

# Psychrometric Bin Analysis for Alternative Cooling Strategies in Data Centers

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## ABSTRACT

*Data centers are significant energy users and require continuous cooling to maintain high levels of computing performance. The majority of data centers have direct-expansion cooling, which typically accounts for approximately 50% of the energy usage of data centers. However, using typical meteorological year 3 (TMY3) weather data and a simple psychrometric bin analysis, alternative cooling strategies using a combination of economizer, evaporative, and supplemental direct expansion (DX) cooling have been shown to be applicable in all climate zones in the United States. Average data center cooling energy savings across the U.S. was approximately 80%. An analysis of cooling energy savings is presented for various ASHRAE climate zones. The psychrometric bin analysis is conducted for the ASHRAE recommended and allowable operating environment zones as well as a modified allowable operating environment. Control strategies are discussed. Finally, examples of energy-efficient data centers using alternative cooling strategies are presented.*

## INTRODUCTION

Over the past decade, energy use associated with data centers has nearly quadrupled and is currently estimated at nearly 100 billion kWh annually. It has been projected that the power costs for data center equipment over its useful life will exceed the cost of the original capital investment. By 2020, the carbon footprint of data centers is expected to exceed that of the airline industry.<sup>14</sup> In recent years, the opportunity for energy efficiency has resulted in increased attention to data center energy use as contributing to federal mandates for reduced energy use throughout the United States and beyond.

The ASHRAE Technical Committee (TC) 9.9, Mission Critical Facilities, Technology Spaces, and Electronic Equipment, focuses on energy use in datacom facilities and is recognized as the unbiased engineering leader and effective provider for technical datacom information. Along with providing workshops on data center energy efficiency in partnership with the U.S. Department of Energy (DOE), TC 9.9 has been integral in developing the ASHRAE Datacom guidelines for increased energy efficiency.<sup>2</sup>

Building energy metrics such as kBtu/ft<sup>2</sup>-yr do not adequately capture the influence of data centers. Less than half the power used by a typical data center powers its IT equipment. The balance of the energy used in these facilities is attributed to cooling, uninterruptable power supply (UPS) system losses, power distribution, and lighting. Two metrics have been developed to characterize this energy use in data centers: Power Use Effectiveness (PUE) and Data Center Infrastructure Efficiency (DCiE). Data center PUE is defined as the ratio of the total power to run the data center facility to the total power drawn by all IT equipment. An average data center has a PUE of 2.0; however, super-efficient data centers have been known to achieve a PUE as low as 1.1. The DCiE is defined as the ratio of the total power drawn by all IT equipment to the total power to run the data center, or the inverse of PUE. Green Grid, a global consortium of IT companies and professionals seeking to improve energy efficiency in data centers, has developed benchmarking protocols for each metric.<sup>4</sup>

In looking at ways to increase energy efficiency in data centers (lower PUE), the ratio of energy used to support the IT equipment (lighting, HVAC, UPS systems) needs to be optimized, and energy efficiency strategies for operating IT equipment need to maintain allowable operating conditions with increased load. Some of these strategies include

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consolidation and virtualization of the IT equipment as well as heating ventilating and air conditioning (HVAC) strategies such as alternative cooling strategies, as discussed in this paper,<sup>3</sup>

The DOE has two programs addressing energy efficiency in federal data centers, including the Industrial Technologies Program's *Save Energy Now in Data Centers* and the Federal Energy Management Program's *Data Center Efficiency for Federal Agencies*.<sup>12</sup> These programs provide great information and publications for energy efficiency in data centers. The Environmental Protection Agency (EPA), through its Energy Star brand, offers both equipment ratings and product specifications for energy efficient data center systems: *ENERGY STAR Rating for Data Centers* and *ENERGY STAR Data Center Product Specifications*.<sup>13</sup>

## ANALYSIS METHODS

Four different cooling technologies, including direct expansion (DX), the air-side economizer, the direct evaporative cooler, and the multistage indirect evaporative cooler, are examined for climate appropriateness and cooling energy reduction in data centers. These technologies are examined individually and in combination with others to categorize seven distinct alternative cooling strategies. These alternative cooling strategies are characterized by bins or zones on the psychrometric chart. These bin zones are bound by the capability of each technology's thermodynamic processes to achieve supply air in the ASHRAE recommended or allowable environmental envelopes for IT equipment. Typical meteorological year (TMY3) data, annual hourly weather data that represents "typical" climatic conditions based on a 30-year sample,<sup>15</sup> is analyzed and processed to perform a summation of how many hours of the year fall into each bin category. Percent energy reduction is calculated based on the reduced energy consumption of each alternative cooling strategy compared to a standard direct expansion mechanical cooling system with a coefficient of performance of three. Direct evaporative coolers are assumed to have a power consumption of 0.2 Watts/CFM, while multistage indirect evaporative coolers are assumed to have a power consumption of 0.4 Watts/CFM.<sup>8</sup> These power consumption values are based on laboratory test data.<sup>15</sup> Bin zones that require a combination of technologies quantify energy use based on the characteristics of the technology and the thermodynamic process required to achieve the desired air properties. Energy savings potential is quantified for a relative comparison between data center cooling strategies. It is not expected that the energy savings potential can be achieved in all cases, since many other factors can influence energy consumption.

## Data Center Cooling Approaches Background

**Direct Expansion.** Packaged DX air conditioners are the most common type of cooling equipment in smaller data centers.<sup>10</sup> These units are generally available as an off-the-shelf technology and commonly described as Computer Room Air Conditioning (CRAC) units. The efficiency (EER) of air cooled CRAC units typically ranges from 8-14, and they are usually the least efficient cooling technology for data centers.<sup>4</sup>

**Airside Economizer.** Airside economizers take advantage of favorable outside air conditions, such as at nighttime and during mild winter conditions. This approach is typically the lowest-cost option to cool data centers. Control strategies to deal with temperature and humidity fluctuations must also be considered along with contamination concerns over particulates or gaseous pollutants.

**Direct Evaporative Cooling.** Another form of free cooling can be provided via a direct evaporative cooling unit. Direct evaporative cooling systems typically have wet-bulb effectiveness on the order of 80%-90% and will reduce cooling system energy use over a standard air-cooled CRAC unit by 70% in low wet-bulb regions.

**Multistage Indirect Evaporative Cooling.** High-performance evaporative coolers that surpass historic evaporative cooling paradigms have recently been developed. Specifically, an internally manifolded design has made dewpoint temperature, rather than wet-bulb, the new low temperature limit for evaporative cooling. DOE lab testing has proven these coolers' ability to supply air at or below ambient wet-bulb temperature (100%-120% wet-bulb effectiveness) without adding any humidity to the supply air. These systems can achieve EERs consistently over 20 and exceeding 60 at part-load and significantly enhance the climate range for evaporative cooling.<sup>5,8,10,11</sup>

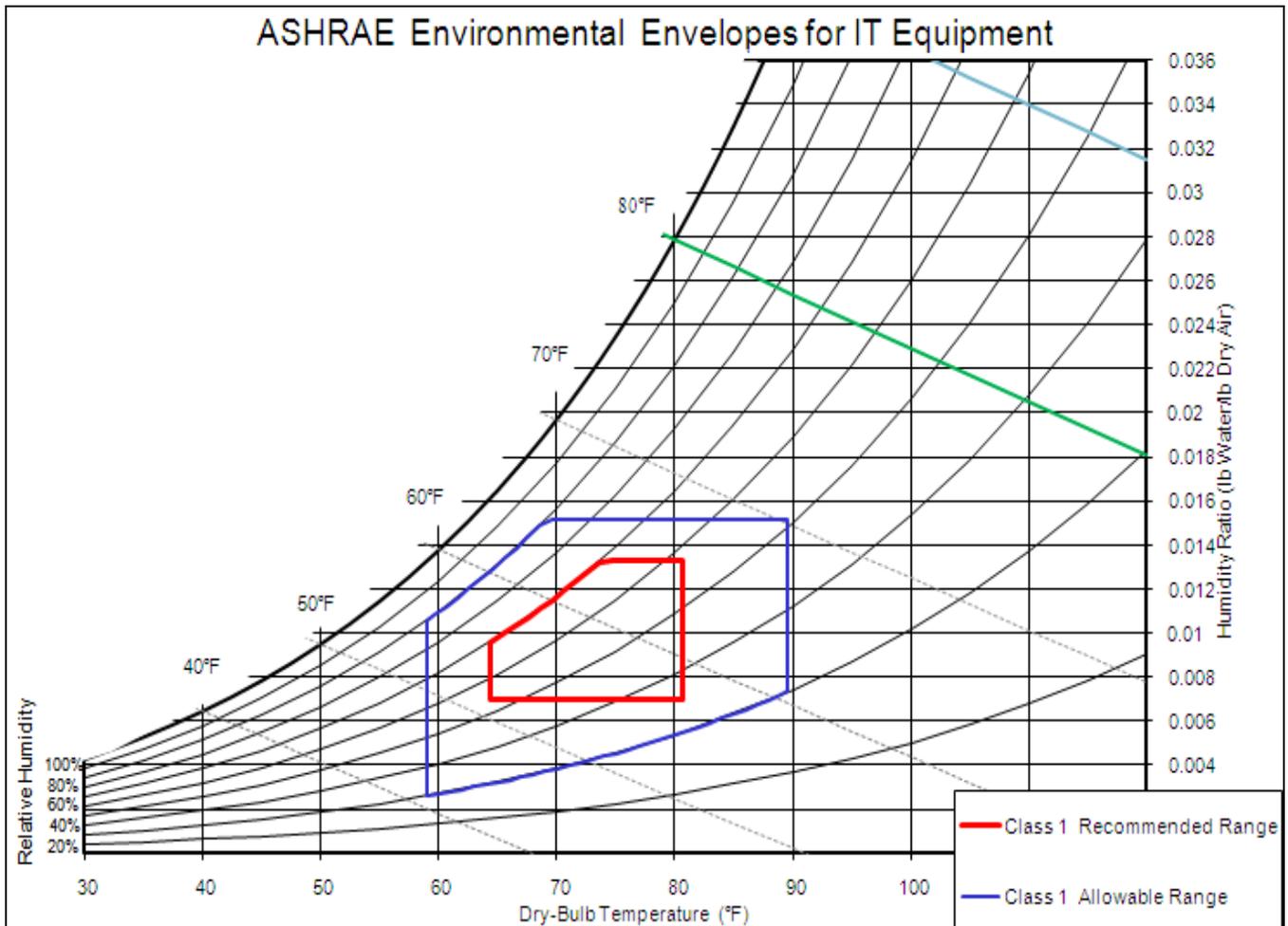
## Psychrometric Bins

The psychrometric chart is a graphical representation of the thermodynamic properties of moist air. This chart is commonly used to graph the thermodynamic properties of air at different stages of conditioning processes.<sup>1</sup> The method of

analyzing alternative cooling strategies for data centers presented in this paper uses ASHRAE published recommended environmental envelopes for IT equipment to divide the psychrometric chart into bins where different cooling strategies are applicable. **Table 1** shows the temperature and moisture boundaries that define the ASHRAE recommended and allowable environmental envelopes. **Figure 1** shows these boundaries on the psychrometric chart.

**Table 1. ASHRAE Recommended and Allowable Environmental Envelopes for IT Equipment (2008)<sup>2</sup>**

	Recommended Envelope	Allowable Envelope
Low End Temperature	64.4°F (18°C)	59°F (15°C)
High End Temperature	80.6°F (27°C)	89.6°F (32°C)
Low End Moisture	41.9°F DP (5.5°C)	20% RH
High End Moisture	60% RH and 59°F DP (15°C)	80% RH and 62.6°F DP (16.8°C)

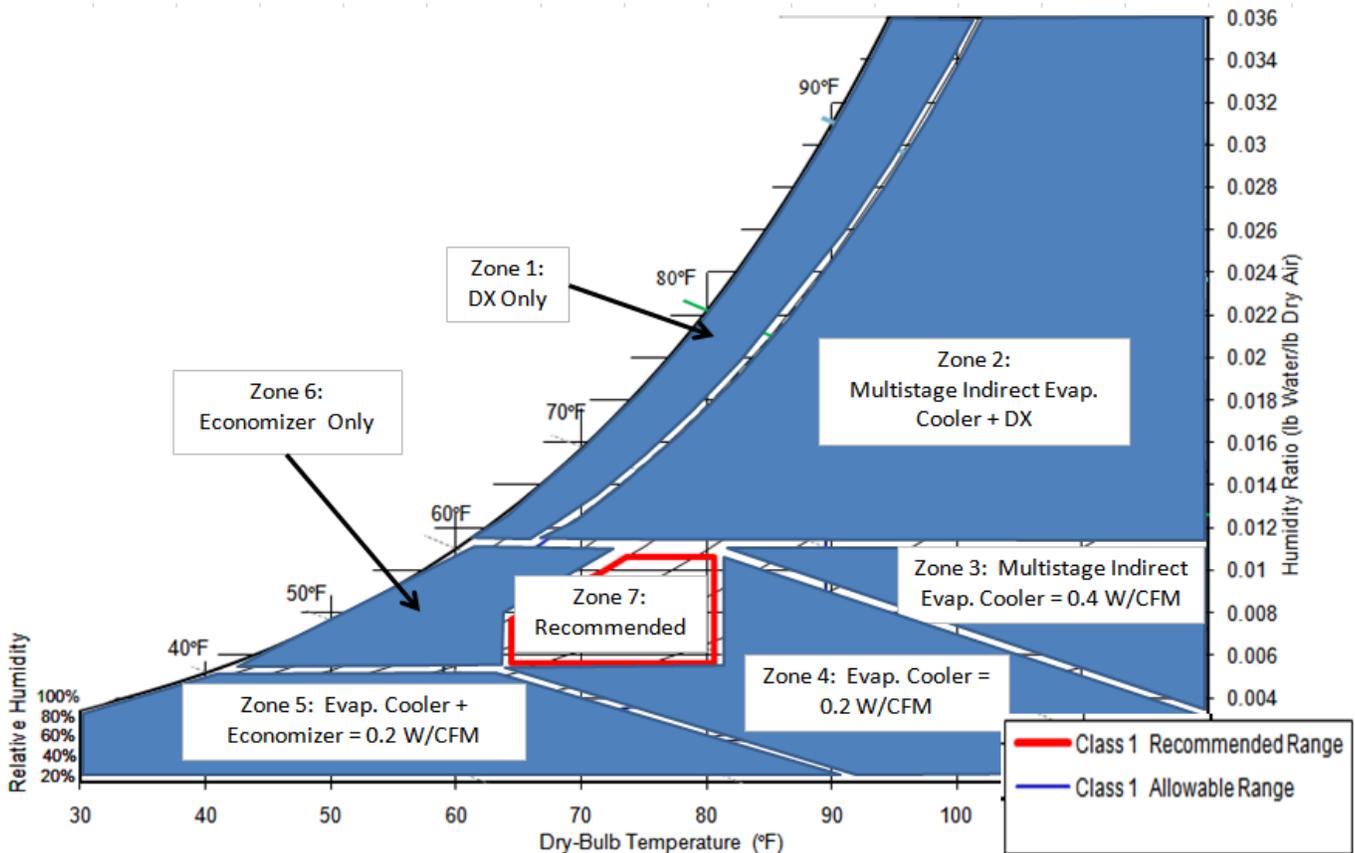


**Figure 1** Psychrometric chart showing ASHRAE recommended and allowable environmental envelopes for IT equipment.<sup>2</sup> (Source: Ian Metzger, NREL)

Psychrometric bins were created for various combinations of four different cooling technologies, including DX, the air-side economizer, the direct evaporative cooler, and the multistage indirect evaporative cooler. The bins are bound by the capability of each technology’s thermodynamic processes to achieve supply air in the ASHRAE recommended or allowable environmental envelopes for IT equipment. **Table 2** defines the boundaries of each psychrometric bin and a description of the associated air conditioning process for the recommended envelope. **Figure 2** shows the bins graphically on the psychrometric chart for the recommended environmental envelope. Similar bins’ boundaries are defined for the allowable environmental envelope, but are not shown in this paper.

**Table 2. Bin Zone Boundaries for Recommended Environmental Envelope for IT Equipment**

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6+Zone 7
Alternative Cooling Strategy	Direct Expansion (DX)	Multistage Indirect Evap. Cooler + DX	Multistage Indirect Evap. Cooler	Direct Evap. Cooler	Evap. Cooler + Economizer	Economizer + Recommended Envelope
Low End Temperature	NA	NA	65.6°F WB (18.7°C)	If DP < 41.9°F DP (5.5°C) Then 51.4°F WB (10.8°C) and 64.4°F DB (18°C) Else 80.6°F (27°C)	NA	NA
High End Temperature	NA	NA	NA	65.6°F WB (18.7°C)	51.4°F WB (10.8°C)	80.6°F (27°C)
Low End Moisture	59°F DP (15°C) and 80% RH	59°F DP (15°C)	NA	NA	NA	41.9°F DP (5.5°C)
High End Moisture	NA	80% RH	59°F DP (15°C)	If DB < 80.6°F DB (27°C) Then 41.9°F DP (5.5°C) Else 59°F DP (15°C)	41.9°F DP (5.5°C)	59°F DP (15°C)



**Figure 2** Psychrometric chart displaying bin zones for the recommended envelope and alternative cooling strategies. (Source: Ian Metzger, NREL)

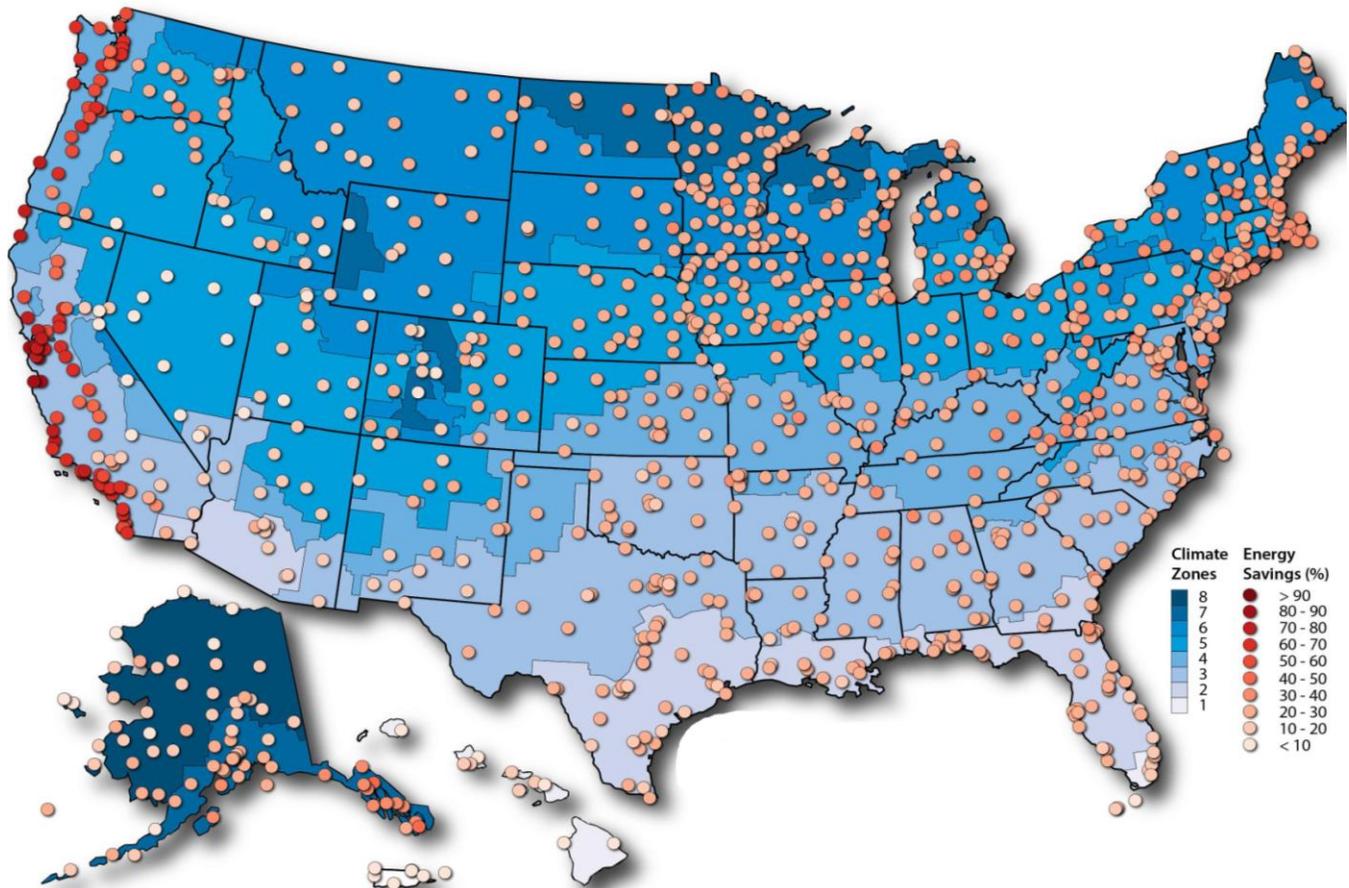
**Simulation Method**

Visual Basic for Applications and Microsoft Excel are used for the programming language and interface for the analysis tool developed for the simulation. However, this method can be easily repeated in other programming language. TMY3 weather data is analyzed and processed to perform a summation of how many hours of the year fall into each bin category.

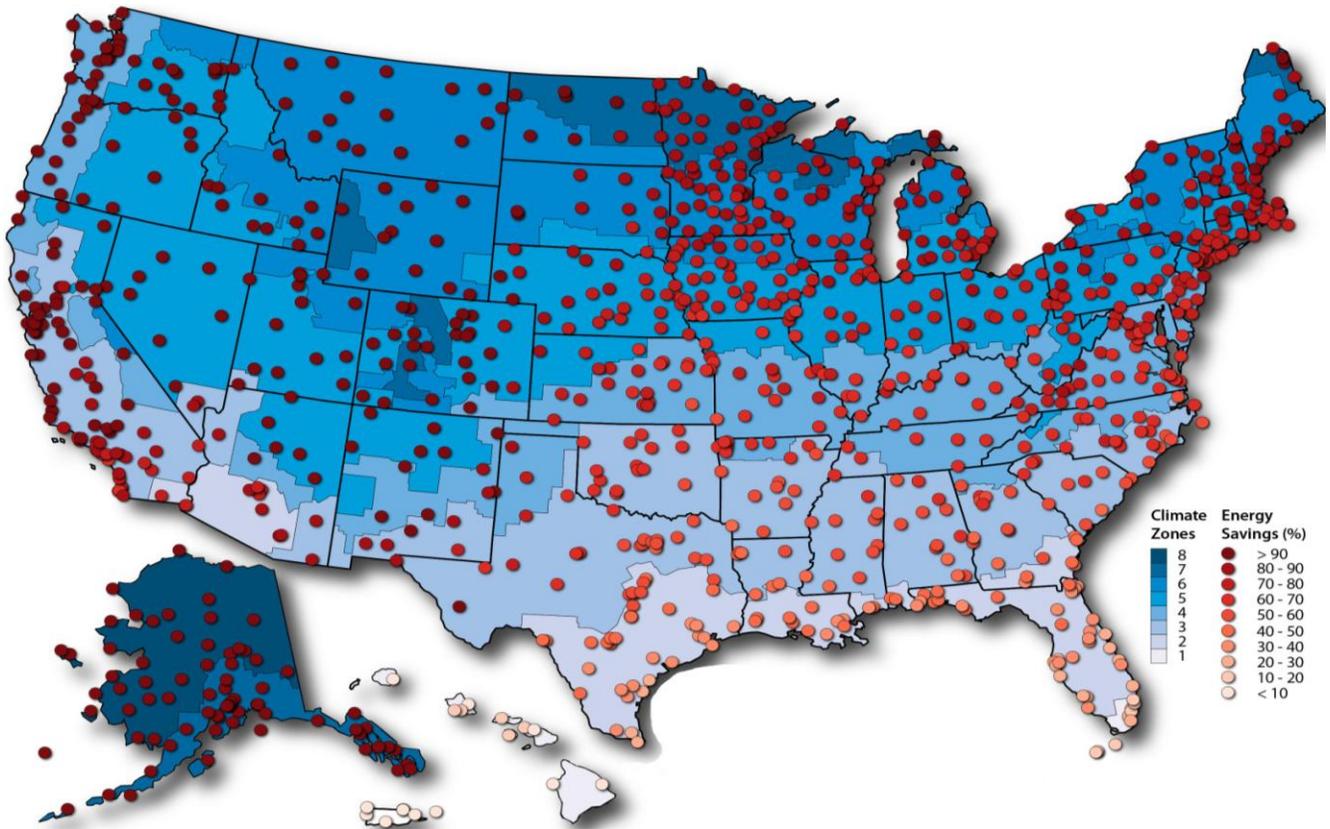
Psychrometric relationships are used to calculate the necessary thermodynamic properties of moist air for every hour of the year. Through a series of conditional statements representing the bin zone boundaries, each hour is assigned to a counter for the appropriate bin zone. Each alternative cooling strategy has a designated counter to calculate how many hours of the year that strategy is applicable for a given location. Percent energy reduction is calculated based on the number of hours and the reduced energy consumption of each alternative cooling strategy compared to a standard DX mechanical cooling system with a coefficient of performance of three. TMY3 weather files for 1,020 locations across the United States are analyzed and mapped graphically using geographical information system (GIS) software.

## RESULTS

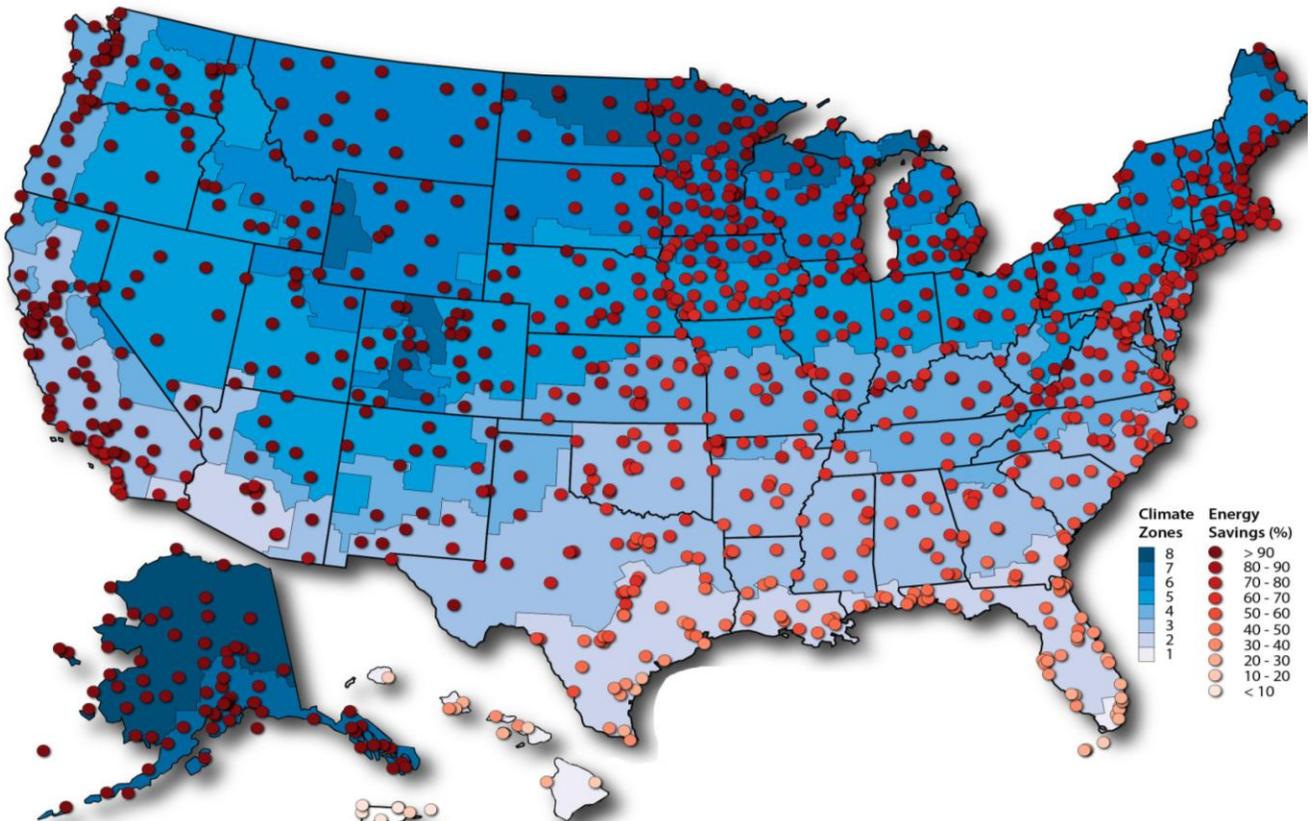
Figures 3-5 display the results for each weather file analyzed across the United States for the recommended envelope and associated alternative cooling strategy bins. The results are broken into three stages. Stage 1 represents potential energy savings from using an air-side economizer (bin zones 6 and 7). Stage 2 represents potential energy savings from using a direct evaporative cooler (bin zones 4 and 5) and an air-side economizer (bin zones 6 and 7). Stage 3 represents potential energy savings from using a multistage indirect evaporative cooler (bin zones 2 and 3), a direct evaporative cooler (bin zones 4 and 5) and an air-side economizer (bin zones 6 and 7). Similar results are obtained for the allowable environmental envelope, but are not shown in this paper.



**Figure 3** Energy savings potential for recommended envelope, Stage 1: Economizer Cooling.<sup>15</sup> (Source: Billy Roberts, NREL)



**Figure 4** Energy savings potential for recommended envelope, Stage 2: Economizer + Direct Evap. Cooling.<sup>15</sup>  
 (Source: Billy Roberts, NREL)



**Figure 5** Energy savings potential for recommended envelope, Stage 3: Economizer + Direct Evap. + Multistage Indirect Evap. Cooling.<sup>15</sup> (Source: Billy Roberts, NREL)

## CONCLUSION

Alternative cooling strategies can significantly reduce energy consumption and improve power utilization effectiveness in data centers. Results show significant savings for each alternative cooling strategy. Stage 1, economizer cooling, shows an average of 30%-40% energy savings potential, with a higher savings potential on the West Coast. Stage 2, economizer and direct evaporative cooling, shows an average of 80%-90% energy savings potential, with a notably lower savings potential in the southeastern part of the United States. Stage 3, economizer and direct evaporative and multistage indirect evaporative cooling, shows an average of greater than 90% energy savings potential, again with a considerably lower savings potential in the southeastern part of the United States, Hawaii, and Puerto Rico.

Humidity constraints on the recommended environmental envelope had a significant effect on the energy savings potential for each technology. In Stage 1, economizer cooling savings potential was lower than expected because of the low end humidity limit of the recommended zone. As a result, the energy savings potential of the direct evaporative and economizer combination in Stage 2 significantly increased because of its ability to add moisture to the air at low energy and take advantage of the free economizer cooling. The low savings potential in the southeastern part of the United States, Hawaii, and Puerto Rico is due to the high end humidity limit of the recommended zone. Any data point above the high end humidity limit required mechanical DX cooling, which significantly reduces the energy savings potential for humid climates.

The results for the allowable environmental envelope improved the results and energy savings potential for all alternative cooling strategies, significantly increasing the savings potential for Stage 1 economizer cooling. However, results still showed lower energy savings potential for the humid climates due to the high end humidity limit. Research and manufacturer data has indicated that IT equipment can operate at higher humidity levels, typically showing a high end humidity limit of 80% relative humidity (RH).<sup>7</sup> An additional simulation was run for a modified allowable range extending the high end humidity limit to 80% RH, and results showed a significant increase in energy savings potential (greater than 90%) in the more humid climates.

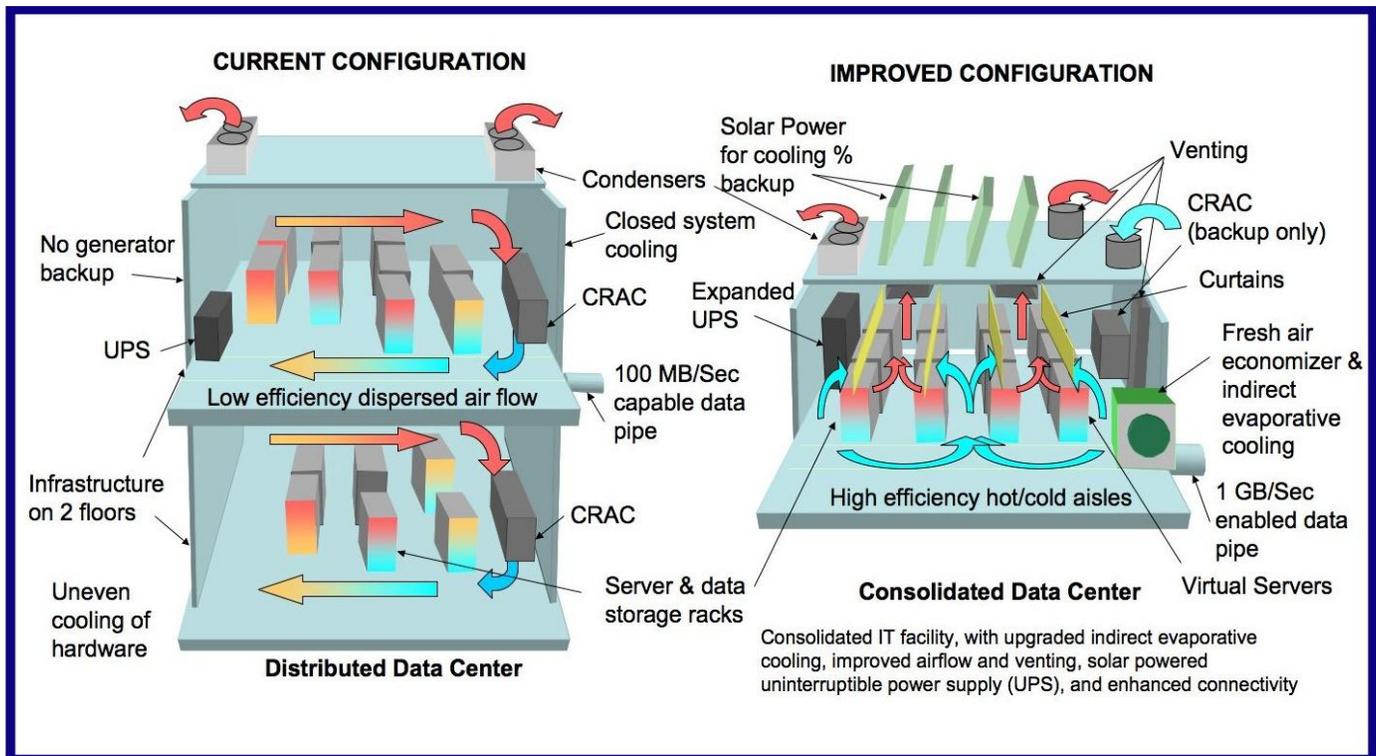
## FUTURE WORK

Future work for this simulation method will incorporate a psychrometric bin analysis method for analyzing data centers for water-cooled IT equipment. Bins will be created based on wet-bulb temperature ranges and approach temperatures for cooling towers. The authors of this paper believe that future data centers will have water-cooled IT equipment and that climate appropriateness will play a large role in the location of these facilities. For example, the National Renewable Energy Laboratory (NREL) located in Golden, Colorado is constructing a new state-of-the-art 10-MW data center in the Energy Systems Integration Facility (ESIF) that will be water-cooled with high-efficiency cooling towers to take advantage of the semi-arid climate.

## CASE STUDIES

**Research Support Facility, National Renewable Energy Laboratory, Golden, Colorado.** In June 2010, NREL finished construction on the Research Support Facility (RSF), a net-zero energy office facility powered by onsite photovoltaic (PV) systems with a 1,900 ft<sup>2</sup> data center. The NREL data center housed in the RSF uses economizer and evaporative cooling to handle 99% of the cooling load. The data center servers are configured in a hard-walled “hot isle/cold isle” arrangement to minimize cooling fan energy and utilize waste heat from the hot isle to help heat the building when heat is needed. The RSF data center is being extensively monitored for real-time and historical energy management applications to include PUE, which is currently operating at a PUE of 1.15. This compares to the legacy data center, cooled by CRAC units, operated at a PUE of 3.3.<sup>15</sup>

**University of Colorado, Boulder, Colorado.** The National Snow and Ice Data Center (NSIDC) at the University of Colorado will be installing an energy-efficient upgrade to its computing facility. The project includes: economizer and indirect/direct evaporative cooling; consolidation of facilities; server virtualization; and a hot/cold aisle. Figure 6 shows a schematic of the old and new data center designs. The data center upgrades are expected to reduce the energy use for cooling by over 90%.<sup>6</sup>



**Figure 6** University of Colorado, Boulder NSIDC data center retrofit: current and improved designs.<sup>6</sup> (Source: Gallaher, David. National Snow and Ice Data Center (NSIDC). University of Colorado, Boulder.)

## ACKNOWLEDGMENTS

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