Evaluation and Modeling of Data Center Energy Efficiency Measures for an Existing Office Building

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Abstract

This paper evaluates energy efficiency measures in a data center using a calibrated energy model. In the study, an existing office building with embedded data center located at Laramie, Wyoming was chosen. A combination of SketchUp, the OpenStudio plug-in, and EnergyPlus version 8.6.0 were used in modeling, calibration, and annual energy simulation of the building model.

Five energy efficiency measures are evaluated by controlling the set point of humidity, chilled water temperature, supply air temperature, return air temperature and enabling free cooling in the data center's cooling system. The impact of the energy efficiency measures is evaluated in terms of "total chilled water energy use". The results of the study indicate a potential data center chilled water energy savings rangingupto to 5.43% by tweaking the setpoints of return air temperature. Also, enabling free cooling awards a huge 76.58% redution in chilled water energy use and a holistic implementation of all discussed measures would save chilled water energy upto 93.68%.

Nomenclature/Abbreviations

ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers

CRAH – Computer Room Air Handler

CHW- Chilled Water

EEM – Energy Efficiency Measure

°F – degree(s) Fahrenheit

HVAC – Heating, Ventilating, and Air-Conditioning

IT – Information Technology

PUE – Power Usage Effectiveness

UPS – Uninterruptible Power Supply

VAV – Variable Air Volume

VFD – Variable Frequency Drive

Introduction

According to United States Data Center Energy Usage Report (Shehabi et al. 2016), data centers in the U.S. consumed an estimated 70 billion kWh in 2014; this represents about 1.8% of total U.S. electricity consumption during that period. The report also projected the U.S. data centers to consume approximately 73 billion kWh in 2020. The study also reveals the potential impact of adopting additional energy efficiency strategies of 45% reduction in electricity demand when compared to current efficiency trends.

Significant additional research is encouraged in improving the energy efficiency of data center design and operations. Many of the explored efficiency strategies are successfully employed in some data centers while others are emerging technologies under evaluation. The energy efficiency measures in data centers can be grouped under three categories: the facility systems (Table 1), the IT equipment itself, and the integration of those systems (Ceron.M, 2012).

Table 1: Facility-related Efficiency Techniques (Source: Ceron. M, 2012)

Facility efficiency technique	Complexity	Return on investment
Site consolidation	High	High
High efficiency hardware	High	High
Autonomic cooling adjustment	High	High
Free cooling	High	High
Alternative power	High	High
High DC voltage	High	Low
High or low-density zone configuration	Medium	Medium
In-row cooling	Medium	Medium
Scalable, modular data center	Medium	High
Direct rack duct cooling	Low	High

Environmental conditions analysis	Low	Medium to high
Hot/cold Aisle configuration	Low	High
Structured cable management	Low	Low

Our study focuses on environmental conditions analysis measures in the data center. The stringency of the IT equipment's environmental operating parameters drives the facility power consumption. The subsequent sections describe some of the common measures associated with environmental conditions that save energy in data centers.

Air Management

Air management, or "optimizing the delivery of cool air and the collection of waste heat," is an important concept in the process to increase energy efficiency within a data center (Greenberg et al. 2006). In order to improve air management, many design and equipment considerations should be addressed, including short-circuiting of hot and cold air, design and operation of underfloor air distribution systems, and location and design of computer room air handling (CRAH) equipment. Air systems that are custom-designed were found to perform better, and centralized systems are typically more efficient than decentralized units.

Measures that may improve air management within a data center include optimizing the underfloor air distribution system (Greenberg et al. 2006), specifically improving floor diffusers, minimizing airflow obstructions, and sealing unwanted openings within the floor system and racks. Additionally, the configuration of equipment can be optimized through hot and cold aisle placement of computer racks and strategic placement of CRAH units.

A data center's environmental conditions are a factor in both IT performance and energy usage. Three parameters are considered high in priority when improving efficiency in a computer room: supply temperature, humidity range, and return temperature. A supply temperature of less than 60 ºF is considered to be "standard," while a temperature between 61 and 74 ºF is "good" and greater than 75 ºF is "better" (Mathew et al. 2010). The ASHRAE recommended range of temperature entering the IT equipment is 64.4 to 80.6 ºF (ASHRAE 2015). Higher supply temperatures allow mechanical systems to run more efficiently and allow for increased implementation of free cooling strategies.

Humidity control within a computer room can contribute to inefficiency, and is often rarely needed or not necessary at all in modern data centers, as technology has moved away from mainframe and tape storage used in the past (Greenberg et al. 2006). A range usually defines relative humidity setpoint in a computer room. When the range of allowed relative humidity is larger, more energy can be saved (Mathew et al. 2010). A range of 20-55% is considered standard for data center rooms, and a range of 25-60% is a "good" range. The ASHRAE recommended range of humidity entering the IT equipment is 15.8 to 59 ºF dewpoint with a maximum relative humidity of 60% (ASHRAE 2015). Ideally, the "better" solution is to have no control of humidity.

Return temperature index (RTI) is another metric for consideration in data centers. RTI is defined as the percentage resulting from the mean temperature difference across the CRAHs, divided by the mean temperature difference across the racks (Mathew et al. 2010). 100% is ideal; over 100% indicates low CRAH airflow relative to rack airflow (net recirculation); below 100% indicates high CRAH airflow relative to rack airflow (net bypass).

The effect of temperature and humidity adjustment on the IT equipment must be weighed against the savings gained by these measures.

Cooling Systems

Many strategies for air-cooling are used within data centers, including chilled water. Optimizing the central plant can be a way to further save energy in conjunction with a data center. This can be done through adjusting design temperature, using a VFD chiller, and with proper preventive maintenance and monitoring of the chiller plant's efficiency. Overall cooling system efficiency is defined as average cooling system power divided by average cooling load in the data center (Mathew et al. 2010). Values greater than 1 kW/ton are considered to be "standard," while values between 0.5 and 1 are "good," and values below 0.5 kW/ton are "better".

Many systems are designed to accommodate an arbitrary future load based on projected growth of the data center, and thus, many centers operate on a partial load. Cooling system sizing factor can be used to assess the opportunity to improve efficiency. This factor is defined as the installed chiller capacity divided by the peak chiller load, and values between 1 and 1.5 have low potential, values between 1.5 and 2 have medium potential, and values greater than 2 have high potential for energy efficiency improvement (Mathew et al. 2010). Again, the part load efficiency of the system can be improved with integration of VFDs on the chiller compressor as well as cooling tower fans and pumps for chilled water and condenser water.

Additionally, using liquid cooling, rather than air, is much more efficient when cooling computer racks (Greenberg et al. 2006).

Many metrics are considered when assessing cooling systems for a data center, including efficiency, sizing factor, airside economizer utilization factor, waterside economizer utilization factor, and airflow efficiency (Mathew et al. 2010).

Existing studies of data centers have evaluated the energy efficiency of the facilities and identified various EEMs that can be applied to the data center. Although the calibrated energy model approach is widely employed in the building industry for evaluating retrofit energy efficiency measures, very few references were found using a building energy model to evaluate the potential energy savings of data center EEMs. Hong et al. (2008) compared an EnergyPlus data center model to one of DOE-2.2, and found similar results between the two, with EnergyPlus having more modelling capabilities than DOE-2.2. In fact, EnergyPlus version 8.3.0 has included new simulation capabilities for IT equipment and data center mechanical systems (EnergyPlus 2016). This paper discusses the creation and calibration of an EnergyPlus model for evaluation of potential energy efficiency measures and its impact on total building energy use.

Building Description

The chosen building with a data center for this study is located in Laramie, WY. It was built in 2007, with three above-grade stories and a small basement. The gross floor area of the building is 86,664 ft^2. The building is part of university campus and it houses typical academic functional spaces such as office space for professors and students, conference rooms, computer labs and a data center.

The typical hours of operation of the building are normal university business hours, which are usually 8:00 AM (8:00) to 5:00 PM (17:00), Monday through Friday, and closed on weekends and holidays. There are, however, exceptions to this rule, as the data center runs 24 hours a day, 7 days a week, and the open computer lab, as well as some spaces on the first floor, are typically accessible 24/7.

Data Center

The Data Center takes up approximately 6,000 ft^2 of the building, which would allow space for over 200 computer server cabinets. The data center has a 3-foot raised floor, and the ceiling is tapered from the adjacent mechanical gallery wall to enable efficient return air extraction. The data center configuration is a TIER II+ redundancy with a hot aisle/cold-aisle arrangement. Electrically, the space designed for 620 kW IT load, with the ability to expand capacity in the future. The 36 electrical busways supply the necessary power to server cabinets with two redundant electrical bus ways per cabinet. Additionally, a one MW standby diesel generator is available in the event of power loss. The data center was not sub-metered separately. Hence, IT equipment is sub-metered temporarily for a short period (1.5 month). Based on measured data the averages IT equipment load is 257 kW and hourly load fluctuates between 211 kW to 288 kW.

The IT equipment is distinctly divided into two, with a few servers for office support and the remaining are dedicated for research activity. The loads on office servers are almost constant throughout the year whereas in the research servers the loads are highly unpredictable. The HVAC systems are designed to provide quick response to meet the cooling load.

HVAC & Control Systems

The two chilled water single-duct Air Handling systems (See Table-2) are provided to meet the comfort requirements of office, conference, and Laboratories. The AHU-1 supplies 38,600 cfm to serve comfort and ventilation air to the areas in second and third floor and AHU-2 supplies 30,000 cfm to serve the basement and first floor. Thermostats and VAV boxes with reheat coils at each terminal monitor and control the space temperature. The occupied and unoccupied cooling setpoint temperatures for typical office space are 76 ºF and 80 ºF, respectively. Similarly, the heating setpoint temperatures are 70 ºF for occupied hours and 64 ºF for unoccupied hours.

Five dedicated computer room air handlers (CRAH's) installed in the adjacent mechanical gallery provide the cooling for the data center. These CRAH units cool the UPS and power distribution equipment housed within the mechanical gallery and data center room. The IT equipment racks are arranged in a hot and cold aisle configuration, with office use servers arranged in one side and intense use research servers located separately within the data center room.

The cold air to the server room is distributed through an underfloor plenum at 55 ºF through perforated floor tiles. The return air relative humidity is set to vary within the range of 25-80%. To meet the lower humidity limit three humidifiers are installed to add moisture whenever return air RH fall below 25%. The data center's room return air temperature is around 65ºF.

A common chilled-water system serves the entire building, not just the data center. Temperature typically ranges between 44 ºF and 46 ºF. The chilled water and hot water are from the campus central plant. A 125-ton chiller serves as back up for cooling of the IT building in the event that campus chilled water is unavailable. The Building Automation System or Energy Management Control System are in place and used to track utility data regularly.

Table 2: Air handling unit & CRAH unit schedule

IDENT	Cooling (MBH)	Heating (MBH)	Supply (CFM)	OA (CFM)	TSP in WC
AHU-1	919.0	348.0	38600	7300	4.3
AHU-2	714.3	323.0	30000	5600	4.5
CRAH -1 to 5	390		18000		0.3

"As-built" Model

The "as-built" model represents the existing performance of the envelope, the HVAC system, the lighting system and the control system based on the installation. The building energy model is created using EnergyPlus 8.6.0. Available graphical user interface such as SketchUp and the OpenStudio plug-in for SketchUp to generate the IDF suitable for execution in EnergyPlus simulation engine. Figure 1 represents the "as-built" model in SketchUp environment.

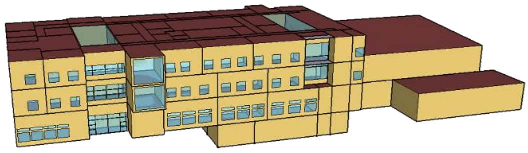


Figure 1: The office building 3D view in SketchUp

The construction assembly for building surfaces is taken from architectural drawings and inputted as layer-by-layer, using material properties from the OpenStudio Building Component Library (BCL). The fenestration is double glazed unit with low Solar Heat Gain Coefficient.

With the help of mechanical drawings and BMS set points, several thermal zones were created in the computer model to reflect the thermal and physical properties of each space. In total, there are 120 thermal zones between all four levels. Figure 2 indicates the locations of the Data Center and its corresponding mechanical room.

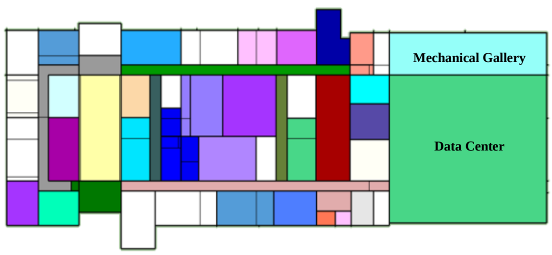


Figure 2: Thermal zones distribution in Second floor.

Mechanical systems were modeled as close as possible to as built. However, due to limitation in EnergyPlus software, a single HVAC system is modeled combining the five CRAH units serving the data center. In addition, the hot and cold aisles are separated within data center for energy efficiency. Computational fluid dynamics simulation were normally employed for detailed air distribution modelling.

Model Calibration Methodology

The "as-built" model results are calibrated using manual iterative calibration method. With the available "as-built" model as the starting point of the calibration process, the model is calibrated to replicate the annual chilled water consumption. First, the "as-built" model set to reflect the local weather condition using an hourly EnergyPlus format weather file for the corresponding measurement period (11/1/2015 to 11/31/2016) of chilled water. The weather file information is from NCDC website.

The manual calibration is done following a bottom up approach (Ji & Xu 2015) by employing combinations of inverse calibration method, graphical-based method, and trial and error method. The power consumption of IT equipment and data center environmental measurements were obtained for short durations of time (1.5 months). The schedules for the office area are set to follow the default schedules for occupancy, lighting and equipment as defined in the ASHRAE 90.1-2013 User manual and HVAC from the Building Automation Systems settings. With the help of monitored 10-minute interval chilled water usage (ton-hrs) and the electricity demand data of the IT equipment, the hourly input schedule file for ITE is replicated. This hourly equipment schedule accurately reflects the corresponding data center cooling load requirement.

From the initial run results comparison, the default input parameters of lighting, electric equipment and occupancy schedules are tuned iteratively on a trial and error basis to balance the internal load gain. The model temperature and humidity outputs are continuously verified against measured data so that comfort level and data center thermal environment requirements are not compromised. The differences between measured and computed results are visualized graphically in Hydro Quebec's VIZBEM tool to identify error range following each manual parameter tuning (See Figure 3).

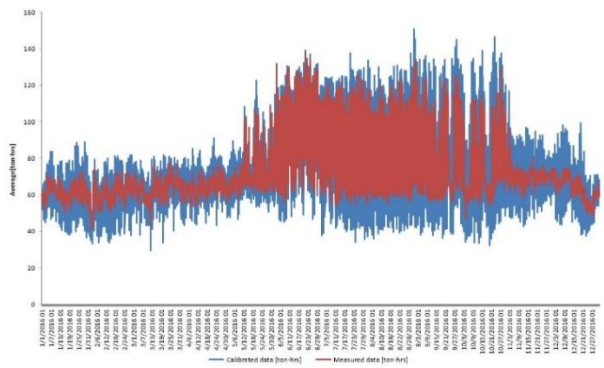


Figure 3: Comparison of calibrated model CHW usage to measured CHW data

The iterative process is repeated until the results calibrated to match measured data within acceptable error threshold (see Table 3) outlined in ASHRAE Guideline 14-2002. Statistical indices NMBE and CVRMSE were used to measure the Goodness of fit of the energy model.

Table 3: Acceptance ranges for these indices for monthly and hourly data

Standard/ Guideline	**Monthly Criteria (%)**		**Hourly Criteria (%)**	
	NMBE	**CV (RMSE)**	**NMBE**	**CV (RMSE)**
ASHRAE Guideline 14		15	10	30

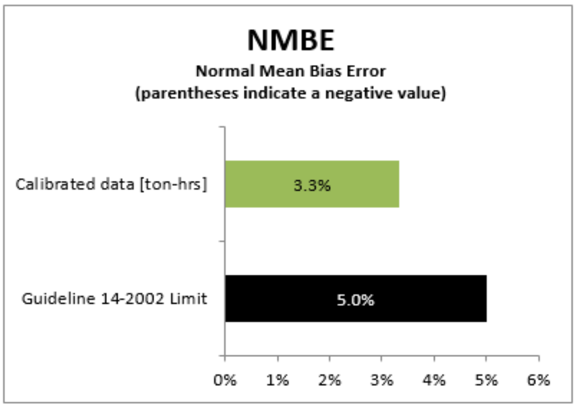
Table 4 shows the annual chilled water energy consumption of total building and data center in the final calibrated model.

Table 4: Baseline Simulation Results

Baseline Simulation	**Total building CHW energy use [Ton·hr]**	660,667	**Data center CHW energy use [Ton·hr]**	445,662

Clearly, building energy usage is immense, with the 67.45% of chilled water energy consumed at the data center.

The NMBE for the calibrated model with hourly data varied by month between 0.2% to 6.6% and CVRMSE varied from 9.6% to 24.3% (see Figure 4).



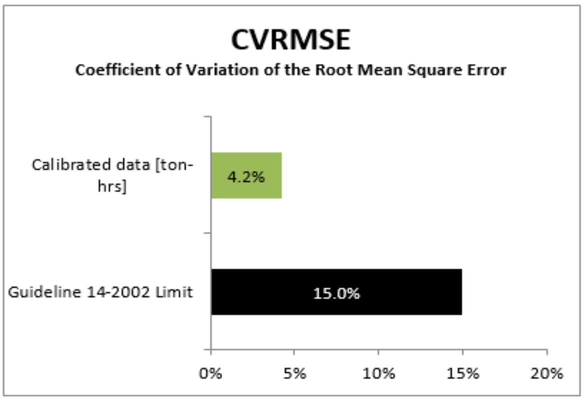


Figure 4: Monthly NMBE and CVRMSE of final calibrated model.

This final model is employed as the baseline model to investigate the targeted energy efficiency measures in this study.

Energy Efficiency Measures

Based on literature review and building mechanical system compatibility five energy efficiency measures (EEMs) associated with the data center's environmental condition and a holistic approach were identified to evaluate their impact. The EEMs include adjusting humidity control, the chilled water temperature, the supply air temperature from CRAH units, the return air temperature setpoint of the data center, and airside economizer. These five EEMs are easy to implement and have high potential for energy savings. The impact of the identified EEMs on annual chilled water energy use for data center were evaluated and discussed in this section.

a) *Humidity control*

Ideally, a data center's relative humidity will be within the range of 40-50%. The ASHRAE recommended range of humidity entering the IT equipment is 15.8 to 59 ºF dewpoint with a maximum relative humidity of 60%. Maintaining a tight relative humidity in data center environment will increase the energy consumption. The current operation of the data center allowed relative humidity to vary within a wide range of 25-80% and no specific humidity setpoint was maintained. This indicates the best practice is followed. However, two scenarios with relative humidity setpoint 25% and 45% selected within typical data center operation RH range are simulated.

Table 5: Humidity Control Simulation Results

Simulation	Data center CHW use [Ton·hr]	Percent Reduction [%]
25% RH	446,840	-0.26%
45% RH	447,278	-0.36%

As expected the results of simulation (Table-5) shows an increased chilled water consumption of 0.26% and 0.36% than the baseline model. The increase is marginal because the building is located in a relatively dry climate were the humidity limit is maintained without ever needing to actively dehumidify the inlet air.

b) *Chilled water temperature*

The chilled water for data center CRAH units is supplied from the campus central energy plant at a typical temperature ranges between 44 ºF and 46 ºF, with an average of 45°F. Three cases with higher chilled water temperatures of 50 ºF, 55 ºF and 60 ºF are simulated. The results of the runs (Table-6) indicate no change in chilled water usage with the increase in chilled water supply temperature.

Table 6: Chilled Water Temperature Adjustment Results

Simulation	Data center chilled water energy use [Ton·hr]	Percent Reduction [%]
Temp. 50 ºF	445,944	-0.08%
Temp. 55 ºF	445,944	-0.08%
Temp. 60 ºF	445,944	-0.08%

Raising the CHW temperature does not change the cooling load, but it does change the chiller energy use. In an embedded data center, the CHW temperature may be constrained by the rest of the building. In winter, it should be possible to take full advantage of raising the CHW temperature.

c) *Supply Air Temperature from CRAH units*

The measured supply air temperatures of CRAH units are 55 ºF which is much cooler than necessary. In fact, this is below the minimum recommended temperature at the IT inlet. Two simulations were subsequently run:

1) Supply air temperature of 58 ºF
2) Supply air temperature of 60 ºF

Table 4: CRAH Air Temperature Adjustment Results

Simulation	Data center chilled water energy use [Ton·hr]	Percent Reduction [%]
Temp. 58 ºF	445,392	0.042%
Temp. 60 ºF	44065.1	0.340%

The results of the runs (Table-4) indicate a marginal reduction. Because, the cooling load from IT and UPS is still the same, the reduction of chilled water energy use is reported at the cost of setpoint unmet in the data center.

d) *Return Air Temperature setpoint*

The current return air temperature of the data center is maintained at 65 ºF. Significant energy can be saved by controlling the set points so that the IT inlet conditions conform to the ASHRAE class A2 environmental recommended range of 50ºF up to 95ºF air temperature. Three simulations were subsequently run with higher return air temperature setpoint 75 ºF, 80 ºF and 90 ºF.

Table 5: Data Center Zone Air Temperature Setpoint Adjustment Results

Simulation	Data center chilled water energy use [Ton·hr]	Percent Reduction [%]
Temp. 75 ºF	431,508	3.16%
Temp. 80 ºF	426,671	4.24%
Temp. 90 ºF	421,368	5.43%

Increase in zone air temperature decrease the cooling requirements hours thereby reduce the chilled water energy consumption of the data center.

e) *Free cooling*

Provided the data center is in a cold and dry climate (climate zone 7), with mean maximum temperature 72 ºF an air economizer can reduce the chiller plant load just by taking advantage of outside air in lieu of mechanical cooling. The CRAH unit is enabled to operate in air economizer mode when the outside air temperature is conducive. The fixed dry bulb shut-off control is modeled with the high shut-off limit of 75 ºF corresponding to the limit defined for climate zone 7.

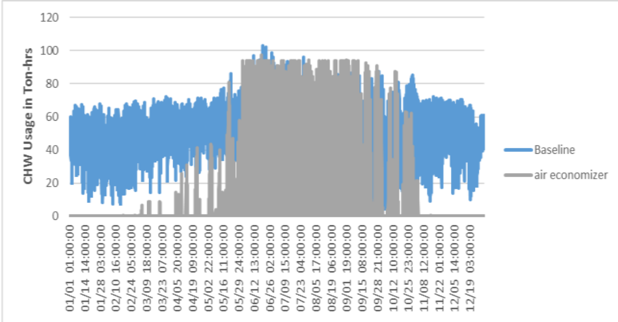


Figure 5: Hourly chilled water usage of baseline vs air economizer measures.

The resulting simulation shows free cooling meets the data center load for approximately 7 months of the year. The chilled water-cooling is needed only during the hot months of the year with peak cooling load dropping by 6% from 103.08 tons to 97.32 tons and the annual chilled water reduction of 341,227 ton-hrs (76.58% reduction).

f) *Holistic approach*

This is a combination of all EEMs discussed above. This measure assumes airside economizer with 75ºF shutoff limit, Supply air temperature setpoint at 75 ºF and return temperature set point at 90 ºF with RH floating between 25-80%.

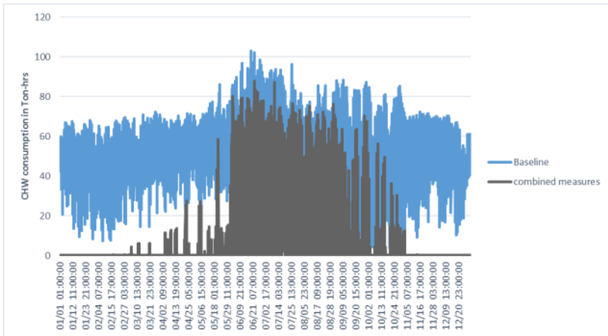


Figure 6: Hourly chilled water usage of baseline vs combined measures.

The analysis of results shows the combined EEMs simulation reduced the data center chilled water use to 28149.35 ton-hrs (93.68% reduction from baseline use). In addition, the chilled water-cooling is needed only during the hot months of the year with peak cooling load requirement dropping from 103 tons to 84.83 tons.

Conclusion

Data centers use an immense amount of energy due to their IT and mechanical equipment usage. We simulated energy saving measures for a data center in Laramie, Wyoming. The adjustment in setpoint of relative humidity, Supply air temperature and chilled water temperature does not affect the chilled water energy consumption in data center. Currently, the data center RH is set to floating. However, raising the CHW, temperature does not change the cooling load, but it does change the chiller energy use. Similarly, the supply air temperature increase allows the CHW temperature to be raised, and more hours of economizer operation. Increasing the return air temperature by 25 ^{o}F can save upto 5.43% of data center chilled water energy use. The most effective energy saving measures in the study is enabling air economizer mode operation, to allows free cooling this reduce the chilled water energy consumption by 76.58% and peak chilled water demand to 84 tons (6% reduction). The combined implementation of above discussed measures would save up to 93.68% reduction in chilled water energy use. Further work, will involve including the impact on electricity usage of EEMs and identifying the optimal EEMs that strike a balance between CHW and electric use of this data center.

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