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A review of air conditioning energy performance in data centers

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ABSTRACT

During the last years, many countries are experiencing rapid expansions in the number and size of data centers to keep pace with their internet and cloud computing needs. High energy consumption of the data center has gradually attracted public attention. However, there are no common efficiency standards governing the design or operation of data centers and the associated air conditioning systems. And the statistical research on air conditioning energy performance is still sorely lacking. This paper presents a summary of 100 data centers air conditioning energy performance. Energy efficiency metrics and benchmarks are also provided so that operators can use these information to track the performance of and identify opportunities to reduce energy use of air conditioning systems in their data centers. The collected data from articles and reports show that the average of HVAC system effectiveness index is 1.44. More than half of the data centers' air conditioning systems are inefficient. In total, HVAC systems account for about 38% of facility energy consumption. The range for this usage was 21% for the most efficient system and 61% for the least efficient system. Moreover it would be necessary to review some currently available energy efficiency strategies such as economizer cycles, airflow optimization, energy management, and simulations tools.

Contents

1. Introduction

A data center is a facility housing computer systems and

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associated components, such as telecommunications and storage systems. It generally includes backup power supplies, redundant data communications connection, environmental controls (e.g., air conditioning and fire suppression) and various security devices [1]. During the last years, many countries are experiencing rapid expansions in the number and size of data centers to keep pace with their internet and cloud computing needs. Because the high density of information technologies equipment (ITE) and the fact that they run 24 h a day, the 365 days of the year, the energy consumption of data center is tremendous. The energy demand per square meter of data centers, which is up to 100 times higher than for office accommodations, increased significantly during recent years [2]. In an Environmental Protection Agency (EPA) report to Congress in 2007, 1.5% of the total United States' energy consumption of 61 billion kWh was attributed to data centers in 2006 [3]. In 2013, U.S. data centers consumed an estimated 91 billion kWh of electricity. Data center electricity consumption is projected to increase to roughly 140 billion kWh annually by 2020 [4].

ITE exposed to high temperature, or to high thermal gradients, can experience thermal failure, particularly when repeatedly exposed to such high thermal gradients. The high heat density of the equipment combined with its thermal sensitivity is a volatile combination, and any loss or disruption to temperature and humidity control, even for a very short time, can lead to ITE damage or loss of data [5]. An interruption caused by ITE failure would entail costly repairs and replacement. Any disruption to ITE operation typically results in a loss of revenue for the end user. The business may lose thousands or even millions of dollars for every minute of downtime [6]. The air conditioning systems that provide for environmental control of temperature, humidity and air contaminant are essential to data centers.

The predominant cooling load of air conditioning system in almost all data centers is the sensible ITE load. The heat density of certain types of ITE is increasing dramatically. The projected heat load growth of 1U compute servers is 20–45% from 2010 to 2020. The 2U compute servers with two-socket configuration has the highest percent growth from 2010 to 2020 of all the servers: 67% [7]. The increase of ITE heat load lead to many uplift of air conditioning system energy consumption. Case studies of 44 data centers conducted by Salim and Tozer showed that the air conditioning system accounted for an average of 40% of the total energy consumption of the data center. The range for this usage was 24% for the most efficient system and 61% for the least efficient system [8]. This means that close attention needs to be given to air conditioning systems to minimize data center energy consumption. But there are little research on air conditioning energy performance in data centers.

Efficiency standards are required for performing a serious analysis of energy efficiency. However, there are no common efficiency standards governing the design or operation of data centers and the associated air conditioning systems, and no consistent test procedures for checking compliance. In order to evaluate the performance of a data center facility and analyze the best energy efficiency strategies, personnel who have responsibility for managing energy use in existing data centers need to compare it to similar facilities. Comparisons are a quick and easy way to identify poorly operating areas, which typically have the highest potential for economical modifications that reduce operating cost and increase the load capacity of a data center.

The intent of this study is to provide the reader with detailed information on the energy performance of air conditioning systems in data centers. The air conditioning system accounted for an average of a large part of the total energy consumption of the data center. However, the statistical research on air conditioning energy performance is still sorely lacking. Meanwhile, energy efficiency standards governing the design or operation of air conditioning systems in data centers are also lacking in the industry. Consequently, it is hard to evaluate the practical energy efficiency of a data center. In this article, the statistical data of air conditioning energy performance and its associated metrics' benchmark value are provided. So operators could compare their data center to peers and identify the effectiveness of its air conditioning systems. This review paper is presented in three sections. In the first section, a comprehensible literature review is given in environmental guidelines, cooling methods, and air distribution. In the second sections, energy efficiency metrics and benchmarking values are summarized so that readers can use these information to track the performance and identify opportunities to reduce energy use of data center air conditioning systems. This section also presents a detailed review of air conditioning energy performance which provides the reader with a broad and detailed background on data center energy operating conditions. In the third sections, many energy efficiency strategies are explained through a review of the past, current, and projected future growth trend of data center industry. It is hoped that this paper will be helpful to researchers in this field.

2. Air conditioning

2.1. Indoor thermal guidelines

The indoor thermal conditions have a significant impact on air conditioning energy consumption. The air conditioning systems control the temperature, humidity and air contaminant in data centers. Wang et al. estimated the energy consumption of air conditioners at different temperature set points. The results shown that the percentage of energy saving was 4.3–9.8% for every 1 °C rise in temperature set points [9]. However, the long-term effect of operating in the high temperatures will result in shortened life of the ITE [5]. So many owners have yet to implement higher ITE intake temperatures within their data centers [10]. Raising temperatures requires a systemic engineering and commissioning approach because each data center, its ITE, air conditioning systems, etc., are unique [11]. High relative humidity (RH) may cause various problems to ITE, such as tape media errors and corrosion. Low RH increases the magnitude and propensity for electrostatic discharge (ESD), which can damage ITE [12]. Compared with absolute humidity, RH is more important [13]. The RH change from 25 to 8% will increase the probability of ESD-related failure in a data center 1–3 times [14]. In addition to temperature and humidity control, dust and gaseous contamination should also be monitored and controlled. These additional environmental measures are especially important for data centers located near industries and/or other sources that pollute the environment [15].

The thermal standard for data centers is strict in China. The recommended environment range of dry-bulb temperature is 22–24 °C. And the RH range is 40–50%. The strict environmental guideline makes no contribution to the goal of reduced energy consumption in data centers. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) created the first edition of *Thermal Guidelines for Data Processing Environments* in 2004. In order to give guidance to data center operators on maintaining high reliability and also operating their data centers in the most energy efficient manner, ASHRAE updated this guideline in 2008 and 2011 [16]. The edition currently available is the third edition, published in 2012 [17]. The suitable environmental conditions for ITE are summarized in Table 1. Moreover, Fig. 1 shows the temperatures and RH recommended in a psychrometric chart. The revision of this envelope allows greater flexibility in facility operations, and contributes to reducing the

Table 1
Summary of 2011 ASHRAE thermal guidelines for data centers [17].

	Dry-bulb Temperature	Humidity range	Maximum Dew point
	Recommended		
Class A1 and A4	18–27 °C	5.5 °C DP to 60% RH and 15 °C DP	–
	Allowable		
Class A1	15–32 °C	20–80%	17 °C
Class A2	10–35 °C	20–80%	21 °C
Class A3	5–40 °C	8–85%	24 °C
Class A4	5–45 °C	8–90%	24 °C

overall energy consumption. Based on recent ASHRAE research, however, Technical Committee (TC) 9.9 (Mission Critical Facilities, Technology Spaces, and Electronic Equipment) has recently voted out an expansion of the Recommended and Allowable Ranges to include lower humidity levels. The fourth edition, which will publish these expanded ranges, is expected to be available by ASHRAE's 2016 Winter Conference [18]. Currently, the global tendency of indoor thermal guidelines for data centers is loosening in order to achieve higher level of energy conservation.

Based on the discussion above, the balance between energy conservation by loosening indoor thermal guidelines and availability of ITE should be handled carefully.

2.2. Cooling methods

The cooling methods of data centers can be divide into air cooling and liquid Cooling. The first computers were typically quite large, and consisted of a core processing machine with peripherals. Many of the early mainframes were liquid cooled. A large portion of mainframes shipped throughout the 1970s and 1980s used water-cooling technologies to cool the high power density bipolar semiconductor chips [19]. In the early 1990s, the market shifted from bipolar technologies to semiconductors where the power dissipation was an order of magnitude less and air cooling was the most cost-effective choice for removing heat [20]. The changing semiconductor technology resulted in a revolutionary shift from liquid cooling to air cooling.

Packaged computer room air conditioning (CRAC) units and central station air handling systems are the two main air cooling methods. Currently, CRAC units are the most popular data center air cooling solution. The cooling air is supplied to the inlets of the ITE for convection cooling of the heat rejected by the components of the ITE within the rack [21]. A significant amount of wasted energy has been found in many existing data centers, often due to fighting between adjacent CRAC units to maintain unnecessarily tight tolerances. Historically, CRAC was selected for a supply air temperature in the range of 12.8–15.6 °C [22]. An inlet temperature of 12.8 °C is too cold for the ITE. Since the cooler coil can result in overcooling of the space, the colder discharge air is often reheated in constant volume systems, resulting in high energy use through simultaneous heating and cooling. And therefore, lots of large data centers use central station air handling units to avoid such fighting between adjacent CRAC units. Central station supply systems should be designed to accommodate a full range of loads in data center ITE areas with good part-load efficiency. Due to their larger capacity, central station supply systems may be able to provide more efficient energy recovery options than CRAC units. Sullivan et al. introduced using the heat wheel to cool data centers. The heat wheel cooling system could reduce the operating cost by $5 M to $6 M a year, for a 5 MW installation [23].

Nowadays, the heat load in server racks may be exceeding air cooling limits both the microprocessor level and within a data center. Thereby driving designs back to employ liquid-cooled solutions [24]. Liquid cooling is defined that conditioned liquid is supplied to the inlets of the ITE. Unlike air cooling solution, the heat rejection media to the building cooling device outside the rack is liquid. Liquids are much more effective in the removal of heat than air, making liquid cooling a more viable choice for high density data centers [25]. David et al. presented a chiller-less data center where server-level cooling is achieved through a combination of warm water cooling hardware and recirculated air; eventual heat rejection to ambient air is achieved using a closed secondary liquid loop to ambient-air heat exchanger. The result showed that significant energy savings can be achieved at the data center level of approximately 25% which represents greater than 90% reduction in the cooling energy usage compared to conventional refrigeration based systems [26]. However, there is often a concern over the presence of water near ITE. Refrigerants can be used either in a pumped loop technique or vapor compression

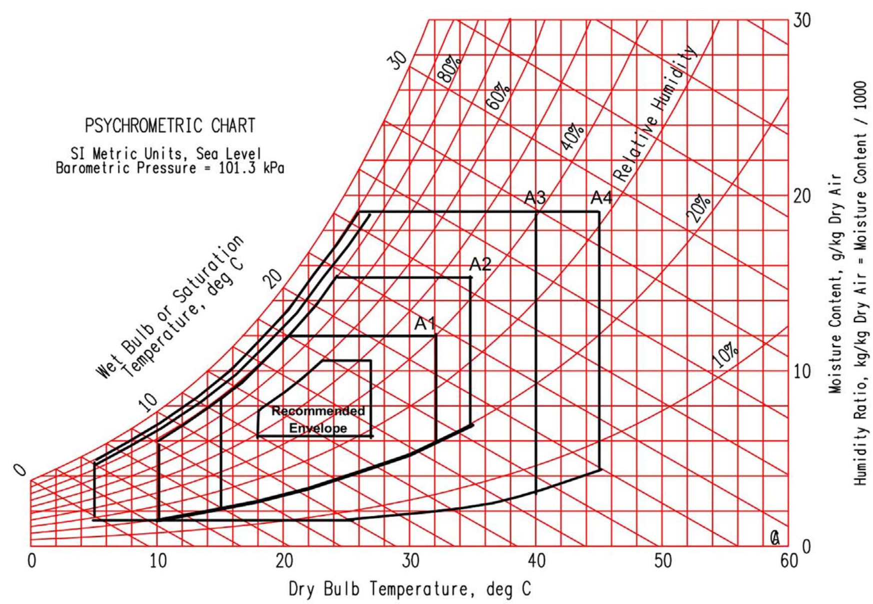

Fig. 1. ASHRAE thermal guidelines for data center operating environments [17].

cycle. The advantages of using refrigerants are that they can contact the electronics without shorting out any of the electronics. When compared with traditional air cooling systems, the energy consumption of the datacenter could be reduced by as much as 50% when using a liquid pumping cycle and 41% when using a vapor compression cycle [27].

The concept of availability is very important when considering air conditioning systems for data centers. The high heat density of the ITE combined with its thermal sensitivity is a volatile combination. Any loss or disruption to cooling or humidity control, even for a very short period, can lead to ITE damage or loss of data. The most common method used to attain greater system availability is to add redundant parallel components to avoid having a single component failure trigger a system-wide failure [28]. But the right balance and tradeoffs need to be determined with energy efficiency [29]. Air conditioning is an area where further research is needed to allow for the calculation of system availability as a function of component availability and level of redundancy.

2.3. Air distribution

Air distribution plays a major role in determining the temperature and RH in the data center. It is a challenging task that delivering the appropriate amount of cold air at the ITE inlets. Meanwhile, returning the hot air without mixing with the cold air is also important. Recirculation and excessive mixing of hot return and cold supply airstream could be detrimental to the performance and life of the ITE. Also, short-circuiting of cold air back to air conditioners without passing through the ITE can significantly affect the performance and the energy efficiency of the air conditioning units [30].

Underfloor air distribution (UFAD) system is, by far, the most common type of air delivery method for data centers. CRAC units supply conditioned air into the raised-floor air space. Then, the air exits this air space through perforated floor tiles located near the inlets of the ITE [6]. The hot aisle/cold aisle arrangement, as shown in Fig. 2, can create a steady supply of cold air from the front of the racks and extract the hot exhaust air from the rear of the racks. This is best accomplished by aligning racks in rows such that they face front-to-front and rear-to-rear with supply air delivered only to the cold aisles [31].

A lot of studies have focused on the factors that affect the air delivery and overall performance of a raised-floor data center. The key to controlling the airflow distribution is the ability to influence the pressure variation in the plenum. The effect of plenum height and open area of perforated tiles is significant [32]. Arghode and Joshi investigated air flow development above a perforated tile and its entry into an adjacent rack. With decrease in effective tile porosity from 36.7 to 21.1%, significantly higher air bypass from the top of the rack is observed [33]. High flow tiles can allow more airflow at a given pressure but lead to less uniform and predictable distributions. 25%-open perforated tiles are usually used. Because they could provide a good balance of low pressure drop and relatively uniform underfloor pressure [34]. The layout of perforated tiles can lead to significant variations and possibly reversed flow or warm air being drawn down into the plenum from the facility [35]. Cable cutouts and gaps around tiles and other openings in the raised floor result in leakage airflow. Radmehr indicated that leakage airflow can amount to anywhere from 10 to 15% of the total airflow supplied to the raised-floor air space [36]. High leakage rates result in poor uniformity of airflow through the perforated tiles and poor cooling efficiency [37]. Underfloor obstructions can substantially disrupt the distribution of supply air in the raised-floor air space. Bhopte et al. studied the effect of underfloor blockages on data center air distribution performance. Additional blockages in critical flow path are shown to reduce the flow rate of supply tiles by 19%. On the other hand blockages in safe flow path are shown to reduce the supply tile flow rates by 3% [38]. Raised-floor air space depth should generally be designed for a minimum of 610 mm of clear space. Greater raised-floor air space depth can help achieve a more uniform pressure distribution in some cases [39].

In addition, there are a small amount of non-raised floor data centers that usually adopt overhead supply air distribution. This protocol refers to the delivery of air from overhead ductwork.

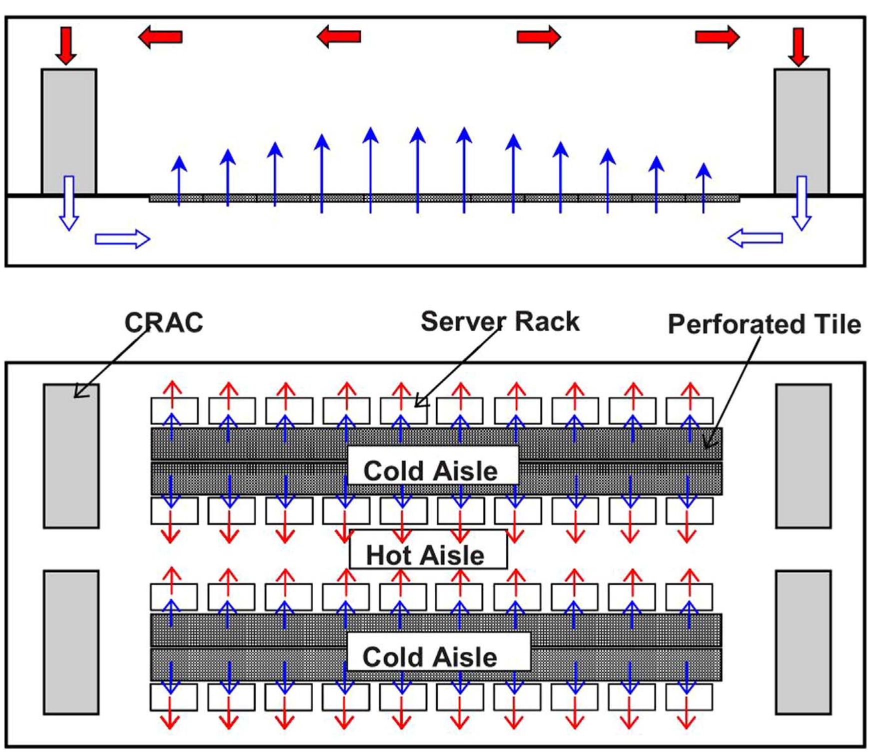

Fig. 2. The hot aisle/cold aisle arrangement in a raised-floor data center [6].

Sorell indicated that under certain room configurations and design conditions, overhead supply air distribution systems can achieve more uniform inlet conditions at the racks when compared to raised-floor air distribution systems [40].

3. Energy performance

3.1. Metrics and benchmarks

Energy efficiency metrics and benchmarks can be used to evaluate the performance of and identify potential opportunities to reduce energy use in data centers. For some of the metrics listed in this section, benchmarking values are also provided for reference. These values are based on a data center benchmarking study carried out by LBNL and the National Renewable Energy Laboratory (NREL) [41].

The most widely used and accepted efficiency metric are the Power Usage Effectiveness (PUE) and the Datacenter Infrastructure Efficiency (DCiE) which is the reciprocal of PUE. Both the two metrics were introduced by the Green Grid in 2007 [42]. PUE has become the widely accepted industry de facto standard [43]. This metric is defined as the ratio of the total facility power in the data center over the power of the ITE on the raised floor. The lower the PUE ratio, the better it is. The metric's purpose is to reflect the power overhead needed to run the IT under desired conditions. But PUE does not consider the useful work done by the data center nor its performance [44].

Besides PUE and DCiE, there are several other metrics use to determine the energy efficiency of a data center. These metrics and corresponding benchmark values are summarized in Table 2. Bruschi et al. proposed that the HVAC system effectiveness can be used to evaluate the effectiveness of air conditioning systems. A lower HVAC system effectiveness corresponds to a relatively high HVAC system energy use. And the energy efficiency potential is higher. Airflow efficiency provides an overall measure of how efficiently air is moved through the data center, from the supply to the return, and takes into account low pressure drop design as well as fan system efficiency. Cooling system efficiency is the most common metric used to measure the efficiency of an air conditioning system. A cooling system efficiency of 0.8 kW/ton is considered good practice while an efficiency of 0.6 kW/ton is considered a better benchmark value [41]. These metrics can be used to measure the efficiency of an air conditioning system.

Thermal management and air distribution performance are assuming a key role for achieving the energy saving and ITE reliability for data centers. Various methods have been proposed to quantify the air conditioning system effectiveness. A lot of thermal and airflow performance metrics were introduced in literature to enable real time feedback and control of data centers. The summary of most thermal metrics and benchmark values can be found in Table 3.

Sharma et al. have proposed dimensionless parameters to evaluate thermal performance of data centers. SHI (Supply Heat Index) indices to quantify the extent of mixing of return air with supply air. RHI (Return Heat Index) indices to quantify the extent of bypass of supply air to the return airstream [45]. A value of 0 for SHI and 1 for RHI means that there is no recirculation of hot air, and the air inlet temperature of the racks is equal to the air supply temperature from the CRAC unit. As benchmark, it is considered good performance a value of SHI <0.2 and RHI >0.8 [46]. However, the SHI and RHI do not characterize the localized nature of data center hot spots. A data center could display very favorable values for SHI (low) and RHI (high), while possessing significant local hot spots which result in device failure. β can capture this local inefficiency. The range for β is between 0 and 1. A value of 0 indicates no impact of hot air recirculation [47]. Herrlin proposed RCI (Rack Cooling Index) in 2005. The index is divided into RCI_{HI} and RCI_{LO}. RCI_{HI} is a measure of the absence of over-temperatures; 100% means that no over-temperatures exist. On the other hand, the low RCI_{LO} value is due to a low supply temperature [48]. RTI (Return Temperature Index) was also introduced by Herrlin. RTI equal to 100% is the ideal condition. RTI $>100\%$ indicates recirculation. And RTI $<100\%$ indicate a bypass [49]. Some other metrics were introduced by Tozer et al. to characterize how the air flow rate supply is distributed in the data center. NP (Negative Pressure) measures the ambient air infiltration into the under floor. BP (bypass) measures the rate of air which doesn't get inside ITE. R (Recirculation) indicates the rate of hot air that goes into the ITE. BAL (balance) measures the difference between cold air produced by the air conditioners and the ITE request. The ideal NP is equal to 0. If BP $=1$, all CRAC cooling air would be bypassed, with no air available for ITE. If R$=1$, all ITE air would be re-circulated, with no cooling air entering from the CRAC units. The ideal value of BAL is 1 [50].

3.2. Three aspect of air conditioning energy performance

In order to optimize any HVAC system in data centers, it is crucial to accurately assess its current performance. Lawrence Berkeley National Laboratory (LBNL) has developed a benchmarking guide for data center energy performance [51]. This guide is intended to show data center owners and operators how to perform a comprehensive measurement, or benchmarking, of their own facilities' energy use. Energy benchmarking offers a very effective way to evaluate the performance of a data center facility and compare it to similar facilities. Benchmarking is a powerful

Table 2
Energy efficiency metrics and benchmark values.

Introduced by	Metrics		Benchmark Values		
			Standard	Good	Better
The Green Grid[42]	PUE	$PUE=\frac{Total\ Facility\ Power}{IT\ Equipment\ Power}$	2	1.4	1.1
The Green Grid[42]	DCiE	$DCiE=\frac{IT\ Equipment\ Power}{Total\ Facility\ Power}$	0.5	0.7	0.9
NREL[41]	HVAC Effectiveness Index	HVAC System Effectiveness$=\frac{Annual\ IT\ Equipment\ Energy}{Annual\ HVAC\ System\ Energy}$	0.7	1.4	2.5
NREL[41]	Airflow Efficiency	Airflow Efficiency$=\frac{Total\ Fan\ Power}{Total\ Fan\ Airflow}$	1.25 W/cfm	0.75 W/cfm	0.5 W/cfm
NREL[41]	Cooling System Efficiency	Cooling System Efficiency$=\frac{Average\ Cooling\ System\ Power}{Average\ Cooling\ Load}$	1.1 kW/ton	0.8 kW/ton	0.6 kW/ton

Table 3
Summary of most thermal metrics and benchmark values.

Introduced by	Metric	Explanation	Information provided	Input parameters	Formula	Benchmark value	
Sharma et al. [45]	SHI	Supply Heat Index	Quantify the extent of mixing of return air	airflow supply temperature from CRAC unit, rack inlet and outlet airflow temperatures	$SHI = \frac{\sum_i \sum_j (T^r_{in_{i,j}} - T^C_{sup})}{\sum_i \sum_j (T^r_{out_{i,j}} - T^C_{sup})}$	ideal good	0 < 0.2
Sharma et al. [45]	RHI	Return Heat Index	Quantify the extent of bypass of supply air	mass flow rate supply from CRAC unit, mass flow rate across equipment, airflow return temperature at CRAC, airflow supply temperature from CRAC unit, airflow temperature exhaust from rack	RHI = 1-SHI	ideal good	1 > 0.8
Schmidt et al. [47]	β Index	Beta Index	Presence of recirculation and over heating	Local airflow inlet supply and outlet temperatures	$\beta = \frac{T^r_{in}(z) - T^C_{sup}}{T^r_{out} - T^r_{in}}$	ideal	0
Herrlin[48]	RCI_{LO}	Rack Cooling Index Low	Quantify the rack health at the high end of the temperature range	Rack intake air temperatures distribution, maximum recommended and allowable temperature according to some guideline or standard	$RCI_{LO} = \left[1 - \frac{\sum (T_{min-rec} - T_x)_{T_x < T_{min-rec}}}{(T_{min-rec} - T_{min-all}) \times n}\right] \times 100\%$	ideal good acceptable poor	1 $\geq 96\%$ 91–95% $\leq 90\%$
Herrlin[48]	RCI_{HI}	Rack Cooling Index High	Quantify the rack health at the low end of the temperature range	Rack intake air temperatures distribution, minimum recommended and allowable temperature according to some guideline or standard	$RCI_{HI} = \left[1 - \frac{\sum (T_x - T_{max-rec})_{T_x > T_{max-rec}}}{(T_{max-all} - T_{max-rec}) \times n}\right] \times 100\%$	ideal good acceptable poor	1 $\geq 96\%$ 91–95% $\leq 90\%$
Tozer et al.[50]	NP	Negative Pressure ratio	Airflow infiltration into underfloor plenum	return air temperature to CRAC, discharge air temperature from CRAC, floor void temperature	$NP = \frac{T^{uf}_{sup} - T^C_{sup}}{T^C_{ret} - T^{uf}_{sup}}$	ideal	0
Tozer et al.[50]	BP	Bypass ratio	the rate of air which leaves the floor grills and returns directly to the CRAC unit without cooling servers	return air temperature to CRAC, floor void temperature, server outlet air temperature	$BP = \frac{T^S_{out} - T^C_{ret}}{T^S_{out} - T^{uf}_{sup}}$	ideal good acceptable	0 0–0.05 0.05–0.2
Tozer et al.[50]	R	Recirculation ratio	the rate of hot air which goes into the IT equipment	server inlet and outlet air temperature, floor void temperature	$P = \frac{T^S_{in} - T^{uf}_{sup}}{T^S_{out} - T^{uf}_{sup}}$	ideal good	0 < 0.2
Tozer et al.[50]	BAL	Balance ratio	the difference between cold air produced by the cooling plant and the server request	server inlet and outlet air temperature, return air temperature to CRAC, discharge air temperature from CRAC	$BAL = \frac{T^S_{out} - T^S_{in}}{T^C_{ret} - T^C_{sup}}$	ideal	1
Herrlin[49]	RTI	Return Temperature Index	Presence of recirculation or bypass phenomena	server inlet and outlet air temperature, return air temperature to CRAC, discharge air temperature from CRAC	$RTI = \frac{T^C_{ret} - T^C_{sup}}{T^r_{out} - T^r_{in}} \times 100\%$	ideal good	100% 95–105%

tool for improving the quality, reliability, and performance of data center facilities. Once the magnitude of power use is identified on a system basis, limited resources can be prioritized for the areas where the greatest savings can be achieved.

In total, 100 data centers in different places collected for comparing and analyzing the air conditioning energy performance using

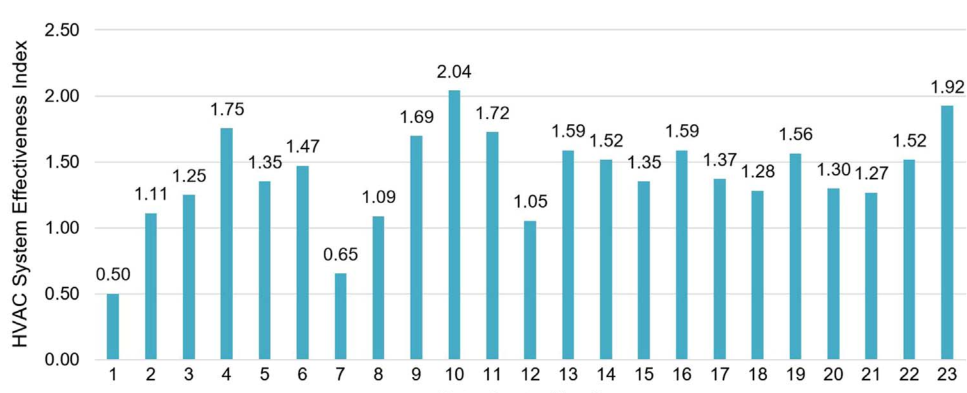

Fig. 3. Annual average HVAC system effectiveness site assessments in Singapore.

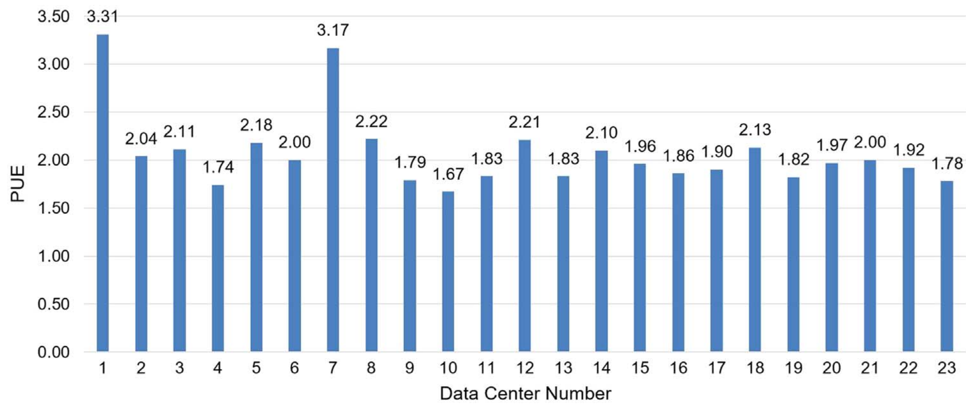

Fig. 4. Annual average PUE of 23 data centers in Singapore.

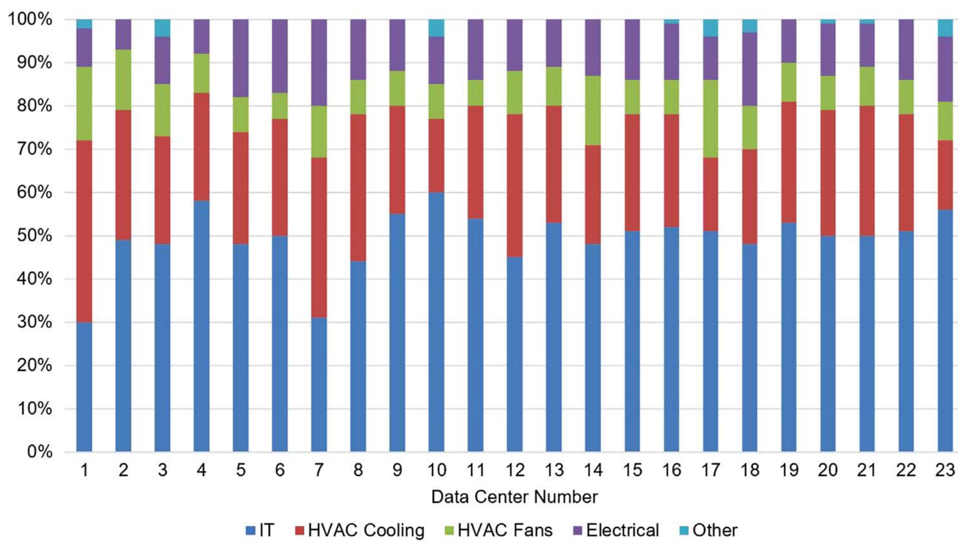

Fig. 5. Variation in data center energy end use of 23 data centers in Singapore.

the metrics discussed above. Data centers can be conditioned with a wide variety of systems, including CRAC units and central station air handling systems. The specific power consumption of CRAC system is usually about 1.45 kW/ton of cooling while the same number for central station air handling systems of those legacy data centers is around 0.8 kW/ton [8]. The air conditioning energy consumption can be grouped into three categories: mechanical cooling equipment, cooling distribution equipment, and heat rejection equipment.

3.2.1. Mechanical cooling equipment

Cooling equipment comprises the central portion of the air conditioning system. Water chillers and small refrigerant compressors are typically two types of mechanical cooling equipment. The CRAC units with small refrigerant compressors are usually

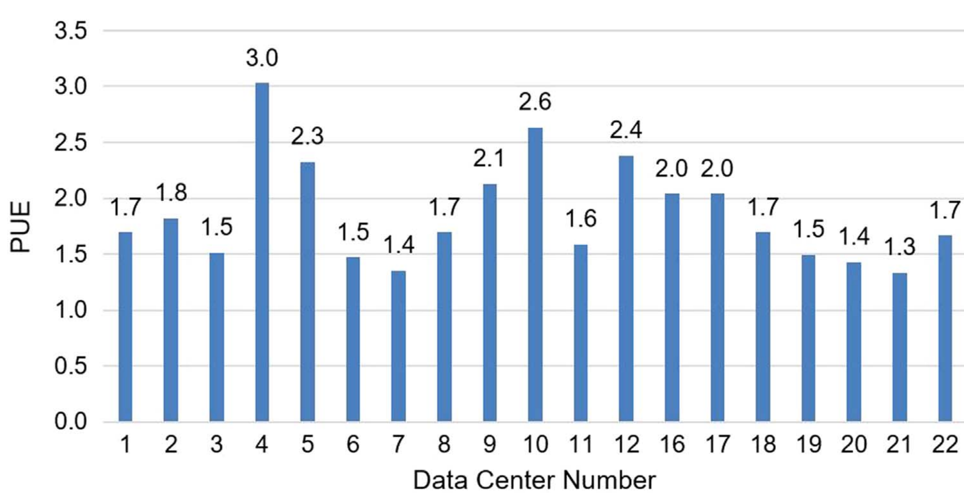

Fig. 6. PUE chart of surveyed data centers.

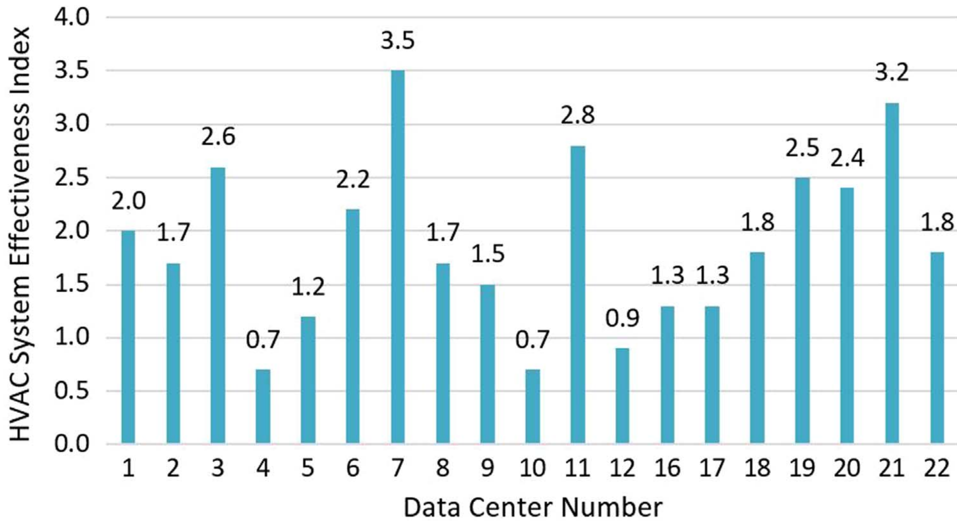

Fig. 7. HVAC system effectiveness chart of surveyed data centers.

used for small data centers, and chilled-water systems are used for larger data centers. National Environment Agency (NEA) benchmarked 23 data centers energy performance in Singapore [52]. They used mechanical PUE to describe air conditioning energy performance. Mechanical PUE was simply defined as the ratio of air conditioning power to ITE power. HVAC system effectiveness is the reciprocal of mechanical PUE. The values of HVAC system effectiveness is shown in Fig. 3. Data centers using water cooled chillers achieved the best HVAC system effectiveness. The least efficient cooling system was air cooled chillers. In Singapore, large and purpose built data center complexes tend to employ water cooled chilled water plants for their primary cooling requirements. The PUE is shown in Fig. 4. The variation in data center energy use is presented in Fig. 5.

Chillers are typically one of the largest users of energy in the large data center. The thermodynamic efficiency of a chiller can increase if leaving chilled-water temperature augment. Many data centers have historically used 7.2 °C chilled water as the supply temperature to a facility. Steve et al. benchmarked 22 data centers energy performance. They supposed that a medium-temperature chilled water loop design using 10–15.6 °C chilled water increases chiller efficiency and eliminates uncontrolled phantom dehumidification loads. The computer power consumption index which is the reciprocal of PUE was used to help gauge the energy efficiency of data centers. Fig. 6 is PUE of 22 data centers after the conversion. And the HVAC system effectiveness are shown in Fig. 7. Data centers which have lower PUE show the higher HVAC system effectiveness [53]. According to the benchmarking data of NEA, increasing the chilled water leaving temperature set point leads to a reduction in energy consumption of the chiller's compressor to a certain extent 1–1.5% per Centigrade degree increase for constant speed chillers). And each Centigrade degree reduction of condenser entering air temperature reduces chiller compressor power consumption by 0.8–1.3% [52]. The part-load efficiency of a chiller can increase after utilizing variable-frequency drives (VFD) [53]. But the capital cost of a chiller with a VFD drive is greater. One method of reducing facility costs for a chilled water plant is by adding an economizer. The water-side economizer made it possible to achieve a maximum energy performance improvement of about 16.6% over the reference base cooling system, whereas the air-side economizer made it possible to achieve about 42.4% improvement [54].

Sun and Lee investigated energy use of two data centers in commercial office buildings in Singapore. The small data center

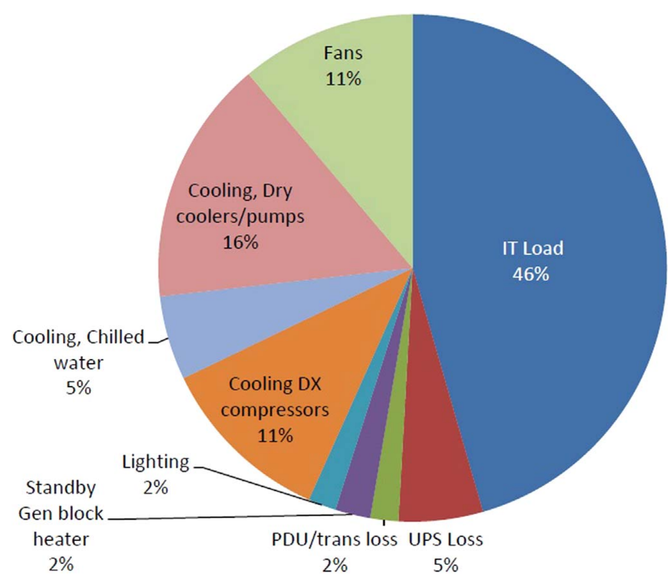

Fig. 8. Breaks out current Data center 1 electrical power use by end use [56].

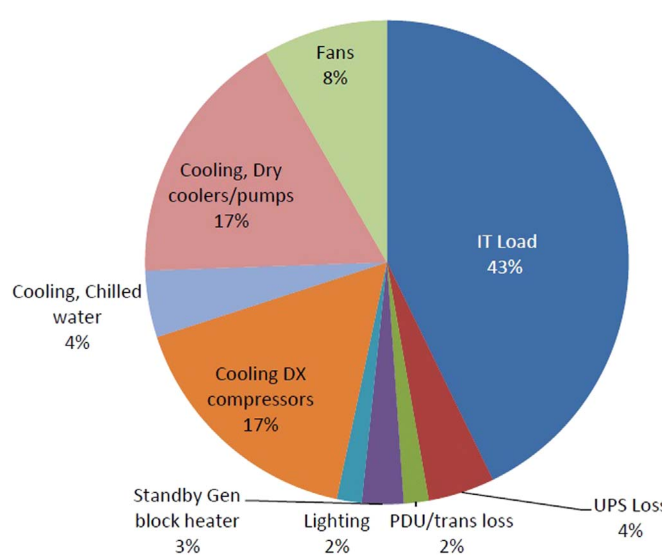

Fig. 9. Breaks out current Data center 2 electrical power use by end use [56].

used CRAC units. And the large data center adopted central station air handling systems to cool ITE. The HVAC system effectiveness of small data center is 1.19, while this value of large data center is 0.51. The main reasons for the inefficiency of air conditioning system is oversizing of equipment. The overall air conditioning system was oversized by a factor of 5 [55]. By conducting energy conservation measures, nearly 75% of the large data center energy can be saved. Although the energy performance is relatively good, the energy consumption of the small data center can reduce 40%. Mahdavi investigated the energy performance of two data centers in Saint Louis. As shown in Figs. 8 and 9, mechanical cooling equipment accounted for 11% and 17% of the total energy consumption of the data center, respectively. And mechanical cooling equipment accounted for 26% and 36% of the total air conditioning energy consumption, respectively. The PUE values are 2.2 and 2.34, while the HVAC system effectiveness are 1.05 and 0.92 [56]. The chilled water supply set point can be increased from 6.4 °C to 12.8 °C as a minimum. This is equal to a more than 15% improvement in chiller efficiency. With a higher temperature difference between the chilled water supply and the chilled water return, the chilled water flow can be reduced, thus saving pumping energy. Lu et al. investigated the air conditioning energy performance in a data center in Finland. 10% of total power consumption is from the chiller. They pointed out that 1.5–2.5% of facility power from the chiller in the data center could be possibly save [57].

3.2.2. Cooling distribution equipment

Cooling distribution equipment includes air distribution equipment and chilled-water distribution equipment. The study conducted by Lu et al. showed that 8% of total power consumption is from the CRAC fans, which was lower than the chiller [57]. The choice of cooling distribution equipment directly affects energy consumption through fan power and cooling power. With fan power, the greater the pressure drop the fan must overcome, the greater the energy consumption. With cooling power, within some practical limits, the greater the degree of separation between the cool supply and the hot return air flows, the greater the operating efficiency of the CRAC units.

Fan energy consumption in distribution equipment can be significant, especially since most fans in a data center facility run 24 h per day, 365 days per year. According to the benchmarking data of NEA, fans accounted for an average of 10.2% of the total energy consumption of the data center. Only 15% of fans utilized VFD [52]. Salim and Tozer presented a summary of the energy audit on more than 40 data centers. The result showed that CRAC unit with VFD were operated at 60–80% of the nominal speed thus consuming fraction of the nominal fan power. Those units were proven to have low fan power consumption accounts for less than 7% of the total data center power [8]. The annual average PUE is shown in Fig. 10. They used $PUE_{mechanical}$ to evaluate air conditioning energy performance. $PUE_{mechanical}$ is the reciprocal of HVAC system effectiveness. The values of HVAC system effectiveness is shown in Fig. 11 after the conversion. From the results, they found that water cooled chilled water plants were more efficient than air cooled direct expansion systems. The average of all of the data halls' bypass and recirculation flow ratios are 0.5 and 0.5, respectively. This indicates that there is a large opportunity to improve that and bring those points closer to ideal (0, 0).

Adequate airflow distribution impacts the fans power consumption. Mahdavi used ASHRAE 2011 Class 1 temperature recommendations to calculate RCI. And the values of RCI_{LO} and RCI_{HI} are 94% and 100%, respectively. This imply that some racks are overcooled but not any overheated. RTI is 125%. Fair amount of air is recirculating in the data center. The value of Airflow Efficiency is 0.52 W/cfm. This means that air is efficiently moved through the data center. The average supply temperature of CRAC units is 16.2 °C. With improved air management, this temperature can be increased to 27 °C. And the energy used by the cooling systems could be reduced [56]. Lu et al. calculated the air management performance metrics. All the SHI values were near zero. This indicates that the recirculation of hot air was negligible and that the hot and cold air streams were perfectly separated. The RTI was estimated as 41%. The CRAC airflow could be reduced by 59%. And the fan energy could be reduced by 93% if VFD is installed [57]. Tozer and Flucker assessed a data center airflow distribution. 80% of the CRAC supply air was being bypassed and around 20% of server intake air was recirculated warm air. Installation of blanking plates within cabinets can improve air management [58]. Choo et al. studied the cold aisle containment in a data center. Energy savings of 132.0 MWh/year by cold aisle containment is obtained by reducing the chilled water pumping power by increasing the return air temperature of the CRACs from 20 °C to 29.1 °C [59].

3.2.3. Heat rejection equipment

Heat rejection to the exterior of a data center typically occurs to the atmosphere. Cooling towers and dry coolers are the most common forms of heat rejection in the data center industry.

Cooling towers are an efficient means of heat rejection. According to a research conducted by Sun and Lee, the cooling towers accounted for 2.3% of the total air conditioning energy consumption of the data center [55]. Zhang et al. focused on the heat extraction process of a data center in Beijing, in which a cooling tower is adopted for free cooling. The results showed that 2.9% of the air conditioning energy is consumed by the cooling tower during the mechanical cooling period. And the cooling tower energy consumption accounted for 10.2% during the free cooling period [60]. Premium efficiency motors and VFD can be used to minimize energy consumption in cooling towers.

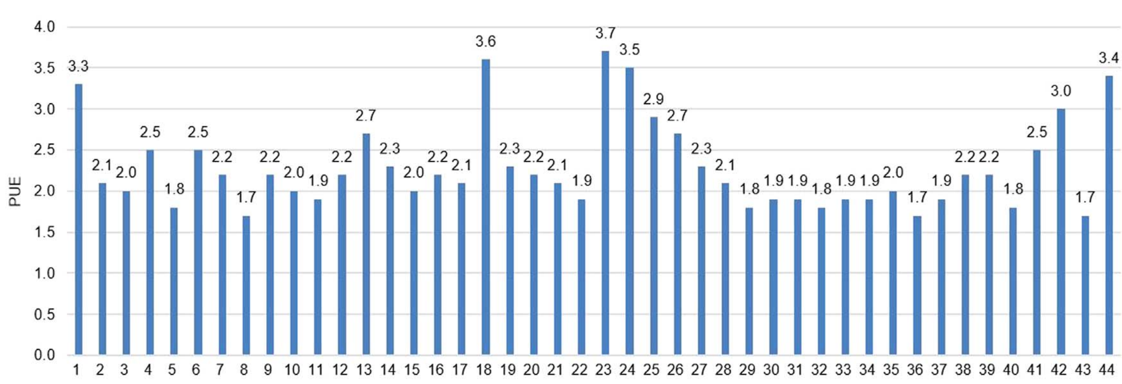

Fig. 10. Annual average PUE of 44 data centers.

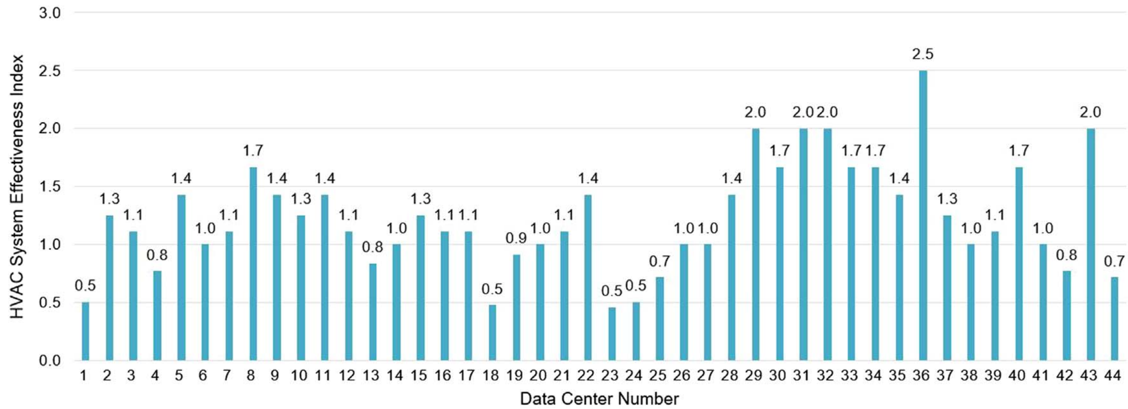

Fig. 11. Annual average HVAC system effectiveness of 44 data centers.

Small data centers usually adopted the dry coolers. The only energy use specific to the dry cooler equipment is fan energy. Mahdavi indicated that dry coolers accounted for an average of 36% of the total air conditioning energy consumption of the data center [56]. Some data centers employ evaporative spray cooling for a while. A lower leaving water temperature on the hottest days of the summer can be achieved. This results in considerable electrical demand and energy savings. Kim et al. propose the integration of a hot water cooling system with a desiccant-assisted evaporative cooling system for air conditioning a data center. The results show that the proposed system saves more than 95% of the peak power demand and 84% of annual operating energy consumption with respect to the conventional air conditioning system for the data center [61].

Besides the air conditioning equipment discussed above, the impact of climate zone on data center air conditioning energy efficiency is another important dimension. Sun and Lee performed a correlation ship analysis between outdoor climatic conditions and air conditioning energy use in data centers. There was no significant relationship between the outdoor dry-bulb temperature and energy use of air conditioning system in both data centers. Similar results were found in the analysis of other weather conditions [55]. Salim and Tozer draw a conclusion that poor correlation existed between cooling system power consumption and cooling degree days. No clear determination of the impact of the climate zone is identified [8]. Hence, it is correct to directly compare energy use of data centers air conditioning in different countries and regions where the weathers vary significantly.

Interestingly, different size data centers shows various energy efficiency. Larger data centers have lower average PUE than the small ones, as shown in Table 4. Large data centers were found to implement more energy saving techniques. However, small data centers were observed to have oversized and aging air conditioning systems, higher levels of air mixing, and no implementation [8]. 57% US servers are housed in small data centers, which comprise 99% of all server spaces in the US. Cheung et al. surveyed 30 small data centers across eight institutions, and selected four of them for detailed assessments. PUE and HVAC system effectiveness are presented in Fig. 12. As shown in Fig. 13, the

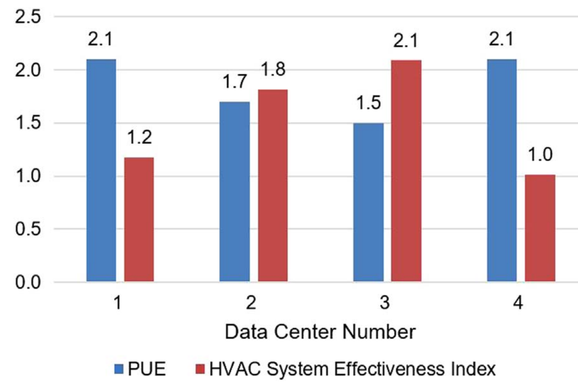

Fig. 12. PUE and HVAC system effectiveness of 4 small data centers2.

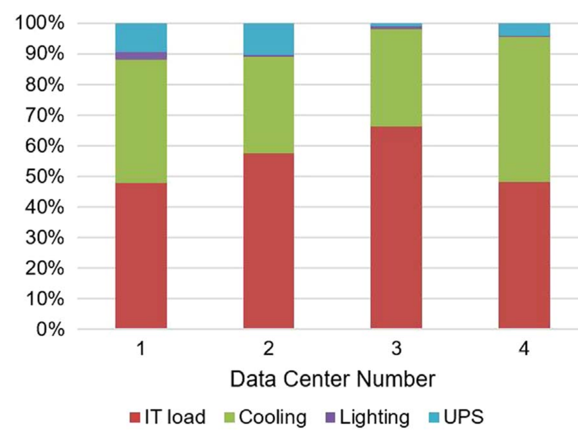

Fig. 13. PUE breakdown of 4 small data centers.

Table 4
Analysis of energy efficiency in different size data centers.

Investigator (s)	Data center size	Area range	Average HVAC system effectiveness	Average PUE	Target PUE	Average annual energy reduction (%)	Average CO_2 avoidance (metric tons)
Salim and Tozer [8]	Small	Up to 929 m^2	NA	2.80	2.30	24	294
	Medium	929–2787 m^2	NA	2.20	1.90	14	615
	Large	> 2787 m^2	NA	2.10	1.80	12	1831
National Environment Agency [52]	Small	Up to 300 m^2	1.20	2.18	1.94	11	69
	Medium	301–1000 m^2	1.22	2.06	1.81	11.4	132
	Large	> 1000 m^2	1.37	2.07	1.73	8.2	758

Table 5
Comparison of air conditioning energy performance in data centers.

Investigator (s)	The number of data centers	Location	Types of air conditioning system	Data source	Average PUE	Average HVAC system effectiveness	Results
Salim and Tozer[8]	44	The globe	Central station air handling systems and CRAC	Benchmarking	2.29	1.22	The database indicated that small data centers have higher average PUE than the larger ones. The cooling load can be reduced by implementing VFD on the chillers and raising the chilled water set points and implementing condenser water reset control as weather permits. Similarly, implementing variable air flow can reduce the fan power consumption by up to 40%.
National Environment Agency[52]	23	Singapore	Central station air handling systems and CRAC	Benchmarking	2.07	1.39	The primary cause of a Lower HVAC system effectiveness level was due to under loading and poor operating practices. Sites using water-cooled chillers were found to have the lowest average mechanical PUE, followed by CRAC and air-cooled chillers.
Steve et al.[53]	22	The globe	Central station air handling systems	Benchmarking	1.86	1.88	A medium-temperature chilled water loop design using 10–15.6 °C chilled water increases chiller efficiency and eliminates controlled phantom dehumidification loads. The condenser loop should also be optimized; a 2.8–3.9 °C approach cooling tower plant with a condenser water temperature reset pairs nicely with a variable speed (VFD) chiller to offer large energy savings.
Cho et al.[54]	1	South Korea	Central station air handling systems	Simulation by using TRNSYS	1.92	1.37	The datacenter with economizer system delivers the PUE ratio of 1.62 (air-side economizer) to 1.81 (water-side economizer), a significant improvement over even the typical datacenters with central chilled water systems.
Sun and Lee[55]	1	Singapore	Central station air handling systems	Field measurement	2.05	1.19	Air conditioning system stands for the largest part of both energy and cost savings (78%). There was no significant relationship between the outdoor dry-bulb temperature and energy use of air conditioning system in the data center. Similar results were found in the analysis of other weather conditions.
Sun and Lee[55]	1	Singapore	CRAC	Field measurement	3.90	0.51	Oversizing of equipment was the major cause for the inefficiency of air conditioning. By conducting energy conservation measures, nearly 75% of air conditioning energy can be saved.
Mahdavi[56]	2	Saint Louis, US	Central station air handling systems	Field measurement	2.26	0.99	Increasing the temperature difference between the intake and exhaust of ITE to 11 °C provides an opportunity to save energy by lowering CRAC airflow and fan power. With improved air management, the CRAC supply air temperature can be increased to 27 °C.
Lu et al.[57]	1	Finland	CRAC	Field measurement	1.33	3.57	21% of total power consumption is from the air conditioning system. The total power consumption of CRAC fans is close to the chiller. The CRAC airflow could be reduced by 59%. And the fan energy could be reduced by 93% if VFD is installed.
Tozer and Flucker[58]	1	NA	Central station air handling systems	Field measurement	2.29	1.61	PUE was reduced by 34% to 1.4 which was achieved through implementation of air management improvements, optimization of cooling unit fan control, chilled water temperature set points, and installation of a free cooling circuit.
Kim et al.[61]	1	NA	Central station air handling systems	Simulation by using TRNSYS	1.41	1.98	The integration of a hot water cooling system with a desiccant-assisted evaporative cooling system can save over 84% of annual operating energy compared with the conventional system.
Choo et al.[59]	1	Maryland, US	CRAC	Field measurement and simulation using the 6Sigma	2.73	1.11	96.4 MWh/year can be saved by eliminating unnecessary CRACs. 111.2–152.4 MWh/year can be saved by increasing the return set point temperature at the CRACs. 132 MWh/year can be saved by providing cold aisle containment. 770–901 MWh/

Table 5 (*continued*)

Investigator (s)	The number of data centers	Location	Types of air conditioning system	Data source	Average PUE	Average HVAC system effectiveness	Results
							year can be saved by implementing fresh air cooling.
Cheung et al.[62]	4	US	Central station air handling systems and CRAC	Field measurement	1.85	1.53	Most ITE is over cooled and maintained a temperature of 23 °C or lower in small data centers, using unnecessary. High levels of air mixing (recirculation and bypass air) is observed.
Pan et al.[93]	2	Shanghai, China	CRAC	Simulation by EnergyPlus	1.47	2.62	The energy performance of the proposed design is much better than China Code, with approximately 27% yearly cost savings. Meanwhile, it is also better than ASHRAE budget building, with approximately 21% cost savings.

Table 6
Data center classification by metrics and benchmark values.

Metrics	Benchmark Values		Amount of Data Centers	% of Total
PUE	Better	≤ 1.1	0	0%
	Good	1.1–1.4	3	3%
	Standard	1.4–2	48	48%
	Poor	> 2	49	49%
HVAC System Effectiveness Index	Better	≥ 2.5	8	8%
	Good	1.4–2.5	38	38%
	Standard	0.7–1.4	47	47%
	Poor	< 0.7	7	7%

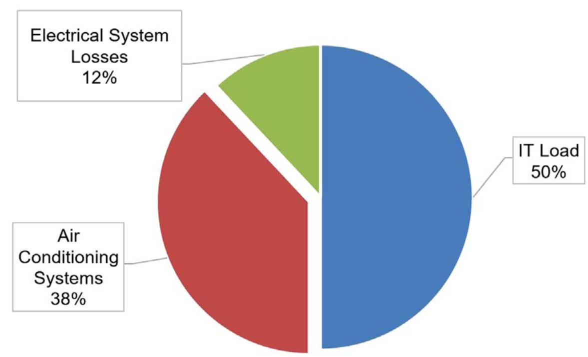

Fig. 14. Breakdown of energy usage by systems for 94 data centers.

energy consumed by the air conditioning system takes up the second power consuming component. According to the survey results, most data centers were over-cooled and maintained a temperature of 23 °C or lower, using unnecessary. Many small data centers were not designed to operate as data centers. Accordingly, some of them were too small to allow for air separation, and exhaust air from the ITE mixed with cooler inlet air, requiring more cooling energy than necessary [62]. Small data centers have greater energy saving space than the large ones, as shown in Table 4. Consequently, the air conditioning energy performance of small data centers should attract attention.

Comparison of air conditioning energy performance in data centers is shown in Table 5. It can be seen from this section that the PUE ranges from 1.33 to 3.85 with an average of 2.13 based on 100 data centers. These data centers analyzed in this section are further classified based on metrics' benchmark values and listed in Table 6. Nearly half of data centers' PUE are over 2. The average of HVAC system effectiveness index is 1.44. Fig. 14 shows the overall breakdown of energy usage from the IT, air conditioning and electrical systems. While most facilities had air conditioning system energy consumption near the 38% average, the range for this usage was 21% for the most efficient system and 61% for the least efficient system, indicating that close attention needs to be given to air conditioning systems to minimize data center energy consumption.

4. Energy efficiency strategies

4.1. Economizer cycles

The standard meaning of economizer cycles in the HVAC industry is the utilization of outdoor air under certain conditions to allow chillers and/or other mechanical cooling systems to be shut off or operated at reduced capacity. Operating in an economizer mode is often also known as "free cooling." There are two basic types of economizers: airside economizer and waterside economizer [63].

An airside economizer is a system that has been designed to use outdoor air for cooling, partially or fully, when the outdoor air meets certain criteria. Airside economizers have a lengthy history of application within commercial buildings, but the initial reaction in the data center industry has been very controversial. By 2010, ASHRAE approved a significant change in the Title, Purpose, and Scope of Standard 90.1 to include data centers. In doing so, they introduced prescriptive requirements for economizers, including airside economizers. Economizers continue to be viewed as opportunity for improving PUE and have been deployed in dozens of data centers [64]. Ham et al. analyzed the applicability of various airside economizers and their energy saving potential in modular data centers. From the results, they found that the total air conditioning energy savings of the economizers ranged from 47.5–67.2%. Indirect airside economizers with high-effectiveness heat exchangers were found to yield significant energy saving (63.6%) and have simple system configurations [65]. Alipour investigated the airside economizer energy performance of a data center in Santa Clara, Calif [66]. The experimental results revealed that the data center can achieve 30% energy saving.

Due to the data center being strict requirements for humidity and cleanliness, so the control of humidify and filtering should be processed before outdoor air pulls into the data center [67]. Lee and Chen examined the potential energy savings of the airside economizer with differential enthalpy control used in data centers in 17 climate zones [68]. Because significant humidification is required to adjust outdoor air in climate zones with a lower dew point temperature, such as very-cold, subarctic, cool-dry, and cold-dry climate zones, the power consumed is even higher after employed airside economizer. Davidson analyzed the efficiency of the dehumidification process needed to utilize this high dew point outdoor air to allow for airside economizer operation [69]. According to his study, desiccant dehumidification will be economical if there is a source of free heat for reactivation. Wang and Song developed an optimal economizer outside air high-limit curve of outside air on a psychometric chart by simulating and com-paring the total energy cost of cooling coil mechanical cooling and humidifier steam under the economizer and minimum outside air modes [70]. The investigation reveals that the optimal economizer out-side air zone can be extended beyond the traditional control with at least 9.3 kW/(m^3/s) energy savings when a minimum of 30% space RH is required. Moreover, values of particulate concentrations increased during economizer operation. The addition of filters with higher filtration efficiency will typically increase fan energy, and this will act to reduce the net energy savings of airside economizers. If MERV 14 outdoor air filters are substituted for the MERV 7 filters, it should be possible to reduce particulate concentrations during economizer operation to those of current data centers that do not use air-side economizers [71]. According to the study in Ref. [71], even during a warm summer month in northern California, chiller energy savings from economizer use greatly outweighed the increase in fan energy associated with improved filtration.

Airside economizers offer a tremendous opportunity for energy savings and higher HVAC system effectiveness, particularly when combined with the wider thermal envelopes in the Ref. [72]. However, the industry is currently void of the appropriate research and rating standards for the performance of airside economizers within data center applications [64]. This is an area where further research is needed.

Waterside economizers use cool outdoor dry-bulb or wet-bulb conditions to generate condenser water that can partially or fully meet the facility's cooling requirements. There are two basic types of water-side economizers: direct and indirect free cooling. In a direct system, natural cold water is used directly to cool the data center without any steps of heat transfer. In an indirect system, a heat exchanger is added to separate the condenser water and chilled water loops [73]. Waterside economizers used in conjunction with central chilled-water plants can be arranged in series. Chilled water flows through both the heat exchanger and chiller in series, resulting in a significant number of partial free cooling hours, with the only additional energy expense being the energy required to pump water through both the heat exchanger and the chiller [74]. Griffin investigated the waterside economizer energy performance of a data center in America. The result shows that the overall savings would be approximately 530 kW [75]. Waterside economizers should be considered in conjunction with airside economizers. There is wide climatic variability in the percentage of the year that economizers can be used. Some climates are better for waterside economizers and some are better for airside economizers, depending on ambient humidity levels. Climate is the most important variable in comparing airside and waterside economizer savings [76].

4.2. Airflow optimization

Good airflow management is critical to an energy efficient data center. Currently, the technique of airflow management focuses largely on optimizing the flow paths of both cold supply air and hot return air. The objective of such optimization is to minimize unnecessary mixing of these two streams which can adversely affect the energy efficiency of data centers. Aisle containment which could separate flow paths for cold and hot air streams is one of the most common energy efficiency strategies deployed in data centers. However, contained solutions are still susceptible to the same sensitivities to cold air supply and IT load distributions as legacy data centers [77]. Khankari analyzed the impact of leakage area, supply air ratio, and rack cooling load on the performance of hot aisle containment system. The result indicates that air leakages can occur at the same rate irrespective of the cooling loads in the racks, and therefore, have a little impact on the rate of leakage and performance of the hot aisle containment systems [78]. Another aim of containment is to raise CRAC supply air temperature set points [79]. When cold aisle and hot aisle is in an open condition, 18 °C of supply air temperature is the most energy efficient. The temperature can be increased up to 22 °C if containment are used [80]. The aisle containment system has many advantages but carries with it special considerations that must be accounted for. Since most of the airflow passes through the servers, unit airflow must be closely matched to the cumulative server airflow [81]. Moreover, aisle containment has introduced challenges to fire protection requirements and fire safety in data centers. Aisle containment project should meet both energy objectives and fire-safety requirements [82].

Temperatures within a specified range at the ITE inlets is the ultimate goal of air conditioning systems. As discussed in 2.3, UFAD is widely used in data centers. To achieve this goal, most UFAD data centers are designed to deliver the same airflow rate through each perforated tile. If only one type of perforated tile is deployed, the airflow will be uniform provided the raised floor air space is uniformly pressurized. Raised floor air space pressure uniformity is affected by a number of factors [83]. Computational fluid dynamics (CFD) modeling can be a valuable tool for use in determining the pressure distribution in the raised floor air space. Moss suggested that under floor static pressure control is a viable and often superior alternative to return air temperature control [84]. Air leakage from under floor plenum is a commonly encountered problem and occurs primarily at areas where the cables pass through the floor tiles. A popular solution to this problem is the use of grommets, which seal around the cable penetrations and reduce leakage [85]. Careful sealing of other raised floor openings and holes in perimeter walls is also important to maintain good cooling efficiency.

4.3. Energy management

Many energy managers believe that energy efficiency is simply to reduce energy use. As data centers require high reliability, the reduction of energy use may reduce reliability at the same time. So they are reluctant to take energy efficiency strategies. This is a misunderstanding of energy efficiency in data centers. The authentic interpretation of energy efficiency is to achieve the best match between the energy demand and supply instead of simply reduce energy use.

The supply chilled water and supply air temperatures should be raised as high as possible in data centers, while still providing the necessary cooling. Many data centers are over-cooled. This results in no real operational benefits and increases energy use. The environmental control equipment has traditionally been operated to maintain return conditions at the inlet to the CRAC unit in data centers. Supply temperatures from the air conditioners are usually found between 10 and 16 °C, which are colder than what is necessary to maintain the inlet conditions to the ITE between 18 and 27 °C. Changing the control system to control supply air temperature ensures that all supply air temperatures are the same and enables greater energy efficiency [86]. The higher temperatures not only increase the thermodynamic efficiency of the air conditioning systems, but also greatly increase economizer hours of operation in most climates. Operating the air conditioning system at the warmest possible temperature that can meet the cooling load offers the most opportunity for energy savings. Meanwhile, the process to raise the temperatures involves many steps to do it properly, safely, reliably, and with accountable results [11].

A significant percentage of the energy of a data center can be consumed by humidification and dehumidification. RH can be difficult to control to recommended tolerances in a data center, particularly if there is a wide variation in supply air temperatures. The main opportunity for energy reduction from humidification is a reduction in the required set point [12]. Little humidity is internally generated in a data center because of low human occupancy. This provides an opportunity to centrally control the humidity in an efficient manner in large data centers. Normally the internal humidity load in a data center facility is quite low and the sensible load is quite high. The most significant humidification load is generally infiltration. Therefore, if a dedicated outdoor air system can pressurize the space to prevent infiltration, all of the humidification and dehumidification requirements of the facility can be met by the outdoor air system. Central control of humidification can allow cooling coils to run dry, allowing for chilled-water reset at light loads without impacting RH. The need to overcool and reheat to maintain RH can be eliminated [22].

4.4. Simulation tools

Optimizing air conditioning performance of a data center is a challenging task. Physical measurements and field testing are not only time and labor intensive but sometimes impossible. And therefore, simulation tools are valuable means for analyzing air conditioning energy performance in data centers.

CFD simulations can predict the air velocities, pressure, and temperature distribution in the entire data center facility. The airflow of a data center is too complex to simulate with entirely accuracy. The major hurdle to overcome this problem is the lack of simplified and computationally efficient models capable of capturing such complex energy and mass flows within data center and performing transient cooling analysis [2]. Modeling the rack is one of the critical pieces in the CFD simulation process. Often this is done as a black box rather than modeling the rack in detail [87]. Pardey et al. proposed a standard compact server model for transient data center simulations. This model provides the computing efficiency benefits of a black-box approach while still accounting for the effect of thermal mass in transient data center CFD simulations [88]. Erden et al. introduced a fast-executing hybrid CFD model for predicting ITE inlet temperatures. The model uses initial steady-state CFD or experimental data in combination with several lumped-capacitance models of the various thermal masses in the data center. The model predictions have been found to agree well with the experimental measurements [89]. Jian et al. compared the CFD simulation of the thermal performance of a large data center to the experimental measurements. The overall agreement is quite good considering the experimental uncertainties and the simplifications of the numerical model [90].

Energy simulation is an efficient way to examine data center air conditioning energy consumption. It has been used to study energy conservation measures for data centers. More than one hundred building energy simulation programs are used in research and practice now. Among these tools, EnergyPlus and DOE-2 have been two popular tools used by the data center industry. A comparison between EnergyPlus and DOE-2 showed that EnergyPlus has advantages over DOE-2 in the simulation of energy performance of data centers [91]. Ham et al. developed a server model which effectively represents the server thermal characteristics and its effect was evaluated through an energy consumption simulation. This model can easily be applied to hourly cooling energy consumption simulations of a data center [92]. Pan et al. developed an energy simulation models with EnergyPlus for two office buildings with data center. The whole building energy simulation results show that the yearly energy cost saving of the proposed design will be approximately 27% from China Code building and 21% from ASHRAE budget building [93]. The system energy simulation analysis is often used in conjunction with a CFD model to obtain a full understanding of data centers and to aid in energy optimization.

It should be noted that there still exists a large gap between the modeling tools capabilities and the requirements for accurate data center energy modeling. Currently, CFD programs are not designed for integration with energy modeling programs. CFD results must be run independently, with outputs plugged into spreadsheets and energy modeling tools as non-converged assumptions without optimization of temperatures and airflow rates on ITE and air conditioning system [18]. These gaps are significant and will take significant time for the industry to close.

5. Conclusions

This paper presents a summary of air conditioning energy performance from one hundred data centers. The collected data from articles and reports show that the PUE ranges from 1.33 to 3.85 with an average of 2.13. Nearly half of data centers' PUE are over 2. This means that numerous data centers are not running in the energy efficient way. The average of HVAC system effectiveness index is 1.44. More than half of the data centers air conditioning systems are inefficient. In total, air conditioning systems account for about 38% of facility energy consumption. The range for this usage was 21% for the most efficient system and 61% for the least efficient system. Due to no common efficiency standards governing the design or operation of data centers and the associated air conditioning systems, most data centers operators don't know if their center is good or bad. And the statistical research on air conditioning energy performance is still sorely lacking. Consequently, based on the statistical data and discussion in this paper, operators could compare their center to peers and identify poorly operating areas which have potential opportunities to reduce energy use in data centers.

A number of currently available and developmental energy efficiency strategies are reviewed. The advantages and disadvantages of each technology are also discussed. Economizer cycles have the greatest energy conservation potential in data centers. And the aisle containment is most certainly the future for data center design as it gives far more scope for elevated temperatures and associated efficiency gains than legacy data centers. The control strategy of temperature and humidity influences the energy efficiency of air conditioning systems in data centers. Currently, the global tendency of indoor thermal guidelines for data centers is loosening in order to achieve higher level of energy conservation. Meanwhile, the reduction of indoor thermal requirement would lead to the decrease of availability of ITE. Based on the discussion so far, the balance between energy conservation by loosening indoor thermal guidelines and availability of ITE should be handled carefully. Furthermore, CFD and energy simulations can be valuable tools for use in analyzing the airflow and energy performance of data centers. However, there still exists a large gap between the modeling tools capabilities and the requirements for accurate data center energy modeling. At present CFD programs are not designed for integration with energy modeling programs. Accordingly, future research shall make great efforts to let CFD and energy modeling tools performing co-simulations, whereby iterative time-steps could be specified for the convergence of CFD outputs and energy modeling outputs.

Energy benchmarking provides a very effective way to evaluate the performance of a data center and compare it to similar facilities. More air conditioning energy performance benchmarking studies are imperative for data centers. The industry is currently void of the appropriate research and rating standards for air conditioning energy efficiency of data centers. Future work, if funding is available, shall develop the air conditioning energy efficiency rating standards study of data centers.

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