Outside of the Box: Climate Appropriate Hybrid Air Conditioning as a Paradigm Shift for Commercial Rooftop Packaged Units

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ABSTRACT

Conventional air conditioning technology has reached 'max-tech'. Fundamentally, vapor compression alone cannot provide the efficiency improvements needed for zero net energy commercial buildings, and cannot significantly reduce peak electrical demand associated with cooling.

Recently, several manufacturers have introduced hybrid cooling solutions that incorporate the advantages of multiple cooling components into variable speed, multi-mode, machines. These technologies may utilize indirect evaporative cooling, exhaust air heat recovery, desiccant dehumidification (or other components) in combination with vapor compression. Such hybrid systems are climate appropriate solutions that recognize how cooling needs and efficiency opportunities are different in each region.

This study presents a synthesis of findings from several laboratory tests, and the successes and failures from more than 30 monitored installations of different hybrid air conditioning solutions. We find that these strategies can reduce full load demand from cooling and ventilation by more than 40%, and deliver annual savings of 65% or more.

Hybrid solutions are making significant market inroads (including broad regional adoption by at least one major retailer). However, a number of barriers hinder quick uptake of these measures. Codes do not yet fully recognize these strategies, industry ratings do not properly represent their performance, building energy simulation tools do not allow practitioners to model these systems, and resources such as standards and application guidelines are limited.

We discuss pathways to navigate these challenges, and review a range of market transformation efforts under way including: codes and standards enhancements, design and management of commercial programs, and development of user-oriented simulation tools for hybrid commercial air conditioning.

Introduction

The U.S. is responsible for 19% of global annual primary energy consumption, 41% of this energy is consumed in the buildings sector, roughly half of which is used in commercial buildings. In aggregate, HVAC is responsible for 43% of the site energy consumption for commercial buildings in the U.S., about 37% of which is from electricity for cooling and ventilation (DOE 2012). Efficiency for HVAC systems has enormous potential to reduce our energy consumption, energy expenses, and environmental footprint.

The majority of cooling and ventilation in commercial buildings is provided by simple rooftop packaged units. For example almost 80% of the individual HVAC systems in California commercial building are rooftop units, serving approximately 65% of commercial floor area (CEC 2006). The efficiency of these systems has been very slow to improve, especially compared to modern advancements in other end use categories such as lighting, appliances, and electronics.

Although research and development into advanced vapor compression cycles is likely to bring incremental increases to the full load efficiency for packaged air conditioners (Park et al 2015), the expected energy and demand savings from these developments is small overall and not adequate to support a path toward zero energy buildings (Lord 2015).

Variable speed fans and compressors are making a slow but steady entrée to the rooftop unit market. Compared to ASHRAE 90.1-2013, these strategies can reduce annual energy consumption for cooling and ventilation by more than 50% (DOE 2014). However, the savings from variable speed rooftop units can be attributed mainly to reduced fan energy consumption during part load operating periods, and not to substantial improvements in full load cooling efficiency. During peak demand periods, variable speed air conditioners still operate at full capacity. Therefore, variable speed vapor compression systems do not alleviate summertime peak demand challenges.

Since rooftop packaged units have largely been designed as a one-size-fits-all solution that can operate reliably in any climate, these systems have traditionally overlooked significant efficiency opportunities in every climate. For example, in humid regions, dehumidification requirements can result in overcooling by vapor compression systems, which often introduces the need for reheat. Meanwhile, in dry climates, incidental dehumidification can increase the overall energy used for sensible cooling by roughly 20%.

There are more efficient cooling solutions than vapor compression. In this paper we discuss a range of market-available climate-appropriate hybrid cooling technologies that can provide cooling and ventilation with much less energy input than basic rooftop units. In general, hybrid solutions mix the function of various components and modes of operation to optimize performance as loads and climate conditions change. These strategies tend to integrate components in unique ways that provide mutual benefits which would not be realized by independent systems. For example, by combining exhaust air heat recovery with desiccant dehumidification a hybrid system can reduce sensible cooling loads, while simultaneously enhancing the performance of desiccant regeneration.

Some hybrid strategies are designed as retrofits to improve the performance of existing rooftop units, while others replace, or operate in parallel with, conventional rooftop units. Many hybrid strategies propose alternate building design approaches, such as separating ventilation from sensible room cooling by using a Dedicated Outdoor Air Supply (DOAS). For this paper, we restrict our scope to forced-air hybrid air conditioners for the light commercial building market. We include concepts like DOAS, but we do not explore the variety of solutions (eg. VRF systems) that use alternate methods for thermal distribution.

We present three different technologies in detail, and summarize the findings from numerous laboratory and field studies of their performance. We offer some single-point comparisons to manufacturer-stated performance of conventional air conditioners, but we do not present any controlled pre-post assessments of energy savings, or modeled annual savings estimates. While the climate-appropriate hybrid concept extends to all climates, the three solutions we explore here each leverage evaporative cooling and deliver greater energy savings in hotter and drier climates.

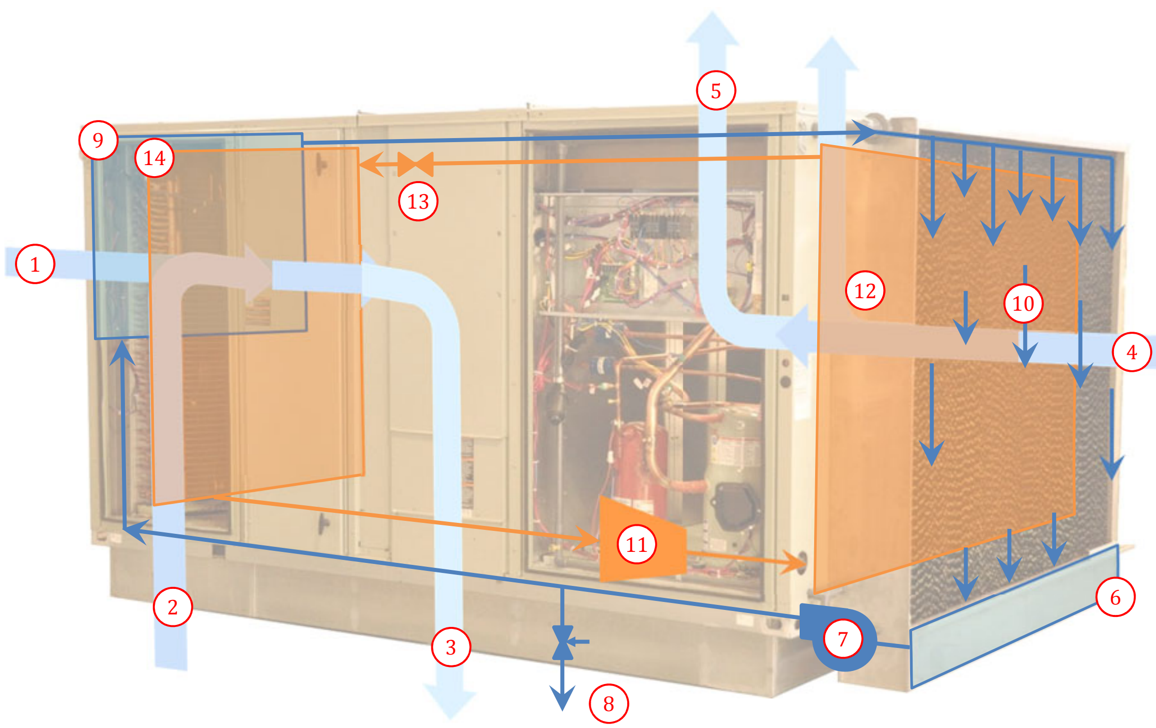
We discuss some of the technical advantages and disadvantages for each technology, and summarize the most pressing barriers to broader market adoption. Furthermore, we recommend some opportunities to alleviate challenges with market transformation, and we review a range of current efforts to develop tools and standards that could advance broader application of these strategies.

Three climate-appropriate hybrid cooling technologies

In the following sections, we describe three climate appropriate hybrid cooling strategies and summarize the technical findings from numerous laboratory tests and field installations conducted over the past seven years.

Dual evaporative pre-cooling

Dual-evaporative pre-cooling is designed as a wrapper addition for conventional air-cooled vapor-compression rooftop packaged units. The strategy uses evaporation from a wetted media to cool air at the condenser inlet, then circulates the evaporatively cooled sump water through an air-to-water heat exchanger located at the ventilation air inlet. The approach reduces the sensible load associated with cooling ventilation air - without adding moisture to the indoor environment - then also reduces the compressor power by reducing the condenser temperature and the lift required for heat rejection. The strategy simultaneously increases cooling capacity and reduces electric demand. Uniquely, the technology can be installed either as an in-situ retrofit for existing rooftop units, or as a factory-integrated component with new equipment. Figure 1 presents a schematic of the system.



1	*Outside Air (Ventilation)*	6	*Sump*	11	*Compressor(s)*
2	*Return Air*	7	*Circulation Pump*	12	*Condenser Coil*
3	*Supply Air*	8	*Bleed Drain*	13	*Expansion Valve*
4	*Outside Air (Condenser)*	9	*Water-to-Air Cooling Coil*	14	*Evaporator Coil*
5	*Condenser Exhaust Air*	10	*Direct Evaporative Cooler*	15	*Gas Heat*

Figure 1: Schematic for dual-evaporative pre-cooling

The technology has demonstrated excellent performance in two laboratory tests and more than twenty field installations observed over the past seven years. Most notably, laboratory testing indicates that energy intensity for full load cooling at peak conditions in hot dry climates is more than 40% lower than vapor compression alone. Savings decreases as outside temperature decreases, and below roughly 70°F - where integrated economizer operation begins to have significant value - dual-evaporative pre-cooling does not have beneficial effects (Woolley 2012, Woolley 2014, Modera 2014, Dichter 2016, Davis 2015).

The solution couples advantageously with variable speed rooftop units. Part capacity modes improve efficiency at lower ambient conditions and dual evaporative pre-cooling delivers substantial savings during warmer periods - and especially at peak. Figure 2 presents the cooling efficiency for this system in application. For comparison, manufacturer stated performance of a minimum efficiency rooftop unit in the same conditions would achieve sensible system COP=2.75 (EER=9.4) at 105ºF.

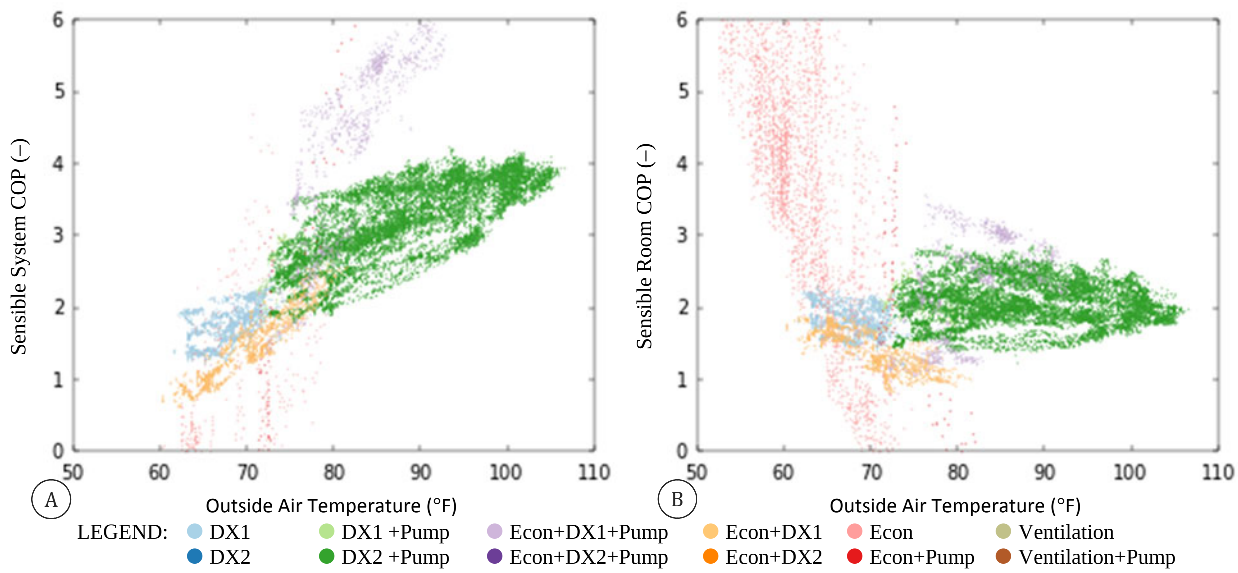


Figure 2. A) Sensible system efficiency and B) sensible room efficiency for hybrid rooftop unit with dual-evaporative pre-cooling for every minute of operation one month. Efficiency is calculated as the ratio of sensible cooling rate to electric power input.

In Figure 2, and throughout this paper, the "sensible system" cooling rate represents the net amount of thermal energy extracted by the machine between all inlets and outlets. The "sensible room" cooling capacity describes the net amount of thermal energy extracted from the room that is served by the air conditioner. These two numbers are different because these machines introduce and cool ventilation air, in addition to room air.

$$Q_{SENS\ SYSTEM} = m \cdot c_p \cdot (T_{ROOM} + OSAF \cdot (T_{OSA} - T_{ROOM}) - T_{SUPPLY})$$

$$Q_{SENS\ ROOM} = m \cdot c_p \cdot (T_{ROOM} - T_{SUPPLY})$$

Since the technology reduces energy use for cooling ventilation air, it is most appropriately applied on equipment that provides ventilation air. For buildings with many rooftop units it may be worthwhile to concentrate the ventilation supply through a few units that use dual-evaporative pre-cooling and control other units as needed for room cooling only. The performance advantages or disadvantages of such a grouping have not been measured, but the approach does reduce installed cost because it reduces the scope of retrofit.

One major advantage of this measure is that it requires little adaptation to current building designs and controls. The technology can bolt-on to existing air conditioners and uses a stand-alone controller that does not require integration with manufacturer-specific on-board electronics nor building energy management and control systems. This bypasses many opportunities for conflict and failure from scenarios where third parties unfamiliar with the technology would be critically involved in ensuring appropriate operation for the strategy.

The technology has recently been adopted at scale by a least one major big-box retailer for dozens of stores across the western U.S. In these recent installations, the technology has incorporated a stand-alone wireless controller that provides remote diagnostics and fault detection. The author is currently beginning a research project that will use this controller to provide dispatchable demand response capabilities and real time savings estimates for the technology.

In more than twenty installations observed, the most significant challenges encountered were related to improper service and seasonal management, as well as improper setup and control of baseline rooftop units to which the retrofit was added. For example, in one installation the water management system was not properly balanced - resulting in excessive water consumption (Modera 2014). In other installations, fan airflow and economizer operations for the existing units were not properly managed by equipment service contractors (Woolley 2014, Modera 2014). These issues with the baseline equipment reduced the value of dual evaporative pre-cooling. In one installation the evaporative components were disabled because field technicians were not familiar with the technology and blamed it for other problems with the systems (Dichter 2016). To address these challenges in recent installations, the manufacturer includes a long term service contract for every unit through which they provide remote monitoring, warranty assurance, and seasonal maintenance.

Stand-alone indirect evaporative cooling

There are many types of indirect evaporative coolers. The Western Cooling Efficiency Center's laboratory and field research has focused largely on equipment that uses a cascading airflow design which can provide supply air at or below the wet bulb temperature. One system we've tested typically achieves 100-120% wet bulb effectiveness at full airflow. Although water evaporation is the only cooling effect, no moisture is added to the conditioned zone because all evaporation occurs in a secondary air stream. These systems cool outside air, and do not cool recirculated air. Accordingly, they are used most effectively to supply ventilation airflow requirements. However, since they cool below the wet bulb temperature, these systems can provide a substantial amount of room cooling and it is energetically beneficial to size these systems larger than the minimum ventilation requirement.

Indirect evaporative heat exchangers can be integrated into custom built hybrid air handlers that also incorporate vapor compression, heating, or other elements; however current products are marketed as stand-alone packaged indirect evaporative-only systems with integrated fans and controls. These systems have demonstrated outstanding efficiency. At full load for peak conditions in hot dry climates, indirect evaporative cooling achieves EER>50. At part load in cooler periods and at partial airflow rates we have observed EER>85. It must be noted that these systems usually do not have enough cooling capacity to cover all room cooling requirements during peak load periods, except when applied in mild climates, or with higher-than-standard air change rates. The system sensible cooling capacity increases as outside temperature increases, where:

$$Q_{SENS\ SYS} = m \cdot c_p \cdot (T_{OUTSIDE} - T_{SUPPLY})$$

However, the room cooling capacity decreases somewhat as outside temperature increases because supply air temperature increases:

$$Q_{SENS\ ROOM} = m \cdot c_p \cdot (T_{ROOM} - T_{SUPPLY})$$

Despite this, in the installations we have observed these systems continue to provide positive room cooling during peak conditions, and although the capacity may not be enough to cover all room cooling loads at that time, the cooling they contribute is provided with excellent room cooling efficiency EER_{ROOM}>20. At part load conditions, these systems may provide all of the cooling required. Figure 3 illustrates the measured efficiency for one indirect evaporative system installed in Rocklin, California. Figure 3A plots the sensible system efficiency for every one minute increment that was observed over a three month period, while Figure 3B plots the sensible room efficiency for the same instances.

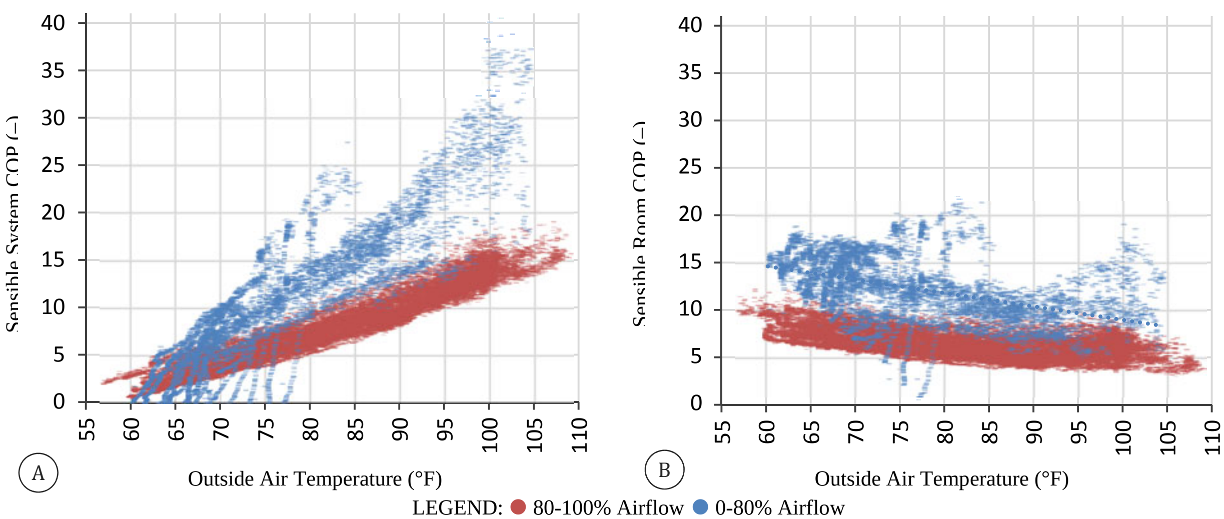


Figure 3. A) Sensible system efficiency and B) sensible room efficiency for indirect evaporative cooling for every minute of operation over a 3 month period.

The energy savings and peak demand reduction from indirect evaporative cooling depends largely on the ways that these systems are applied. Since it is usually necessary for indirect evaporative cooling to operate as one element in a whole building hybrid system with multiple modes of operation, the energy savings and peak demand reduction from indirect evaporative cooling depend largely on the ways that the system is applied. For example, indirect evaporative cooling could supply cooled air to the outside air inlet of a rooftop unit, or it could be installed in parallel with other rooftop units. It could be sized to provide only the minimum ventilation airflow, or it could be designed to address as much of the building cooling load as possible. Furthermore, there are numerous ways that each system configuration could be controlled.

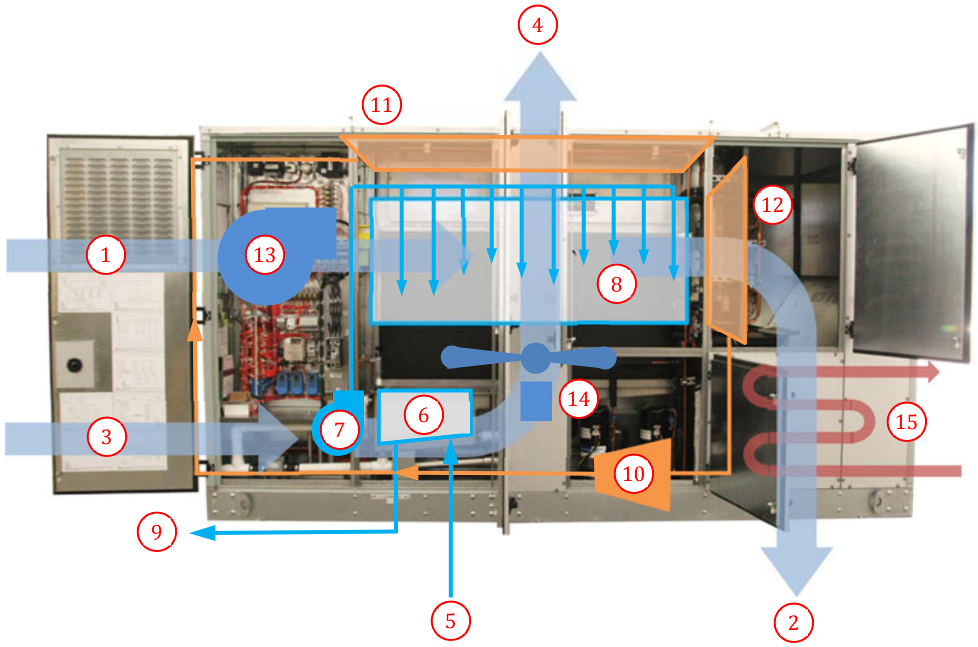
In a recent laboratory test that paired one such system to operate together with a conventional rooftop unit, we demonstrated that the solution could reduce peak electrical demand for cooling by 25% while reducing annual energy use for cooling by more than 65% (Harrington 2015). Through a field evaluation where indirect evaporative cooling was installed for a data center, we observed daily energy savings exceeding 75% on the hottest days (Mande, 2015). The Western Cooling Efficiency Center is currently conducting a study that will use indirect evaporative cooling as DOAS in buildings with variable refrigerant flow (VRF) systems in order to improve whole building energy performance, increase indoor air quality, and reduce the size and cost of VRF equipment.

Indirect evaporative cooling can achieve exceptional efficiency, but application of these systems in practice has not been without challenges. We have monitored and carefully studied more than 10 of these systems installed throughout California since 2009. In all instances, the equipment has performed well technically, with very few faults, but in several cases we have encountered issues with physical integration and proper control. The challenges have all been engineering and facilities management problems, and not issues with the equipment function per se.

The major issue is that practitioners on every level are not familiar with the implications of this strategy, and so don't know how to accommodate it properly within a whole building system. For example, in one installation the indirect evaporative cooler was not controlled as the priority cooling source within the building, and so didn’t carry as much cooling load as it should have (Woolley and Young 2015). In another installation, the airflow distribution scheme employed for the indirect evaporative cooler was such that the system did not properly address building loads and resulted in increased overall energy consumption (Mande 2015). In that case, the indirect evaporative system generated lots of cooling very efficiently, but it was not distributed appropriately because the installing contractor was not familiar with the implications of using a 100% outside air system instead of a recirculated cooling system.

Indirect evaporative + vapor compression hybrid DOAS

Some manufacturers have integrated indirect evaporative cooling into hybrid air handlers that also incorporate vapor compression cooling. In some cases these systems have also included desiccant dehumidification or heat recovery. The packaged hybrid design can be advantageous for a number of reasons, not least of which is the fact that doing so reduces the complication for engineers and installers associated with integration and control of multiple systems. Also, packaged hybrid systems can have technical performance benefits. For example, the cool but humid exhaust from an indirect evaporative cooler can be used to cool the vapor compression condenser. For hybrid air handlers that couple desiccant dehumidification with vapor compression cooling, the condenser exhaust can be used to regenerate the desiccant.



1	Outside Air (Primary Inlet)		6	Sump		11	DX Condenser	
2	Supply Air		7	Circulation Pump		12	DX Evaporator	
3	Outside Air (Secondary Inlet)		8	EPX (Indirect Evap. Heat Exch.)		13	Blower (Primary Air)	
4	Exhaust Air		9	Drain		14	Fan (Secondary Air)	
5	Water Supply		10	Compressors (2 parallel circuits)		15	Gas Heat	

Figure 4: Schematic of a packaged hybrid DOAS

Figure 4 presents the schematic for one hybrid air handler that we have studied extensively. This system is designed as a DOAS for hot dry climates - it uses a polymer-construction tube-in-flow heat exchanger as the indirect evaporative cooler, and can use return air as the secondary air stream. The utilization of return air allows the indirect evaporative cooler to achieve a higher capacity than when outside air is used as the secondary air stream, it also allows the dry heat exchanger to provide heat recovery for ventilation in the heating season. For periods when indirect evaporative cooling does not generate enough capacity, this hybrid also has two stages of vapor compression cooling. As discussed previously, exhaust from the indirect evaporative cooler is used to cool the condenser.

Laboratory and field studies of this system suggest that it could reduce whole building peak electrical demand from HVAC by more than 20% (Woolley and Davis 2014, Woolley and McMurry 2015). This is an outstanding opportunity particularly because it does not require replacement or upgrade for any existing rooftop units. At full capacity and peak cooling conditions ($T_{DB\ OSA}$=105°F, $T_{WB\ OSA}$= 73°F), this system generated ventilation supply air at 63°F with sensible system COP=5.3 (EER=18). A vapor compression DOAS in comparable circumstances would operate with sensible system COP 2.9 (EER=10) or less. Figure 5 plots the sensible system cooling efficiency, and sensible room cooling efficiency for the hybrid DOAS, observed in each mode of operation, over a one month period.

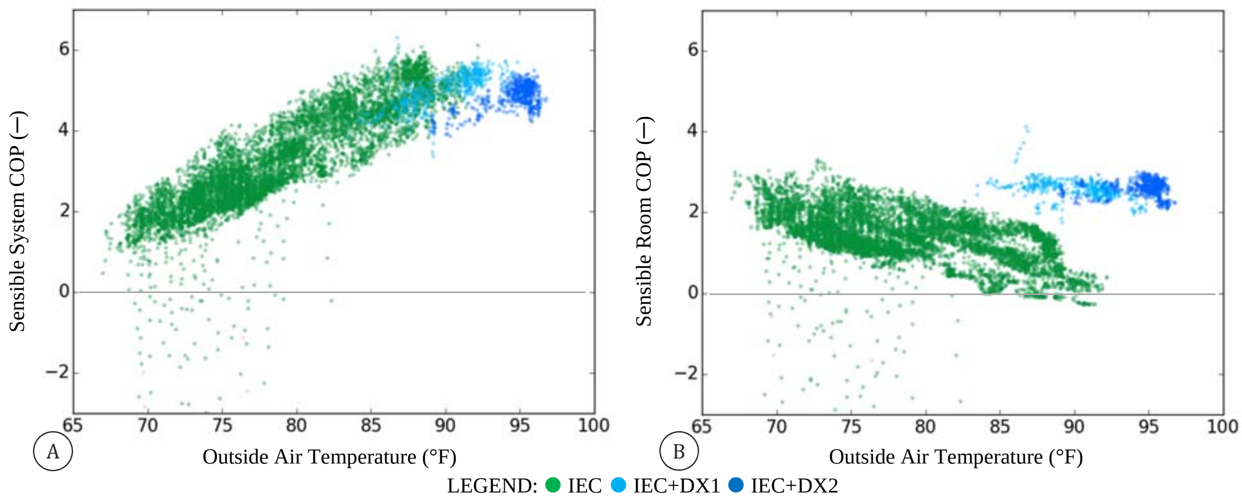


Figure 5. A) Sensible system efficiency and B) sensible room efficiency for the hybrid DOAS in each mode of operation for every minute of operation in one month.

Were this hybrid DOAS unit deployed together with variable speed rooftop units that use condenser pre-cooling, annual energy use for cooling and peak demand could be reduced even more substantially.

Despite the fact that this packaged hybrid configuration is less complex than a custom arrangement of stand-alone indirect evaporative coolers within a whole building system, the field study still encountered numerous challenges because practitioners on every level are not familiar with how to apply and operate this innovative equipment. At first, the unit was not cooling because the building energy management and control system had failed to stage its operation ahead of cooling from conventional rooftop units that serve the building. As a result, in effect, the efficient hybrid unit had been reduced to a fan only system that delivered unconditioned outside air to the building. Moreover, the installing team had overlooked the fact that existing rooftop units should no longer provide continuous ventilation in a DOAS ventilation scheme.

Later, we encountered problems with simultaneous heating and cooling because the building controls had been programmed in a way that attempted to use the indirect evaporative cooler for dehumidification. At multiple points in our field study of the system we observed that the unit faulted to OFF on an alarm because air filters had become overloaded. DOAS systems require more frequent filter changes because they treat more outside air, and service contractors and facilities managers are not familiar with appropriate servicing schedules. All of these observations speak to the need for more guidance, support, training, and expert review in commissioning to ensure that these innovative strategies are deployed effectively, and to build experience with the measures for practitioners at all levels.

Summary of findings

We have carefully mapped the characteristic performance for numerous climate-appropriate hybrid air conditioning systems. In all cases we have observed that these systems achieve excellent cooling efficiency compared to conventional vapor compression rooftop units. Importantly, these strategies provide dramatic electrical demand reduction at peak conditions, while many other cooling efficiency measures mainly achieve energy savings at part load conditions. The major findings for three types of systems studied are discussed in this paper, but for greater detail we recommend accessing the numerous technical reports associated with this study that are included as references.

On the path to market transformation

There are many market-available hybrid air conditioning products, and their adoption is making inroads, but total uptake is very small in comparison to the status quo rooftop packaged unit. The largest successes to date appear to be in niche markets, such as data centers, where energy for cooling represents a major operating expense. Most of these products can take advantage of climate-specific efficiency opportunities to reduce energy use, but their performance in application will depend on the way the systems are installed, controlled, and maintained. In our experience, the single largest market barrier for hybrid air conditioners is the current lack of awareness and familiarity with these systems, and the lack of guidance and tools that are necessary to support their application. (Outcault, 2015) This observation may be surprising for readers who assume that economic considerations, or onerous maintenance requirements are the biggest hindrances. In regard to cost, although these technologies tend to have a higher first cost, they can achieve annual ROI >100% in some circumstances (Woolley and Jawin, 2015). In regard to maintenance requirements, it is important to note that although the needs are different for evaporative systems, maintenance is not necessarily more complicated. Maintenance oversights have occasionally caused technical problems, but in most instances we observe that the root of the problem is with industry familiarity, and do not with equipment design.

Aside from manufacturer literature, which is sparse and not standardized, there are few, if any, industry or public resources to broaden understanding. There are no industry standards to support testing these systems in common ways, no generalized design guidance, no best practice case studies, no prescriptive code structures, no minimum equipment efficiency requirements, and no professional training efforts. The California Public Utilities Commission Energy Efficiency Strategic Plan established a number of policy goals surrounding a move toward climate-appropriate HVAC solutions, but so far there are few structural changes to facilitate such an evolution.

With research funding from federal, state and utility entities, we have developed a strong understanding about the technical performance for these systems, about design opportunities and challenges, and about specific needs for commissioning and operation. Climate appropriate cooling equipment is poised for broader market adoption, and deserves focused attention from utilities, policy makers, energy efficiency advocates, and industry organizations in order to cultivate ability and motivation amongst practitioners who design, purchase, install and operate HVAC systems.

One option to facilitate broader uptake for these solutions would be for building energy efficiency standards to use indirect evaporative DOAS air conditioning, or the comparable climate-appropriate hybrid solution, as the baseline for performance compliance in commercial buildings. This type of change was recently adopted by the Washington State Energy Code, and is being proposed in California within the 2019 code revisions cycle. Alternatively, these solutions could be included as an option within a menu of prescriptive measures that building designers and engineers could be allowed to choose from.

Another major need is related to modeling tools. There is not currently an appropriate performance compliance pathway to accommodate hybrid air conditioning systems, so projects are often not granted performance credit for the efficiency advantages they provide. Moreover, building energy simulation software tools are not yet equipped with modules to accommodate these systems, there is currently not a common industry method for representation of performance data, and data about hybrid system performance is not readily available from manufacturers. At the moment, the simulation of hybrid air conditioners requires an expert modeler and carefully constructed custom software to emulate the arrangement and control of each unique hybrid system.

The HVAC industry is aware of these challenges, recognizes the emerging prevalence of multi-mode hybrid systems, and is beginning to enact changes that would support more straightforward modeling. For example, ASHRAE currently hosts a standards project committee, SPC 205, which is focused on developing standards for representation of equipment performance data for use in simulations. The purpose of this committee is to facilitate sharing of equipment characteristics for performance simulation by defining standard representations such as data models, data formats, and automation interfaces.

Currently, the author is working with a consortium of industry partners, and with development teams at two national laboratories to construct a common data structure for representing performance for hybrid rooftop units, as well as a modeling tool for EnergyPlus to accommodate these systems. The developments planned will use the National Renewable Energy Laboratory's (NREL) Technology Performance Exchange (https://www.tpex.org/) and Building Component Library (https://bcl.nrel.gov/) as the distribution platform for data. This will enable manufacturers, and others, to populate a publicly available library of performance curves for hybrid air conditioning systems, from which, EnergyPlus users can download performance curves that are structured for simulation in EnergyPlus.

Conclusions

Hybrid air conditioning offers a variety of climate-appropriate efficiency opportunities for commercial cooling, and ventilation. We have studied several commercially available hybrid systems designed for hot dry climates that use indirect evaporative cooling together with vapor compression in a variety of ways. Three of those systems are reviewed in this paper. The technical benefits are excellent. At full load and in peak cooling conditions, some of these systems achieve COP>15 (EER>50). Cooling efficiency can be even higher at part capacity operation. However, the savings achieved in practice depends largely on the way that these systems are installed, controlled, and maintained.

We have observed many buildings that have successfully incorporated indirect evaporative cooling and hybrid air conditioners, and also many projects that have suffered from ongoing complications. The most significant challenges appear to have resulted from a lack of familiarity amongst the practitioners responsible for systems engineering, installation, control, commissioning, management and service. We have rarely encountered problems with equipment malfunctions, failures, or performance degradation. These cooling solutions are new, and very few practitioners have experience incorporating them into buildings. Hybrid air conditioners are poised for broader market adoption and promise large efficiency gains, but there is a great need for industry standards, policy instruments, practical design guidelines, technical training, and simulation software developments to facilitate successful adoption.

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