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Real-time monitoring and evaluation of energy efficiency and thermal management of data centers

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ABSTRACT

The rapid growth of IT industry and the miniaturization of semiconductors have resulted in substantial increase in energy consumption, power density of IT equipment and, subsequently, heat dissipated from data center racks. Metrics have been proposed to overcome these energy efficiency and thermal management challenges. Measuring the performance of the data centers using a combination of wisely chosen metrics can increase the opportunity for considerable energy reduction. A variety of metrics developed and applied for such evaluation are reviewed herein. The energy and cooling efficiency of a small data center is then evaluated by applying several metrics. To perform the analysis, real-time monitoring of 25 parameters over a period of six weeks was performed through design and implementation of a wireless monitoring network. The results are analyzed and current energy efficiency and thermal management issues are discussed with respect to the relative effectiveness of the various metrics.

1. Introduction

Real-time, automated energy monitoring and control of manufacturing processes offers the potential to reduce energy use and improve environmental performance [1]. The ever-increasing demand of IT support, however, along with the developments in semiconductor miniaturization have led to higher density processors and a sharp increase in the energy consumption and the heat dissipated per unit volume of racks in data centers [2]. A data center is a facility housing networked computers and servers as well as associated infrastructure, for the purposes of storage and management of large amount of data and information [3].

The United States Environmental Protection Agency (EPA) reported that the annual energy consumption of U.S. data centers is approximately 61 billion kWh, which is about 1.5% of the total U.S. electricity consumption [4]. It is also reported that data center electricity consumption in 2006 was nearly double that in 2000 [4]. Energy in data centers is consumed by two main categories of equipment: IT equipment and infrastructure that supports the IT facilities and provides reliable cooling and the thermal environment needed for IT equipment to operate.

Since the power consumed by IT equipment is converted into heat dissipated through the racks [5], reliable thermal management is imperative to provide an adequate environment for IT devices. Due to rapid growth of the IT equipment miniaturization and significant increase in rack level power densities, many thermal management challenges have been rising over the past few decades [6–8]. Poor thermal management lowers energy efficiency and can lead to higher risks of server failures and lower IT equipment longevity.

The data center cooling system often accounts for a significant portion of total energy consumption, and cooling cost drives the total operational cost of a typical data center [9]. It is estimated that about five times the server cost is spent on cooling and supporting infrastructure when a $1500 server is operated in an adequate thermal environment [10]. A successfully implemented thermal management system can significantly reduce operational cost by increasing the energy efficiency [6]. Thus, many efforts have been made to increase the efficiency and effectiveness of cooling system and thermal management of data centers.

The power usage effectiveness (PUE) of data centers, one of the most practiced metrics, was studied by Lawrence Berkeley National Laboratory [11]. Benchmarking 22 data centers revealed a PUE drop of 16% in 2005 when compared with that in 2003 (1.95–1.63). Despite all the efforts that have been taken, energy consumption of cooling systems is still a major concern, and there is plenty of room for efficiency improvements. In traditional data centers, there

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is additional pressure to cool the ever-increasing rack power densities using novel strategies due to inefficiencies of conventional thermal management. The first step in implementing new strategies is by evaluating data center performance. Thus, a challenge is to effectively monitor the energy consumption and environmental conditions.

Microelectromechanical system (MEMS) technology [12] has empowered wireless sensor networks (WSNs) by introducing more reliable, smaller, and inexpensive sensors that allow wider utilization of ad hoc wireless systems in industrial applications [13]. WSNs facilitate better insight into the industrial systems by real-time monitoring and provide the opportunity to improve the efficiency and productivity by evaluation and control of industrial operations. The monitoring applications of WSNs include environmental monitoring (indoor/outdoor), power monitoring, process automation, and structural monitoring, among other types of monitoring [14].

In this research, a data center in the city hall of Gresham, Oregon was evaluated. The data center consists of a row of seven racks, which was monitored by installing a wireless sensor network (WSN) to collect energy use, temperature, and humidity data for a period of six weeks. Energy efficiency and thermal management of the data center was evaluated using a combination of energy and thermal metrics. This study forms a pilot project for installation and performance monitoring of a new data center cooling technology to be installed for the data center [15]. The current split system AC units will be replaced with a rooftop mounted indirect evaporative cooling unit. Energy loads will be evaluated with the existing system (baseline) and new system over extended periods to account for seasonal variation. Ultimately, the goal is to evaluate and compare data center energy efficiency and thermal management performance in each case.

The following sections review a variety of metrics to be applied to data collected for the data center. The equipment configuration and setup is then described and results are presented. Finally, conclusions are drawn from the work and opportunities for future work are discussed.

2. Energy efficiency and thermal management metrics for data centers

Higher energy efficiency leads to lower operational costs in data centers. In order to improve and optimize the energy consumption and thermal management in data centers, appropriate metrics are imperative to evaluate their efficiency and performance. Measuring the performance of a data center based upon a standard metric provides the opportunity to track improvements and changes, to estimate the impact of changes, and to draw comparisons to other technologies and data center configurations.

A variety of metrics have been proposed [8] to quantify data center efficiency and performance. In this study, metrics were selected which would enable better insight into energy efficiency and thermal management issues from among the most widely used metrics. The metrics reviewed below help in understanding the operational health and the load on different types of equipment. The objective is to measure baseline performance of the data center, so performance-related impacts of future changes, such as installation of a new cooling system, can be evaluated. Metrics have been previously introduced to evaluate the performance of servers inside the racks, which are not the focus of this paper.

3. Power usage effectiveness (PUE) and data center infrastructure energy (DCiE) metrics

Two primary metrics, power usage effectiveness (PUE) and data center infrastructure energy (DCiE), were introduced by the Green Grid industry consortium over the past decade [16] to measure data center energy efficiency. PUE is defined as the total energy delivered to the data center over the total energy drawn by the IT equipment. IT equipment energy is defined as "the energy consumed by equipment that is used to manage, process, store, or route data within the compute space" [16]. PUE is the most widely-used metric and can be calculated using Eq. (1).

$$\mathrm{PUE} = \frac{P_{\mathrm{inf.}} + P_{\mathrm{IT}}}{P_{\mathrm{IT}}} \tag{1}$$

In this equation, $P_{\mathrm{inf.}}$ is the power input into the supporting infrastructure, mainly the cooling system, and P_{IT} is the power consumed by the IT equipment in the racks.

Ideally, PUE would hold a value of 1.0, meaning all the power into the data center is consumed by the IT equipment. However, in reality, due to the heat dissipated, energy consuming cooling strategies are imperative to reject heat from the racks. Additional power used for rack cooling purposes increases the value of PUE as suggested by Eq. (1). Higher values of PUE imply inefficiency in cooling systems and thermal management of data center. An average data center PUE of 2.0 is reported by the U.S. Department of Energy, while several efficient data centers have reported a PUEs of about 1.1 [17].

DCiE represents a reciprocal of PUE and, thus, can be calculated using Eq. (2).

$$\mathrm{DCiE} = \mathrm{PUE}^{-1} = \frac{P_{\mathrm{IT}}}{P_{\mathrm{inf.}} + P_{\mathrm{IT}}} \tag{2}$$

As seen in the above equations, PUE and DCiE measure the portion of the total power into the data center that is consumed by the IT equipment and infrastructure.

3.1. Rack cooling index (RCI)

The rack cooling index (RCI) proposed by Herrlin [18] measures the degree to which the IT equipment inside the racks are maintained in the rack intake air temperature range recommended by American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) [19]. Thus, the RCI metric evaluates how effectively an adequate environment is provided for the racks and is expressed by the range defined by Eqs. (3) and (4).

$$\mathrm{RCI_{HI}} = \left[1 - \frac{\sum (T_{\mathrm{intake}} - T_{\mathrm{max-rec}})_{T_{\mathrm{intake}} > T_{\mathrm{max-rec}}}}{(T_{\mathrm{max-all}} - T_{\mathrm{max-rec}})n}\right] \times 100\% \tag{3}$$

$$\mathrm{RCI_{LO}} = \left[1 - \frac{\sum (\mathrm{T_{min-rec}} - \mathrm{T_{intake}})_{\mathrm{T_{intake}} < \mathrm{T_{min-rec}}}}{(\mathrm{T_{min-rec}} - \mathrm{T_{min-all}})\mathrm{n}}\right] \times 100\% \tag{4}$$

$\mathrm{RCI_{HI}}$ is the rack cooling index value at the high end of the recommended temperature spectrum, $\mathrm{RCI_{LO}}$ is the value at the low end of the recommended temperature spectrum, T_{intake} is the rack intake air temperature, n is the total number of intakes, $T_{\mathrm{max\text{-}rec}}$ is the maximum recommended temperature, $T_{\mathrm{max\text{-}all}}$ is the maximum allowable temperature, $T_{\mathrm{min\text{-}rec}}$ is the minimum recommended temperature, and $T_{\mathrm{min\text{-}all}}$ is the minimum allowable temperature.

According to ASHRAE, the recommended and allowable ranges for rack intake temperature is 18–25 °C (64–77 °F) and 15–32 °C (59–90 °F), respectively [19]. An RCI of 100% reflects intake temperatures within the recommended range. Lower percentages of $\mathrm{RCI_{HI}}$ imply that heat rejection from the racks is not effective and there is a possibility of hot spots within the racks. Similarly, lower percentages of $\mathrm{RCI_{LO}}$ indicate that the racks are overcooled, which suggests low cooling power efficiency due to poor thermal management.

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3.2. Return temperature index (RTI)

In order to evaluate the air management effectiveness of data centers, the return temperature index (RTI) was proposed [20], which can be calculated using Eq. (5).

$$\mathrm{RTI} = \left[\frac{T_{\mathrm{Return}} - T_{\mathrm{Supply}}}{\Delta T_{\mathrm{Rack}}}\right] \times 100\% \quad (5)$$

T_{Return} is the temperature of air leaving the data center, T_{Supply} is the supplied air temperature, and ΔT_{Rack} is the temperature difference between the rack intake and exit air. RTI assesses the extent to which the air bypasses the rack equipment, as well as the air recirculation in the racks. Air bypass and recirculation impact data center thermal management and energy performance. Bypassed air does not contribute to cooling the IT equipment and depresses the temperature of the air leaving the room. Likewise, air recirculated through the racks produces hot spots in the IT equipment, which in turn increases the temperature of the air returned to the cooling system.

Therefore, higher deviations from an ideal RTI (100%) imply a poor air management system in the data center. Recirculation dominates when an RTI of above 100% is obtained, indicating an elevated return air temperature. Similarly, an RTI of below 100% due to return air depression suggests air bypass as the primary reason for poor air management performance.

3.3. Supply and return heat indices (SHI, RHI)

In order to improve air management and prevent mixing of cold and warm air streams, it is imperative to separate the cold and hot aisles of the data center using containment strategies. It can be noted that the cold aisle is located on the air intake side of a row of racks, while the hot aisle is located on the air exit side. Effective containment strategies maximize the temperature differences between the data center supply air and air returned to the cooling system, which minimizes the overall cooling load. Lower cooling loads lead to higher efficiency data centers.

Sharma et al. [2] proposed the supply and return heat indices to measure the level of separation of supplied and returned air streams. The supply heat index (SHI) is the ratio of sensible heat gained in the cold aisle to the heat gained at the rack exit (Eq. (6)).

$$\mathrm{SHI} = \frac{T_{\mathrm{intake}} - T_{\mathrm{Supply}}}{T_{\mathrm{exit}} - T_{\mathrm{Supply}}} \quad (6)$$

T_{intake} is the rack intake air temperature, T_{exit} is the temperature of rack exit air, and T_{Supply} is the temperature of air supplied to the data center. Lower values of SHI suggest less mixing of warm and cold streams in the cold aisle due to effective containment strategies.

The return heat index (RHI) is defined as the ratio of heat extracted by the cooling system to the sensible heat gained at the rack exit (Eq. (7)).

$$\mathrm{RHI} = \frac{T_{\mathrm{return}} - T_{\mathrm{Supply}}}{T_{\mathrm{exit}} - T_{\mathrm{Supply}}} \quad (7)$$

RHI measures the degree to which supply air is mixed with the return air stream. A high RHI value implies that insignificant mixing of rack exit and cold aisle air streams takes place before the air is returned to the cooling unit. RHI and SHI hold values between 0 and 1. Higher RHI and lower SHI values imply effective separation of the cold and hot aisles. The next section introduces the data collection system implemented to evaluate the above metrics for an actual data center over a period of time.

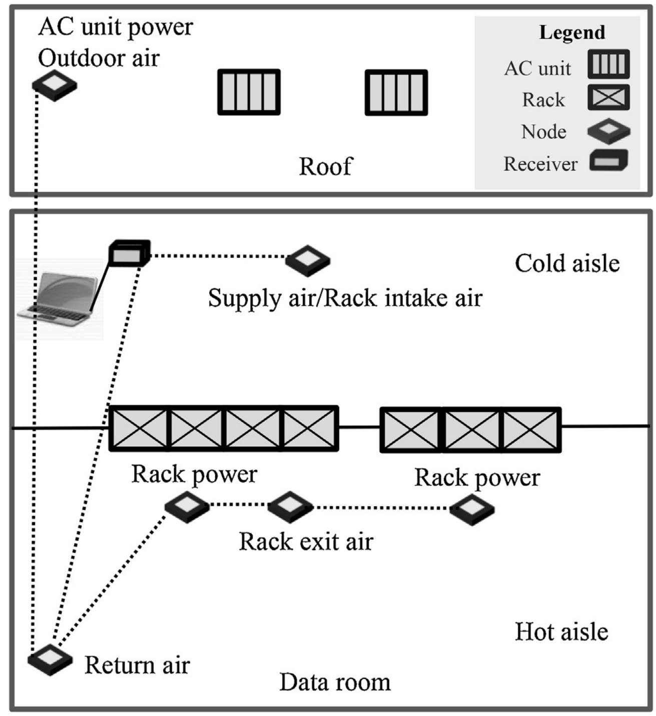

Fig. 1. Schematic top view of the wireless sensor network (WSN) installed at the Gresham City Hall (Gresham, OR).

4. Experimental setup

A wireless monitoring network was developed and installed at the data center located in the Gresham City Hall (Fig. 1). The network includes data collection nodes within the data center, as well as those in close proximity to the data center cooling system located on the roof. All evaluation nodes on the roof and in the data center were connected in a single wireless network.

The monitoring equipment on the roof, including a dry bulb temperature sensor, a relative humidity (RH) sensor, and current transducers, provides the outdoor air status as well as the cooling system load. The nodes that log data from temperature/RH sensors in the data center enable measuring the quality of rack intake and exit air, as well as the air supplied to the room and returned to the cooling units at the HVAC air duct vents. The IT equipment load is measured by monitoring the power draw of each of the 14 rack power cords (two cords per rack).

Each of the data loggers was scheduled to record the data with an interval of 1 min. In order to increase the robustness of the network, a router was added into the monitoring system to improve the communication path from the equipment on the roof to the receiver. A receiver connected to a laptop in data center collects data transferred by data loggers and saves it to the database.

Recorded data from nodes in the wireless network are automatically saved to a single file. The network is programmed to save a copy of the updated file to a local drive, send a copy to the Oregon State University Energy Efficiency Center via email, and save a copy to an Oregon State University FTP address every 24 h. An alarm is set to alert the research team when a logger reading is out of range or a node is identified as missing from the network. Also, a "heartbeat" alarm notifies researchers every 12 h that the network is active and the receiver is collecting and recording data from the nodes.

With the system thus implemented, it is possible to collect detailed data for the IT equipment and cooling system for extended time periods, which can then be used to evaluate the efficiency of the data center using the metrics defined above. These results are

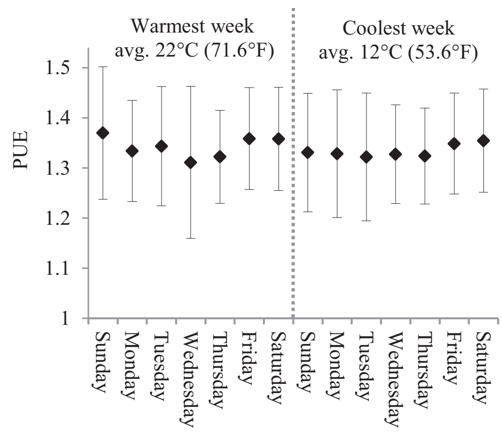

Fig. 2. Average and standard deviation of PUE over the warmest and coolest weeks of the monitoring period.

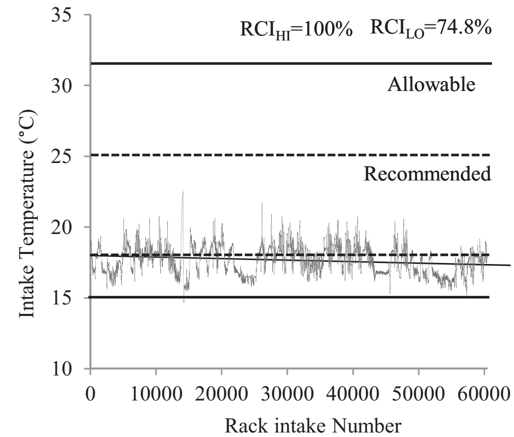

Fig. 4. IT rack intake temperature compared to ASHRAE environmental guidelines [19].

provided in the next section for a period extending from late summer to early fall, which allows for some seasonal variation effects to be elucidated.

5. Results and discussion

The energy efficiency and thermal management metrics discussed above are used and the data center baseline performance is evaluated and summarized based upon the data collected over a monitoring period of six weeks. A total of 1,512,000 data points for all of the 25 parameters (over 60,000 data points for each parameter) were collected. Fig. 2 demonstrates the measured PUE over the warmest and coolest weeks of the monitoring period. As can be seen in the figure, the average PUE tends to slightly decrease with a reduction of outdoor temperature (1.34–1.33).

An overall average PUE of 1.33 (DCiE of 75%) was measured, which suggests that about 0.35 W of power is consumed to condition the data center air and remove the heat from the racks for every watt of electricity delivered to the IT equipment.

To examine the impact of the outdoor temperature and cooling power on PUE, the trend lines of the relationships are plotted over the warmest day of monitoring period in Fig. 3. As the plot illustrates, a temperature rise of 10 °C corresponds to a cooling load increase of about 300 W, which in turn elevates the PUE value by about 0.02.

Due to significant variations in the cooling power (relative standard deviation of 38%) and slight variations of the IT load (relative standard deviation of 1%) a greater effect of outdoor temperature on cooling load and PUE was expected. The PUE analysis implies that the cooling system is operating sub-optimally and there is a potential for improvement of energy efficiency. In order to investigate the cooling efficiency of the data center the thermal metrics are evaluated. Fig. 4 provides a picture of how the temperature of the air entering the racks fulfills the ASHRAE guidelines, using the RCI method.

The calculated RCI_{HI} of 100% indicates the absence of overheating. In other words, the rack intake air temperature falls within the ASHRAE recommended range over the entire monitoring period. Calculated RCI_{LO} values below 100% indicate that the racks are cooled below the low temperature recommended by ASHRAE during the monitoring period.

A similar analysis can be conducted by evaluating collected intake air temperature and relative humidity data using a psychrometric chart (Fig. 5). It can be seen from the chart that the data mostly fall below the recommended temperature range suggested by ASHRAE (none are above), which confirms the results of the rack cooling indices. The psychrometric chart suggests that a shift in rack intake air to the right within the recommended envelope (higher temperature and lower relative humidity) will enable a considerable saving in energy due to a reduced cooling system

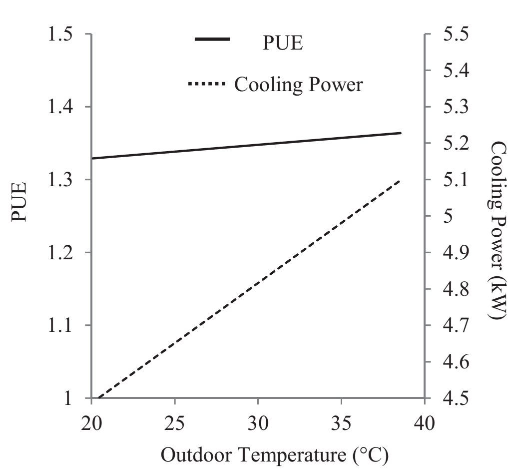

Fig. 3. The impact of outdoor temperature and cooling power on PUE.

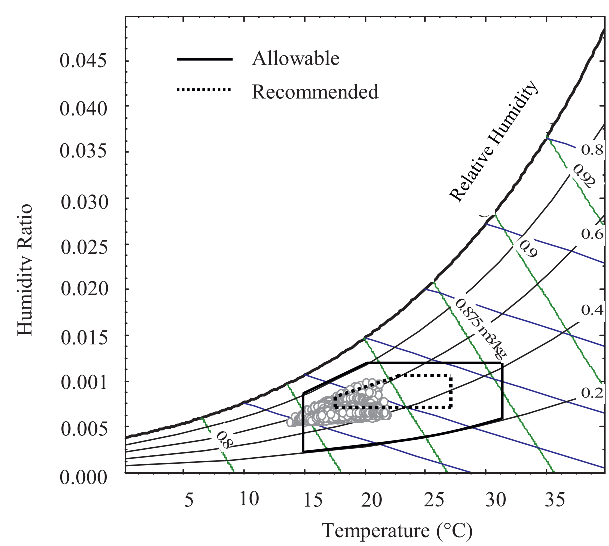

Fig. 5. Psychrometric chart of IT rack intake temperatures with ASHRAE guideline envelopes shown.

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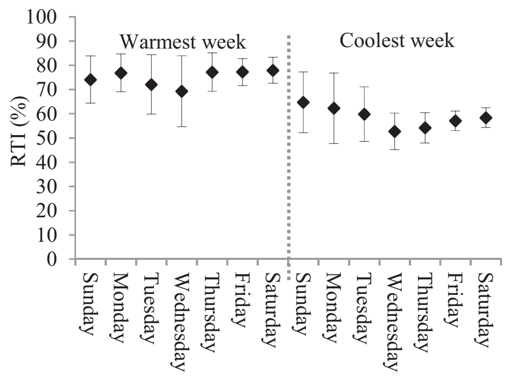

Fig. 6. Average and standard deviation of RTI over the warmest and coolest weeks of the monitoring period.

load. Overcooling the racks elevates the cooling load and lowers the power efficiency, which in turn increases the PUE value.

Return temperature index (RTI) values are plotted in Fig. 6 for the warmest and coolest weeks. RTI provides a picture of the effectiveness of air management strategies in the data center, such as hot aisle/cold aisle isolation and air bypass prevention. Deviations from ideal RTI (100%) suggest presence of air recirculation and bypass due to ineffective air management strategies. Average RTIs of about 75% and 58% were observed at the warmest and coolest weeks, respectively. An RTI below the ideal value of 100% suggests that a portion of the air supplied to the racks bypasses the IT equipment and enters the hot aisle, resulting in a temperature reduction of the air exiting the data center. During the cooler week, the RTI deviation from 100% is greater, implying that air management is less efficient due to larger bypassed air.

In order to evaluate the containment strategy employed, supply and return heat indices are measured. Hot/cold aisle containment curtains are placed in line with the racks, while the racks are fitted with doors that facilitate air flow over the IT equipment. The racks are relatively open, internally.

As Fig. 7 illustrates, averages of about 16% and 74% were calculated for SHI and RHI respectively, which indicate the level of separation of the cold and hot aisles. The deviations of the measured SHI and RHI from ideal values of 0 and 1, respectively, illustrate that air flow effectiveness can be improved with other containment strategies.

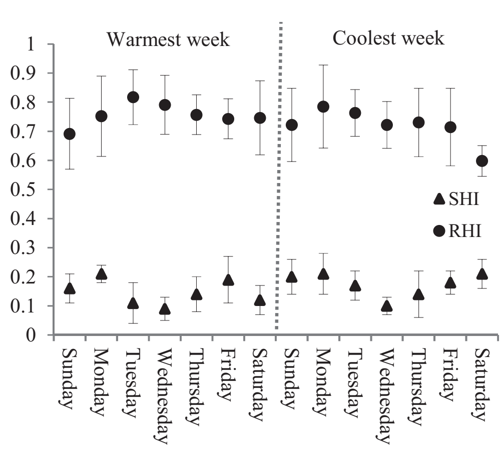

Fig. 7. Daily average and standard deviation of SHI and RHI over the warmest and coolest weeks of the monitoring period.

6. Conclusions and future work

Monitoring of energy use and environmental conditions is imperative in order to assess data center energy efficiency and thermal management effectiveness. Related metrics that have been developed by the IT community enable measurement of performance and evaluation of the impact of IT equipment and infrastructure changes on data center performance. Selecting and continuously evaluating the appropriate metrics will enable better insights into data center efficiency improvement strategies.

A wireless sensor network (WSN) was established at the selected data center in Gresham, Oregon to facilitate remote monitoring of real-time data for equipment power use and the inside and outside environmental conditions. Through the application of various metrics that have been developed by the IT community, this monitoring network provided the opportunity to identify the performance issues that could be addressed in redesign to improve in energy efficiency and thermal management of the data center. As a result, the measurement and analysis of energy efficiency and thermal management metrics for the data center suggests the potential for performance improvement through a change in cooling system and hot/cold aisle containment strategies.

It was observed that the IT racks were overcooled for over 25% of the monitoring period. Air delivered to the racks was often below the ASHRAE recommended guideline envelope for temperature and humidity ratio, and often outside both limits for relative humidity. The low return temperature index (RTI) indicated that a considerable portion of the air delivered to the racks bypassed the IT equipment in the racks. The value of supply and return heat indices (16% and 74%, respectively) showed inadequate separation of hot/cold aisles. Thus, hot/cold aisle containment and air flow management can be improved to enhance the overall efficiency of the center.

Despite the development of various metrics for evaluating the efficiency of data centers, no metric has been proposed to simultaneously evaluate the impact of the center level and rack level (i.e., infrastructure and IT equipment) changes on energy efficiency. The most commonly applied existing metric (PUE) is limited due to both infrastructure and IT loads appearing in the denominator of the expression. Thus, if improvements are made to IT equipment energy use without simultaneous changes to infrastructure energy use, the PUE metric value will actually increase.

Due to the challenges and limitations of existing metrics, future work should focus on developing a metric to more effectively evaluate energy efficiency and the impact of changes in data centers. This would allow higher level decision makers to evaluate results based on a single metric, rather than necessitating the measurement, analysis, and evaluation of a set of metrics. Such an approach would be more straightforward and time effective, and potentially reduce the effect of valuation of competing metric results, should they occur.

In addition, future work could explore the potential for optimization of metrics to improve overall data center performance through operational adjustments in response to real-time performance measurement data. Monitoring over an extended time period could be leveraged in predicting power consumption of IT equipment which in turn allows quick response to environmental conditions surrounding IT equipment. Predictive modeling could also reveal the need for maintenance, changes to infrastructure or operating conditions, or new IT equipment technology.

From the foregoing discussion, it can be seen that demands for data center and IT solutions continue to increase, including demands within the manufacturing sector to understand process and equipment operating conditions in real time to improve energy, environmental, and quality performance. This demand is driving the installation of dedicated data centers both within and outside of existing building infrastructure, which necessitates thermal management of those spaces – often through conventional refrigeration cooling systems. These data centers thus represent a significant energy load, which in turn must be managed through new technologies and control strategies.

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