-6), which show the desiccant conditioner and scavenging air regenerator. The liquid desiccant is absorbed into the conditioner (absorber) where the inlet ambient air is dehumidified. The liquid desiccant is regenerated in the regenerator (desorber) where the water vapor desorbs into the EA stream. This technology is called *low flow liquid desiccant A/C*, because the desiccant flow is minimized in both HMXs to the flow rate needed to absorb the necessary moisture from the air stream. The HMXs must therefore have integral heating and cooling sources (55°–85°F cooling tower water is supplied to the conditioner). The regenerator uses hot water or hot steam at 160°–212°F. The cooling or heating water flows internal to the heat exchange plates shown. The desiccant flows on the external side of the HMX plates. The plates are flocked, which effectively spreads the desiccant. This creates direct contact surfaces between the air and desiccant flows. The air passes between the plates, which are spaced 0.25 in. apart. Figure 2-6 also shows a 20-ton packaged version on a supermarket in Los Angeles, California. Lowenstein (2005) provides more detailed descriptions of these devices.

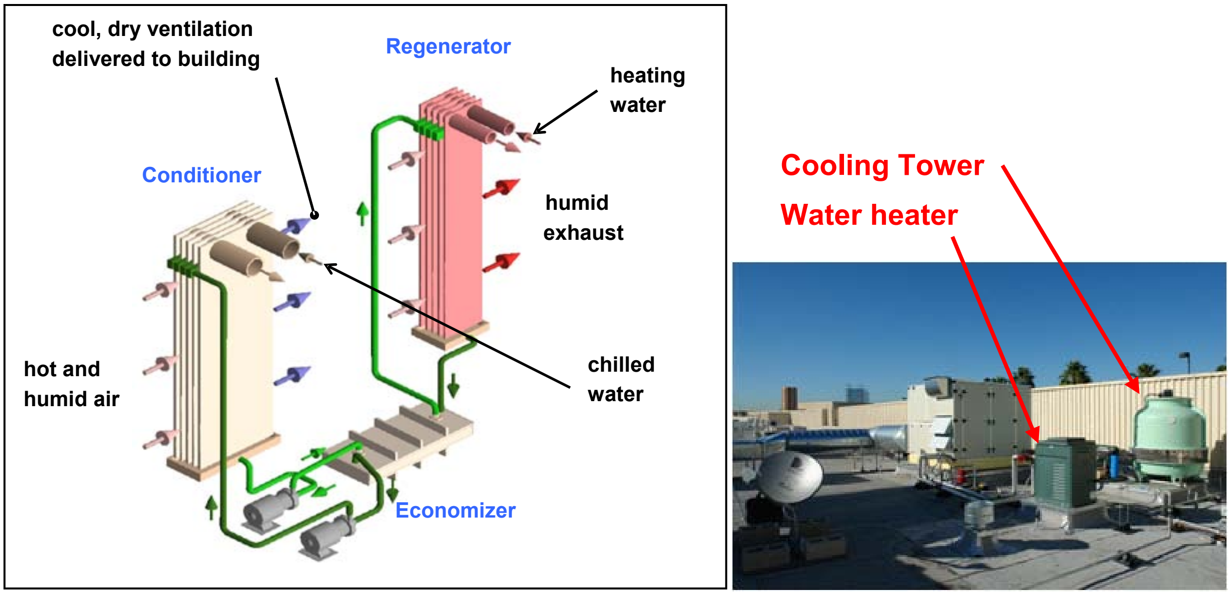


Figure 2-6 Major components and packaging of the AILR LDAC (Photograph shows packaged HMXs, water heater and cooling tower)

(Photos used with permission from AIL Research)

A double-effect regenerator expands on the scavenging air regenerator by first boiling the water out of the liquid desiccant solution (250°–280°F) and reusing the steam by sending it through the scavenging air regenerator. This two-stage regeneration system can achieve a latent COP of 1.1–1.4. NREL is working with AILR to develop this product. A typical solar regenerator would consist of either a hot water supply to a scavenging regenerator (which would result in a single-effect device that would have about a 60% solar conversion efficiency based on absorber area). We are currently monitoring more advanced concepts that generate steam by boiling either water or liquid desiccant internal to a Dewar-style evacuated tube. If filled with water to create steam, efficiency up to 70% is possible. An advanced version would boil desiccant directly in the solar collector to create steam that is then used in the scavenging regenerator. This would increase solar conversion efficiency to 120%. This work is ongoing and results are not yet available.

Table 2-4 Technology Options for Residential and Commercial Buildings
(Based on NREL calculations and laboratory data, available on request)

Regenerator	COP
Solar	60%–120% solar conversion
Single effect*	0.7–0.8
Double effect*	1.1–1.4

* Based on the higher heating value of natural gas

For the low-flow LDAC, the regenerator and conditioner systems are shown connected in Figure 2-7, which illustrates the three basic ways to regenerate the desiccant system with a thermal source: solar, water heater, and a double effect. The water heater or boiler can be fueled by many sources, including natural gas, combined heat and power (CHP), or even biofuels.

Also shown is the desiccant storage option that allows an A/C system to effectively bridge the time gap between thermal energy source availability and cooling load. Desiccant storage at 8% concentration differential will result in about 5 gal/latent ton·h. In comparison, ice storage is approximately 13–15 gal/ton·h (theoretically 10 gal/ton·h, but in practice only 67% of the volume is frozen (Ice Energy 2010). This storage can be useful to enable maximum thermal use from solar or on-site CHP. LDACs leverage the latent storage capacity by producing more total cooling than the stored latent cooling. For example, an LDAC may use 2 ton·h of latent storage, but deliver 4 ton·h of total cooling. This is derived from an additional 2 tons of sensible cooling accomplished by the evaporative cooling system.

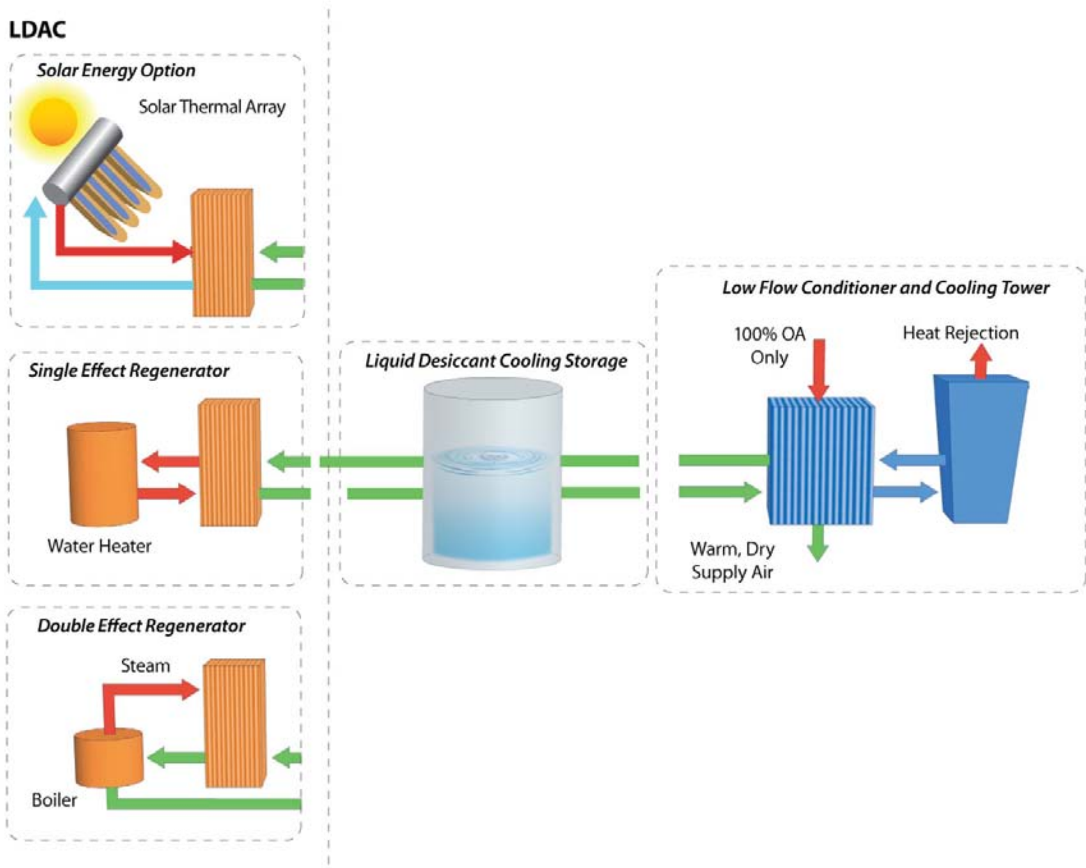


Figure 2-7 LDAC schematic

The latent COP for DEVap is 1.2–1.4, because it requires only modest salt concentration to function properly (30%–38% LiCl). Figure 2-8 shows the calculated efficiency of a two-stage regenerator using natural gas as the heat source. Moisture removal rate is also shown where the nominal rate is 3 tons of latent removal.

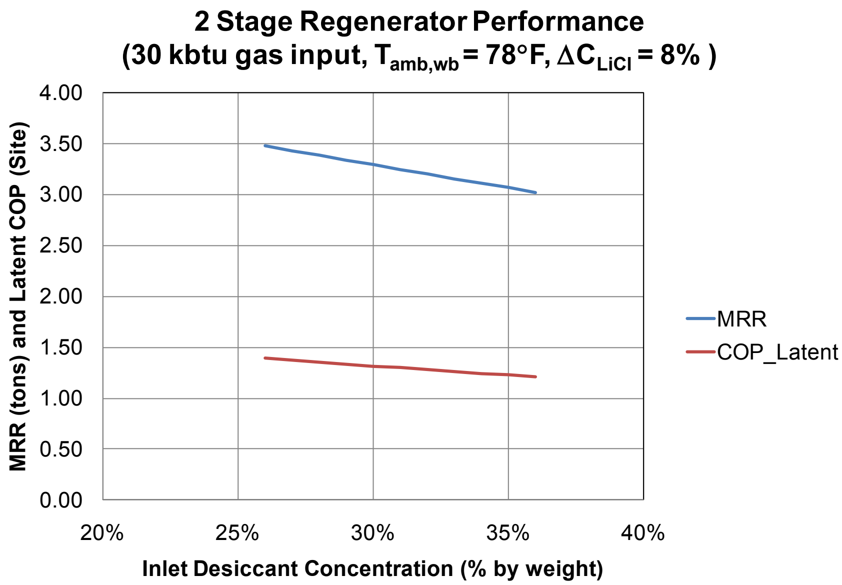


Figure 2-8 Calculated two-stage regenerator moisture removal rate and efficiency performance

2.3.2 DEVap Process: Air Flow Channel Using Membranes (NREL Patented Design)

This section describes how the LDAC process is enhanced with NREL's DEVap concept. The DEVap process follows:

1. Ventilation air [1] and warm indoor air [2] are mixed into a single air stream.
2. This mixed air stream (now the product air) is drawn through the top channel in the heat exchange pair.
3. The product air stream is brought into intimate contact with the drying potential of the liquid desiccant [d] through a vapor-permeable membrane [e].
4. Dehumidification [ii] occurs as the desiccant absorbs water vapor from the product air.
5. The product air stream is cooled and dehumidified, then supplied to the building space [3].
6. A portion of the product air, which has had its dew point reduced (dehumidified), is drawn through the bottom channel of the heat exchange pair and acts as the secondary air stream.
7. The secondary air stream is brought into intimate contact with the water layer [c] through a vapor-permeable membrane [b].
8. The two air streams are structurally separated by thin plastic sheets [a] through which thermal energy flows, including the heat of absorption [i].
9. Water evaporates through the membranes and is transferred to the air stream [iii].
10. The secondary air stream is exhausted [4] to the outside as hot humid air.

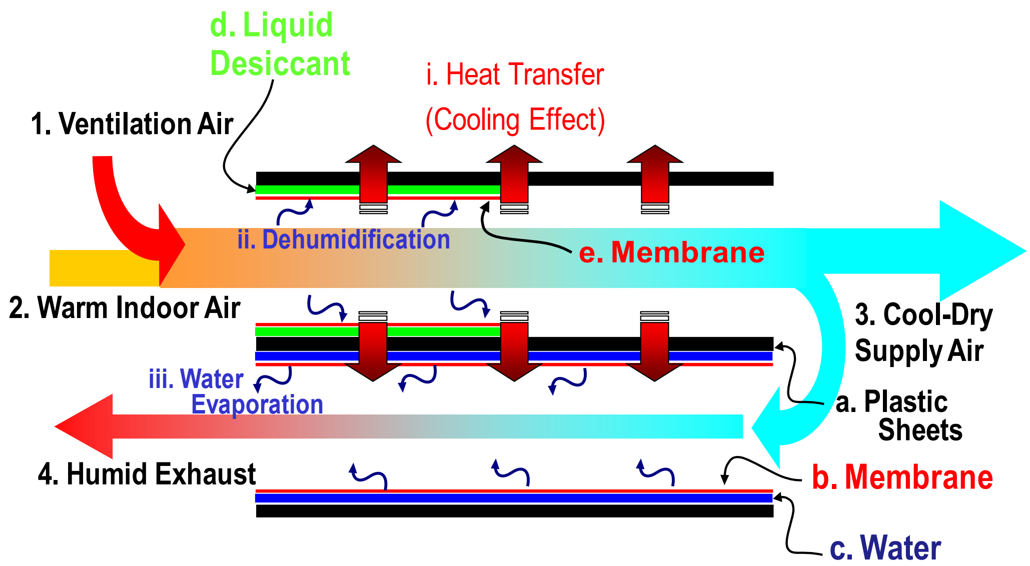


Figure 2-9 Physical DEVap concept description

NREL has applied for international patent protection for the DEVap concept and variations (Alliance for Sustainable Energy LLC 2008).

The water-side membrane implementation of DEVap is part of the original concept, but is not a necessary component. Its advantages are:

- **Complete water containment.** It completely solves problems with sumps and water droplets entrained into the air stream.
- **Dry surfaces.** The surface of the membrane becomes a “dry to the touch” surface that is made completely of plastic and resists biological growth.

The water-side membrane may not be necessary in the DEVap configuration, according to strong evidence from companies (e.g., Coolerado Cooler, Speakman – OASys) that have used wicked surfaces to create successful evaporative coolers. Omitting this membrane would result in cost savings.

The desiccant-side membrane is necessary to guarantee complete containment of the desiccant droplets and create a closed circuit to prevent desiccant leaks. It should have the following properties:

- **Complete desiccant containment.** Breakthrough pressure (at which desiccant can be pushed through the micro-size pores) should be about 20 psi or greater.
- **Water vapor permeability.** The membrane should be thin (~25 µm) and have a pore size of about 0.1 µm. Its open area should exceed 70% to promote vapor transport.

Several membranes, such as a product from Celgard made from polypropylene, have been identified as possible candidates (see Figure 2-10).

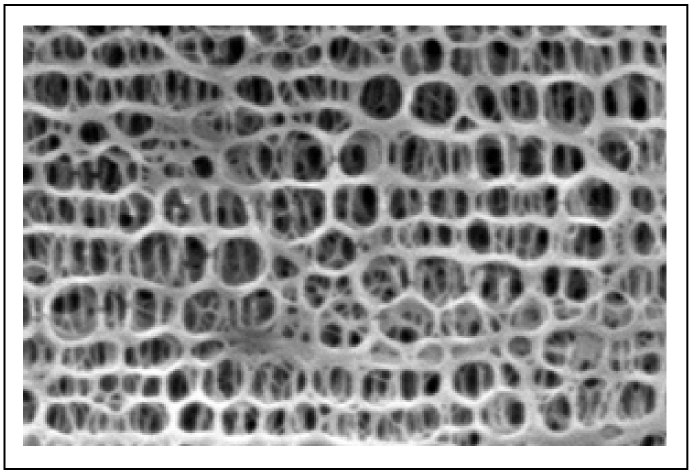



Figure 2-10 Scanning electron microscope photograph of a micro porous membrane (Patent Pending, Celgard product literature)

(Photos used with permission from Celgard, LLC)

The DEVap cooling core (Figure 2–11) is an idealized implementation of the air flows. A higher performing air flow configuration (Figure 2–12) shows the cooling device split into two distinct areas and depicts the air flow channels from the top vantage point. The mixed ventilation air and return air enter from the bottom and exit at the top. The location of the desiccant drying section is shown in green; the location of the evaporative post cooling is shown in blue. Using OA to cool the dehumidification section improves the design by enabling higher air flow rates to provide more cooling. Thus, the left half of the exhaust channel (Figure 2–11) is replaced by an OA stream that flows into the page (Exhaust Airflow #1). The deep cooling of the indirect evaporative cooler section requires a dry cooling sink; thus, some dry supply air is siphoned off (5%–30% under maximum cooling load) to provide this exhaust air stream (Exhaust Airflow #2). This section is placed in a counterflow arrangement to maximize the use of this air stream. This is essential because it has been dried with desiccant, and thus has a higher embodied energy than unconditioned air. The result is that the temperature of supply air is limited by its dew point and will come out between 55°–75°F depending on how much is siphoned off. Combined with the desiccant's variable drying ability, the DEVap A/C system controls sensible and latent cooling independently and thus has a variable SHR between < 0 (latent cooling with some heating done) and 1.0.

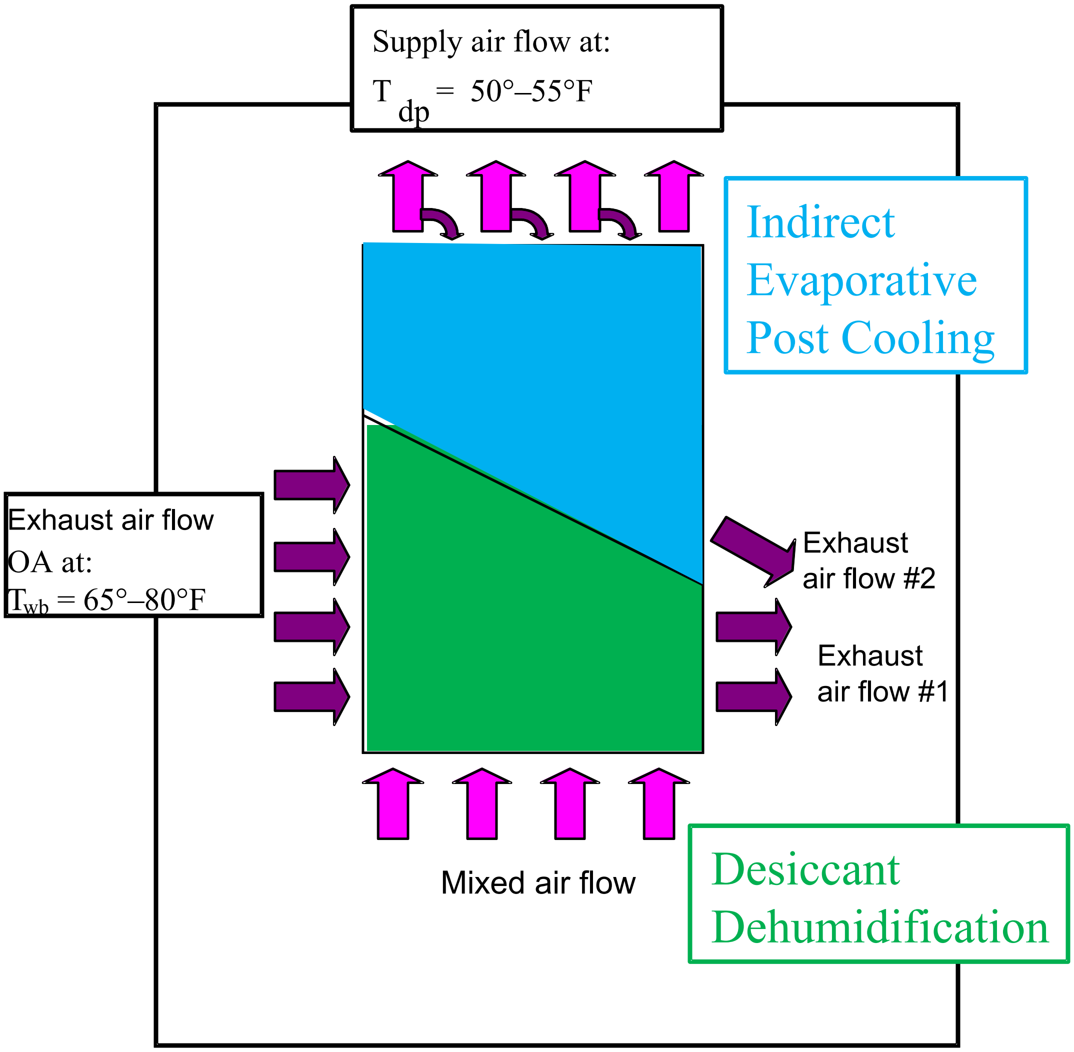


Figure 2-11 DEVap HMX air flows

The DEVap core is only half of a complete air conditioner. Figure 2-12 depicts how the DEVap cooling core enhances the already developed LDAC technology and converts it from a dedicated outdoor air system to an air conditioner that performs space temperature and humidity control and provides all the necessary ventilation air. In fact, DEVap can be configured to provide 30%–100% ventilation air. Furthermore, DEVap does not require a cooling tower, which reduces its maintenance requirements.

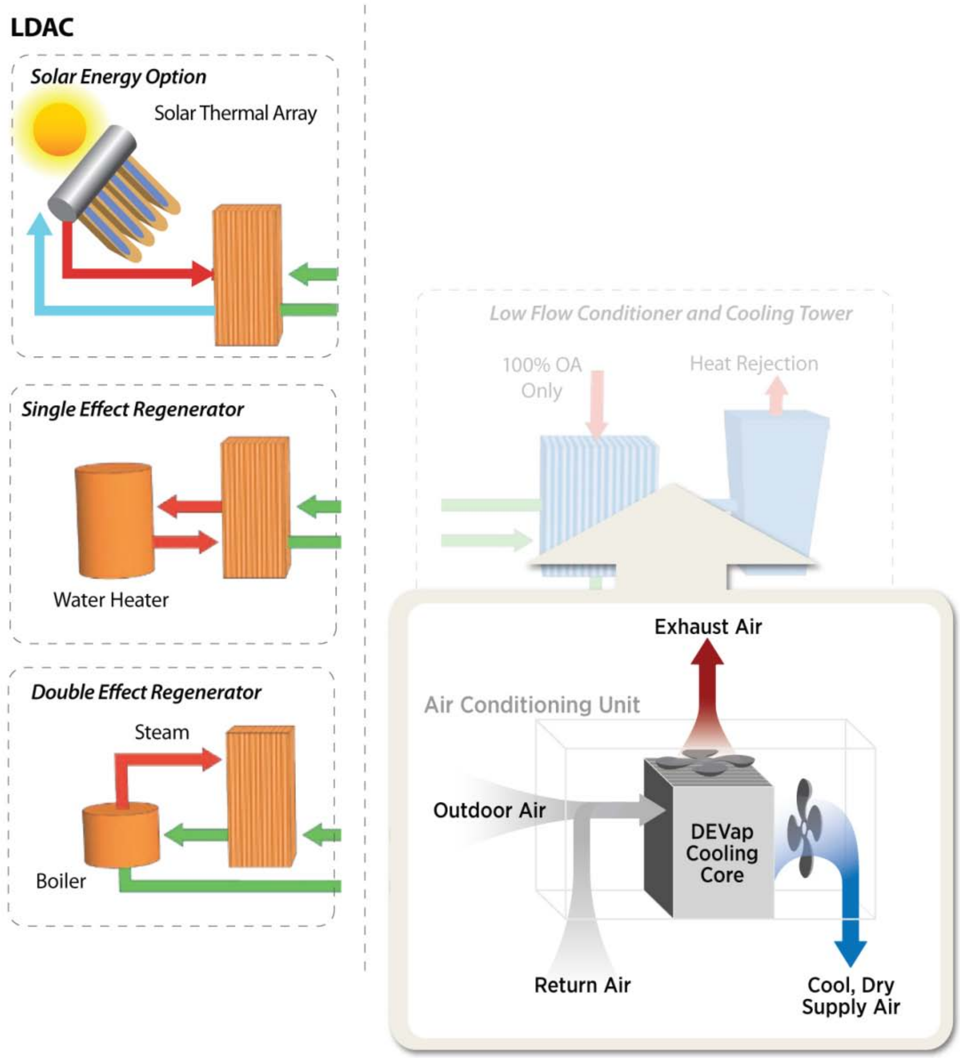


Figure 2-12 DEVap enhancement for LDAC

2.4 DEVap Cooling Performance

Because the drying process creates sufficiently dry air, the evaporative process is no longer a function of climate. Therefore, DEVap will work in all climates, whether hot and humid or hot and dry. Its most challenging operational condition is at a peak Gulf Coast condition (Figure 2-13) (typical of Tampa, Florida, and Houston, Texas). In this example, DEVap mixes 70% return air with 30% OA, resulting in a 30% ventilation rate. The mixed air stream is first dehumidified to 51°F dew point. Then the post-evaporative cooler decreases the temperature to 59°F and uses 30% of the mixed air flow. The result is that the supply and return air flows are equal, as are as the OA and EA flows. The system provides 7 Btu/lb of total cooling and 11.5 Btu/lb to the mixed air stream (7 Btu/lb of space cooling is equivalent to 380 cfm/ton). This is a critical design parameter that is acceptable in the HVAC industry to provide air that is of proper temperature and sufficiently low air volume delivery. This is all done while providing an SHR of 0.6 to the space. Simply by decreasing the post-cooling, the SHR can be lowered further to the necessary level. This is more critical when the ambient conditions impose a much lower

SHR onto the building. An example of such a condition would be a cool April day when it is 65°–70°F and raining.

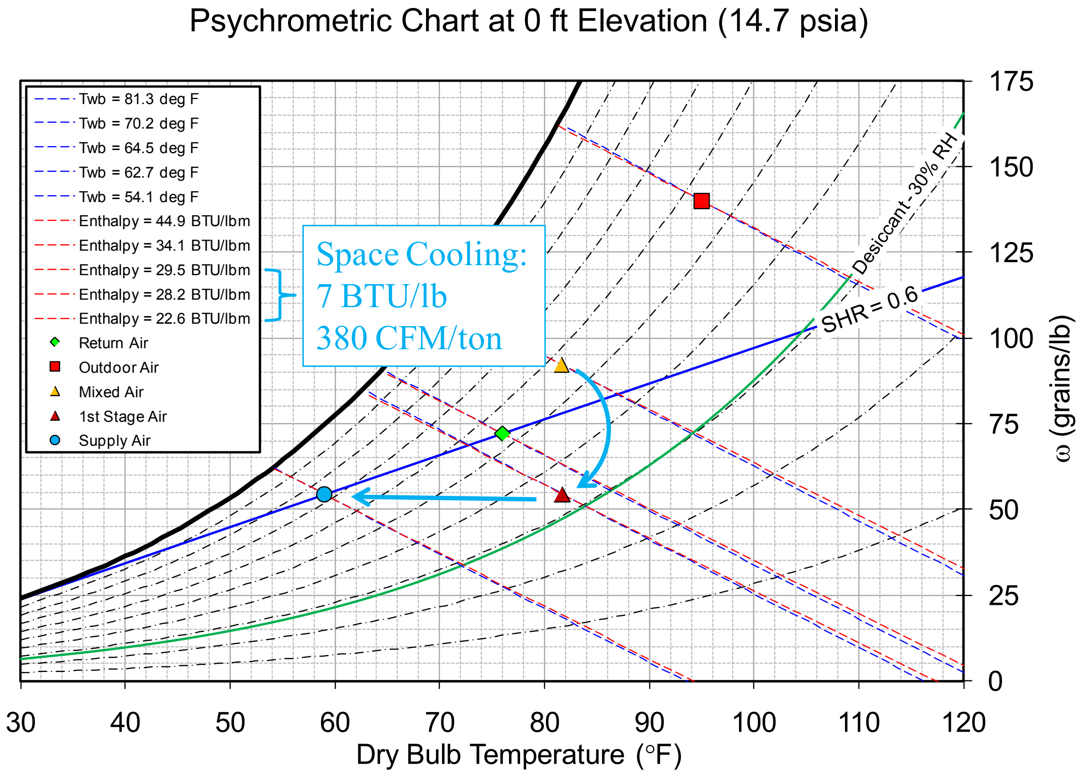


Figure 2-13 DEVap cooling process in a typical Gulf Coast design condition

At the condition shown, the combined energy DEVap uses results in a total cooling source level COP of 1.4. This assumes the 30% ventilation air can be credited toward the cooling load and the regenerator latent COP is 1.2, a conservative value. If no ventilation air can be credited, the source COP is 0.85. As OA humidity drops (shown at 77°F dew point), the source COP increases. At the point where the ambient dew point drops below about 55°F, the desiccant can be turned off and no further thermal energy is required. This simplistic explanation indicates that as the climate becomes dryer (regardless of OA temperature), DEVap efficiency improves. As the sensible load decreases, DEVap uses less EA to provide sensible cooling. The balanced EA and OA result in less OA and less moisture removal by the regeneration system.

2.5 DEVap Implementation

2.5.1 New and Retrofit Residential

A 3-ton DEVap A/C cooling core is expected to be about 18 in. deep and have a 20-in. × 20-in. frontal area if made square (see Section 3.1). This imposes no significant packaging problems in a residential sized A/C system. DEVap air flow rate and cooling delivery are designed to match exactly DX A/C (at 7 Btu/lb), thus the return and supply air duct design will work well. However, DEVap conditions the space air and rejects heat to the atmosphere, so air to and from the ambient air must be brought to the DEVap device, either by placing the DEVap cooling cores close to the outside, or by ducting these air streams. This requirement makes implementing DEVap different than standard DX A/C.

The regenerator for a 3-ton DEVap A/C contains a 30-kBtu boiler (compared to today's on-demand water heaters, which are about 200 kBtu) and a 50-cfm, 1-ft^3 HMX scavenging regenerator. These two main components comprise the bulk of the regenerator, so the packaging is very small and can be accommodated in many spaces, including:

- Outside (the regenerator contains no freeze-prone liquids)
- Next to the DEVap and furnace
- Next to the domestic hot water tank.

The regenerator uses natural gas or thermal heat and a standard 15 Amp, 120-V electrical connection. The DEVap core can be integrated with the furnace and air handler, if there is one. Figure 2-14 illustrates a possible configuration for a DEVap A/C installed in a typical U.S. home. The regenerator component is powered by thermal sources such as natural gas and solar thermal heat.

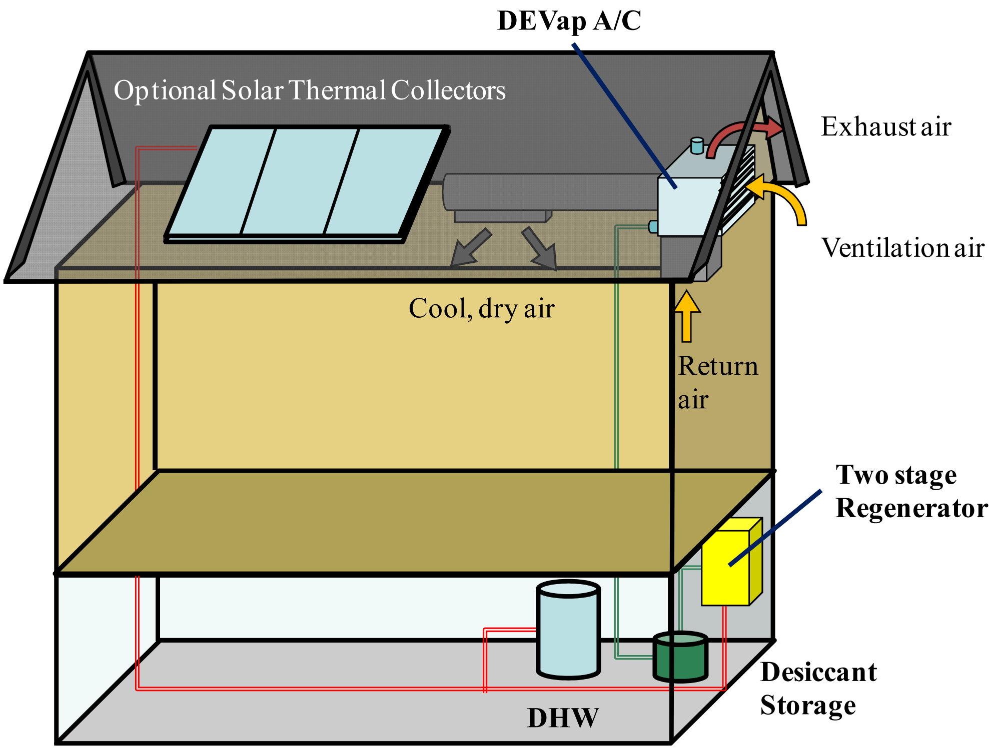


Figure 2-14 Example diagram of a residential installation of DEVap A/C showing the solar option (green lines represent desiccant flows)

In a home application, DEVap performs the following functions:

- Air conditioner with independent temperature and humidity control
- Dedicated dehumidifier
- Mechanical ventilator

2.5.2 New and Retrofit Commercial

In a commercial application, DEVap performs all the same functions of a DX A/C system. The most common commercial cooling implementation is the rooftop unit (RTU). Figure 2–15 illustrates how a packaged DEVap RTU (which is expected to be smaller) may be implemented. The DEVap core is marginally bigger than a DX evaporator coil; however, the regenerator is compact. There is no large DX condenser section in a DEVap RTU. The DEVap RTU air flows will integrate with the building much like a standard RTU, and will impose no significant change in the installation and ducting process. As with the residential unit, the DEVap unit will supply air at 380 or less cfm/ton.

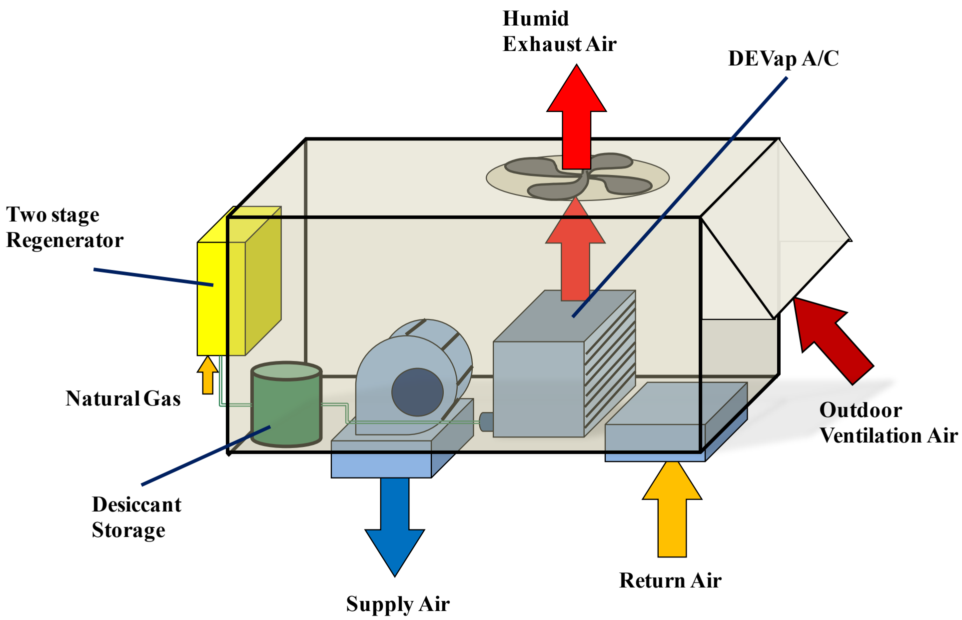


Figure 2-15 Example diagram of a packaged DEVap A/C

Figure 2–16 illustrates how a DEVap RTU would be installed on a commercial building application. The thermal sources for regeneration could again come from natural gas or solar thermal heat. However, the commercial application also opens the door to use waste heat from a source such as on-site CHP. The figure illustrates many options for heat sources, with many possible scenarios. Three possibilities are:

- Natural gas only
- CHP with or without natural gas backup
- Solar heat with or without natural gas backup.

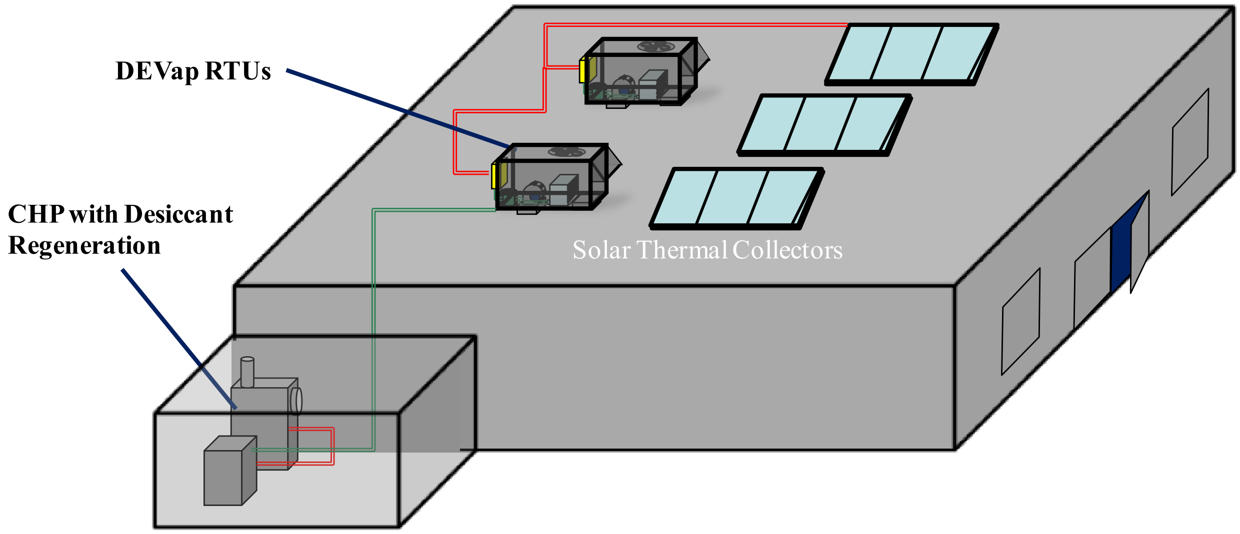


Figure 2-16 Example diagram of a commercial installation of DEVap A/C showing the solar and CHP options
(green lines represent desiccant flows)

DEVap can be installed in buildings that contain central air handlers, similarly to a residential installation. However, for commercial buildings, this type of installation would be highly variable in scope and heat sources for regeneration, and is not discussed in this report. The examples are intended to inform a knowledgeable A/C designer enough to extrapolate to different scenarios.

3.0 Modeling

This section describes the building-energy models used to compare a DEVap A/C with a standard DX A/C. Simulations were completed for residential new construction and retrofit cases and for commercial new construction.

3.1 Fundamental Modeling for the DEVap Cooling Core

The design chosen for this analysis is represented in Figure 3-2 with no water-side membrane and LiCl as the desiccant. The detailed heat and mass transfer in the DEVap core is simulated using the Engineering Equation Solver framework. A two-dimensional, finite-difference model calculates each air stream's temperature and humidity, and the desiccant concentration at each point along the different flow channels. The heat and vapor transport rates between each flow (mixed/supply air stream, exhaust air streams, desiccant flow, and water flow) are estimated at each point with a resistance-in-series network. Figure 3-1 shows the state of each finite difference node plotted on a psychrometric chart. The exiting enthalpy of the air from the second-stage exhaust stream is at nearly the same enthalpy as the entering first-stage EA (OA). The first-stage EA can be two to three times the flow rate as the second-stage stream and thus provide more cooling in the dehumidification stage. In this model, membrane resistances are estimated using standard practice from the membrane science field. The air-side convection coefficients and friction factors are based on experimentally measured data of the DAIS energy recovery ventilator, which uses a similar flow enhancement spacer as that planned for the DEVap prototype.

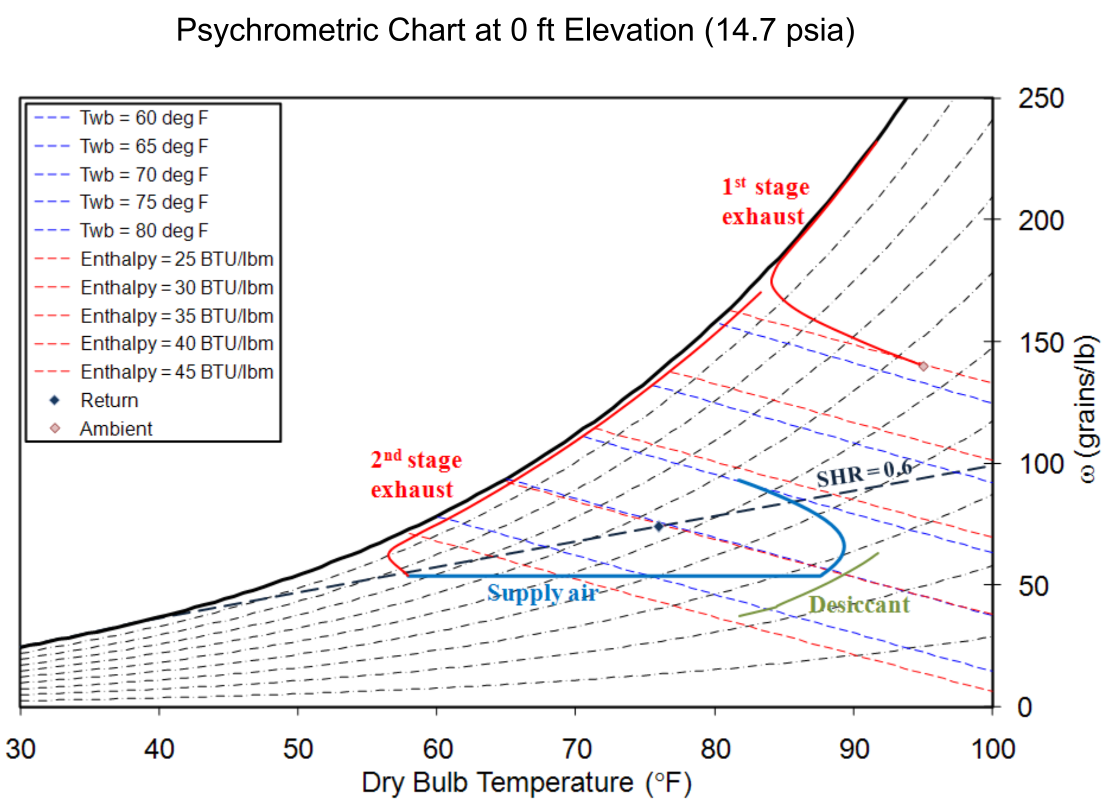


Figure 3-1 Temperature and humidity profiles of DEVap process using the Engineering Equation Solver model

The design condition for determining the size and form factor of the DEVap device is shown in Figure 3-1. This represents a typical Gulf Coast design condition. The design criteria were to supply cooling to the building at 7 Btu/lb (380 cfm/ton) and an SHR of 0.6 while maintaining 55% indoor RH. The preferred form factor, along with the required number of channels for a 1-ton unit, is shown in Table 3-1 and illustrated in Figure 3-2. The model uses this design to create performance maps for all potential indoor and ambient conditions. These maps are used in the building energy model discussed in Section 3.2.

Table 3-1 DEVap 1-Ton Prototype Dimensions

Parameter	Value
Length, L	1.57 ft
L1 (desiccant section)	0.40 ft
L2 (indirect evaporative cooler section)	1.17 ft
Height, H	2.0 ft
Width, W	1.64 ft
# of pairs of channels	100
Supply channel	0.1 in.
Membrane	3 mil
Desiccant flow thickness	10 mil
Plastic sheet	10 mil
Water film	10 mil
Exhaust channel	0.08 in.

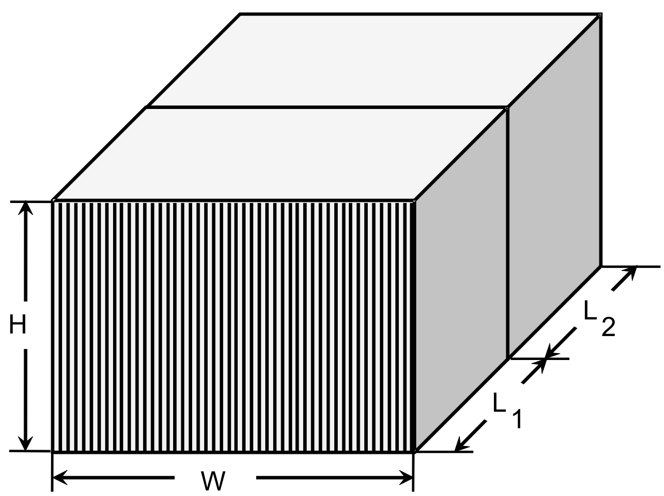


Figure 3-2 DEVap cooling core design

3.2 Building Energy Models

3.2.1 Residential New and Retrofit

The residential building energy model is implemented in the Transient System Simulations (TRNSYS) program. Four simulations were performed for each of the eight cities representing various U.S. climates (Table 3-2). Sizes were incremented in increments of 1 ton in order to meet 100% sensible load using the TMY3 input weather file.

- New construction, standard DX A/C
- New construction, DEVap A/C
- Retrofit, DX A/C
- Retrofit, DEVap A/C.

Table 3-2 A/C System Capacity in Each City Simulated

	Phoenix	San Francisco	Washington, DC	Tampa	Atlanta	Chicago	Boston	Houston
New construction								
DX	4 ton	3 ton	3 ton	3 ton	3 ton	3 ton	3 ton	3 ton
DEVap	4 ton	3 ton	3 ton	3 ton	3 ton	3 ton	3 ton	3 ton
Retrofit								
DX	4 ton	3 ton	3 ton	3 ton	4 ton	3 ton	3 ton	4 ton
DEVap	4 ton	3 ton	3 ton	4 ton	4 ton	3 ton	3 ton	4 ton

In the DEVap system, the DEVap conditioner provides cooling, dehumidification, and ventilation. The DEVap system uses a two-stage regenerator operating with a constant latent COP of 1.2 and variable-speed supply and exhaust fans with 50% efficiency. Table 3-3 shows modeled pressure losses for DEVap at full fan speed. The DX system consists of a seasonal energy efficiency ratio (SEER)-13 air conditioner and a stand-alone dehumidifier, with ventilation provided by a separate fan. For the DX system, we assume the fan uses energy at 0.59 W/cfm, which includes fan efficiency and pressure losses from ducts, filters, the furnace, and the cooling coil.

Table 3-3 Modeled Pressure Losses at Maximum Air Flow Rate in Pascals

Component	ΔP (Pa)
DEVap A/C	
Cooling core, supply	125
Cooling core, exhaust 1	125
Cooling core, exhaust 2	10
Balance of system*	250
Two exhaust ducts (each)	125

* Balance of system losses include losses from ducts, furnace (supply only) and filters.

Each component mentioned in the previous paragraph is modeled with a performance map. The DEVap map is based on parametric runs from the model described in Section 3.1, the air conditioner map is based on the default map from TRNSYS, and the dehumidifier map is from NREL experimental data on an Ultra-Aire dehumidifier (Christensen 2009). The system sizes are shown in Table 3-2. The DX system in each city (except Phoenix) has a dehumidifier with a 65 pints/day capacity. No dehumidifier is required in Phoenix. The simulated building is a 2500-ft^2 house with a 42-ft × 30-ft footprint. The building has an unconditioned basement in the cold climates and a slab-on-grade construction for mild climates. Slab and basement ground coupling are modeled using the simplified model found in ASHRAE (2009). The building envelope U-values (walls, windows, floors, ceilings, and roof), infiltration, and internal gains for the new building are from Hendron (2010); the retrofit case uses a mid-1990s home from Hendron (2008). The new construction home has mechanical ventilation per ASHRAE 62.2-2007; the retrofit building has no mechanical ventilation. The weather for each location is simulated with TMY3 data (National Solar Radiation Data Base). The details of these houses are presented in Appendix A.1.

The HVAC systems are controlled such that the building is maintained at 74°–76°F in the summer and 70°–72°F in the winter. Dehumidification is provided whenever the indoor RH exceeds 55%. An on/off controller with a deadband is used for the DX system; a proportional controller is used for the DEVap system.

3.2.2 New and Retrofit Commercial – EnergyPlus-Generated Load Following

The commercial analysis was based on a small office benchmark building (Deru et al, 2010) run in standard thermostat control with a DX A/C system. The new versus retrofit definitions for commercial groups are not yet clearly defined and are not discussed here. The difference in the analysis is not likely to have a large impact, because the cooling loads for commercial buildings are primarily dominated by ventilation and internal gains and not by differences in envelope and building construction. Thus for the modeling exercise, the commercial new and retrofit are considered equal.

This modeling was done with EnergyPlus as the load generation engine in Phoenix, Arizona, and Houston, Texas. The loads were created using a standard 16 SEER A/C without humidity control, so the building had many hours when the conditions were 60%–90% RH. Implementing humidity control in EnergyPlus was problematic when these loads were developed (summer 2008) and the issue was not resolved. New loads were not generated for this study because the benefits of higher accuracy modeling do not warrant the effort. Furthermore, because humidity is not controlled, comparisons to the estimated DX A/C energy use estimate will be conservative.

The DEVap A/C model was set up to load follow the EnergyPlus results with the DX A/C. Although not ideal, this creates the situation where the DEVap device must meet the same SHR as the DX system. The result is that the DEVap system is run sub optimally with higher than normal air flow rates. DEVap will run more optimally if the space RH is reduced and air flow rate can be managed to a more reasonable cfm/ton. The preceding arguments lend to a conservative estimate for DEVap A/C energy savings.

The small office benchmark A/C capacity is 10 tons in both the DEVap and DX A/C cases. The ventilation rate was a constant 12% of total air flow, which was set at 475 cfm/ton.

3.3 Cost Model

3.3.1 Initial Cost Estimates

Costs for the DEVap A/C are uncertain, but several similar products can be used to estimate. Costs from the Coolerado heat and mass exchanger are used to estimate costs for the DEVap conditioner; a cost estimate from AILR is used for the regenerator. The Coolerado is estimated to contain 205 ft^2 of heat exchanger area per cooling core, and we estimate the manufacturing cost to be \$0.68/ft^2. We assume an additional cost of \$1.02/ft^2 (\$0.93 for the membrane, \$0.09 for attaching the membrane) for the first section, which results in a total cost of \$1119/ton. The other cost assumptions are listed in Appendix A.7. These estimates are predicated on costs of the system as built in similar fashion as the Coolerado Cooler and at modest entry-level volumes. We do not attempt to estimate future improvements in designs and cost that would allow the system to approach the volumes of the DX A/C market, and thus reduce costs further. (See Table 3–4.)

Table 3-4 DEVap Retail Cost Estimate, Immature Product

DEVap Model	Retail Cost Estimate
3-ton DEVap A/C	$7,484
4-ton DEVap A/C	$8,680
10-ton DEVap A/C RTU	$20,461

The conventional system costs are shown in Table 3-5.

Table 3-5 Initial DX A/C Cost Estimate

A/C System	Retail Cost Estimate
SEER-13 air conditioner ($/ton)*	$1,160
Dehumidifier	$1,200
3-ton A/C + dehumidifier retail cost	$4,680
4-ton system retail cost	$5,840
10-ton, SEER 15, DX A/C RTU at $1,520/ton**	$15,200

* Estimate for air conditioners (DOE 2002)
** Estimate for 5-ton SEER 15 packaged RTU (Trane quotation)

3.3.2 Economic Analysis Assumptions for New and Retrofit Residential

To compare costs between conventional and DEVap systems, we calculate the annualized cost of cooling in dollars per year. This cost includes the annual cost of loan repayment and the annual operating costs (electricity, gas, and water). This analysis is based on the assumptions listed in Table 3-6.

Table 3-6 Economic Analysis Assumptions

Assumptions	New Construction	Retrofit
Market discount rate	0.08	0.08
Loan rate	0.05	0.07
Inflation rate	0.02	0.02
Analysis period	15	15
Loan period	30	5
Effective income tax rate	0.3	
Property tax rate	0.02	
Ratio of down payment to initial investment	0.1	
Ratio of assessed value to installed cost	0.7	
P_1 (ratio of life cycle costs to first-year costs)	9.60	9.60
P_2 (ratio of life cycle costs to initial investment)	0.59	0.97
PWF_0 (present worth factor for given discount rate and analysis period)	8.56	8.56

The life cycle cost (LCC) is calculated with:

where C_{init} is the initial cost of the system as described in Section 3.3.1 and $C_{yr,util}$ is the annual cost of utilities (natural gas, electricity, water), which is calculated based on region-specific utility prices. The monthly gas and electricity prices were estimated with utility tariffs from each city for 2010 and are tabulated in Appendix A.8. This was done to estimate the marginal cost of energy (not including any fixed monthly charge). We also consider the case where gas prices are 50% higher than 2010 prices. Water prices were estimated at $3/1000 gal for all locations.

The annualized cost of cooling is then:

$$\text{Annualized cost of cooling} = \frac{LCC}{PWF_0}$$

where PWF_0 is the present worth factor based on the market discount rate (d) and the analysis period (15 years):

$$PWF_0 = \frac{1}{d}\left[1 - \left(\frac{1}{1-d}\right)^{15}\right]$$

3.3.3 *Economic Analysis Assumptions for New and Retrofit Commercial*

For the commercial economic analysis, we first assume that the DEVap A/C costs more than DX SEER 16 A/C. Thus, the decision to implement DEVap A/C is based on return on investment. A simple internal rate of return (IRR) is calculated. The period of analysis is taken to be 15 years due to the expected lifetime of commercial A/C equipment (DOE 2009). For this analysis, nonfuel-related O&M expenses are presumed to be equal. The expected return is calculated solely on the combined energy and water costs improvement that DEVap provides. The analysis uses monthly average rates for electricity and natural gas for the years of 2005–2009 (EIA 2010). Consideration for peak power reduction or utility incentives is not accounted for, resulting in a conservative economic estimate.

3.4 Cooling Performance

For residential performance assessment, DEVap and standard A/C are sized to meet 100% of the sensible load using TMY3 data in each city. Load sizes are chosen to have zero hours of temperature excursion over 78°F. The tops and bottoms of the deadbands in all cities are 76°F and 74°F (note exception from the Building America baseline). For standard A/C, an ENERGY STAR dehumidifier described in section 3.2 is used to control humidity with a deadband of 50%–55% RH.

For the residential analysis, DEVap cooling performance is based on controlling humidity via three modes of operation:

- **Standard cooling mode.** The outlet humidity is set to 51°F dew point and the sensible cooling is modulated with the evaporative post cooler.
- **Sensible only cooling mode.** The outlet humidity is allowed to float with no desiccant dehumidification.
- **Dehumidification only mode.** The DEVap A/C is run in an “adiabatic” mode with the desiccant portion of the A/C performing near adiabatic dehumidification. This can be implemented by running DEVap with no first- and second-stage exhaust air flows.

These modes are controlled by using proportional control logic:

- Sensible cooling is proportionally increased by increasing the amount of purge air through the evaporative post cooler from the minimum OA ventilation rate to 30% of the mixed air flow as the room air increases from 74° to 76°F.

- Sensible only cooling mode is activated when the ambient dew point is below 56°F.
- Dehumidification only mode is turned on when the indoor RH reaches 54%. The air flow through the device is modulated from 40% to 100% of max flow as humidity ranges from 54% to 60%. (RH was not expected to rise above 55% in this scheme.)

Figure 3-3 shows the typical outlet air conditions and resulting return air conditions during a new residential simulation using the DEVap A/C. The points plotted are only when the DEVap A/C is ON, which takes away all the floating and wintertime conditions when the furnace is ON. Where the supply air conditions align with the 51°F dew point, the DEVap A/C is in standard cooling mode. Sensible only mode is represented where the supply air conditions do not align with 51°F dew point and are cooler than the return air. Dehumidification mode is represented where the supply air conditions are warm (above 80°F) and at approximately 27% RH. The coincident indoor air conditions for the dehumidification points align where the indoor air is at approximately 54%–55% RH.

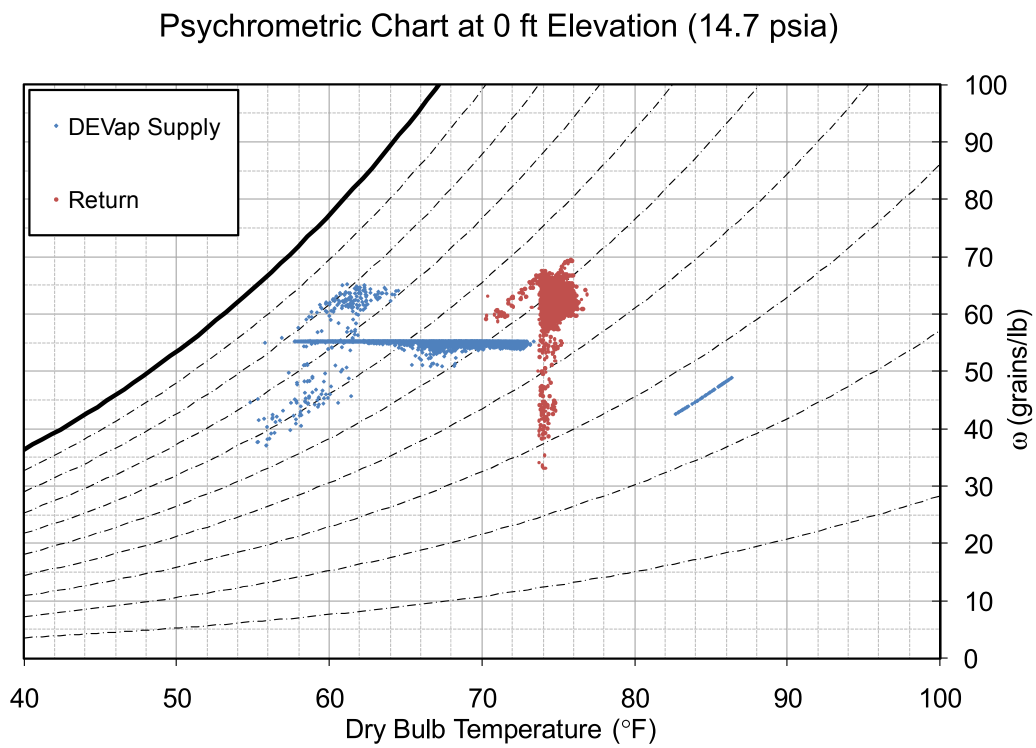


Figure 3-3 Residential/new – Houston simulation showing the return air and supply air from the DEVap A/C

Figure 3-4 shows the return and supply air conditions of the standard A/C with a dehumidifier when either of the two systems is ON. The A/C supply air conditions are largely indicative of 380 cfm/ton operation. The dehumidifier outlet conditions are largely grouped around 20% RH and warm.

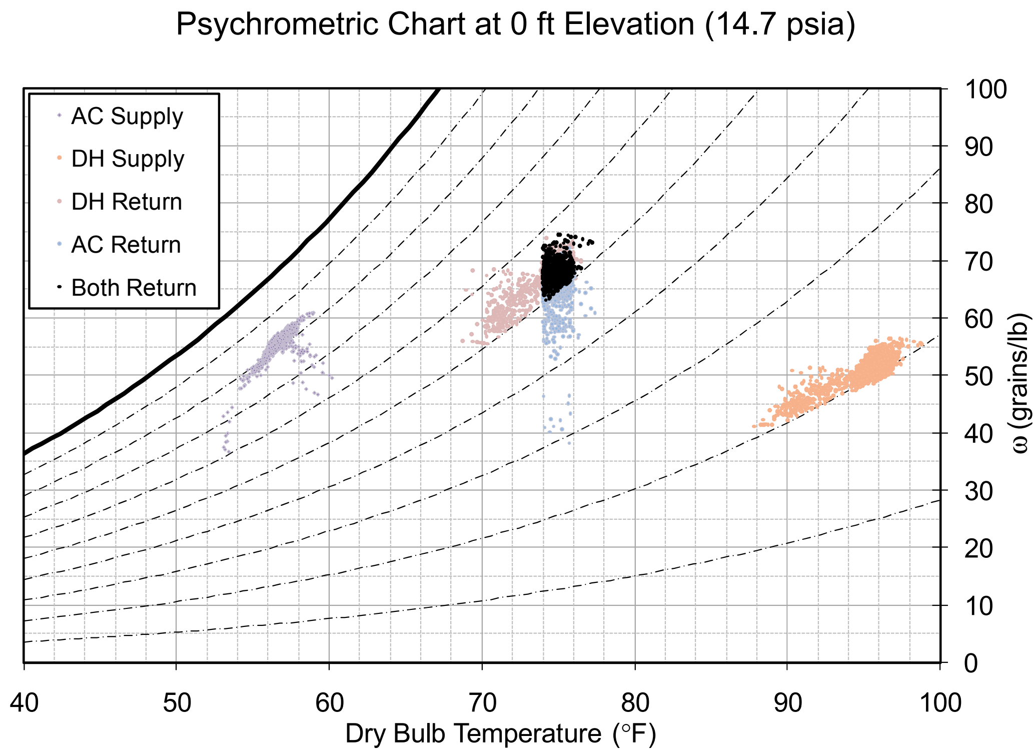


Figure 3-4 Return and supply air from the DX A/C and dehumidifier (shown as "DH") in a new residential building in Houston

Figure 3-5 shows the effects of having or not having a whole house dehumidifier for a new residential building in Houston. These results are consistent with the results found by Fang et al. (2010). Significant RH excursions above 60% and 70% are prevalent with the no dehumidifier case.

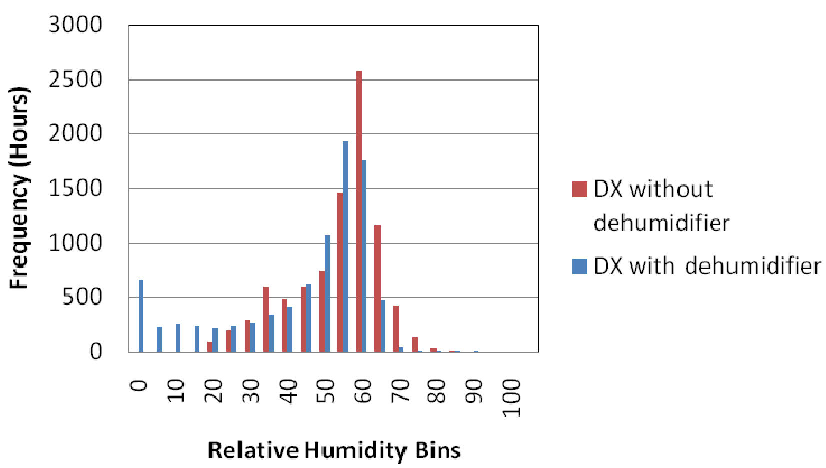


Figure 3-5 Effect of a whole-house dehumidifier when used with DX A/C in a new residential building in Houston

3.4.1 New Residential

When comparing the DEVap and DX systems the primary concern is the indoor humidity performance, because DEVap and the DX A/C systems meet indoor temperature set point and maintain temperature below 78°F for 100% of the hours. Figure 3-6 shows the performance of both systems in controlling RH in Houston. All 8,760 hours are shown and bins are labeled with the value at the top of the bin. DEVap has a larger percentage of bins below 50% than does the DX system modeled. The difference is more clearly seen by looking at summertime bins where cooling load is dominant. Figure 3-7 shows June – August indoor RH for both DX and DEVap A/C in Houston. As designed, DEVap lowers the humidity in the space to a lower RH during the peak cooling season due to DEVap's ability to achieve lower SHR at peak. Because the DEVap device controls humidity to a level lower than DX A/C, the DEVap A/C uses more energy than necessary, thus further optimization of the DEVap control strategy is needed. During the swing season, there are many hours when the dehumidification only mode of the DEVap A/C controls to 55% RH.

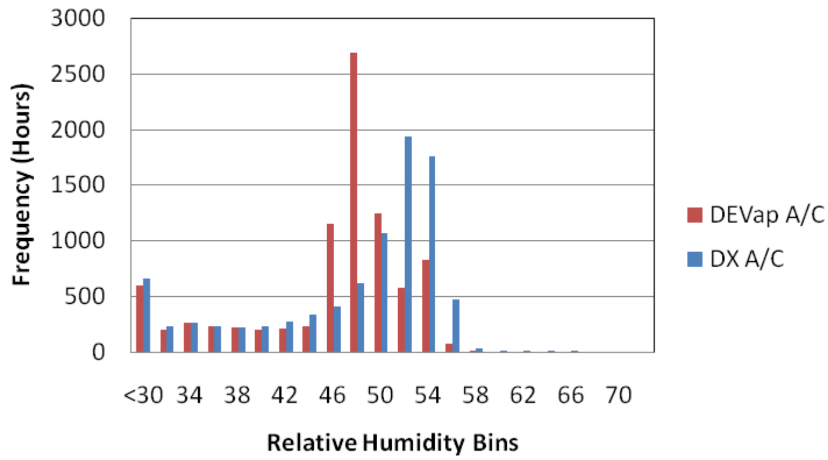


Figure 3-6 Indoor RH histograms for Houston throughout the year

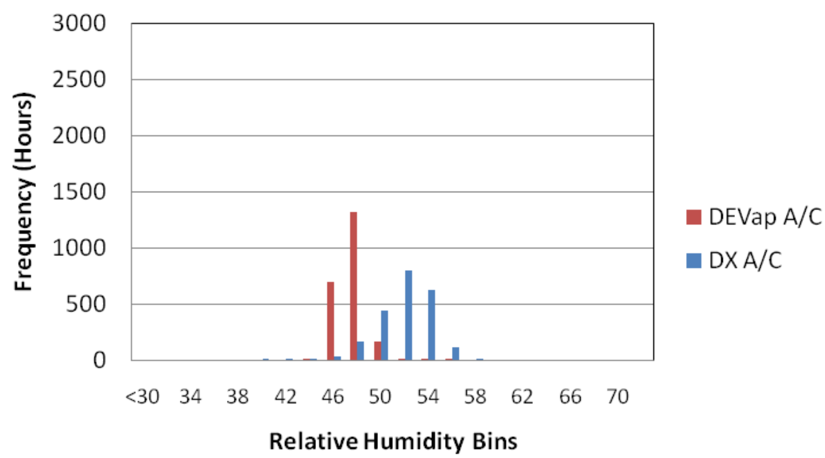


Figure 3-7 Indoor RH histograms for Houston in June–August

Figure 3-8 shows the bins of SHR for Houston. The DEVap device is able to modulate its sensible heat ratio down to 0.2 to exactly meet the buildings load during those hours. Hours with SHR > 1 is indicative of dehumidification mode where total and sensible cooling are both negative. Not shown for the DX case is run-time for the dehumidifier.

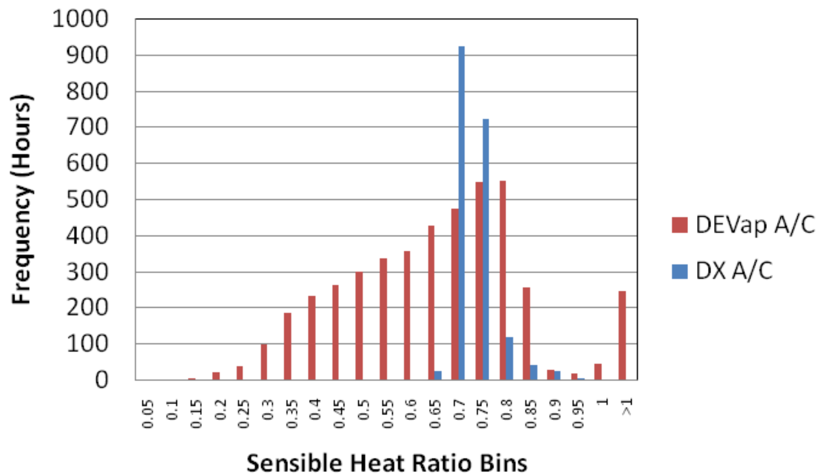


Figure 3-8 Houston DEVap A/C SHR bins for meeting cooling load

3.4.2 Retrofit Residential

Similar results for comfort as the new residential case are shown in Figure 3-9 and Figure 3-10. DEVap maintains a lower RH in the building than the standard DX A/C. In general the DEVap A/C maintains an RH of 2%–4% dryer than the DX A/C + dehumidifier in the humid climates. Again, further optimization of the control strategy of the DEVap device is required to prevent the space from over drying.

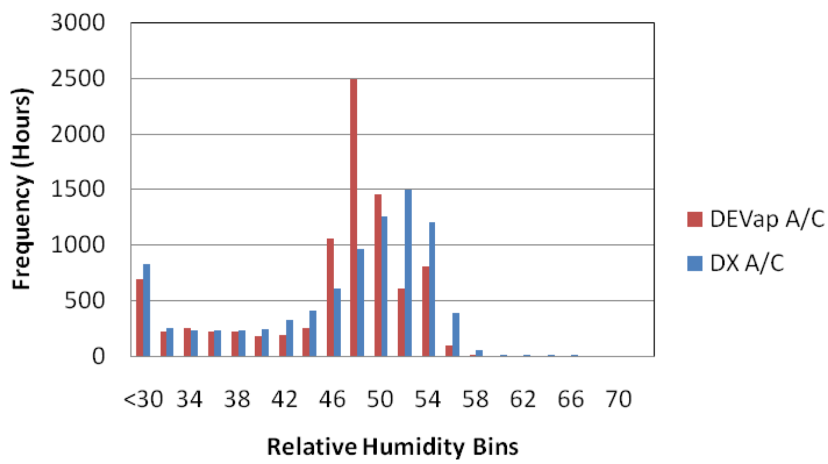


Figure 3-9 Indoor RH histograms for Houston throughout the year

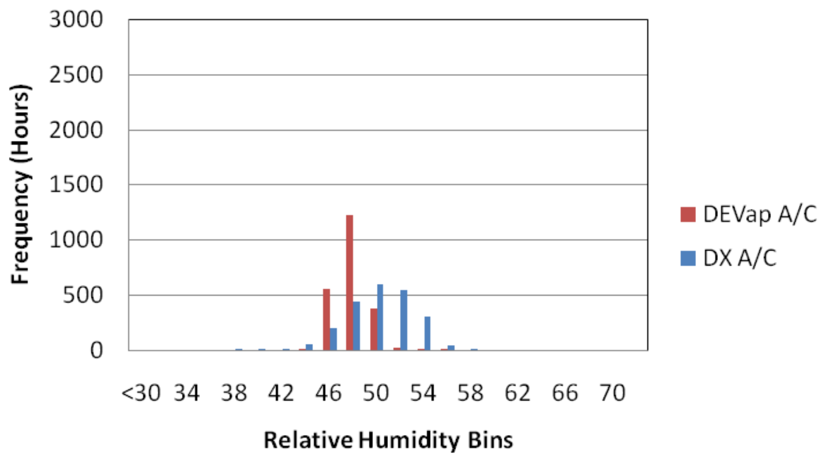


Figure 3-10 Indoor RH histograms for Houston in June–August

3.4.3 New and Retrofit Commercial

The EnergyPlus model completed in 2008 experienced issues that prevented humidity control from being implemented for the load profile in EnergyPlus. As a result, the RH frequently went out of control (see Figure 3-11 and Figure 3-12). This generally happens when the building is empty and the air conditioner is shut down (nights and weekends). This results in high latent removal (generally in the morning), during the building warm-up period. The DEVap is driven to achieve the same load profile that the A/C provided, thus the DEVap building would have the same RH histogram. The DEVap and DX A/C latent removal are equal.

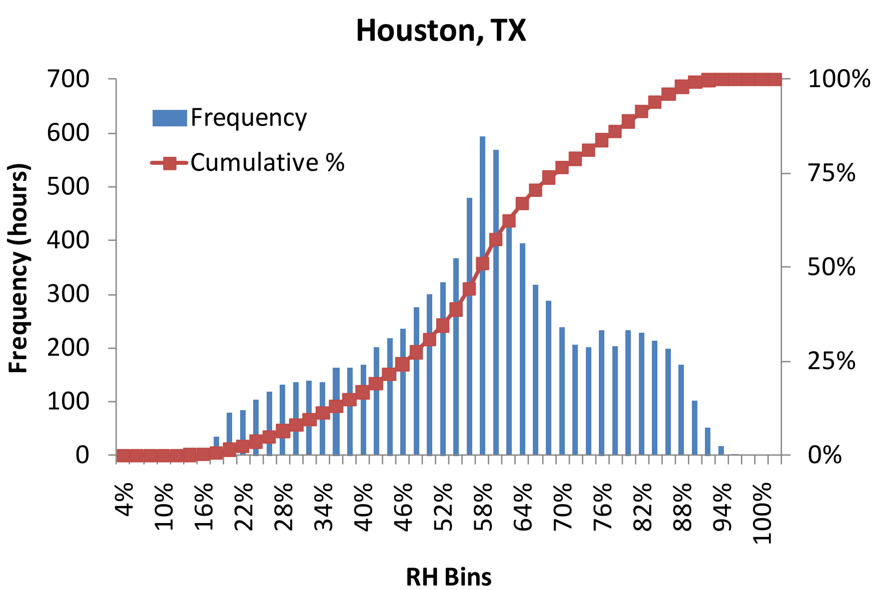


Figure 3-11 RH histogram for a small office benchmark in Houston

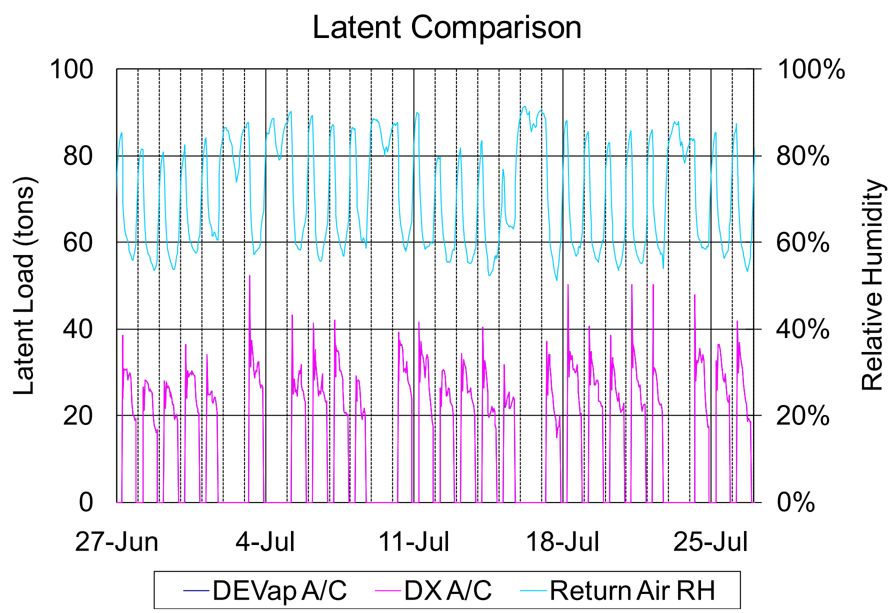


Figure 3-12 Latent load comparison and resultant space RH in Houston

(DEVap A/C and DX A/C latent load profiles overlap)

3.5 Energy Performance

For all energy performance calculations, the conversion factors in Table 3–7 are used.

Table 3-7 Source Energy Conversion Factors (Deru et al, 2007)

Source	Factor
Electric source energy	3.365
Natural gas source energy	1.092

For the new residential simulations, the total source energy was for the sum of all the electric and thermal source energy to run the A/C systems, mechanical ventilator, and dehumidifier. For retrofit residential simulations, no mechanical ventilation is required in the DX case.

For commercial, the source energy for cooling is the sum of all the electrical energy to run the DX system, only when there is a call for cooling. Similarly for the DEVap A/C, electrical and thermal energy is summed only for periods when there is a call for cooling.

Water use impacts for the DEVap and DX A/C are summed to include on-site and off-site water use. Electric power plants evaporate at 0.5–4.4 gal/kWh in the United States (Torcellini et al. 2003). Including on-site and off-site water use on a per ton·h basis is a reasonable metric to determine water impact on a regional scale.

3.5.1 New Residential

Power comparison for Houston is shown in Figure 3-13; peak yearly power consumption is shown in Figure 3-14. From inspection, the peak electricity draw of the DEVap A/C is considerably less than the standard A/C. This is primarily because compressor power is eliminated and replaced with only fan power to push air through the DEVap cooling core. Most of an A/C's energy use is switched from electricity to thermal energy when switching from DX to DEVap. In this analysis, natural gas is used as the thermal source.

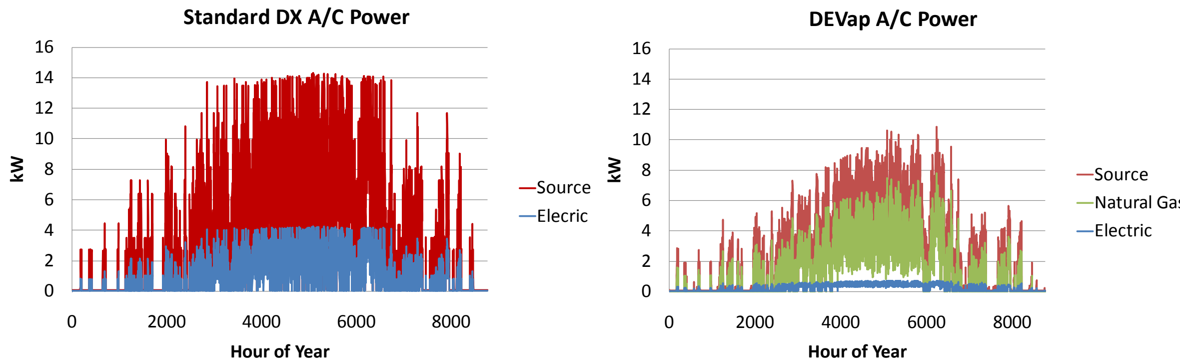
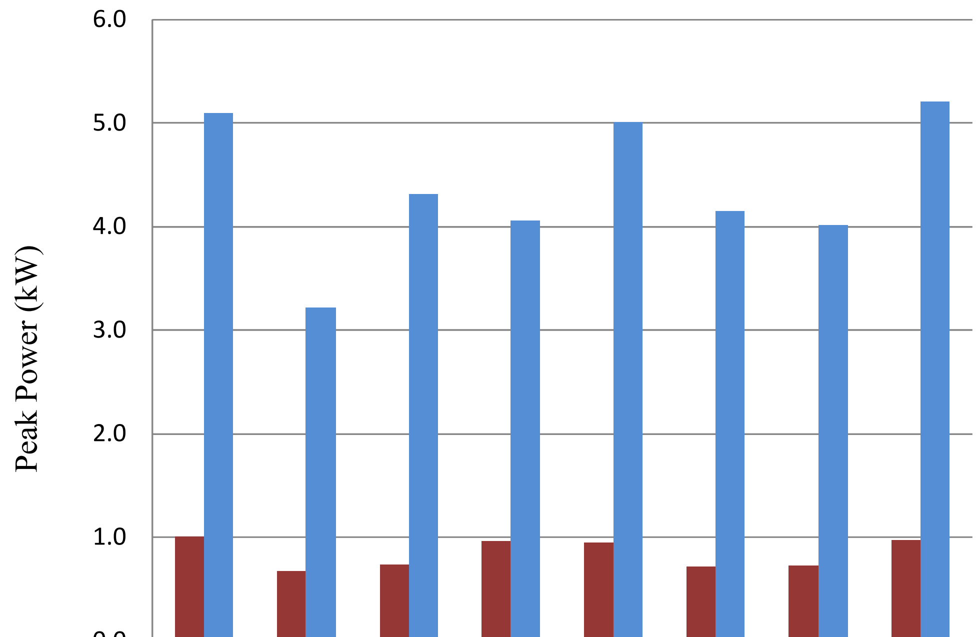


Figure 3-13 A/C power comparison in Houston for residential new construction



	Phoenix	SF	DC	Tampa	Atlanta	Chicago	Boston	Houston
Peak DEVap A/C	1.00	0.67	0.74	0.96	0.95	0.72	0.72	0.97
Peak Standard A/C	5.09	3.22	4.31	4.06	5.01	4.15	4.02	5.21

Figure 3-14 Peak power in all cities, residential new construction

Source energy use is shown in Figure 3-15. DEVap source energy savings are 29%–66% across all the cities modeled. Although significant savings are shown, DEVap has yet to be optimized for energy performance. The lower RH provided by the DEVap A/C comes with an energy penalty. Humidity control and energy use still require additional optimization for a more accurate comparison on an energy basis.

Figure 3-16 shows the specific water use (gal/ton·h) for all the cities modeled in terms of site water use and water use at the power plant (off site). Off-site water is calculated using a conversion of 1 gal/kWh-electric.

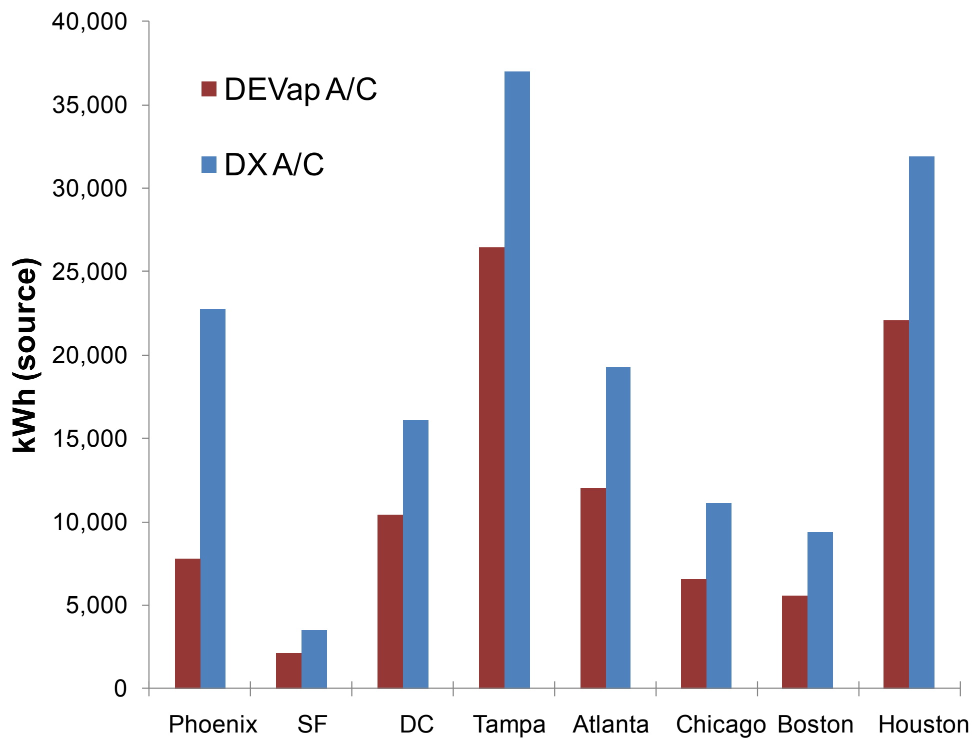


Figure 3-15 Source energy in all cities, residential new construction

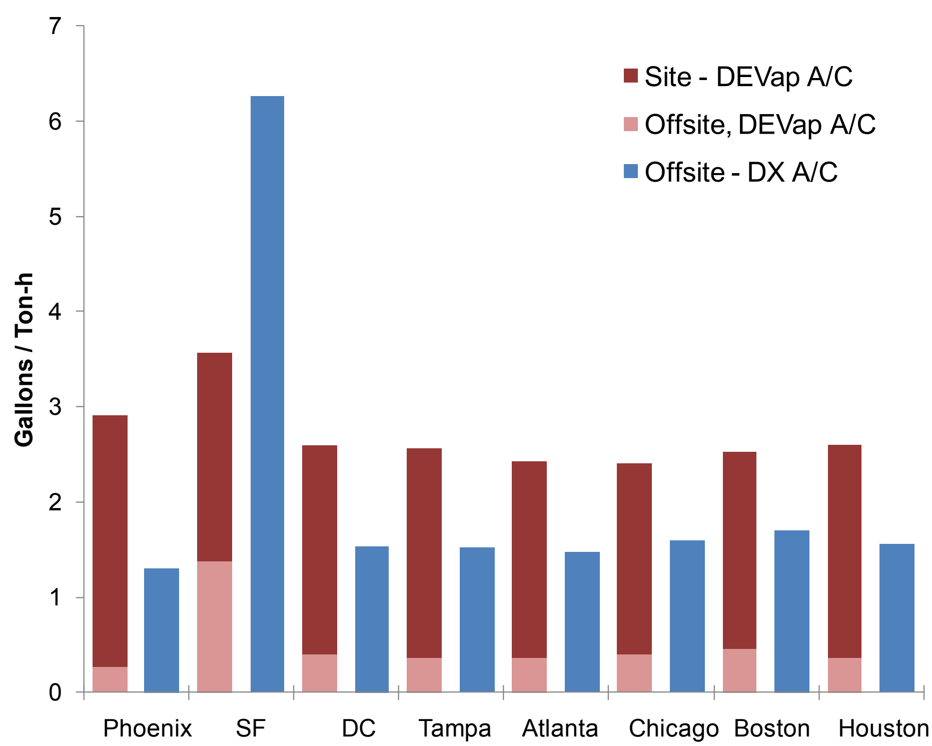


Figure 3-16 Water use (evaporation) in all cities, residential new construction
(assumes 1 gal/kWh for electric generation)

3.5.2 Retrofit Residential

Power comparison for Houston is shown in Figure 3-17; peak power comparisons are shown in Figure 3-18. Similar to the new construction cases, the peak electricity draw of the DEVap A/C is considerably less than the standard A/C.

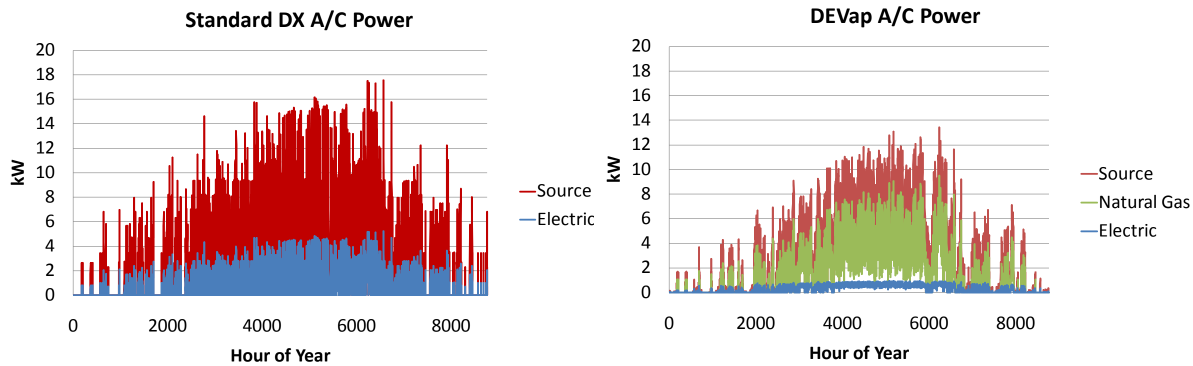
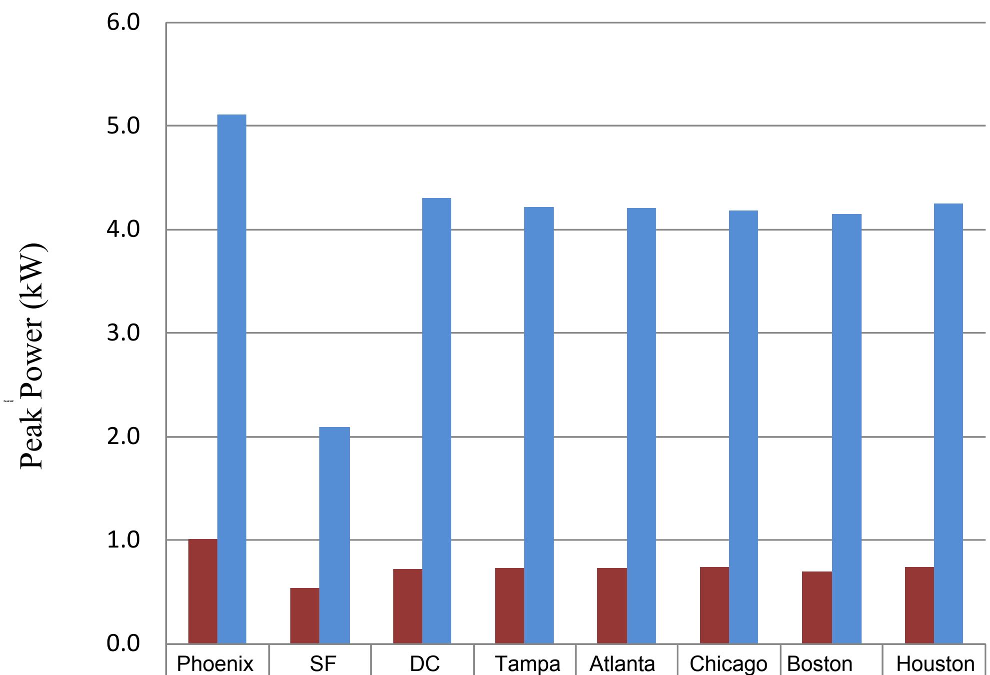


Figure 3-17 A/C power comparison in Houston for residential retrofit case



	Phoenix	SF	DC	Tampa	Atlanta	Chicago	Boston	Houston
Peak DEVap A/C	1.00	0.54	0.72	0.73	0.72	0.74	0.69	0.74
Peak Standard A/C	5.11	2.09	4.30	4.21	4.21	4.18	4.15	4.25

Figure 3-18 Peak power in all cities for residential retrofit case

Source energy use is shown in Figure 3-19. DEVap source energy savings range from 1% to 67% across all the cities modeled. Performance in Tampa and Houston are noticeably different than in the new construction case. In these cases, the standard A/C system is able to provide most of the humidity control without the help of the stand-alone dehumidifier. The retrofit construction case magnifies that DEVap requires additional optimization for energy performance. Figure 3-20 shows the specific water use for all the cities modeled.

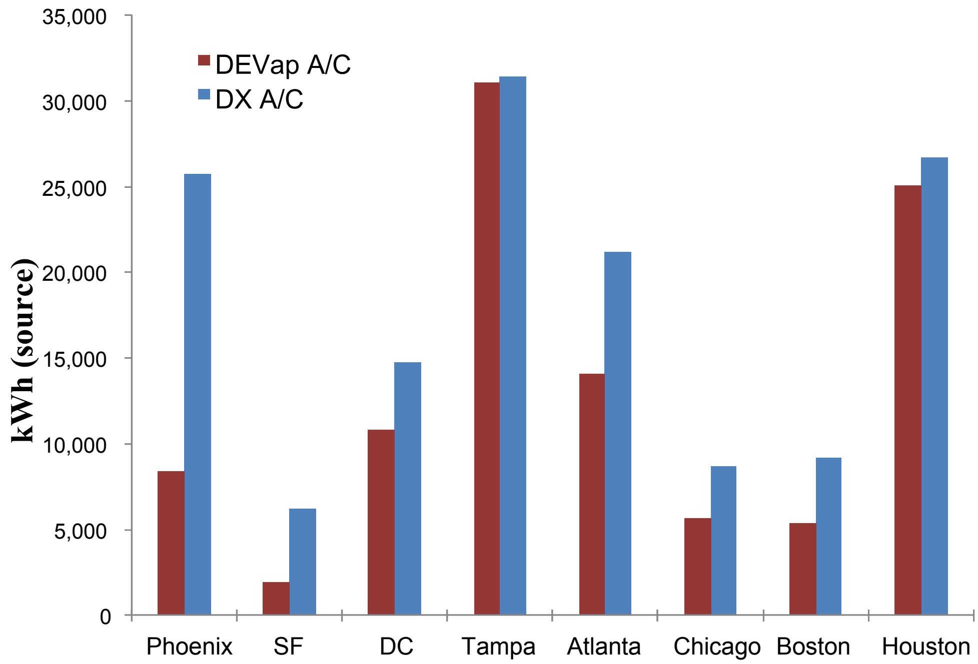


Figure 3-19 Source energy in all cities for residential retrofit case

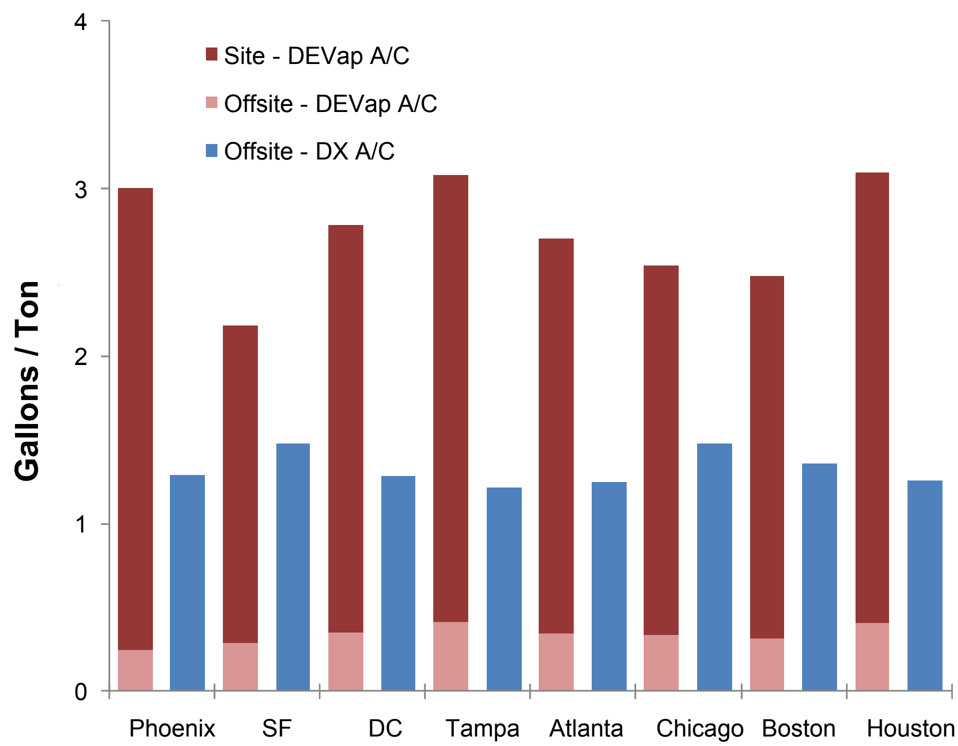


Figure 3-20 Water use (evaporation) in all cities, residential retrofit construction
(assumes 1 gal/kWh for electric generation)

3.5.3 New and Retrofit Commercial

Figure 3-21 and Figure 3-22 show the energy performance of the DX and DEVap A/C in an hourly plot in both Houston and Phoenix. The electricity use and switch to thermal energy (in this case, natural gas) is evident as with the residential cases. In both cities, the peak electricity is reduced by 80%.

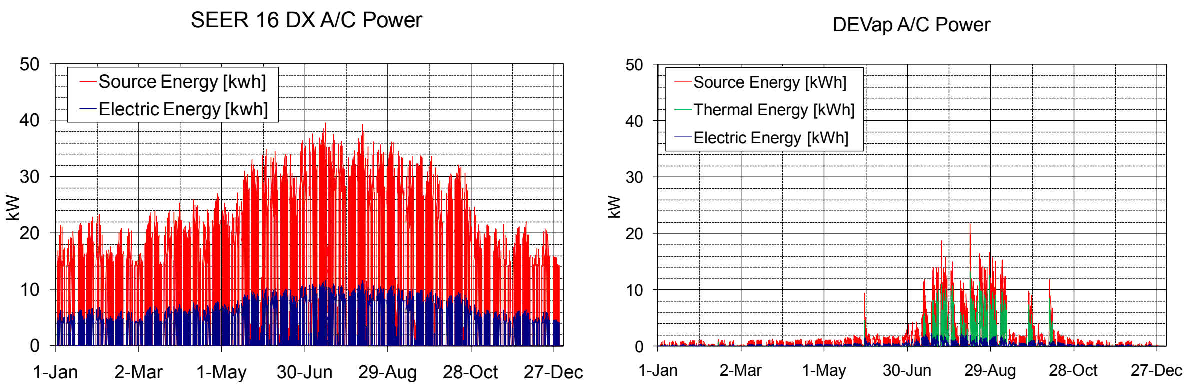


Figure 3-21 A/C power comparison for a small office benchmark in Phoenix

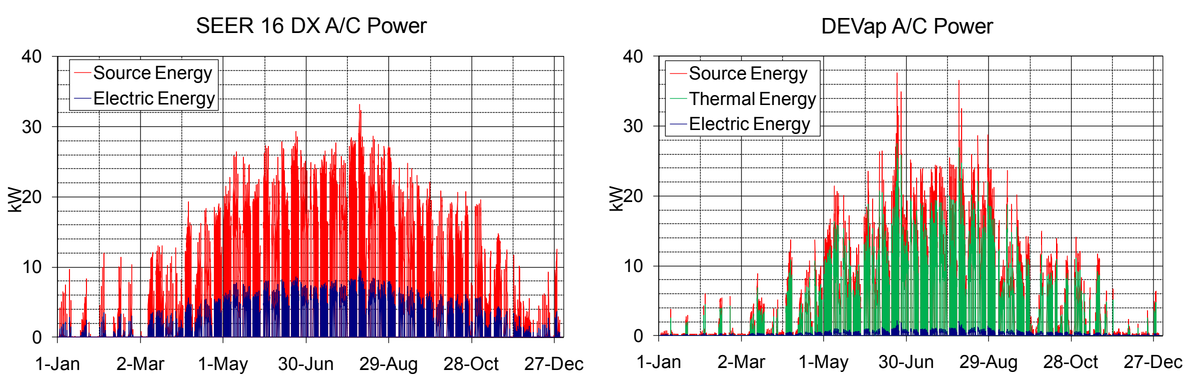


Figure 3-22 A/C power comparison for a small office benchmark in Houston

Table 3-8 and Table 3-9 show the results of the simulation in the two cities. The peak electricity reduction and the total electricity reduction are about 80% and 90%, respectively. The cooling source energy reductions of 39% and 84% are primarily due to the efficiency gain of the DEVap A/C. The total energy reduction accounts for energy used to ventilate and distribute air throughout the year. For the DEVap case, the air flow is set back by 50% during times when there is no A/C or heating. The variable-speed fan in the DEVap A/C results in energy savings, because this mode of operation is easily implemented. DX can, however, also implement a variable-speed fan with added cost. Site water evaporation is 2.08–2.68 gal/ton·h for the two cities. This level of water consumption is similar to the water used by A/C when electric power plant water draw (off-site) is considered. For comparison, a modest 1.0 gal/kWh was assumed for off-site water consumption. Water use by electricity plants was not compared at the state level because electricity is not bound by state borders. Furthermore, a reliable database of per-state water use by utilities is not readily available.

Table 3-8 Results Summary for Phoenix

Simulation	DX	DEVap	Units	Difference (%)
Total cooling	15,724	15,725	ton·h	0%
Sensible cooling	14,915	14,909	ton·h	0%
Latent cooling	809	816	ton·h	1%
Cooling electric energy	18,609	1,717	kWh	–91%
Total electric energy	31255	1,891	kWh	–94%
Cooling thermal energy	0	3,707	kWh	
Cooling source energy	**63,270**	**9,917**	**kWh**	**–84%**
Total source energy	106,268	10,506	kWh	–90%
Cooling electric energy (specific)	1.18	0.11	kW/ton	–91%
Source cooling COP	0.87	5.58	–	538%
Peak electric	**11.63**	**2.33**	**kW**	**–80%**
Total site water evaporation	0	42,224	gal	
Total site water evaporation	0.00	2.69	gal/ton·h	
Total off-site water use (1 gal/kWh)	31,255	1891	gal	–94%
Total off-site water use (1 gal/kWh)	1.99	0.12	gal/ton·h	–94%

Table 3-9 Results Summary for Houston

Simulation	DX	DEVap	Units	Difference (%)
Total cooling	14,819	14,695	ton·h	–1%
Sensible cooling	9,933	9,927	ton·h	0%
Latent cooling	4,886	4,768	ton·h	–2%
Cooling electric energy	15,750	1,579	kWh	–90%
Total electric energy	27,166	1,747	kWh	–94%
Cooling thermal energy	0	24,931	kWh	
Cooling source energy	**53,550**	**32,791**	**kWh**	**–39%**
Total source energy	92,366	33,365	kWh	–64%
Cooling electric energy (specific)	1.06	0.11	kW/ton	–90%
Source cooling COP	0.97	1.58	–	62%
Peak electric	**10.26**	**2.18**	**kW**	**–79%**
Total site water evaporation	0	30511	gal	
Total site water evaporation	0.00	2.08	gal/ton·h	
Total off-site water use (1 gal/kWh)	27,166	1,747	gal	–94%
Total off-site water use (1 gal/kWh)	1.83	0.12	gal/ton·h	–94%

3.6 Residential Cost Performance

Figure 3-23 shows the annualized LCCs for DX and DEVap A/C in new construction. These include loan payments, electricity, natural gas, and water. Using 2010 natural gas prices, the LCCs for DEVap are less than for DX A/C in most cities. The costs of the two systems in many locations are approximately the same given uncertainties in this analysis. Assuming 50% higher gas prices has a larger effect in cities that require much dehumidification.

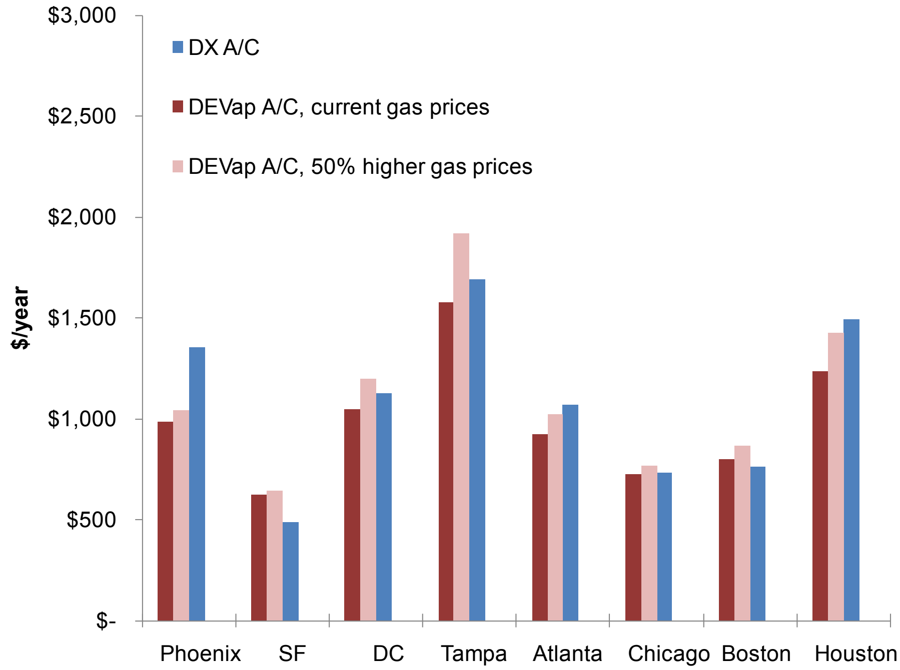


Figure 3-23 Annualized cost comparison for residential new construction

Figure 3-24 illustrates the cost breakdown for Houston and Phoenix. The upfront costs for DEVap A/C are higher than for DX A/C, but the lower energy costs quickly compensate. Gas price uncertainty in places like Tampa and DC (not shown), may result in higher overall cost for DEVap A/C.

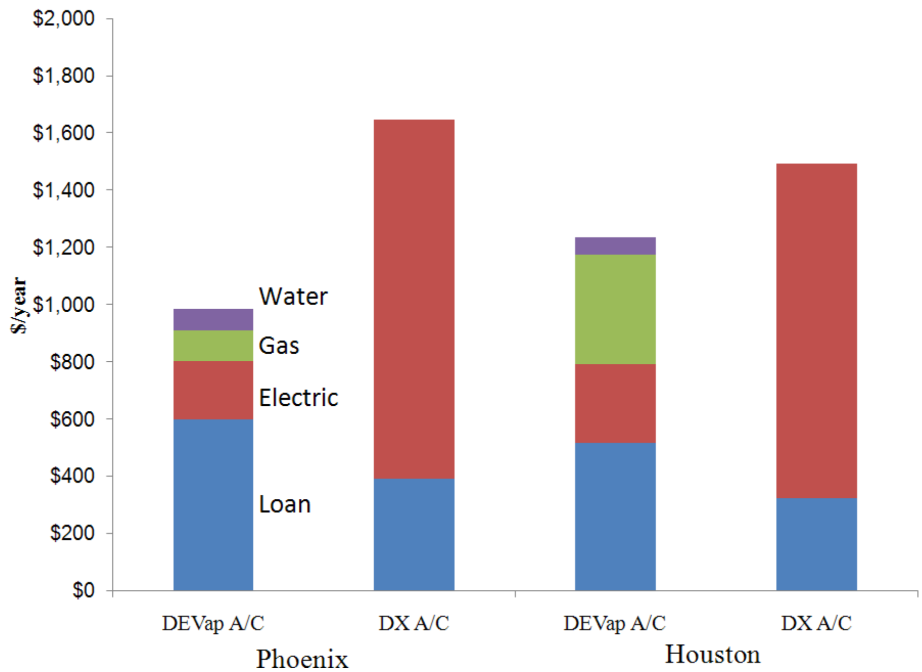


Figure 3-24 LCCs for residential new construction for Phoenix (hot, dry) and Houston (hot, humid)
(loan is the repayment of the loan due to the upfront cost of each system)

Figure 3-25 shows the annualized LCCs for DX A/C and DEVap A/C for the retrofit case. Costs for DEVap are higher in Tampa and lower in Phoenix, but uncertainties prevent a distinct conclusion in other locations. In general, the relative cost of DEVap A/C compared to DX A/C is higher for the retrofit case than for the new construction case because:

- The assumed financing for the retrofit case (5-year loan at 7%) is more sensitive than the new construction case (30-year mortgage at 5%) to upfront costs and DEVap has a higher upfront cost. This is also evident from Figure 3-26, which shows the cost breakdown for each system in Houston and Phoenix.
- Although DEVap still provides mechanical ventilation, none is required for the retrofit case. This results in energy savings for the standard DX A/C, which brings no OA into the house.
- The higher SHRs in the retrofit case compared to new construction result in a smaller energy penalty for DX A/C. As homes become tighter and latent loads comprise a larger portion of the total load, this energy penalty increases for DX A/C and makes DEVap A/C more competitive.

These analyses do not include the effects of time-of-use pricing and potential peak demand charges that may soon come to bear in the residential energy market. Such pricing would inevitably improve the economics of the DEVap A/C because it effects reductions in electricity use.

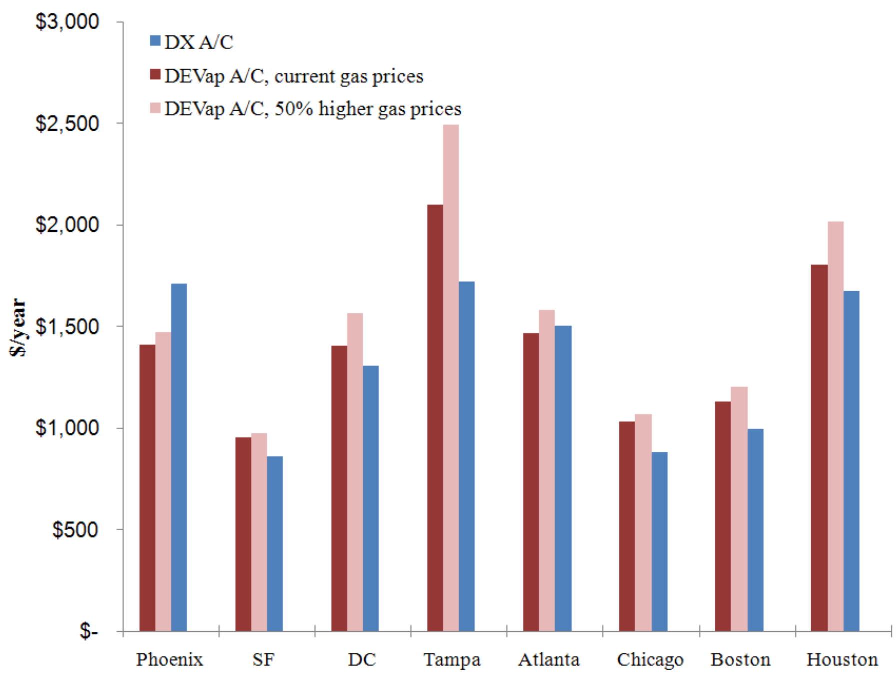


Figure 3-25 Cost comparison for residential retrofit

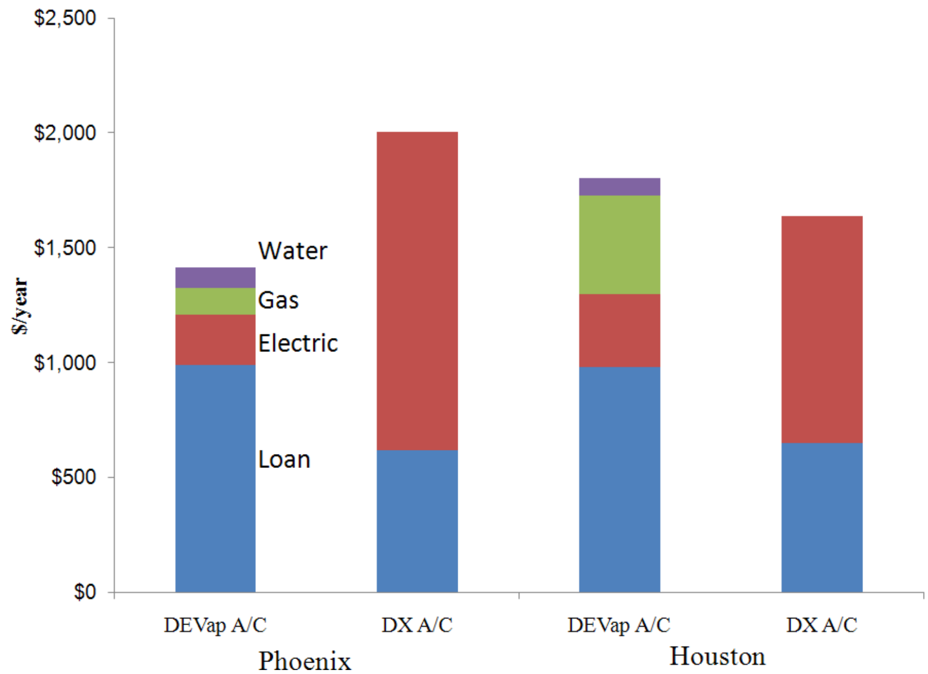


Figure 3-26 LCC breakdown for retrofit for Phoenix (hot, dry) and Houston (hot, humid)
(loan is the repayment of the loan due to the upfront cost of each system)

3.7 Commercial Cost Performance

Table 3-10 and Table 3-11 show the results of the economic analysis for the payback return rate or IRR for each city. Each rate is based on a 15-year product lifetime for each system. Rates for electricity and gas are monthly averages. Time-of-use electricity rates and peak reduction credit are not taken into account. Because A/C power draw drives commercial peak consumption, inclusion of these factors will increase electricity costs. This would inevitably improve the economics of the DEVap A/C.

Table 3-10 Economic Analysis for Houston

Costs	DX	DEVap	Difference
First cost	$15,200	$20,461	35%
Yearly electricity cost	$2,676	$173	–94%
Yearly natural gas cost	$0	$874	
Yearly water cost (at $3/1000 gal)	$0	$110	
Net yearly cost	$2,676	$1,157	–57%
IRR		**28%**	

Table 3-11 Economic Analysis for Phoenix

Costs	DX	DEVap	Difference
First cost	$15,200	$20,461	35%
Yearly electricity cost	$2,646	$164	–94%
Yearly natural gas cost	$0	$157	
Yearly water cost (at $5/1000 gal)	$0	$253	
Net yearly cost	$2,646	$575	–78%
IRR		**39%**	

4.0 Risk Assessment

4.1 Technology Risks

A/C reliability generally means that commercial and residential A/C equipment lifespan is expected to be 15 years and 11 years, respectively (DOE 2009). Longevity of a new technology will always be in question, especially compared to tried-and-true refrigeration-based A/C. Answering all these concerns takes time, although accelerated testing is being devised for DEVap. Longevity of the device would include issues such as:

- Degradation of performance over the lifetime of the equipment
- Maintainability to sustain performance
- Catastrophic failure reducing the expected lifetime
    - Material degradation
    - Inadequate manufacturing techniques
    - Fundamental design issue.

The DEVap A/C will increase site water use by approximately 60 gal/day for a typical home (3-ton air conditioner). This water use is most economical if sourced from the buildings municipal water supply. However, other options such as rainwater harvesting and gray water reuse are available. Despite this, regional water use is not likely to be significantly affected because the volume impact of evaporative cooling when compared to regional uses. DEVap uses approximately 2.5–3-gal/ton·h of regional water (one to two times that of DX A/C) if one assumes 1.0 gal/kWh to generate electricity. However, 1.0 gal/kWh is a “middle of the road” or possibly a conservative estimate of off-site water use by electricity generation stations. Electricity generation accounts for 3.3% of all water use in the United States (Torcellini 2003), and A/C consumes 10% of all electricity produced in the United States (4 of 41 quads) (DOE 2009). Therefore, A/C accounts for approximately 0.3% of U.S. water use. A conservative estimate would thus conclude that DEVap A/C will not increase the aggregated U.S. water use by more than 0.3%. Some markets face localized water supply issues, however, so DEVap A/C in these locations may not be acceptable.

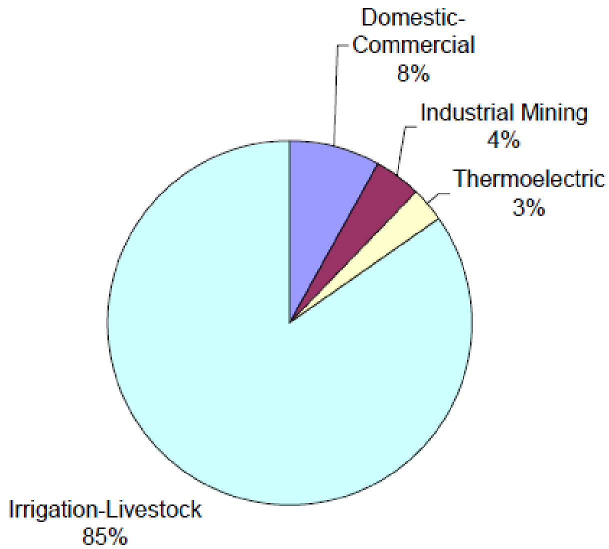


Figure 4-1 U.S. water use profile
(Torcellini et al. 2003)

Table 4-1 Technical Risk Matrix for DEVap A/C

Building Type	New and Retrofit
Residential	1. Longevity/reliability 2. On-site water use increase
Commercial	1. Longevity/reliability 2. On-site water use increase

4.2 Market and Implementation Risks

Most technological risk from DEVap stems from its evaporative aspect. Evaporative devices eject heat from the building to the atmosphere in the same device that cools the building air. This means a second set of exhaust air ductwork must be routed to and from the DEVap A/C and the outside, and constitutes the greatest implementation risk for retrofits. It is also highly dependent on the building type, vintage, and design. For instance, many homes have air handlers in the attic spaces. Duct access to the outside is not difficult from this location; however, some homes have air handlers in internal spaces such as closets. This would likely require some ductwork to be redirected so the air handler (which houses the DEVap device) can be placed close to the outside.

Integrating the DEVap cooling device with air handlers, furnaces, or even RTUs may pose a practical issue. For an RTU, the traditional condenser that takes up about 30%–40% of package volume will be replaced by the "equivalent" regenerator. This component, which has a 30-kBtu boiler and a 50-cfm heat exchanger will be approximately 2 ft high × 2 ft wide × 1 ft deep for a 3–5 ton system. This is substantially smaller than the condenser section of a DX RTU. However, the DEVap conditioner component will be larger with an increase in face area. The net packaging will be smaller, but packaging configuration may be different.

Evaporative cooling will also have the risk of freezing to the DEVap core or water lines. This is manageable through educated implementation. It is primarily a residential issue, as commercial buildings commonly have knowledgeable people to manage evaporative systems. In new construction, such issues can be designed into the building. Cross-linked polyethylene piping is also a possible solution, as it can be freeze-thaw cycled indefinitely without breaking (Burch 2005). The piping would thaw out long before the first demands for cooling in the spring.

Because DEVap switches energy consumption away from electricity to thermal (primarily natural gas), the availability of natural gas may present an impediment to implementing the technology. Other thermal sources, including renewable energy, may need further study. Solar may be able to provide 100% of the thermal energy required and warrants further study. The economics of a solar-driven air conditioner are improved when space and water heating are added to the loads met with the solar system. One study has shown that such "triple play" solar systems are close to parity with conventional energy on a cost of energy basis (Burch 2010). Low-cost collectors reducing costs three to five times relative to today's collectors are plausible, and would put solar-driven DEVap on a par with natural gas regeneration.

Installing the DEVap A/C will require running gas lines and small desiccant lines, which would not be significantly different from current practices. Thus, connecting components of the DEVap system is not likely to be a significant implementation risk.

Water draining issues are not likely to cause implementation problems, as standard A/C also requires water drainage. The DEVap device will direct all excess water to the normal drain.

DEVap will have a different O&M profile that will require new procedures. Such new requirements may place restrictions on where or how DEVap is installed. For instance, the DEVap A/C will have two air filters instead of one. This may require that the O&M personnel access the attic for one filter, and the other will be located indoors as usual. O&M changes to retrofit buildings are likely where issues arise. In new construction, these issues can be more readily addressed during building design.

Desiccant systems primarily use plastics in the design and could pose issues to satisfy regional codes. Many similar products, namely the DAIS ConsERV ventilator, also use significant amounts of plastic and are listed with Underwriters Laboratories. This is possible through a novel way to stop flames and smoke from reaching the plastic components. Similar designs can be used in the DEVap A/C, but this topic is largely unexplored.

Table 4-2 Market and Implementation Risk Matrix for DEVap A/C

Building Type	New	Retrofit
Residential	1. Building design to accommodate new type of ductwork 2. Potential water line freezing 3. Natural gas availability (southeastern United States) 4. Code compliance with plastic construction	1. Ducting modification and addition 2. Potential water line freezing 3. Integration with air handler and furnace 4. Natural gas availability (southeastern United States) 5. Changes to O&M 6. Code compliance with plastic construction
Commercial	1. Building design to accommodate new type of ductwork 2. New RTU packaging. 3. Natural gas availability (southeastern United States) 4. Code compliance with plastic construction	1. Ducting modification and addition (central air handler) 2. Integration with air handler and furnace or RTU 3. Natural gas availability (southeastern United States) 4. Changes to O&M 5. Code compliance with plastic construction

4.3 Risk to Expected Benefits

DEVap, as with any new technology, has unknown consequences in the marketplace. Good design and engineering can result in a product that performs well; however, poor implementation of a good design can affect performance. One such effect is poor commissioning that results in poor energy and comfort performance. Although this risk can be mitigated with good design, it cannot be eliminated. This risk is already inherent in current A/C, as seen by numerous accounts of faulty RTU installations in commercial buildings (economizer and damper faults). However, typical faults such as a damper stuck open are less likely to be issues with a DEVap A/C. For DEVap to provide the necessary cooling, dampers must operate correctly. Thus, a DEVap air conditioner manufacturer has an incentive to properly install damper mechanisms. However, with any new technology, there will be new, as yet unidentified, ways to "mess it up." These issues will become apparent once field prototypes are deployed.

5.0 Future Work

5.1 Laboratory DEVap A/C Demonstration

During FY 2011, NREL will work on a 1-ton "proof-of-performance" prototype in which we will build the DEVap device. The unit will be performance tested when it is connected in the NREL HVAC laboratory. NREL will obtain a complete performance map of the system to create a correlated performance model. This model will then be used in the building simulation models already developed to update results and make them available.

5.2 Regeneration Improvements

We have worked on high-efficiency, thermally powered desiccant regeneration. Other options for desiccant regeneration, which use electricity or modified CHP, are available. These energy sources can be used to run a vapor compression distillation regenerator that runs a "reverse Rankine" or refrigeration cycle with water vapor at modest pressures (about 6 psia). Such a system has already been analyzed and proposed as a project by AILR (2002). It vastly improves the latent COP of the regeneration process and thus the COP of a DEVap A/C.

Because DEVap uses LiCl concentrations of 28%–38%, the resulting latent COP of regeneration could potentially be 2.2–3.5 using natural gas. This would reduce the source energy use of a DEVap A/C by more than 50%. Although this technology has not yet been proposed as a DOE project, it is introduced here to highlight that the DEVap technology is still in its infancy, and there is still significant upward potential.

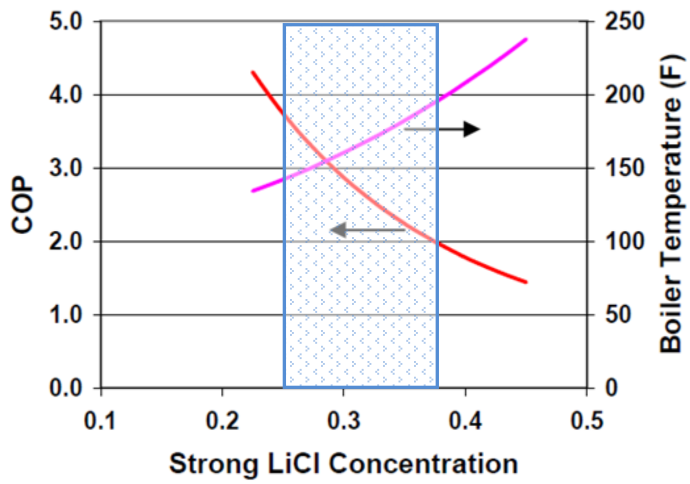


Figure 5-1 Vapor compression distillation regenerator latent COP using natural gas (AILR 2002)
(shaded area shows operating range of the DEVap A/C)

5.3 Solar Thermal Integration

The solar thermal option has been investigated to a small degree. We are working with AILR to increase the integration between LDACs and solar thermal collector with the clear goals of improving system performance and lowering costs. We are developing designs that greatly reduce the cost of evacuated tubes and deliver steam to the regeneration process. These "steam-generating" collectors remove much of the copper and copper/metal seals in today's collectors and can use the lower cost Dewar style tubes. Future work includes a double-effect solar regenerator where desiccant can be boiled to release water vapor in the tubes and the steam heat used in the scavenging regenerator.

6.0 Conclusions

6.1 Residential Performance Comparison

Analyses of the new and retrofit residential benchmark buildings using DX and DEVap A/C generally show a clear advantage for the DEVap A/C. The DEVap A/C is designed around a single typical Gulf Coast condition (Houston). This is a relatively good design condition for producing a 3-ton DEVap system that has the same capacity as a 3-ton DX A/C system. The control scheme for the DEVap still requires optimization, however. In all cases, the DEVap A/C provided more than necessary humidity control. Allowing indoor humidity to rise above 50% RH would have significant energy improvement. In the summertime, when sensible loads are high (high SHR), the DEVap A/C continuously maintained the space at less than 50% RH. This level of humidity control can be reduced to create higher energy savings. However, this level of humidity control may be advantageous from the perspective of building and occupant health, although health science has not yet addressed the health impacts of such small changes in indoor humidity.

In general, new construction with the added ventilation and tighter envelope resulted in the conditions where DEVap performed better, because SHR decreased (which DEVap was designed to accommodate). The new construction is taken to be 2010 IECC building code, which is not as tight as future home designs (Building America 50% homes). Thus, we expect the DEVap A/C to increase its advantage in tighter homes, or as retrofit homes become tighter and better insulated. Furthermore, as ventilation requirements increase, the DEVap advantage increases. DEVap already over ventilates any residential building space under high sensible load conditions (summer days); however, energy credit is not given for this. For DX, there would be an imposed higher load that would result in higher energy use.

Regional water use (site + off-site) for the DEVap system was 2.0–3.0 gal/ton·h for new and retrofit cases, which we argue is similar to the regional impact that DX A/C imposes (off-site only). Proper comparison must include off-site water use (at the utilities' electricity generation stations). The DEVap A/C does increase site water use, but in general, the regional impact is small, especially compared to sectors other than electricity generation (see Figure 4-1).

6.2 Commercial Performance Comparison

Commercial implementation of the DEVap A/C shows a higher energy savings level than do the residential cases, primarily because of the higher cooling loads of commercial buildings and their increased ventilation requirements. The small office building benchmark is taken as a "middle of the road" building type for commercial buildings. It also has minimal ventilation requirements as a percentage of cooling load. For buildings with higher ventilation rates (e.g., commercial retail space), the relative energy savings for the DEVap A/C will increase. DEVap A/C is conservatively estimated because the load-following model is used.

DEVap regional water use is expected to be 2.0–3.0 gal/ton·h for commercial buildings. Similar to the residential case, the DEVap A/C has minimal impact on regional water use compared to DX A/C.

6.3 Residential Cost Comparison

The initial cost estimates for the DEVap A/C are preliminary and based on market entry with the design we have today. Improvements and design for manufacturing and innovation have not been considered. These factors could have significant impact on initial cost. The fundamental concept is simpler, perhaps presaging lower costs for DEVap than for conventional A/C once manufacturing volumes are comparable. Furthermore, the cost estimate does not include the possibility of utility incentives that may be offered because of the potentially high value that the DEVap A/C provides for the utility companies. Their incentive would be based on DEVap A/C's ability to reduce peak electricity demand and thus stabilize the electricity grid. The ability to store cooling energy via desiccant could also be a major consideration. And natural gas prices may not be representative of future prices, especially if its use increases significantly during the summer in residential applications.

In most cases, the cost comparison using the best available data today shows that the DEVap air conditioner is competitive with DX A/C. Retrofit cost is higher on an annualized basis, because, the cost of equipment is amortized into a 5-year home equity loan rather than a 30-year mortgage.

6.4 Commercial Cost Comparison

The upfront cost of a DEVap A/C has a significant return on investment compared to best available (SEER 16) DX A/C. The higher cooling load over residential construction makes the cost savings from the reduced energy consumption a much larger factor. Again, initial cost estimates are based on the best available knowledge for a DEVap A/C and do not include incentives and future design improvements.

6.5 Risk Assessment

The risks have been laid out for technology and market/implementation risks. As with any novel and disruptive technology, the risks are broad and somewhat unknown. Reliability and longevity are the greatest risks to a successful technology, and they must meet or surpass those of today's A/C to have any real market penetration. Furthermore, the increase in site water use may be a technical problem in some places where delivery of site water is scrutinized or of extreme value. Regionally, the water impact of the DEVap A/C compared to DX A/C is minimal.

Most market risks for the DEVap A/C result different system operations. Additional ductwork and system design may be difficult to handle in retrofit applications. New construction can accommodate the different system designs better. The O&M profile of the DEVap will also change and may impose additional burdens to a retrofit application.

Implementation of the DEVap A/C may have unforeseen consequences. Mechanisms that could affect the performance of the DEVap A/C include improper installation and commissioning. An air conditioner that is improperly installed may work counter to the design intent, and not control temperature and humidity efficiently. These risks can be managed through education.

The availability of a thermal source such as natural gas is an issue in some instances, mostly in the southeastern United States and some residential locations. Other sources of energy to regenerate the desiccant would have to be explored. Solar thermal energy could supply much of the thermal energy required in these regions, particularly when integrated in a complete thermal system meeting space and water heating needs. Ongoing development of low-cost, evacuated tube, steam generating collectors will help the economics of solar driven A/C.

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Appendix A Data Tables

A.1 Detailed Specifications for Retrofit Residential Building

	Chicago	Phoenix	San Francisco	Tampa	Atlanta	Boston	Houston	Washington, DC
Foundation type	Basement	Slab-on-grade	Crawlspace	Slab-on-grade	Crawlspace	Basement	Slab-on-grade	Basement
Detached frame wall U	0.052	0.092	0.082	0.092	0.082	0.058	0.092	0.070
Ceiling U	0.027	0.044	0.037	0.048	0.037	0.028	0.043	0.037
Floor U	0.052	0.071	0.052	0.071	0.052	0.052	0.071	0.052
Underground wall U	0.103	n/a	0.135	n/a	0.135	0.106	n/a	0.126
Min R slab unheated	5.350	none	n/a	n/a	n/a	4.760	n/a	4.000
Slab insulation depth (ft)	2.000	none	n/a	n/a	n/a	2.000	n/a	2.000
Window U	0.236	0.277	0.277	0.960	0.277	0.277	0.277	0.277
Window SHGC	0.333	0.721	0.648	0.866	0.721	0.648	0.721	0.648

A.2 Detailed Specifications for New Residential Building

	Chicago	Phoenix	San Francisco	Tampa	Atlanta	Boston	Houston	Washington, DC
Foundation type	Basement	Slab-on-grade	Crawlspace	Slab-on-grade	Crawlspace	Basement	Slab-on-grade	Basement
Detached frame wall U	0.052	0.070	0.070	0.070	0.070	0.052	0.070	0.070
Ceiling U	0.026	0.034	0.034	0.034	0.034	0.026	0.034	0.026
Floor U	0.050	0.071	0.050	0.071	0.050	0.050	0.071	0.050
Underground wall U	0.089	n/a	0.089	n/a	0.089	0.089	n/a	0.089
Min R slab unheated	10.000	n/a	n/a	n/a	n/a	10.000	n/a	10.000
Slab insulation depth (ft)	2.000	n/a	n/a	n/a	n/a	2.000	n/a	2.000
Window U	0.294	0.665	0.665	0.665	0.665	0.294	0.665	0.294
Window SHGC	0.314	0.311	0.311	0.311	0.311	0.314	0.311	0.314

Actual U-values in Btu/(h·ft^2·°F)

A.3 Energy Performance – New Residential

Site	Phoenix		San Francisco		Washington, DC	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Cooling fan (kWh)	1425.09	1368.49	169.29	75.05	976.79	817.92
Mechanical ventilation (kWh)	145.22	240.9	235.36	240.9	181.20	240.9
Dehumidifier (kWh)	0	0.00	0	470.09	0	868.38
A/C (compressor) (kWh)	0	5159.07	0	252.55	0	2854.76
DEVap auxiliary (kWh)	96.96	0	15.85	0	91.99	0
Total electric (kWh)	1667	6768	421	1039	1250	4782
Regenerator (kWh)	1977	0	672	0	5710	0
Source	**Phoenix**		**San Francisco**		**Washington, DC**	
	DEVap	**DX A/C**	**DEVap**	**DX A/C**	**DEVap**	**DX A/C**
Electric (kWh)	5610	22776	1415	3495	4206	16091
Thermal, cooling (kWh)	2159	0	734	0	6236	0
Total (kWh)	7769	22776	2149	3495	10442	16091

Site	Tampa		Atlanta		Chicago	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Cooling fan (kWh)	2278.68	1891.83	1199.86	1009.19	619	543.09
Mechanical ventilation (kWh)	105.62	240.9	169.29	240.9	200	240.9
Dehumidifier (kWh)	0	2276.59	0	975.31	0	640.16
A/C (compressor) (kWh)	0	6583.69	0	3496.18	0	1872.29
DEVap auxiliary (kWh)	221.32	0	107.10	0	60	0
Total electric (kWh)	2606	10993	1476	5722	880	3296
Regenerator (kWh)	16177	0	6422	0	3280	0
Source	**Tampa**		**Atlanta**		**Chicago**	
	DEVap	**DX A/C**	**DEVap**	**DX A/C**	**DEVap**	**DX A/C**
Electric (kWh)	8768	36991	4968	19253	2960	11093
Thermal, cooling (kWh)	17665	0	7013	0	3582	0
Total (kWh)	26433	36991	11981	19253	6542	11093

Site	Boston		Houston	
	DEVap	DX A/C	DEVap	DX A/C
Cooling fan (kWh)	524.77	439.08	1917	1604
Mechanical ventilation (kWh)	207.47	240.9	128	241
Dehumidifier (kWh)	0	603.92	0	1996
A/C (compressor) (kWh)	0	1513.30	0	5636
DEVap auxiliary (kWh)	51.17	0	184	0
Total electric (kWh)	783	2797	2229	9477
Regenerator (kWh)	2672	0	13361	0
Source	**Boston**		**Houston**	
	DEVap	**DX A/C**	**DEVap**	**DX A/C**
Electric (kWh)	2636	9413	7502	31889
Thermal, cooling (kWh)	2918	0	14590	0
Total (kWh)	5554	9413	22092	31889

Water Evaporation	Phoenix		San Francisco		Washington, DC	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Site gal/ton·h	2.65		2.19		2.21	
Off-site gal/ton·h	0.26	1.31	1.38	6.26	0.40	1.53

Water Evaporation	Tampa		Atlanta		Chicago	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Site gal/ton·h	2.20		2.06		2.00	
Off-site gal/ton·h	0.36	1.52	0.36	1.47	0.40	1.60

Water Evaporation	Boston		Houston	
	DEVap	DX A/C	DEVap	DX A/C
Site gal/ton·h	2.07		2.23	
Off-site gal/ton·h	0.45	1.71	0.37	1.56

A.4 Energy Performance – Retrofit Residential

Energy Site	Phoenix		San Francisco		Washington, DC	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Cooling fan (kWh)	1696.80	1617.07	321.47	374.41	1099.75	909.13
Mechanical ventilation (kWh)	0.00	0	0.00	0	0.00	0
Dehumidifier (kWh)	0	0.00	0	224.63	0	319.08
A/C (compressor) (kWh)	0	6025.34	0	1255.25	0	3150.15
DEVap auxiliary (kWh)	106.69	0	34.71	0	100.01	0
Total electric (kWh)	1803	7642	356	1854	1200	4378
Regenerator (kWh)	2135	0	670	0	6188	0
Energy Source	**Phoenix**		**SF**		**DC**	
	DEVap	**DX A/C**	**DEVap**	**DX A/C**	**DEVap**	**DX A/C**
Electric (kWh)	6069	25717	1199	6240	4037	14733
Thermal, cooling (kWh)	2332	0	732	0	6757	0
Total (kWh)	8401	25717	1930	6240	10794	14733

Energy Site	Tampa		Atlanta		Chicago	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Cooling fan (kWh)	2904.41	1965.64	1620.76	1031.08	611	490.76
Mechanical ventilation (kWh)	0.00	0	0.00	0	0	0
Dehumidifier (kWh)	0	588.36	0	243.69	0	395.88
A/C (compressor) (kWh)	0	6791.90	0	5028.52	0	1690.45
DEVap auxiliary (kWh)	239.26	0	118.49	0	60	0
Total electric (kWh)	3144	9346	1739	6303	671	2577
Regenerator (kWh)	18731	0	7520	0	3118	0
Energy Source	**Tampa**		**Atlanta**		**Chicago**	
	DEVap	**DX A/C**	**DEVap**	**DX A/C**	**DEVap**	**DX A/C**
Electric (kWh)	10578	31449	5853	21211	2257	8672
Thermal, cooling (kWh)	20454	0	8212	0	3405	0
Total (kWh)	31032	31449	14064	21211	5662	8672

Energy Site	Boston		Houston	
	DEVap	DX A/C	DEVap	DX A/C
Cooling fan (kWh)	620.07	557.90	2405	1262
Mechanical ventilation (kWh)	0.00	0	0	0
Dehumidifier (kWh)	0	263.14	0	406
A/C (compressor) (kWh)	0	1907.57	0	6270
DEVap auxiliary (kWh)	58.10	0	197	0
Total electric (kWh)	678	2729	2602	7938
Regenerator (kWh)	2846	0	14920	0
Energy Source	**Boston**		**Houston**	
	DEVap	**DX A/C**	**DEVap**	**DX A/C**
Electric (kWh)	2282	9182	8754	26713
Thermal, cooling (kWh)	3108	0	16292	0
Total (kWh)	5390	9182	25046	26713

Water Evaporation	Phoenix		SF		DC	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Site gal/ton·h	2.75		1.89		2.43	
Off-site gal/ton·h	0.25	1.29	0.29	1.48	0.35	1.28

Water Evaporation	Tampa		Atlanta		Chicago	
	DEVap	DX A/C	DEVap	DX A/C	DEVap	DX A/C
Site gal/ton·h	2.67		2.36		2.21	
Off-site gal/ton·h	0.41	1.22	0.34	1.25	0.34	1.48

Water Evaporation	Boston		Houston	
	DEVap	DX A/C	DEVap	DX A/C
Site gal/ton·h	2.16		2.69	
Off-site gal/ton·h	0.32	1.36	0.41	1.26

A.5 Economics – New Residential

Cost	Phoenix		SF		DC		Tampa	
Utilities	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
Electric	$ 181	$ 922	$ 59	$ 145	$ 180	$ 715	$ 266	$ 1,219
Gas	$ 96	$ -	$ 33	$ -	$ 265	$ -	$ 613	$ -
Water	$ 67	$ -	$ 3	$ -	$ 28	$ -	$ 63	$ -
Total	$ 344	$ 922	$ 95	$ 145	$ 473	$ 715	$ 942	$ 1,219

Levelized cost per tonh	Phoenix		SF		DC		Tampa	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 0.095	$ 0.062	$ 1.693	$ 1.949	$ 0.165	$ 0.104	$ 0.072	$ 0.045
Electric	$ 0.032	$ 0.199	$ 0.216	$ 0.983	$ 0.064	$ 0.257	$ 0.042	$ 0.189
Gas	$ 0.017	$ -	$ 0.122	$ -	$ 0.095	$ -	$ 0.096	$ -
Water	$ 0.012	$ -	$ 0.010	$ -	$ 0.010	$ -	$ 0.010	$ -
Total	$ 0.157	$ 0.261	$ 2.041	$ 2.932	$ 0.334	$ 0.360	$ 0.219	$ 0.234

Levelized cost per year	Phoenix		SF		DC		Tampa	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 600	$ 320	$ 517	$ 323	$ 517	$ 323	$ 517	$ 323
Electric	$ 203	$ 1,034	$ 66	$ 163	$ 202	$ 801	$ 298	$ 1,367
Gas	$ 108	$ -	$ 37	$ -	$ 297	$ -	$ 687	$ -
Gas_high	$ 162	$ -	$ 56	$ -	$ 445	$ -	$ 1,031	$ -
Water	$ 75	$ -	$ 3	$ -	$ 31	$ -	$ 71	$ -
Total	$ 986	$ 1,354	$ 624	$ 486	$ 1,047	$ 1,124	$ 1,573	$ 1,690
Total_high	$ 1,040	$ -	$ 642	$ -	$ 1,196	$ -	$ 1,917	$ -

Cost	Atlanta		Chicago		Boston		Houston	
Utilities	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
Electric	$ 152	$ 663	$ 96	$ 363	$ 108	$ 390	$ 245	$ 1,042
Gas	$ 178	$ -	$ 72	$ -	$ 127	$ -	$ 340	$ -
Water	$ 34	$ -	$ 18	$ -	$ 14	$ -	$ 54	$ -
Total	$ 363	$ 663	$ 185	$ 363	$ 249	$ 390	$ 640	$ 1,042

Levelized cost per tonh	Atlanta		Chicago		Boston		Houston	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 0.127	$ 0.083	$ 0.237	$ 0.157	$ 0.300	$ 0.197	$ 0.085	$ 0.053
Electric	$ 0.042	$ 0.191	$ 0.049	$ 0.197	$ 0.070	$ 0.267	$ 0.045	$ 0.192
Gas	$ 0.049	$ -	$ 0.037	$ -	$ 0.083	$ -	$ 0.063	$ -
Water	$ 0.009	$ -	$ 0.009	$ -	$ 0.009	$ -	$ 0.010	$ -
Total	$ 0.227	$ 0.275	$ 0.332	$ 0.354	$ 0.462	$ 0.464	$ 0.203	$ 0.246

Levelized cost per year	Atlanta		Chicago		Boston		Houston	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 517	$ 323	$ 517	$ 323	$ 517	$ 323	$ 517	$ 323
Electric	$ 170	$ 744	$ 107	$ 407	$ 121	$ 437	$ 275	$ 1,169
Gas	$ 199	$ -	$ 81	$ -	$ 143	$ -	$ 382	$ -
Gas_high	$ 299	$ -	$ 121	$ -	$ 214	$ -	$ 572	$ -
Water	$ 38	$ -	$ 20	$ -	$ 16	$ -	$ 61	$ -
Total	$ 924	$ 1,067	$ 725	$ 730	$ 797	$ 760	$ 1,234	$ 1,492
Total_high	$ 1,024	$ -	$ 765	$ -	$ 868	$ -	$ 1,425	$ -

A.6 Economics – Retrofit Residential

Cost	Phoenix		SF		DC		Tampa	
Utilities	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
Electric	$ 196	$ 1,057	$ 50	$ 293	$ 173	$ 689	$ 321	$ 1,059
Gas	$ 104	$ -	$ 33	$ -	$ 287	$ -	$ 710	$ -
Water	$ 79	$ -	$ 9	$ -	$ 33	$ -	$ 81	$ -
Total	$ 379	$ 1,057	$ 92	$ 293	$ 493	$ 689	$ 1,112	$ 1,059

Levelized cost per tonh	Phoenix		SF		DC		Tampa	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 0.138	$ 0.086	$ 0.700	$ 0.376	$ 0.250	$ 0.148	$ 0.112	$ 0.067
Electric	$ 0.031	$ 0.194	$ 0.046	$ 0.232	$ 0.057	$ 0.215	$ 0.047	$ 0.150
Gas	$ 0.016	$ -	$ 0.031	$ -	$ 0.094	$ -	$ 0.104	$ -
Water	$ 0.012	$ -	$ 0.008	$ -	$ 0.011	$ -	$ 0.012	$ -
Total	$ 0.197	$ 0.280	$ 0.785	$ 0.608	$ 0.412	$ 0.363	$ 0.275	$ 0.218

Levelized cost per year	Phoenix		SF		DC		Tampa	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 988	$ 527	$ 851	$ 532	$ 851	$ 532	$ 851	$ 532
Electric	$ 220	$ 1,185	$ 56	$ 329	$ 194	$ 773	$ 359	$ 1,187
Gas	$ 117	$ -	$ 37	$ -	$ 322	$ -	$ 796	$ -
Gas_high	$ 175	$ -	$ 56	$ -	$ 483	$ -	$ 1,193	$ -
Water	$ 88	$ -	$ 10	$ -	$ 37	$ -	$ 91	$ -
Total	$ 1,412	$ 1,712	$ 955	$ 861	$ 1,405	$ 1,305	$ 2,098	$ 1,719
Total_high	$ 1,471	$ -	$ 973	$ -	$ 1,565	$ -	$ 2,495	$ -

Cost	Atlanta		Chicago		Boston		Houston	
Utilities	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
Electric	$ 179	$ 750	$ 74	$ 310	$ 93	$ 414	$ 286	$ 900
Gas	$ 208	$ -	$ 68	$ -	$ 136	$ -	$ 380	$ -
Water	$ 48	$ -	$ 18	$ -	$ 18	$ -	$ 68	$ -
Total	$ 435	$ 750	$ 160	$ 310	$ 247	$ 414	$ 735	$ 900

Levelized cost per tonh	Atlanta		Chicago		Boston		Houston	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 0.193	$ 0.127	$ 0.428	$ 0.279	$ 0.402	$ 0.243	$ 0.154	$ 0.102
Electric	$ 0.039	$ 0.161	$ 0.042	$ 0.182	$ 0.049	$ 0.212	$ 0.050	$ 0.155
Gas	$ 0.046	$ -	$ 0.039	$ -	$ 0.072	$ -	$ 0.067	$ -
Water	$ 0.011	$ -	$ 0.010	$ -	$ 0.010	$ -	$ 0.012	$ -
Total	$ 0.289	$ 0.288	$ 0.518	$ 0.461	$ 0.533	$ 0.455	$ 0.284	$ 0.258

Levelized cost per year	Atlanta		Chicago		Boston		Houston	
	DEVap	AC	DEVap	AC	DEVap	AC	DEVap	AC
capital	$ 979	$ 664	$ 851	$ 532	$ 851	$ 532	$ 979	$ 664
Electric	$ 200	$ 840	$ 83	$ 348	$ 105	$ 464	$ 321	$ 1,009
Gas	$ 234	$ -	$ 77	$ -	$ 152	$ -	$ 426	$ -
Gas_high	$ 350	$ -	$ 115	$ -	$ 228	$ -	$ 639	$ -
Water	$ 54	$ -	$ 20	$ -	$ 21	$ -	$ 77	$ -
Total	$ 1,466	$ 1,504	$ 1,031	$ 880	$ 1,129	$ 996	$ 1,802	$ 1,672
Total_high	$ 1,583	$ -	$ 1,069	$ -	$ 1,205	$ -	$ 2,015	$ -

A.7 Cost Estimates

A/C Markups	Markup				
1 - Manufacturer	1.23				
2 - Distributer	1.49				
3 - Retailer	1.28				
4 - Retail cost	1.00				
DEVap Cost Estimate	**Cost Estimate**	**Price Level**	**Markup**	**Retail Cost**	
$/ton, core	$477	1	2.35	$1,119	Coolerado estimate
$/kg LiCl	$18	4	1.00	$18	$/kg anhydrous
Total fixed costs				$3,894	
2-stage regenerator	$900	1	2.35	$2,111	AILR Estimate - e-mail correspondence
Tank	$50	4	1.00	$50	10-15 gal tank
Supply/mixed-air fan	$180	4	1.00	$180	Based on AILR estimate
Exhaust fan	$150	4	1.00	$150	Based on AILR estimate
Electronics	$400	4	1.00	$400	Estimate based on Coolerado
Packaging	$600	3	1.28	$768	Estimate based on Coolerado distribution cost
2 desiccant pumps	$60	4	1.00	$60	Pumps, 1 gpm each
Solenoid	$75	4	1.00	$75	Retail estimate
Filters	$25	4	1.00	$25	Retail estimate
Pressure regulator	$75	4	1.00	$75	Retail estimate
System Size – 3 ton				3.0	*Tons*
LiCl storage	7.3	kg/tonh_L		0.6	*0.5 hours + 20% for pipe volumes*
	13.1	kg		$231	
System retail cost				$7,484	*3-ton system cost with 30-min storage*
Mark-up level to estimate cost		4		1.00	
Total system cost at level shown above				**$7,484**	
System Size – 4 ton				4.0	*Tons*
LiCl storage	7.3	kg/ton·h L		0.6	*0.5 hours + 20% for pipe volumes*
	17.5	kg		$308	
System retail cost				$680	*4-ton system cost with 30-min storage*
Mark-up level to estimate cost		4		1.00	
Total system cost at level shown above				**$8,680**	
System Size – Commercial 10-ton				10.0	*Tons*
LiCl storage	7.3	kg/ton·h_L		0.6	*0.5 hours + 20% for pipe volumes*
	43.8	kg		$771	
System retail cost				$0,461	*10-ton system cost with 30-min storage*
Markup level to estimate cost		4		1.00	
Total system cost at level shown above				**$20,461**	***Estimates 3X regenerator cost and 2X fan costs***

A.8 Utility Prices From Utility Tariffs for 2010

	Electric ($/kWh)			Natural gas ($/therm[1])		
	Electric utility	**Summer**	**Winter**	**Gas utility**	**Summer**	**Winter**
Atlanta	Georgia Power			Gas South	$0.81	$0.81
< 650 kWh		$0.103	$0.103			
> 650 kWh		$0.140	$0.095			
Boston	National Grid			Yankee Gas	$1.40	$1.24
< 600 kWh		$0.137	$0.137			
> 600 kWh		$0.144	$0.144			
Chicago	ComEd	$0.111	$0.101	People's Gas	$0.64	$0.72
Houston	CenterPoint	$0.110	$0.110	CenterPoint	$0.75	$0.75
Phoenix	AZ Public Service			Southwest Gas	$1.43	$1.43
< 400 kWh		$0.109	$0.106			
400 - 800 kWh		$0.155				
> 800 kWh		$0.183				
San Francisco	PG&E			PG&E	$1.45	$1.45
< 300 kWh		$0.123	$0.123			
300-390 kWh		$0.139	$0.139			
390-600 kWh		$0.300	$0.300			
> 600 kWh		$0.412	$0.412			
Tampa	Tampa Electric			People's Gas	$1.10	$1.30
< 1000 kWh		$0.102	$0.102			
> 1000 kWh		$0.123	$0.123			
Washington, D.C.	Potomoc Electric			Washington Gas	$1.36	$1.36
< 400 kWh		$0.144				
> 400 kWh		$0.157				

[1] 1 therm = 29.3 kWh

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14. ABSTRACT *(Maximum 200 Words)*
NREL has developed the novel concept of a desiccant enhanced evaporative air conditioner (DEVap) with the objective of combining the benefits of liquid desiccant and evaporative cooling technologies into an innovative "cooling core." Liquid desiccant technologies have extraordinary dehumidification potential, but require an efficient cooling sink. DEVap's thermodynamic potential overcomes many shortcomings of standard refrigeration-based direct expansion cooling. DEVap decouples cooling and dehumidification performance, which results in independent temperature and humidity control. The energy input is largely switched away from electricity to low-grade thermal energy that can be sourced from fuels such as natural gas, waste heat, solar, or biofuels.

15. SUBJECT TERMS
desiccant enhanced evaporative air conditioner; devap; liquid dessicant; evaporative cooling; dehumidification

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