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FEDERAL ENERGY MANAGEMENT PROGRAM

Guide to Minimizing Compressor-based Cooling in Data Centers

Prepared for the U.S. Department of Energy Federal Energy Management Program

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FEMP
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Cover photo: Center for Disease Control and Prevention's Arlen Specter Headquarters and Operations Center reached LEED Silver rating through sustainable design and operations that decrease energy consumption by 20% and water consumption by 36% beyond standard codes. *Photo from Center for Disease Control, NREL/PIX 16419*

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1 Introduction

This best practice guide is one in a series created by the Lawrence Berkeley National Laboratory for the Federal Energy Management Program (FEMP), a program of the U.S. Department of Energy. Geared towards architects, engineers, and data center Information Technology (IT) and facility managers, this guide provides information about technologies and practices to use in designing, constructing, and operating sustainable high-performance data centers.

This Guide describes alternative data center cooling systems that consume less energy and have lower total-cost-of-ownership (TCO) than traditional cooling systems. Data center cooling systems have traditionally relied on compressor-based cooling—i.e., Computer Room Air Conditioners (CRAC units) or chillers. For years, this standard method of cooling was considered necessary for air cooled IT equipment, and was widely accepted. As data center electrical loads and associated energy costs continued to rise, alternative cooling solutions became more attractive. Some early cooling solutions involved various forms of liquid cooling that continued to rely on the compression and expansion of a working fluid. More recently, however, a number of alternatives for reliable cooling have been introduced that serve to minimize or eliminate compressor-based cooling. As capital, maintenance, and operating costs for compressor-based systems are high, moving away from compressor-based cooling provides cost savings in addition to energy savings in many areas.

Some of these cooling solutions are made possible by adopting recommendations developed by ASHRAE in conjunction with IT equipment manufacturers. The recommendations expand environmental conditions for air cooled systems, and provide new guidelines for liquid cooling temperatures. Following these recommendations enables many new energy efficient cooling options for data centers – which is the focus of this guide. Generally the industry recommends that environmental conditions stay within the ASHRAE recommended limits. However, IT equipment is designed to operate at higher “allowable” limits and can safely operate in those conditions. Various alternative cooling schemes exist that can provide recommended environmental conditions while drastically reducing capital cost and energy use. Many solutions involve “free cooling”, which is well suited to various climate zones, or alternative solutions can be utilized to reduce the number of hours when compressor cooling is needed. More hours of compressor free cooling are possible by taking advantage of the ASHRAE allowable ranges.

The purpose of this guide is to provide concepts for alternative, more cost-effective cooling solutions, while keeping in mind that the reliability of computing systems and their respective cooling systems as key criteria. Although this guide focuses on cooling alternatives, additional solutions include procuring equipment that is capable of reliably operating within the higher allowable ranges defined by ASHRAE, thus eliminating the need for specialized cooling.

A detailed technical description of refrigerant cooling systems is not provided but can be found in the ASHRAE Handbook of Fundamentals. Various options described in this guide were modeled to illustrate their energy savings potential. Simulations were run for three U.S. locations—Houston, New York, and San Jose and results were compared to a typical compressor-based system.

2 The opportunity

Data center cooling systems incorporate numerous components, comprising a system which can be equated to links in a chain. This "cooling chain" removes heat generated by the IT equipment and ultimately rejects it to the atmosphere. Ideally, this heat could be usefully repurposed for use within the data center. The cooling chain starts with air movement through heat intensive IT equipment, with the air then returned to computer room air handlers. Fan energy in the IT equipment and the computer room air handlers is expended in this part of the chain. If computer room air handlers are used, heat is exchanged to water which flows back to a chiller which further transfers the heat to atmosphere through a cooling tower. This is accomplished with the use of chiller, pump, and fan energy. However, the largest energy use in this scheme occurs in the chiller, which uses a compressor-based technology. Alternatively, CRAC units are often used, which also rely on a vapor-compression cycle to remove heat from the data center. With the use of CRAC units, their compressors are the major energy using component. Typical energy use may account for 30% or more of cooling cost, depending on climate, controls, use of free cooling, and design features.

A chiller or CRAC unit uses the thermodynamic properties of a refrigerant phase change to remove heat and transport it from one location to another by "boiling" the refrigerant at the heat source and "condensing" the refrigerant at a heat sink. Consequently, great amounts of heat can be removed and transported with a refrigerant compressor system; however compressor equipment is costly, requires maintenance, and uses considerable energy. The operation of these compressor systems creates additional heat which must also be removed, adding to the overall cooling load.

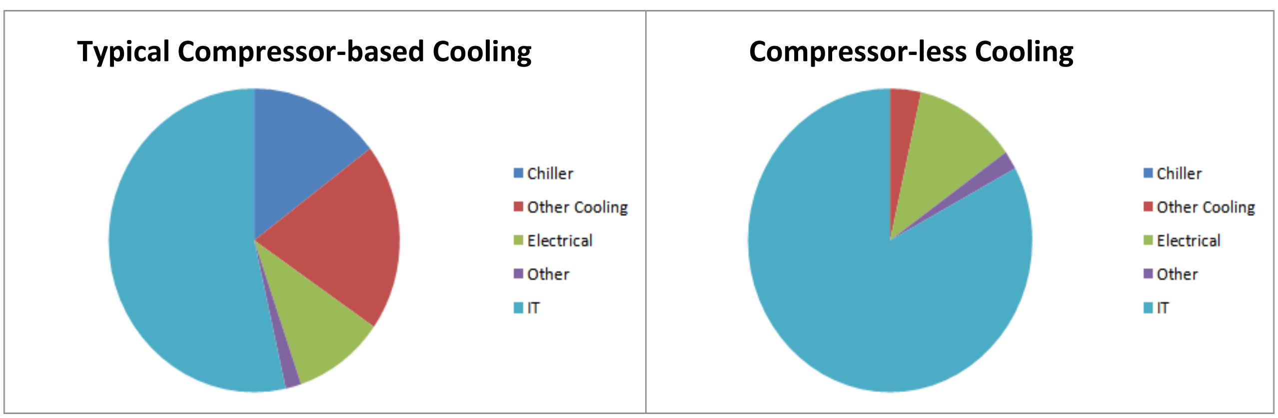

Figure 1: Energy use in compressor-based cooling systems v. compress-less cooling systems

Figure 1, above, illustrates that compressor-less cooling solutions greatly reduce infrastructure energy use.

Operating cooling systems that do not need compressor cooling can eliminate not only the need for chillers or CRAC units but also the cooling towers, pumps, and electrical gear that power them. Maintenance for these components is also required, so eliminating them further reduces costs.

3 Steps for minimizing or eliminating compressor-based cooling

Alternative data center cooling technologies that are currently available can reliably condition the data center environment—even in challenging climates—and need not rely on compressor-based cooling. Proven technologies such as the use of direct free air, evaporative direct or indirect air cooling, or various liquid cooling solutions can effectively cool IT equipment in data centers in virtually all climates. In some extreme climate locations a minimal amount of compressor-based HVAC equipment may be needed for a small number of hours per year to reduce humidity or to peak temperature.

Determining the best solution for a data center involves the following actions:

- Determine the environmental conditions for air cooled IT equipment. For air-cooled systems, operation near the high end of the ASHRAE recommended temperature range and utilization of the wide range of humidity can minimize the amount of cooling needed and provide significant energy savings without sacrificing reliability. Liquid cooling solutions that utilize ASHRAE's higher temperature recommended limits can also eliminate the need for compressor-based cooling.
- Review the climate conditions at the data center location. By reviewing weather data, a determination of the number of hours of free cooling or of partial free cooling can be made.
- Review ability to reduce or shift computing workloads for short periods when environmental conditions may not be desirable. For climates where all but a few hours per year can be cooled without compressor cooling, it may be possible to reduce the IT electrical consumption for short periods of time rather than install costly compressor-based cooling. Commercially available hardware and software solutions exist that can enable load curtailment or load shifting.

3.1 Adopt indoor environmental conditions that promote efficiency of air cooled IT equipment

ASHRAE's Technical Committee TC 9.9 developed what has become the defacto standard for environmental specifications for air cooled IT equipment in data centers. The recommendations were developed to align IT equipment requirements with conditions provided in data centers. The guidelines represent a consensus among all of the IT equipment manufacturers for the conditions that should be supplied at the inlet to the IT equipment. The guideline presents "recommended" and "allowable" ranges of temperature and humidity as well as rate of change. The recommended range represents conditions where the manufacturers expect the most reliable operation. The allowable range, however, represents conditions where the equipment is designed to operate and can do so safely, yet the implication is that there may be some impact on reliability for long term operation in extreme conditions.

In the 2011 version of the ASHRAE guidelines (see Figure 2), additional equipment classes were introduced that greatly expanded the allowable operating conditions. Equipment classes can be selected to match desired reliability and operating conditions; however, note that the equipment classes include operating temperatures of up to 113F which would enable cooling in most climates in the US without compressor-based cooling. Most IT equipment today meets the A1 or A2 class requirements. Additionally, manufacturers are beginning to offer equipment that meets A3 and A4 requirements.

In the 2011 version of the guidelines, a methodology for evaluating the reliability risk of operating IT equipment at elevated temperatures (i.e. in the allowable range) was introduced for the first time. This methodology was developed by IT equipment manufacturers and was primarily meant to assess the impact of allowing the temperature to vary when using outside air free cooling. Credit is given for hours operating below recommended limits and a penalty is imposed for hours operating above recommended limits. By evaluating the number of operating hours per year at various temperatures, factors are determined to estimate potential additional failures of equipment. When IT equipment is evaluated using this methodology, most US climate zones show no significant decrease in reliability, indicating that occasional higher temperatures associated with free air cooling can be safely used.

Classes (a)	Equipment Environmental Specifications							
	Product Operations (b)(c)					Product Power Off (c) (d)		
	Dry-Bulb Temperature (°F) (e) (g)	Humidity Range, non-Condensing (h) (i)	Maximum Dew Point (°F)	Maximum Elevation (f)	Maximum Rate of Change(°F/hr) (f)	Dry-Bulb Temperature (°F)	Relative Humidity (%)	Maximum Dew Point (°F)
Recommended (Applies to all A classes; individual data centers can choose to expand this range based upon the analysis described in this document)								
A1 to A4	64.4 to 80.6	41.9°F DP to 60% RH and 59°F DP						
Allowable								
A1	59 to 89.6	20 to 80% RH	62.6	10,000	9/36	41 to 113	8 to 80	80.6
A2	50 to 95	20 to 80% RH	69.8	10,000	9/36	41 to 113	8 to 80	80.6
A3	41 to 104	10.4°F DP & 8% RH to 85% RH	75.2	10,000	9/36	41 to 113	8 to 85	80.6
A4	41 to 113	10.4°F DP & 8% RH to 90% RH	75.2	10,000	9/36	41 to 113	8 to 90	80.6
B	41 to 95	8% RH to 80% RH	82.4	10,000	NA	41 to 113	8 to 80	84.2
C	41 to 104	8% RH to 80% RH	82.4	10,000	NA	41 to 113	8 to 80	84.2

Figure 2: ASHRAE IT equipment environmental specifications table

3.2 Determine liquid cooled systems' temperature limits

ASHRAE's Technical Committee TC 9.9 also developed guidelines for liquid cooling temperature limits. These were established by a consensus of IT equipment manufacturers in order to standardize the temperatures of liquid cooling systems, yet be able to reliably cool IT equipment and its individual components (e.g. processors). In this way, facilities are able to be designed with known liquid cooling temperatures and related heat removal capability. Similar to the air cooled classes, several classes were established that provide various options for primary heat dissipation. By using higher temperatures of liquid cooling, less complex and lower energy heat dissipation equipment is needed. Table 1 lists the various liquid cooling classes, the expected typical heat dissipation equipment, supplemental cooling equipment (if needed), and the range of liquid cooling temperatures.

<table>
<tr><th colspan="4">Typical Infrastructure Design</th></tr>
<tr><th>Liquid Cooling Classes</th><th>Main Cooling Equipment</th><th>Supplemental Cooling Equipment</th><th>Facility Supply Water Temp(F)</th></tr>
<tr><td>W1</td><td rowspan="2">Chiller/Cooling Tower</td><td rowspan="2">Water-side Economizer

(w drycooler or cooling tower)</td><td>35.6-62.6</td></tr>
<tr><td>W2</td><td>35.6-80.6</td></tr>
<tr><td>W3</td><td>Cooling Tower</td><td>Chiller</td><td>35.6-89.6</td></tr>
<tr><td>W4</td><td>Water-side Economizer

(w drycooler or cooling tower)</td><td>N/A</td><td>35.6-113.0</td></tr>
<tr><td>W5

See Operational Characteristics</td><td>Building Heating System</td><td>Cooling Tower</td><td>>113.0</td></tr>
</table>

Figure 3: 2011 ASHRAE liquid cooled guidelines

3.3 Review weather data

Once the data center location is known (or to help inform siting decisions), weather data— usually typical meteorological year (TMY) data— for the site should be reviewed. This will inform decisions on low energy cooling options which may include direct use of outside air, use of outside air with evaporative cooling (direct or indirect), or various liquid cooled solutions. In addition to weather data, the Green Grid organization has developed a free cooling map tool to aid in quick determination of the yearly number of hours of free cooling (see Figure 4). With this tool, maximum conditions can be specified and then hours per year available for free cooling determined.

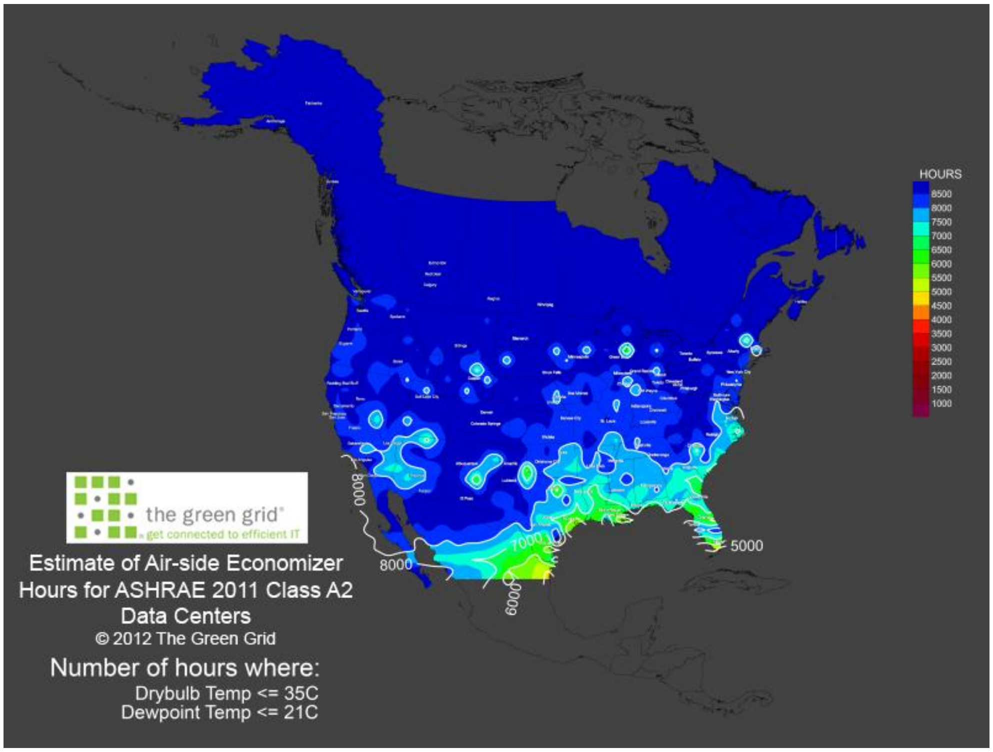

Figure 4: the green grid free air cooling map

Evaporative cooling works in almost every climate during some part of a day or a season. However, high relative humidity or high wet bulb temperatures may limit operation. Recommended and allowable conditions for the various ASHRAE classes of IT equipment are shown superimposed on a psychrometric chart in Figure 5 below. By using weather data and ASHRAE ranges you can determine the number of days where an evaporative cooling system can be used in your climate zone.

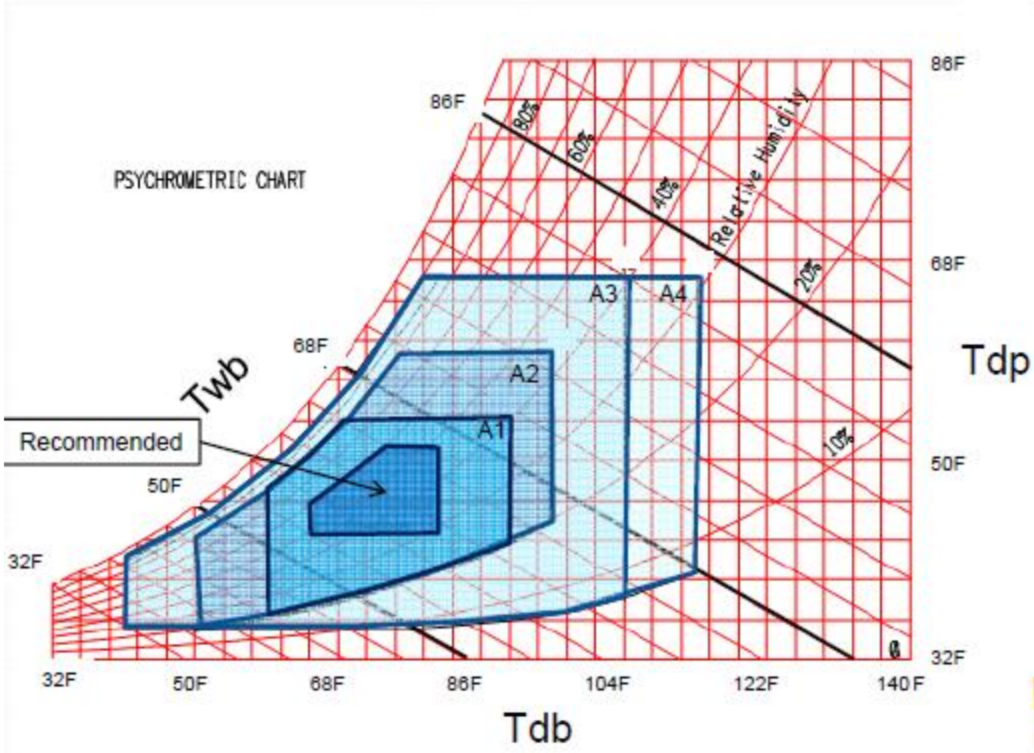

Figure 5: ASHRAE recommended and allowable environmental conditions

4 Solutions to minimize or eliminate compressor use

Cooling solutions that minimize or eliminate compressor-based cooling are described below. These solutions should be investigated for applicability at a given site and may all be implemented with existing technology.

- **Direct outside-air cooling without compressor cooling**

Direct outside-air cooling without compressor cooling is a good option for many sites that have moderate climates and clean air. With this option, air cooling is provided by bringing in outside air and exhausting the heated air. In very cold conditions some of the heated air from the center is mixed with the incoming air. Since there are no compressors (chillers or CRAC units) or cooling towers, this option reduces capital equipment and maintenance cost. It also eliminates water use.

- **Direct outside-air cooling with compressor cooling**

As in the case above, this is a good option for many sites that have moderate climates and clean air. However, there may be a few days a year where free cooling cannot provide the desired conditions. Cooling is supplemented by compressor-based cooling for a small part of the year. To manage an outside contamination event such as a chemical spill or smoke from a wildfire, the compressor cooling would provide for 100% of the cooling load. With this option, there would be additional capital equipment and maintenance cost, however its limited operation would only add a small energy penalty.

- **Liquid cooling**

From an energy perspective, this option is preferred. Liquid cooling overcomes many of the inefficiencies of air cooling IT equipment. Air cooling does not have the heat capacity that liquid cooling provides and requires diligent separation of cool and warm air streams for it to be effective. Fans are much less efficient in transporting heat than their pump counterparts.

There are many variations of commercially available liquid cooling solutions. Solutions may deliver liquid directly into IT equipment or provide cooling at the row or rack level. Various IT equipment manufacturers are offering liquid cooled IT equipment, and various liquid cooling options have emerged in this market. Direct liquid cooling technologies are relatively new, but the solutions eliminate or substantially reduce the need for compressor-based equipment.

If the IT equipment is designed to be cooled with liquid at a high enough temperature, the cooling can be provided with dry coolers, thereby eliminating water use. After cooling the IT equipment, the exiting higher temperature liquid may also facilitate beneficial use of the otherwise wasted heat. The ASHRAE data center technical committee, TC 9.9, has published thermal guidelines for liquid-cooled data processing [1] that are intended to help standardize design conditions.

Some rack level cooling solutions, which have water supplied to the rack, may be used to resolve hotspots in data centers with legacy cooling designs, or may be used throughout the data center. Water cooled racks may provide an ability to use higher temperature cooling water, and if installed with a water-side economizer, many hours of cooling could be provided without the need for compressor-based cooling. Some designs employ fans to circulate air past coils at the row or rack level, so there is some additional fan energy expended. Other solutions use a passive radiator at the back of the rack that uses the fans in the IT equipment for air movement.

Although commercially available liquid cooling solutions tend to be costly, all liquid cooling solutions perform better than air cooling solutions. A life cycle cost analysis will show a higher payback over the life of the infrastructure. If cooling can be provided with predominately liquid solutions, its capital cost can be offset with savings from not requiring compressor-based solutions.

- **Outside-air with direct evaporative cooling**

This option provides free air cooling supplemented with evaporative cooling in the airstream to provide additional cooling when required. In dry climates this provides adequate cooling so that IT equipment can operate within the ASHRAE 2011 recommended or allowable ranges. In hot and humid climates there may be a small number of hours during a typical year when the IT equipment will need supplemental cooling to operate in the ASHRAE allowable ranges A1 or A2. For adequate filtration of the incoming air, ASHRAE recommends using a MERV 13 filter.

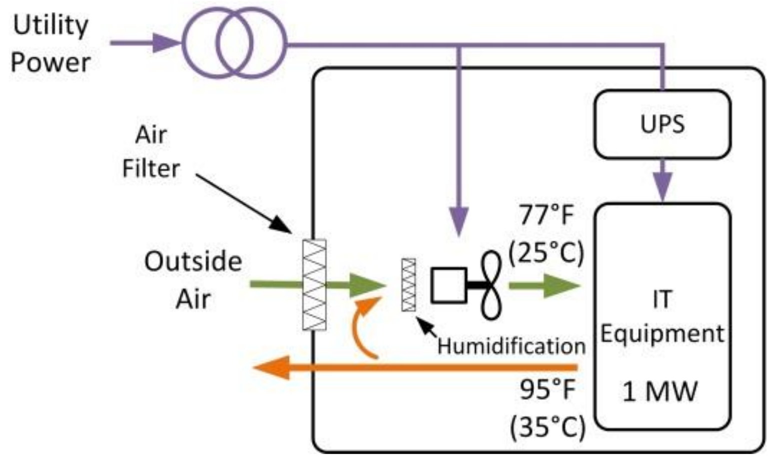

Figure 6: Direct outside air with direct evaporative cooling

As shown in Figure 6, outside air is drawn in through a filter and provided directly to the IT equipment. When conditions require additional cooling, evaporative cooling is introduced into the air stream. After cooling the IT equipment, the heated air is exhausted in to the atmosphere. There is some increased use of water for evaporation in this scheme. Although there will be increased capital costs for the evaporative cooling components, this is offset by eliminating the need for compressor-based systems.

- **Outside-air with indirect evaporative cooling**

Outside-air with indirect evaporative cooling provides free air-cooling yet adds assurance against outside contamination events through the use of a heat exchanger that separates outside air from inside air. Although contamination events are seldom encountered in the US, some severe environments could require the additional assurance provided by the scheme. In mild climates, the server inlet environment will be within the ASHRAE 2011 recommended range. In humid climates there may be a small number of hours during a typical year when the IT equipment will need to operate in the ASHRAE allowable ranges A1 or A2. This option results in a PUE that is close to the direct evaporative cooling option. See Figure 7 below.

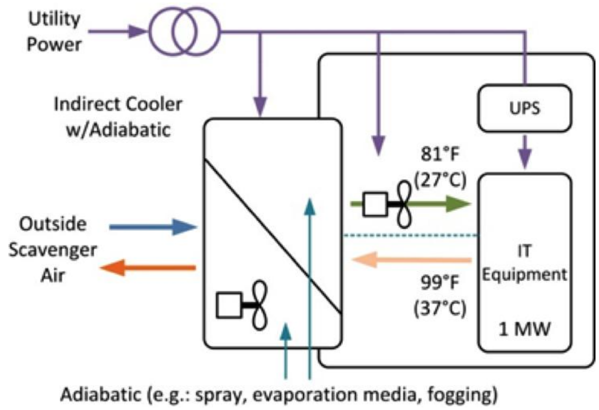

Figure 7: Outside air with indirect evaporative cooling

In this solution, outside air does not mix with the air in the data center. Air is recirculated within the data center and is drawn through the indirect cooler that provides evaporative cooling in a separate chamber from the data center air stream. This scheme also requires some water use for evaporation. As with the direct evaporative cooling scenario, compressor-based systems are not required, saving on capital, maintenance, and operating costs.

- **Outside-air with indirect evaporative cooling and compressor cooling backup**

This option also provides assurance for outside contamination events and provides environments meeting the ASHRAE 2011 recommended thermal guidelines conditions in all climates. There is additional expense for the compressor cooling system capital and maintenance costs. Overall increased energy use is minor for most climates. See Figure 8 below.

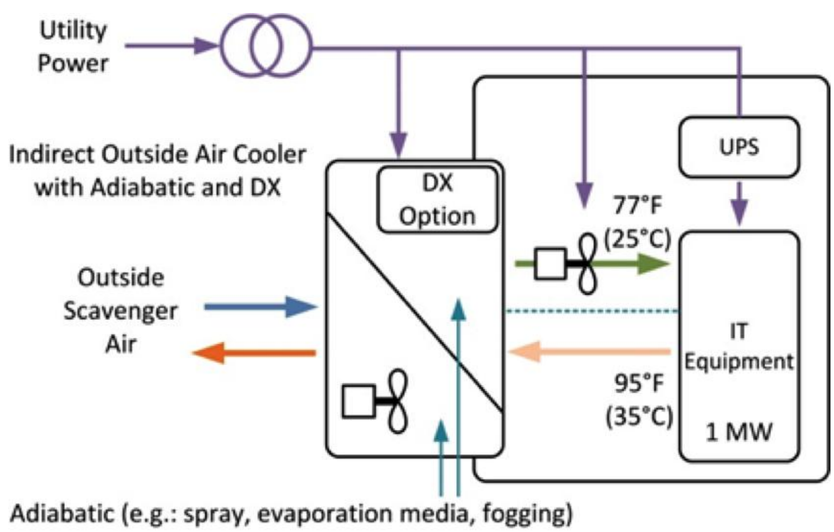

Figure 8: Outside-air with indirect evaporative cooling and compressor cooling backup

This option is similar to the preceding option with the addition of some compressor-based cooling to supplement the cooling when needed in severe climates (e.g. Florida) for some portion of the year. There is additional water use with this design. Here capital and maintenance costs will be incurred, however the few operating hours required will add minimally to the energy cost.

- **Liquid immersion cooling**

This commercially available technology is proving to be viable for typical IT equipment and for very high heat intensity IT equipment, and results in PUE performance under 1.1. In this type of cooling solution the electronics are immersed in a dielectric fluid, which directly cools the heat producing components. One solution uses mineral oil as the dielectric fluid and another uses a fluid that undergoes a phase change when in contact with hot electronic components. In both of these solutions, relatively high temperature liquid removes heat in a secondary loop and since the fluid temperatures are relatively high, the coolant can be produced using a dry cooler in any climate, thereby eliminating chillers, cooling towers, and water use. The cooling system is simple with minimal capital cost compared to traditional chilled water cooling systems. It is likely that this solution would be used alongside other traditionally-cooled equipment but the incremental cost of added compressor-based cooling could be avoided.

4.1 Energy savings potential

Alternative cooling strategies can significantly reduce energy consumption and improve power utilization effectiveness in data centers. Results show significant energy savings for each alternative cooling strategy.

For example, model simulations comparing energy performance of a direct air economizer design to a typical data center cooling design were performed using Romonet modeling software. For this design, the model included variable speed fan controls and showed a PUE improvement from 1.7 to 1.24. For a 1 MW IT equipment load, this would equate to savings of over 4 million kilowatt hours per year - over $400,000 at $.10 kWh. Additional savings may be found in milder climate locations (e.g. West Coast or Pacific Northwest). Direct air economizer cooling may not be viable in climates that have high humidity coincident with high ambient temperatures.

A simulation comparing an indirect air economizer design showed a very similar PUE improvement from 1.7 to 1.25. In climates with high humidity, some compressor-based cooling may be necessary with an indirect air economizer for dehumidification inside the data center, raising the PUE to 1.28. The small amount of energy needed for dehumidification is less than 5% of the IT equipment power in all U.S. locations. Indirect air cooling technologies have a number of advantages including some protection from unexpected outside pollution events, a reduction in water required for humidification during dry climate conditions and possible dehumidification during high humidity conditions.

Humidity constraints on the recommended environmental envelope had an effect on the energy savings potential for some technologies. Taking advantage of the wide operating range of humidity allowed for most IT equipment to result in energy savings. In some climates, the combination of high humidity and high temperatures require the IT equipment to operate within the ASHRAE allowable ranges for short periods of time.

4.2 Applications in new and existing data centers

4.2.1 New data centers

Alternative cooling systems are most easily implemented in new data centers where the appropriate solution for a given climate can be evaluated with a total cost of ownership (TCO) approach. The following options as described above are relevant for new data centers:

- Liquid Cooling
- Indirect free air cooling with evaporative cooling
- Indirect free air cooling with evaporative cooling and compressor backup
- Direct free air cooling
- Direct free air cooling supplemented with compressor-based cooling
- Immersion liquid cooling

4.2.2 Existing data centers

Reducing reliance on compressor-based systems in existing data centers requires some study. The Data Center Energy Practitioner program developed by DOE qualifies assessors to perform data center energy assessments. These practitioners would be able to help identify feasible options for existing centers. For example:

- It may be economically feasible to add free air cooling if the center has access to an exterior wall or roof.
- Another option would be to investigate use of a water-side economizer. Many data centers were built without water side economizers, but this is an economical option that can gain many hours of free cooling annually with a rapid payback.
- Liquid cooling options such as rear door coolers that can function with higher temperature coolant can reduce chilled water requirements and instead operate with water produced by cooling towers or dry coolers.

5 Conclusion

Traditional data center cooling systems were based on the assumption that electronics required very cold air for cooling. In addition, the solution for rising IT equipment heat densities and poor air management practices was often to lower the air temperature in the data center. To achieve these cold temperatures, refrigerated (compressor-based) systems were required. Today, awareness of the need for isolation of cold and hot air streams, i.e. good air management, coupled with the industry’s movement to design equipment that operates in a wide range of environments, is enabling air or liquid cooling solutions that do not require energy intensive compressor cycles.

Figure 9: Chillers are no longer required

As discussed in this guide there are many cooling options that either eliminate the need for compressor cooling altogether, or reduce the need for it to only a few hours per year, depending upon climate. Use of these strategies results in large energy savings compared to traditional systems. Some of the options can also result in lower capital and maintenance costs.

[1] ASHRAE TC 9.9. 2011. Thermal Guidelines for Liquid Cooled Data Processing Environments. http://tc99.ashraetcs.org/documents/ASHRAE%202011%20Liquid%20Cooling%20Whitepaper.pdf

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