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An Analysis Of The Impact Of Datacenter Temperature On Energy Efficiency

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Submitted to the MIT Sloan School of Management and the School of Engineering
In partial fulfillment of the requirements for the Degree of

Master of Science in Engineering and Management
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ABSTRACT

The optimal air temperature for datacenters is one of ways to improve energy efficiency of datacenter cooling systems. Many datacenter owners have been interested in raising the room temperature as a quick and simple method to increase energy efficiency. The purpose of this paper is both to provide recommendations on maximizing the energy efficiency of datacenters by optimizing datacenter temperature setpoint, and to understand the drivers of datacenter costs.

This optimization and the potential energy savings used in cooling system can drive higher energy use in IT equipment and may not be a good trade off. For this reason, this paper provided a detailed look at the overall effect on energy of temperature changes in order to figure out the optimal datacenter temperature setpoint. Since this optimal temperature range varies by equipment and other factors in the datacenter, each datacenter should identify its appropriate temperature based on the optimization calculation in this paper. Sensitivity analysis is used to identify the drivers of the cost of ownership in a datacenter and to identify opportunities for datacenter efficiency improvement. The model is also used to evaluate potential datacenter efficiency.

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1. INTRODUCTION

According to a 2007 U.S. Environmental Protection Agency (EPA) report to Congress, EPA estimated that the nation's servers and datacenters consumed about 61 billion kilowatt-hours (kWh) in 2006, representing 1.5 percent of total U.S. electricity consumption, for a total electricity cost of about $4.5 billion. Datacenter energy consumption is projected to grow by nearly 10% annually as the market for data processing and digital storage continues to grow. As a result, making an effort to maximize energy efficiency in datacenters is critical [1]. As business demand and energy costs for datacenters rise, companies are focusing on efficiency, as well as controlling and reducing recurring costs to drive marketplace competitiveness. A low-cost, low-maintenance, highly reliable infrastructure is now a critical requirement for minimizing the Total Cost of Ownership (TCO) of IT equipment. Moreover, there is significant potential for energy efficiency improvements in datacenters. One of the ways to improve energy efficiency of datacenter is to improve cooling systems since essentially all of the energy consumed by IT equipment is ultimately dissipated as heat. Many datacenter owners have been interested in raising datacenter temperature setpoint because the cooling costs are related to the temperature differential between the equipment and the external environment. Raising server inlet temperatures however can lead to more rapid failures and an increase in power consumption by the fans that cool the CPU's. There is a critical need for a system model to analyze the tradeoffs. Simply raising the inlet temperature may not lead to a reduction in cooling costs.

Currently, there are many datacenter performance metrics to quantitatively measure and evaluate the performance of a datacenter. These metrics are useful to get a high-level view of the actual performance of the datacenter. However, these metrics do not measure sensitivity information of components' performance related to the overall datacenter performance.

This paper develops an optimization model using a simplified energy use model of components in datacenters. This model can be used for identifying optimization possibilities in datacenters. This approach provides a rational method of defining system boundaries in datacenters, and incorporates the component energy consumption model of the datacenter. Furthermore, the sensitivity analysis was proven to be effective for evaluating the cost drivers in datacenters. Specifically, using a case study the use of the analysis to identify importance in annual energy cost saving and assess the impact of decisions on performance was examined. Through case studies, considerations that need to be taken in order to maximize energy efficiency consistently and to capture the appropriate amount of information about the datacenter were explained. In addition to these findings, understanding different sources of uncertainty in the model input provides an approach for using the optimization model not only to design the next generation of datacenters, but also to guide the management of a datacenter.

1.1. Objective

To understand the relationship between datacenter temperature set point and cost of cooling, the following specific objectives were identified:

- Understand the structure and important performance characteristics of a datacenter.
- Develop a quantified model of the cooling systems for a datacenter to increase datacenter efficiency.
- Apply this proposed model to an example datacenter to quantitatively illustrate the application of the model.
- Extend the proposed model for the optimization of datacenter efficiency to any datacenter in general.

1.2. Methodology

From the understanding of the objectives, the following was used to develop a model for improving energy efficiency of a datacenter:

- Analyze datacenter energy flow, and its boundaries.
- Review current datacenter efficiency metrics.
- Analyze correlation between components in a datacenter and inlet temperature.
- Identify cost drivers for various components in a datacenter.
- Analyze the uncertainty in the output of the model to support decision making for datacenter design.

2. DATACENTER POWER FLOW

2.1. Power Flow in a Typical Datacenter

Figure 1 shows the energy flow between the power, cooling, and IT systems of a typical datacenter. The energy flow in a typical datacenter consists of two key parts: facility infrastructure and IT equipment. The source of energy is delivered to a datacenter by the local utility company. Once that utility power enters the datacenter, it stops at the Automatic Transfer Switch (ATS) in the facility infrastructure. In case of an emergency, power comes from the power generator. While the normal power is available, energy flows to a series of distribution breakers, often called "switchgear." The switchgear passes energy to the uninterruptible power supply (UPS) units and other facility infrastructure such as Lighting, Heating, Ventilation, and Air conditioning (HVAC), etc. In addition, the switchgear passes power to chillers, cooling towers, and Computer Room Air Conditioners & Handlers (CRACs/CRAHs). If the normal power source from the utility company is not available, the ATS triggers the power generator. Once the power generator starts up, the ATS switches the load from the normal power to the emergency power. And then power enters the UPS that provides emergency power to a load when the normal power source fails. The UPS are used to protect sensitive IT equipment in a datacenter from power fluctuations and outage. This UPS is connected in-line with the battery backup system. If the ATS senses a utility outage and starts the power generators, power is still supplied to the IT load. After passing the UPS, the power flows to power distribution units (PDUs). The PDUs convert the high voltage to a more usable voltage for IT equipment in a datacenter. Once the voltage is converted, the power is distributed to electrical outlets via a common electrical breaker. At this point, the power leaves the facility infrastructure boundary, and then the PDUs' power flows to each power supply in the rack. The next step in the power flow in IT equipment is fans, which are one of the crucial factors to make datacenters more energy efficient.

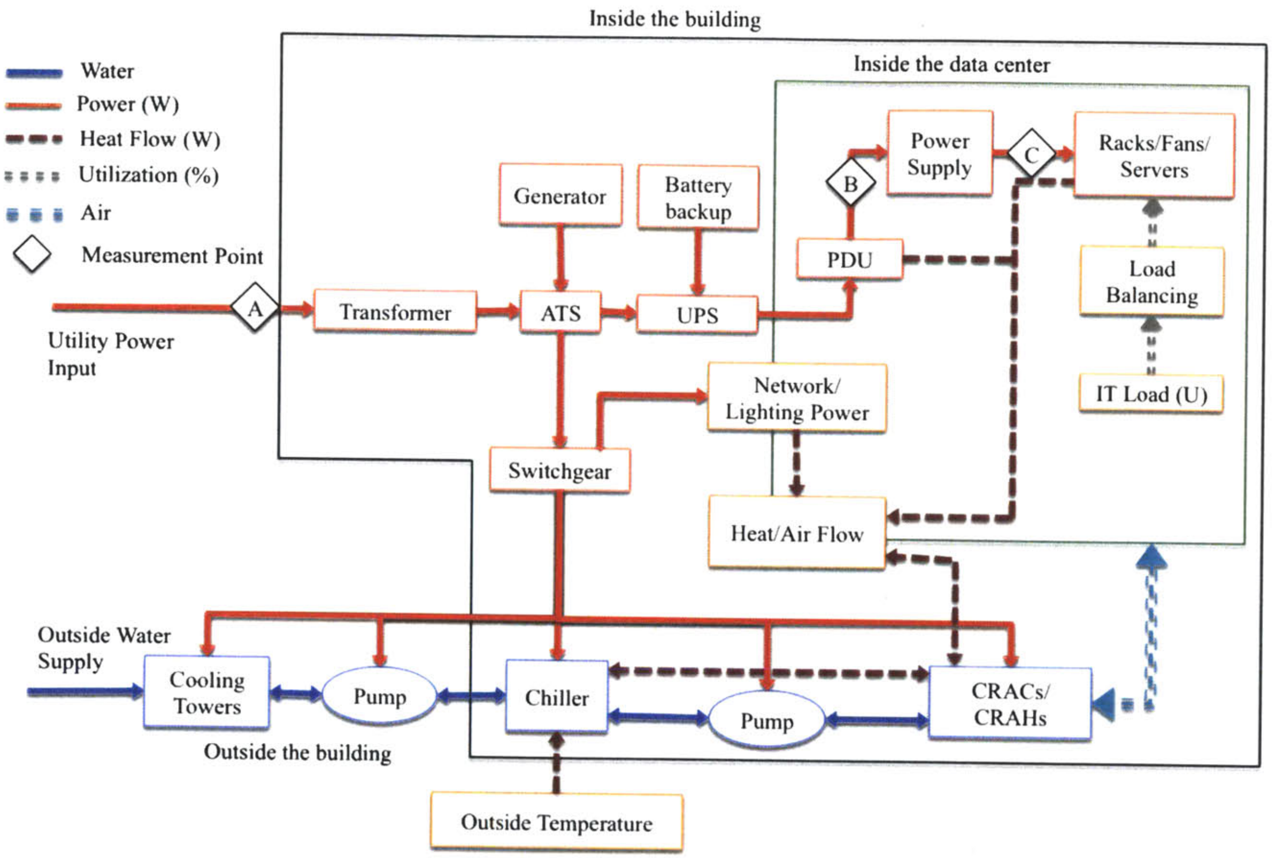

Figure 1. Power, Heat and Utilization Flow

In addition, Figure 1 illustrates relationships between each component's utilization and its power draw. The chiller power draw depends on the amount of heat extracted from the chilled water return, the chilled water return at selected temperature, the water flow rate, the outside temperature, and the outside humidity [2]. Fans play a key role in CRACs/CRAHs, which transfer heat out of the server room to the chilled water loop. Servers and PDUs also generate heat that is related to datacenter utilization. Networking equipment, pumps, and lights also generate heat. However, the contribution of each is not big enough to be considered as a major power consumer. Table 1 shows a typical datacenter power breakdown. Servers, cooling, and PDUs maintain dominant position, and datacenter utilization causes their power draw to vary considerably.

Table 1. Typical Datacenter Power Breakdown [2]

Servers	Cooling	PDUs	Network	Lighting
56%	30%	8%	5%	1%

3. DATACENTER ENERGY EFFICIENCY METRICS

3.1. Datacenter Metrics Overview

In a datacenter, the mechanical and electrical facilities as well as servers, storage, and IT networks are designed for optimal energy efficiency. The first step in energy efficiency planning is measuring current energy usage. The power system is a critical element in the facility's infrastructure, and knowing where that energy is used and by which specific equipment is essential when creating, expanding, or optimizing a datacenter. Energy efficiency metrics can track the performance of a datacenter and identify potential opportunities to reduce energy use in a datacenter.

3.1.1. Existing Metrics for Efficiency of a Datacenter

The operation of various internal components of both the facility and the IT infrastructure impacts the efficiency of a datacenter. The inside relationships of these components are essential to determine their efficiency. Several organizations such as The Green Grid, Uptime Institute, and McKinsey & Co have proposed metrics to quantify the efficiency of power utilization and explain the losses at various points. These metrics are used to identify opportunities for improving energy efficiency and for providing holistic energy management with strategic guidelines on minimizing the impact of energy costs on datacenters. Various important metrics in use are listed in Table 2 [3].

Table 2. Various Important Metrics in Use

Organization	Metric	Definition
Green Grid Corporation	PUE (Power Usage Effectiveness)	Total Facility Power/Total IT Power, 1/DCiE [Point A / Point B]*
	DCiE (Datacenter infrastructure Efficiency)	Total IT Power /Total Facility Power [Point B / Point A]*
	CPE (Compute Power Efficiency)	IT Equipment Utilization * DCiE
	UDC (Datacenter Utilization)	IT Equipment Power / Actual power capacity of the datacenter
	U_{server} (Server Utilization)	Activity of the server processor / Maximum ability in the highest frequency state
	$U_{storage}$ (Storage Utilization)	Percent storage used / Total storage capacity of datacenter
	$U_{network}$ (Network Utilization)	Percent network bandwidth used / Total bandwidth capacity of datacenter
The Uptime Institute	SI-POM (Site Infrastructure Power Overhead Multiplier)	Datacenter power consumption at the utility meter / Total hardware AC power consumption at the plug for all IT equipment
	H-POM (IT Hardware Power Overhead Multiplier)	AC Hardware Load at the plug / DC Hardware Compute Load [Point C / Point B]*
	DH-UR $_{servers}$ (Deployed Hardware Utilization Ratio)	Number of servers running live applications / Total number of servers actually deployed
	DH-UR $_{storage}$ (Deployed Hardware Utilization Ratio)	Number of terabytes of storage holding important, frequently accessed data (within last 90 days) / Total terabytes of storage actually deployed
McKinsey Corporation	CADE (Corporate Average Data Efficiency)	Facility Efficiency * IT Asset Efficiency
	IT Asset Efficiency	IT Utilization (%) * IT Energy Efficiency (%)
	Facility Efficiency	Facility Energy Efficiency (%) x Facility Utilization
	Facility Energy Efficiency (%)	Actual IT load / Total power consumed by the datacenter [Point B / Point A]*
	Facility Utilization (%)	Actual IT load (servers, storage, networking, capacity equipment) used / Facilities
	IT Utilization (%)	Average CPU utilization
	IT Energy Efficiency (%)	CPU Loading / Total CPU power

- Point A, B, C refer to the power measurement points that are marked in the Figure 1.

3.1.2. Power Usage Effectiveness (PUE)

In Table 2, many efficiency metrics are shown, and they not only describe how efficiently a datacenter transfers power from the source to the IT equipment, but also define what establishes an IT load versus what is overhead. The PUE [4] and DCiE metrics are the most crucial among others since they promote both understanding datacenter power consumption and presenting a comprehensive model for total datacenter power draw. In order to identify losses and the impact of power in a datacenter, the simplified power flow enables us to understand how power flows and how to measure it from the higher viewpoint. The simplified power flow based on Figure 1 is shown in Figure 2 below.

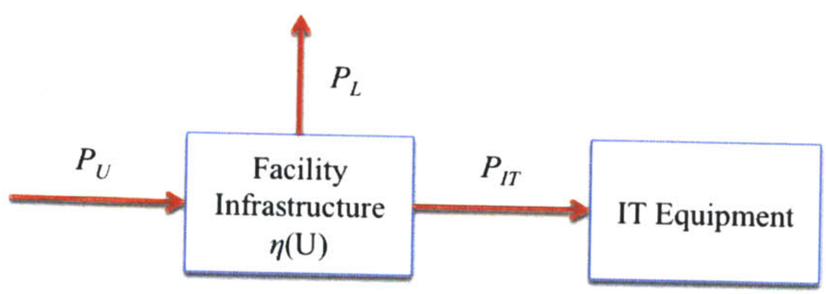

Figure 2 Simplified Datacenter Power Flow

The PUE is a widely used metric, which is supposed to measure how efficient datacenters are. The PUE metric was introduced by the Green Grid, an association of IT professionals focused on increasing the energy efficiency of datacenters. PUE is defined as the ratio of the total power to run the datacenter facility to the total power drawn by all IT equipment [4]:

$$PUE = \frac{Total\ Facilities\ Power}{IT\ Equipment\ Power} = \frac{Point\ A}{Point\ B}$$

$$PUE = \frac{P_U}{P_{IT}} = \frac{P_{IT} + P_U}{P_{IT}} = 1 + \frac{P_U}{P_{IT}}$$

A PUE value of 1 depicts the optimal level of datacenter efficiency. In practical terms, a PUE value of 1 means that all power going into the datacenter is being used to power IT equipment. Anything above a value of 1 means there is datacenter overhead required to support the IT load. In this equation, the total facility power is the energy used by the datacenter as a whole, while IT equipment power consists of energy used specifically by servers, storage, networking switches, and other IT components, which are not including external power delivery systems, cooling systems, lighting, and so on.

The use of the PUE metric to determine the efficiency of datacenters has been gaining momentum in the technology industry. While the definition of PUE is generally understood, there is still little information on actual benchmarking and more importantly, on what is considered an acceptable minimum PUE. Also, understanding the components that make up the PUE will enable a robust analysis of how to maximize the efficiency.

3.1.3. Datacenter Infrastructure Efficiency (DCiE)

The Green Grid also published the Datacenter Infrastructure Efficiency (DCiE). DCiE (η (U)) is defined as the ratio of the total power drawn by all IT equipment to the total power to run the datacenter facility, or the inverse of the PUE. It is calculated as a percentage by taking the total power of the IT equipment and dividing it by the total power entering the datacenter multiplied by 100. A PUE value of 2.0 would equate to a DCiE value of 50%, or suggest that the IT equipment was consuming 50% of the facility's power. The following equations show DCiE as well as the correlation between PUE and the actual power losses in the facility infrastructure:

$$\mu(U) = \frac{1}{PUE}$$

$$P_{IT} = \mu(U) P_U$$

$$P_L = (1 - \mu(U)) P_U$$

Thus,

$$PUE = \frac{1}{\mu(U)}$$

$$PUE = \frac{\mu(U)P_U + (1 - \mu(U))P_U}{\mu(U)P_U}$$

$$PUE = 1 + \frac{P_{IT}}{P_{IT}}$$

$$PUE = 1 + \frac{1}{P_{IT}} \sum_{i=1}^{n} P_{Li}$$

3.2. Definition of System Boundary

To understand how much energy a datacenter is consuming and to optimize its temperature set point in order to reduce energy consumption involves several important steps. The first step is to measure the existing datacenter energy consumption rates so that a baseline can be calculated. A standard industry metric (such as PUE) must be utilized so that the initial baseline measurement is relevant and comparable to any future measurements. The next step is defining the system boundary. It is critical to identify where the energy losses are occurring.

In Figure 3, Total Facility Power is measured at the facility's utility meter(s) to accurately reflect the power entering the datacenter. Power delivery components include UPSs, switchgears, PDUs, batteries, generators, and distribution losses external to the IT equipment. Cooling system components include chillers, CRAC units, pumps, and cooling towers. Other components include datacenter lighting, the fire protection system, etc.

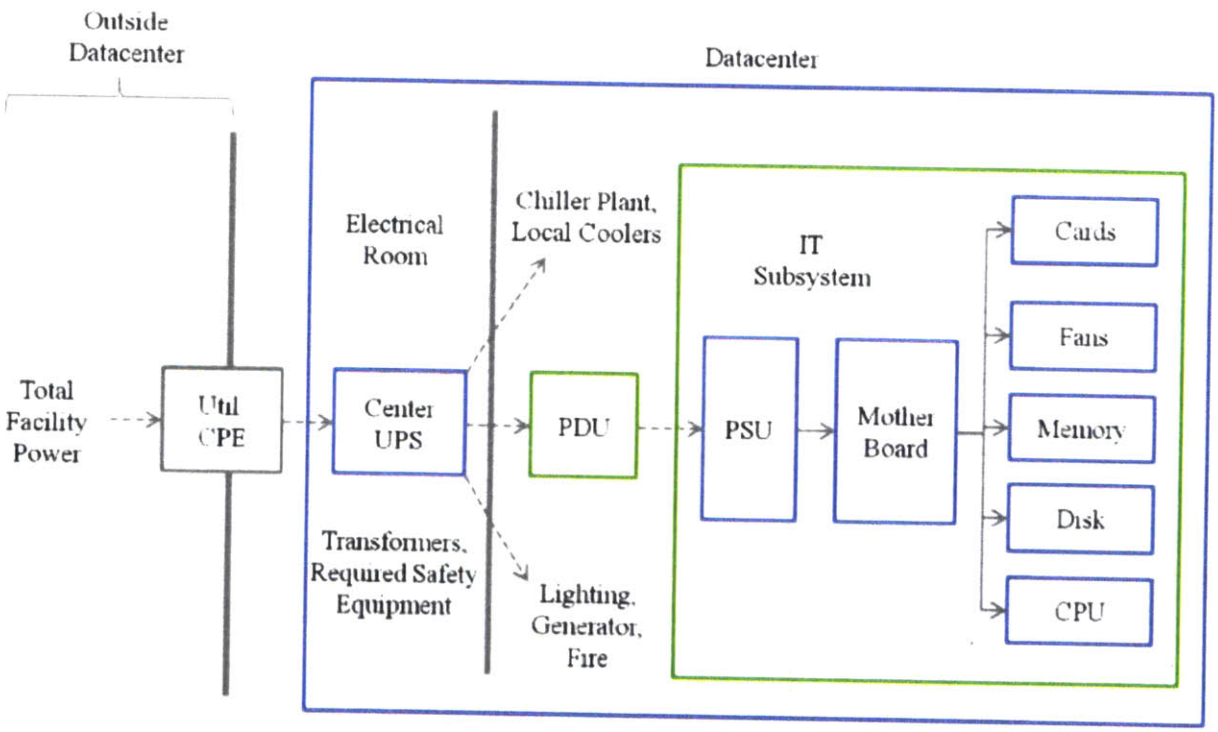

Figure 3. Datacenter System Boundary

Finally, IT equipment power is defined as the load associated with all of the IT equipment such as cards, fans, memory, disk, and CPU. Typically, IT equipment power is measured at the rack level using metered PDUs. A more effective approach can be continuous measuring at the row level in the electrical distribution box using the energy meters.

4. ANALYSIS OF DATACENTER POWER

4.1. Typical Datacenter Power Breakdown

Different datacenters consist of different plant layouts and infrastructural arrangements. Numerous studies discuss various configurations in the datacenters. Maximizing total datacenter power efficiency is difficult because of the diversity and complexity of datacenter infrastructure. The optimization model considers a simple datacenter infrastructure for the analysis. This model includes the IT load and the cooling infrastructure. The main part of the IT load is the servers. Typical datacenter consists of five distinct sub-systems [2]:

- Servers and storage systems
- Power conditioning equipment
- Cooling and humidification systems
- Networking equipment
- Lighting/physical facilities

Figure 4 below shows a typical breakdown of power consumption by a datacenter. The components of datacenters consist of the electrical loads for servers and data equipment, HVAC – fans and compressors, and lighting. The relative proportions of each of these components vary according to the IT load intensity and the efficiency of the infrastructure systems necessary to support the computing. IT infrastructure and the cooling equipment consume more than 80% of the datacenter's energy to maintain proper IT equipment temperatures and airflow [1].

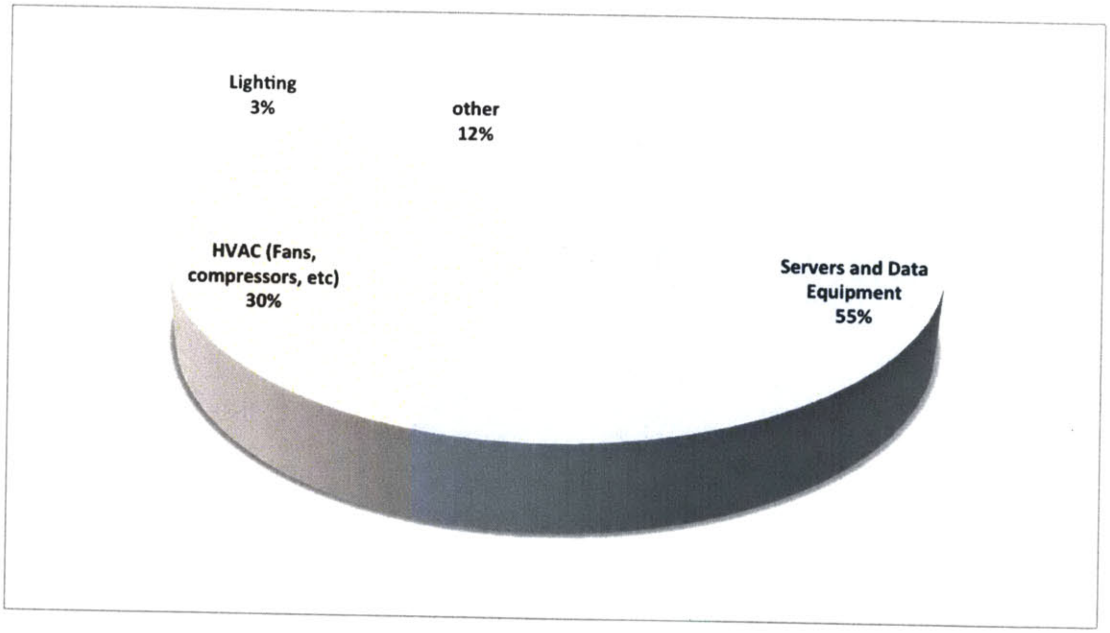

Figure 4. Energy Use Breakdown in High-performance Datacenters [1]

From these sub-systems the model for datacenter power consumption can be developed, and each critical component of datacenter infrastructure will be considered as a main factor to describe how utilization, power, and heat flow among components.

4.2. The Server

The primary components of the server that consume the power are:

- The central processing units (CPUs)
- The server fans
- The memory modules
- The power supply units (PSUs)
- The hard disk drives

Figure 5 below illustrates an example of a typical blade server [5]. The CPU and the server cooling fans are the most essential of these components in terms of raising temperature in the server rack. For this reason this paper will review how temperature influences the main components as well as energy efficiency.

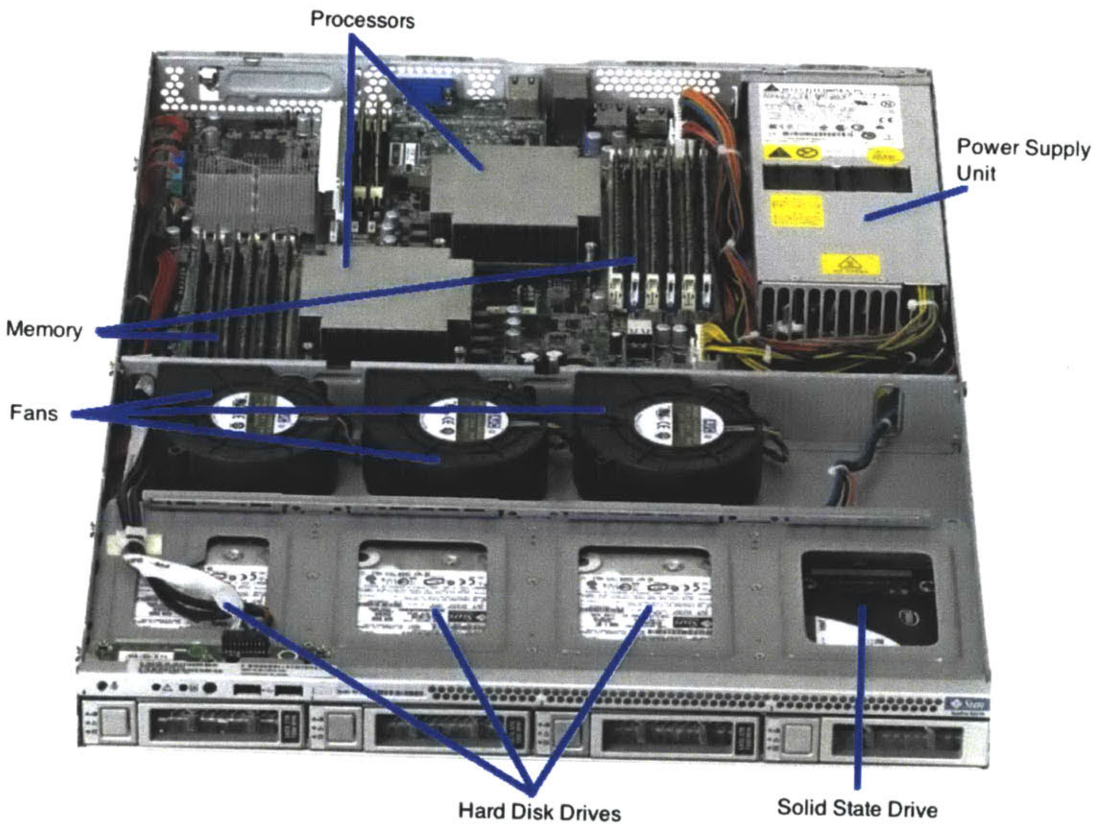

Figure 5. Typical Server Components [5]

Servers operate over a range of DC voltages while utilities deliver power as AC, and at higher voltages than required within servers. In order to convert this current, servers require one or more power supply units (PSUs). Since the failure of one power source affects the operation of the server, many servers have redundant power supplies. These devices add to the heat output of the design. However, for simplicity, the optimization model considers a single power source for all blades within the enclosure. The blade enclosure's power supply provides a single power source for all blades within the enclosure. This single power source may come as a power supply in the enclosure or as a dedicated separate PSU supplying DC to multiple enclosures so that the setup reduces the number of PSUs required to provide a resilient power supply [6].

During operation, the server components generate heat. In order to dissipate the heat to ensure the suitable functioning of the server's components, most blade servers eliminate heat by using fans.

Figure 6 highlights how power is consumed on average within an individual server. Processors and memory consume the most power, followed by the power supply loss. Hard disk drive power only becomes significant in servers with several disk drives.

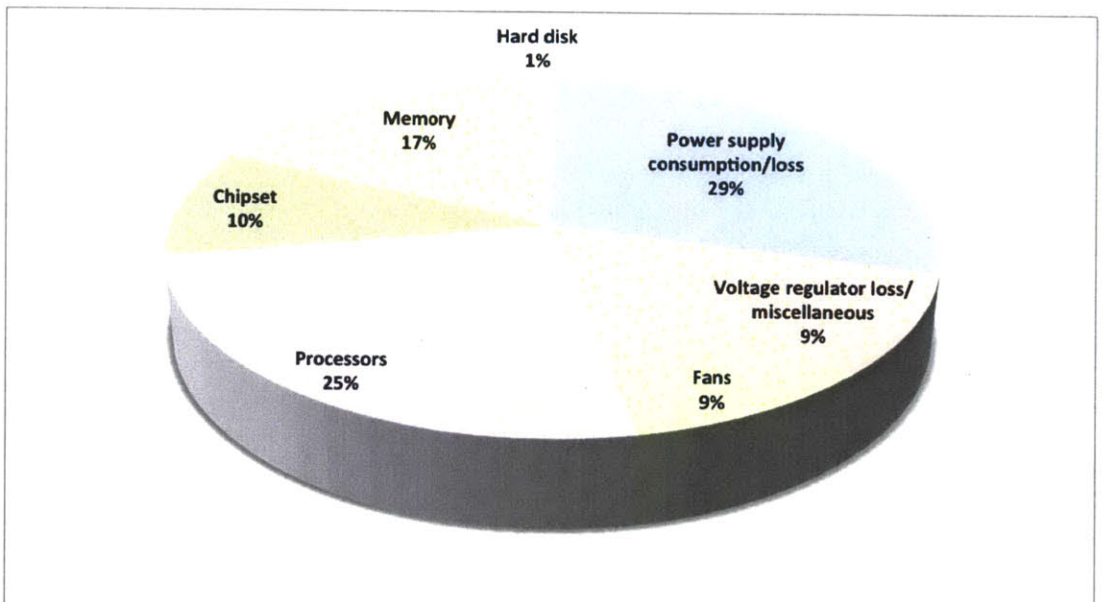

Figure 6. Component Level Power Consumption an a Typical Server, Using Two 50 W Low Voltage Processors [7]

Overall power consumption and the components are discussed in the following sections in terms of the optimization model under consideration.

4.2.1. Server Utilization

The server plays a key role in a datacenter since it processes the computational workload and processes the results needed by the business. In addition, servers require huge amounts of energy to operate. For this reason it is necessary to both improve server efficiency and measure overall server utilization in order to enhance the performance of the datacenter. Overall server utilization can be defined using the following equation:

$$Overall\ Server\ Utilization = \frac{Utilized\ Capacity}{Installed\ Capacity}$$

Utilized capacity is the sum of measured CPU utilization for each of the servers in a datacenter. Installed capacity is the sum of the maximum performance ratings for all installed servers. However, overall server utilization does not include disparities in performance and power characteristics across servers.

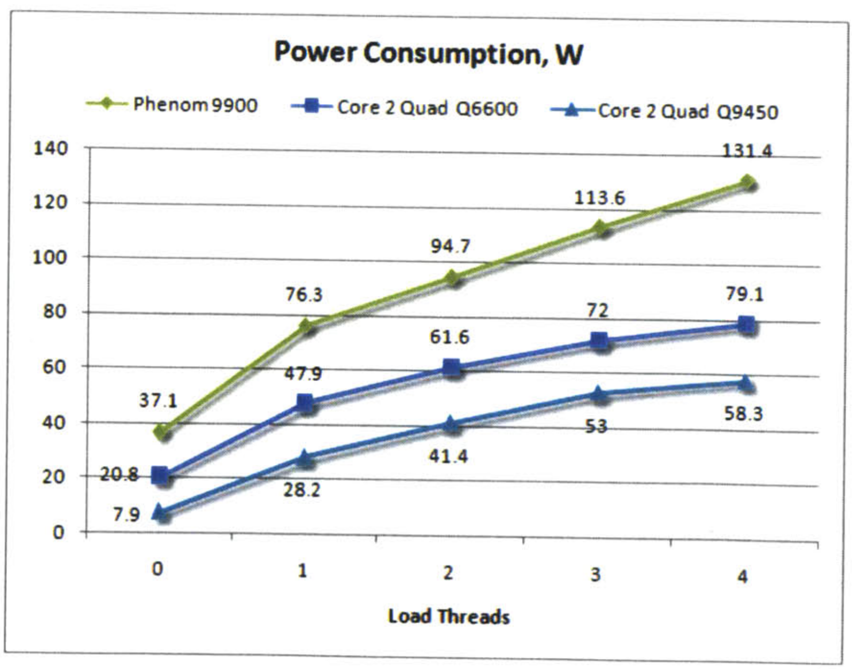

Figure 7. Power Usage of Different Processors [8]

In Figure 7, the graph covers three generations of CPU architecture. The graph indicates the expected trend with a linear increase in power consumption that follows total CPU utilization. The power consumption of a typical processor consists of a base load power and variable power consumption. The base load power is consumed even when the processor is idle, or running at 0% capacity. This variable power usage is linearly dependent on the processor load, and the power usage characteristics of the processor indicate that managing the load distribution and/or using servers with lower base load power consumption can increase the server system efficiency. The overall server utilization is:

$$U = \frac{1}{N_{Servers}} \sum_{i=0}^{n} u_i$$

Where:

U = overall server utilization,

u = individual server utilization,

$N_{Servers}$ = number of servers.

In order to build our optimization model on energy efficiency in a datacenter having various types of servers, the model should be simplified, and assume that the datacenter has servers with the same performance and power characteristics. It is hard to predict the effect on cooling systems in real datacenters consisting of heterogeneous servers [9]. From the simplified server utilization concept, the server's power consumption is linear in utilization between an idle power and peak load power is:

$$P_n = (P_{max} - P_{idle}) * U + P_{idle}$$

$$= (P_{max} - P_{idle}) * \frac{1}{N_{Servers}} \sum_{i=0}^{n} u_i + P_{idle}$$

Where:

P_n = power consumption at n% CPU utilization,

P_{max} = maximum power draw,

P_{idle} = idle power draw.

For instance, if the example datacenter consisting of 900 servers has a maximum utilization across the datacenter of 50%, the server has an average maximum power draw of 300 Watts (W) and an average idle power draw of 200W, then at 50% individual server utilization the power draw would approximate to:

Power Utilization at 50% (P_{50})

= ((300 – 200) * 0.5 + 200) * 900

= (100 * 0.5 + 200) * 900

= 250 * 900

= 225 kW

However, if the example datacenter manages the maximum utilization across the datacenter of 50%, this is an aggregate utilization of 45000%, which equates to 450 servers running at 100%. Furthermore, the datacenter assumes that the datacenter runs with 70% of servers (peak utilization of 71%) to keep sufficient headroom and allow for resilience. Therefore, a power saving equivalent of up to about 257 servers is possible for this datacenter. The energy cost savings can be achieved by analysis of server usage patterns and server utilization.

In addition, modern server processors have begun to incorporate the power saving architectures, resulting in overall system power savings of up to 20% [10]. Reducing the frequency multiplier and the voltage of the CPU are the main drivers for the power saving. The combination of a specific CPU frequency and voltage is known as a performance state (p-state). In order to reduce a server's power consumption, the p-state should be modified at low utilization. However, it can still provide the same peak level of performance when required. The switch between p-states is dynamically controlled by the operating system and occurs in microseconds, causing no perceptible performance degradation [10]. In Figure 8, the graph indicates an impact on power consumption under different CPU utilization loads using AMD Data7 server.

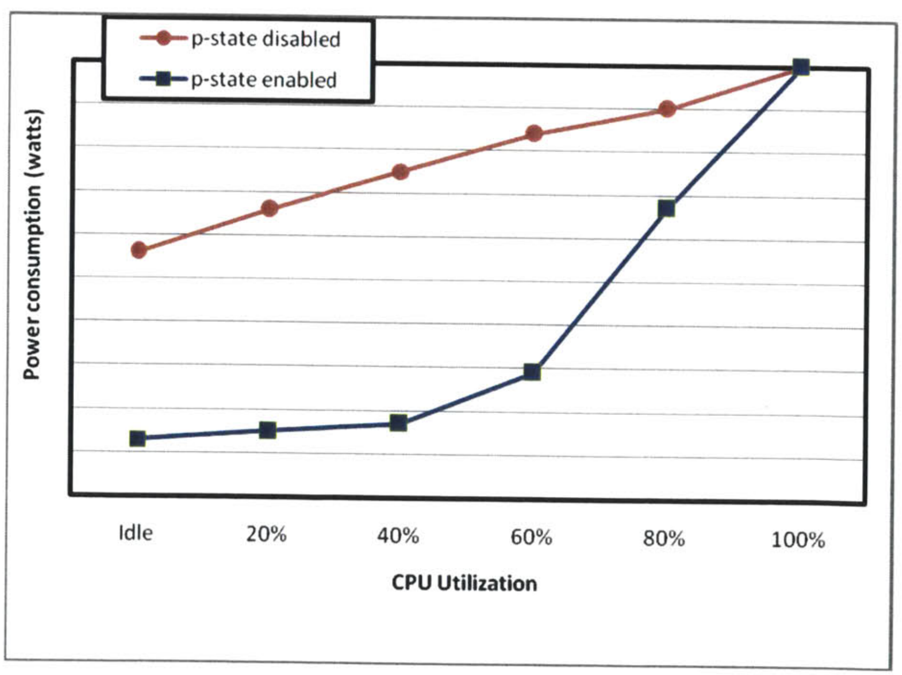

Figure 8. Impact of p-state on Power Consumption (AMD Data7) [10]

Therefore, the optimization model will consider the following modified server's power consumption when the server utilization is less than 60% as:

$$P_n = \left((P_{max} - P_{idle}) * U + P_{idle}\right) * \ 0.8$$

4.2.2. Central Processing Unit (CPUs)

Higher internal temperatures decrease the performance of a computer [11], leading to computer crashes [12]. In addition, the server system can become unstable due to random freeze, hard drive problems, random application crashes, and so forth. Without sufficient cooling or proper ventilation throughout the server rack, any overheating component of the computer can heat up other parts, which might cause them to crash, even if the hot element itself does not [13]. In order to optimize the datacenter's temperature setpoint, it is essential to understand the power consumption of CPU depending on temperature.

The server power depends on both the number of CPUs and the type of platform. Therefore, the static power consumption of CPU is temperature dependent. This static power is primarily due to various leakage currents. Modern processors use the dynamic power control that is relatively independent of the temperature. They also use technologies such as demand based switching and enhanced speed step to reduce the power consumption [14]. The total power of CPU also includes the dynamic power. The dynamic power dissipated by CPU is:

$$P = C \times V^2 \times f$$

Where:

C = capacitance being switched per clock cycle,

V = voltage,

f = switching frequency.

However, the dynamic power consumption of CPU is not temperature dependent. For this reason, the optimization model considers the static power consumption in a processor. In order to define the equation that shows the relationship between the CPU and temperature, electrical power can be presented by using Joule's law combined with Ohm's law. In direct current resistive circuit, Joule's law is expressed as:

$$P = IV$$

Where:

P = electrical power,

I = electrical current,

V = potential difference.

Moreover, Ohm's law is:

$$V = IR$$

Where:

R = electrical resistance.

In the case of linear loads, Ohm's law can be plugged into Joule's law to produce the dissipated power:

$$P = I^2 R$$

As temperature is increased, the electrical resistance of metals typically increases. When the temperature coefficient is known, an adjusted resistivity value can be calculated using the following formula:

$$R = R_{ref} * [1 + \alpha * (T - T_{ref})]$$

Where:

R = conductor resistance at temperature T,

R_{ref} = conductor resistance at reference temperature T_{ref},

α = temperature coefficient of resistance,

T = conductor temperature,

T_{ref} = reference temperature.

Thus, the CPU power is:

$$P = I^2 \left[R_{ref} * [1 + \alpha * (T - T_{ref})]\right]$$

Since the most common heat sink materials are aluminum alloys, the optimization model will consider the aluminum alloy with a temperature coefficient of 0.0039 per degree centigrade at 20°C (68°F). This model applies to the entire length of wire and for each degree of temperature rise above 20°C. The resistances of a mil foot of wire at 20°C and the temperature coefficient for different metallic elements are shown in Table 3. The temperature of a conductor is a main factor to affect its resistance. The resistance of metallic elements is generally given at 20°C in order to comply with the standard used in the American Engineers Handbook. We can determine the resistance of a material at different temperatures by using the temperature coefficient of the material. [15]

Table 3. Resistivity of Materials at 20°C (68°F) [15]

Material	Ω Per Mil-Foot @ 20°C	Temperature Coefficient (Ω per °C)
Aluminum	17	0.0040
Carbon	22,000	-0.0004
Constantan	295	0.000002
Copper	10.4	0.0039
Gold	14	0.0040
Iron	60	0.0055
Lead	126	0.0043
Mercury	590	0.00088
Nichrome	675	0.0002
Nickel	52	0.0050
Platinum	66	0.0036
Silver	9.6	0.0038
Tungsten	33.8	0.0050

For example, for a static power dissipation of 8W CPU operating at 2 volts and 5 ohm consumes 4 amperes, and the static power at 30°C is:

$$P = I^2\left[R_{ref}\times\left[1+\alpha(T-T_{ref})\right]\right]$$

$$= 4^2\times\left[5\times[1+0.0040\times(30-20)]\right]$$

$$= 80\ W$$

4.2.3. Server Fans

In a datacenter, air transfers heat from servers to the cooling system. The server fans are a critical element in the heat transfer process across the server. First, cold air absorbs the heat and the warm air returns to the cooling system. Second, the cooling coils in the cooling system absorb heat from air and transfers to the coolant, thereby warming it. Next, the warm coolant deposits the heat at a chiller. Finally, the heat is dissipated to outside air. Heat transfer equation states the simple formula for heat absorbed by a body:

$$\text{Heat= Specific heat* Mass* } \Delta T$$

Where:

T = temperature.

This relationship can be extended to calculate power conducted by fluids. In general, heat is transferred between a device and fluid according to the following thermal dynamics principle:

$$Q = mc_p(T_{out} - T_{in})$$

$$= \rho V c_p(T_{out} - T_{in})$$

Where:

m = air mass flow rate in kg/s,

c_p = heat transfer coefficient,

T_{out} = outlet air temperature,

T_{in} = inlet air temperature,

ρ = mass density of the fluid,

V = volume flow rate.

From the equation above, one of the controllable factors that determine heat transfer is the temperature difference (ΔT) across the cooling system. Based on this relationship, the heat transfer equation can be extended to the Coefficient of Performance (COP) equation. This equation indicates that higher COP means more efficient system. The equation is:

$$COP = \frac{|Q|}{W}$$

$$= \frac{Q_{in}}{Q_{out} - Q_{in}}$$

$$= \frac{T_{in}}{T_{out} - T_{in}}$$

Where:

Q = heat removed from the cold reservoir,

W =work energy.

Those equations are essential to understand the relationship of energy consumption and a change in datacenter temperature. This paper will show the impact of datacenter temperature on the overall efficiency of the total IT and utility infrastructure system. In Table 4, ASHRAE recommends that the most critical datacenters should be maintained between 18 and 27°C, with an allowable range of 15 to 32°C [16].

Table 4. Class and Upper Temperature Limit Recommended by ASHRAE [16]

Recommended	Allowable			
All 'A' Classes	A1	A2	A3	A4
18 ~ 27°C (64.4 ~ 80.6°F)	15 ~ 32°C (59 ~ 89.6°F)	10 ~ 35°C (50 ~ 95°F)	5 ~ 40°C (41 ~ 104°F)	5 ~ 45°C (41 ~ 113°F)

*Al: Typically an enterprise datacenter with tightly controlled environmental parameters.
*A2/ A3/ A4: Typically an information technology space or office or lab environment with some control of environmental parameters.

This temperature represents the temperature at the inlet to the IT equipment. Optimizing the room setpoint can be a critical factor in the cooling system's energy use and room operation. This paper will consider the energy efficiency of the datacenter as a function of temperature inside that acceptable range. In order to improve datacenter efficiency, this paper also considers the power delivery including the uninterrupted power supply (UPS), and the power distribution unit (PDU).

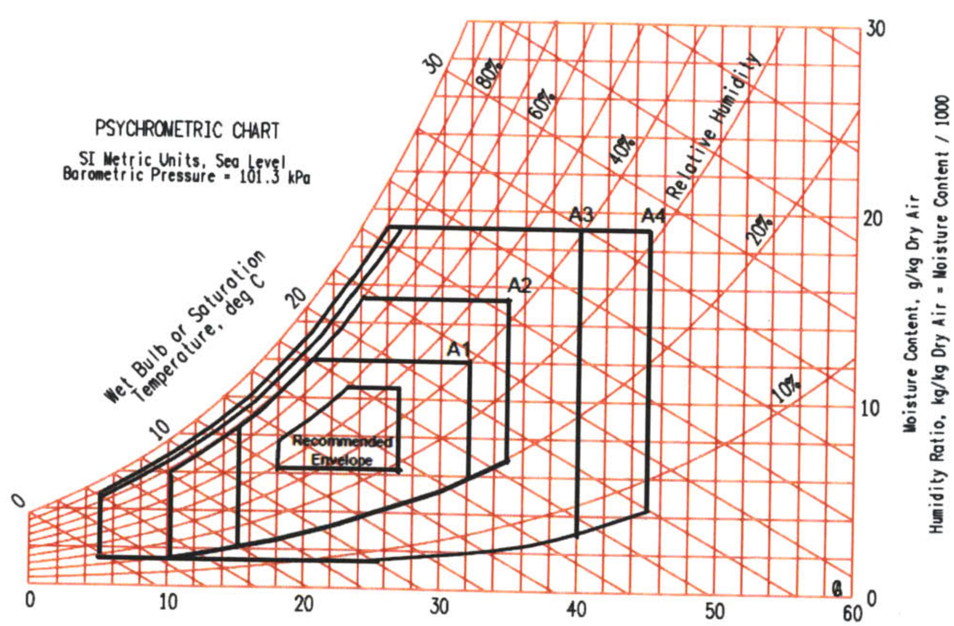

Figure 9. ASHRAE Environmental Classes for Datacenters [16]

In Figure 9, the ASHRAE guidelines issued in 2011 broadened the acceptable temperature range to 15 to 32°C. This paper considers the energy impact of raising the datacenter temperature setpoint with - in the ASHRAE allowable limits (15~32°C). One of the important factors to consider regarding the optimal datacenter temperature is that variable speed fans in the servers are usually controlled to the internal server temperature. The ASHRAE emphasizes the importance of the difference between the recommended and allowable envelopes presented in their guidelines. The recommended environmental envelope provides guidance for operators of datacenters on the energy-efficient operation of datacenters while maintaining high reliability. They also mention that the allowable envelope outlines the environmental boundaries tested by equipment manufacturers for equipment functionality, not reliability. [17]

Operating the datacenter at server inlet air conditions above the recommended range may cause these internal fans to operate at higher speeds and consume more power. Therefore, the effect of increasing server inlet air temperature on server fan power should be carefully weighed against the potential datacenter cooling system energy savings. The following equation shows the relationship of energy consumption and a change in datacenter temperature:

$$P \propto \Delta T = T_{out} - T_{in}$$

Where:

P = power,

T_{out} = temperature outside the datacenter,

T_{in} = inlet temperature of the datacenter.

From the relationship above, this paper will show the energy impact of raising the datacenter temperature within the ASHRAE allowable limits (15~32°C) as well as the relationship between the cooling system power consumption and the temperature.

4.2.4. Fan Speed Control (FSC)

The goal of FSC is to control fan speed not only to meet component thermal requirements, but also to reduce thermal margin. Reduced thermal margin lowers fan speed by using thermal sensors and control logic. The FSC plays a vital role in accomplishing the goal of durable unfailing operation of the processor for energy saving due to ambient temperature variation. Figure 10 indicates the relative efficiencies of the flow control options.

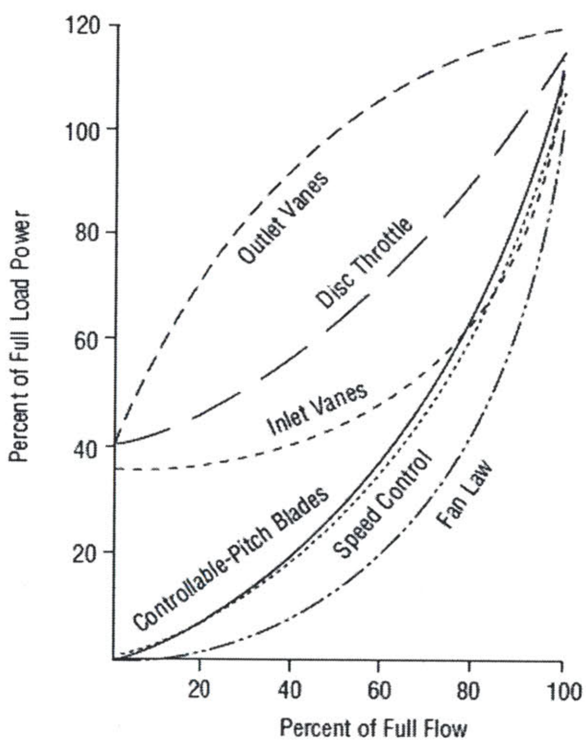

Figure 10. Relative Power Consumption Among Flow Control Options [18]

Fan speed is typically measured in revolutions per minute (rpm). Fan speed has a significant impact on fan performance, as shown by the following fan laws:

$$m_{outlet} = m_{inlet}\left(\frac{V_{outlet}}{V_{inlet}}\right)$$

$$P_{outlet} = P_{inlet}\left(\frac{V_{outlet}}{V_{inlet}}\right)^2$$

$$Q_{outlet} = Q_{inlet}\left(\frac{V_{outlet}}{V_{inlet}}\right)^3$$

Where:

m_{outlet} = air flow rate at outlet point,

m_{inlet} = air flow rate at inlet point,

P_{outlet} = pressure at outlet point,

P_{inlet} = pressure at inlet point,

Q_{outlet} = fan input power at outlet point,

Q_{inlet} = fan input power at inlet point,

V_{outlet} = fan speed at outlet point,

V_{inlet} = fan speed at inlet point.

Also, heat transferred in cooling unit can be calculated as:

$$Q = mc_p(T_{out} - T_{in})$$

The speed of the fan in dry air in meters per second (m/s) is approximately equal to:

$$V = 331.4 + 0.6T$$

Where:

V = speed of fan,

T = temperature ($°C$)

Therefore, in order to calculate the power of fan, this paper will apply the fan power law with power changes being related to flow changes to the 3rd power:

$$\left(\frac{Q_{outlet}}{Q_{inlet}}\right)_{fan} \propto \left(\frac{V_{outlet}}{V_{inlet}}\right)^3$$

From both the equation of fan speed and the fan power law can be represented by the temperature:

$$\frac{Q_{outlet}}{Q_{inlet}} = \left(\frac{V_{outlet}}{V_{inlet}}\right)^3$$

$$\frac{Q_{outlet}}{Q_{inlet}} = \left(\frac{331.4 + 0.6T_{outlet}}{331.4 + 0.6T_{inlet}}\right)^3$$

According to the equation above, power consumption increases to the 3rd power. That is, fan power is the largest temperature dependent power use in the platform. The optimization model will consider the increased fan power with an increase in inlet air temperature from $20°C$ to $32°C$.

4.2.5. The Memory Modules

Memory is also one of the largest power consumers in a server. Recent Internet Protocol

Datacenters, such as Google, Facebook, and Twitter, require intensive search applications. For this reason modern high-performance datacenters increase both use of virtualization and processor core counts in servers. These recent intensive search-based applications require more memory. Figure 11 displays how memory power consumption differs among DIMMs using DDR2 and DDR3 technology.

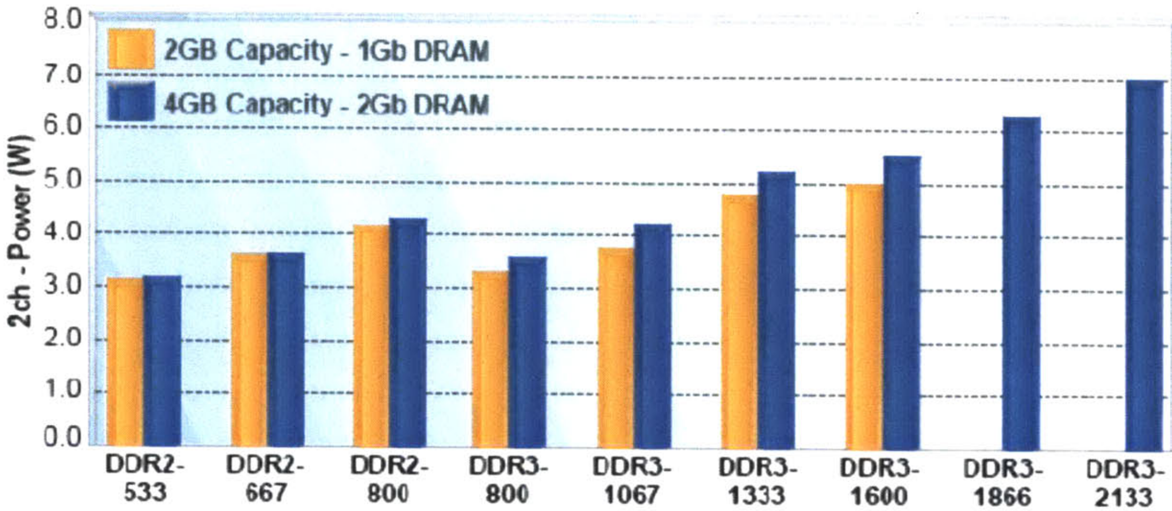

Figure 11. Dual In-line Memory Modules (DIMMs) Power Comparison[1]

As the memory modules in high-performance increase in capacity, their power consumption increases. Table 5 shows DDR3 RDIMM raw cards, DRAM density, capacity and the forecasted power use based on different speed targets of 1066MHz, 1333MHz and 1600MHz. The memory power varies considerably depending upon the memory technology used, the memory configuration, and the vendor. The optimization model assumes an average of 16GB memory consuming 20W per server.

[1] Intel Platform Memory Operation, 2007

Table 5. DIMM Power Consumption by Frequency, Configuration, and Capacity[2]

Sample Card	Frequency (MHz)	DIMM Configuration	DIMM Tech/Capacity	Power/DIMM	64GB System Power
Card A	1066	QR×4	2Gb/8Gb	15.5W	124W
Card B	1333	QR×8	2Gb/8Gb	10.6W	84.8W
Card C	1333	DR×4	1Gb/4Gb	10.6W	169.6W
Card D	1333	QR×4	2Gb/16Gb	20.5W	82W
Card E	1600	QR×8	2Gb/8Gb	10.1W	80.8W
Card F	1600	QR×4	2Gb/8Gb	19.1W	152.8W

4.2.6. The Power Supply Units

Most modern datacenter equipment uses rack mounted alternating current/direct current (AC/DC) power supplies. Power supply units convert the power provided from the outlet into usable power for the components inside the server. The efficiency of the computer power supply units depends on its load. The efficiency of PSUs operated at least 20% of their nominal capacity is between 60% and 80% [19], which meant there were greater losses inside the server than there were going to through the many steps and voltage changes from the high-voltage lines at the utility tower to supply the low-voltage lines at the server [20]. By using higher-quality components and innovative technology, datacenters can utilize power supplies with efficiencies up to 95% [17]. These energy efficient power supplies indirectly reduce a datacenter's cooling system cost as well as rack overheating issues.

Efficient power supplies usually increase cost at the server level. The Server System Infrastructure (SSI) Initiative recommends power supplies that meet their efficiency guidelines. In addition, there are several certification programs to standardize the efficiencies of power supplies for datacenters. For instance, the 80 PLUS program offers certifications for power

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[2] Intel Platform Memory Operation, 2008

supplies with efficiencies of 80% or greater at 20%, 50%, and 100% of their rated loads with power factor of 0.9 or greater. This means that PSUs waste 20% or less electric energy as heat at the specified load levels.

In Figure 12, the loads at 40-60% utilization are the most efficient. At lower capacity levels, the efficiency drops significantly. It does not improve dramatically once the loads have crossed 60% utilization. In order to understand the impact of real operating loads, the optimization model considers a power supply (PSU) efficiency of 95% at the power supply load level at 50%.

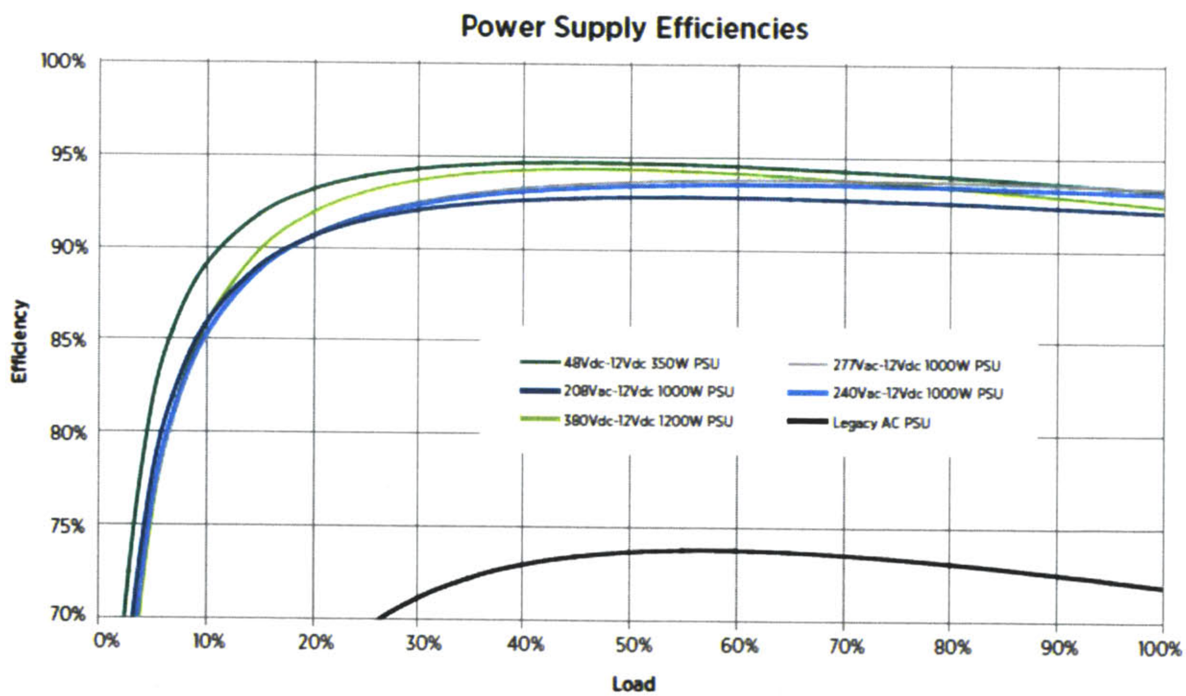

Figure 12. Efficiencies at Varying Load Levels for Typical Power Supplies[3]

4.2.7. The Hard Disk Drives

The power consumption by hard drives is closely related to the workload the server is

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[3] Quantitative Efficiency Analysis of Power Distribution Configurations for Data Centers, The Green Grid

processing. The increasing storage capacity and necessary redundancy of datacenters and other large-scale IT facilities has drawn attention to the issue of reducing the power consumption of hard drives. However, the power consumption of hard drives to determine typical runtime power profiles is out of scope for the research, since it requires a fine-grained level to present results that provide insight into the mechanical and electronic power consumption of hard drives at runtime. Also, hard drives consume a small amount of power. Therefore, the research considers average IT power that is consumed by hard drives. The average power consumption of hard drives can be calculated by measuring the power consumption of a hard drive during both idle operations and read/write operations. A basic server with four hard disk drives (HDDs) consumes between 24W and 48W for storage.

4.3. The Computer Room Air Conditioning/Handlers (CRAC/CRAH) Unit

CRAC units provide precise temperature and humidity control for mission critical environments. They accept the heat energy generated by IT equipment and cool the heat. Furthermore, they return the heat back to the equipment in order to provide recurrent heat exchange. Figure 13 illustrates the layout and cooling system in a typical datacenter. The datacenter room has raised floor, and power lines, cables, and cooling supplies are placed between the floor slab and the floor tiles. Although this under-floor area is often used to route power lines and cables to racks, its primary use is to flow cool air from the CRAC to the server rack. The CRAC units blow cold air into the raised floor plenum, and pressurize the plenum. This cold air flows from the plenum through perforated tiles and then flows through the servers. In order to prevent mixing hot and cold air, racks are arranged in long aisles that alternate between hot aisles and cold aisles. The hot air from the servers flows to the intakes of the CRAC units to be cooled, and then the cold air produced by the CRAC units flows through the raised floor plenum again. A liquid coolant flows through coils in the CRAC units, and then fans push air through and around coils to cool it down. Cold coolant from a set of redundant pumps is circulated to the CRAC units, and then warm coolant flows to a chiller in order to eject the heat to the outside datacenter. According to the industry studies in term of the CRAC units, the typical incoming coolant is at 12 ~ 14°C, and the air exiting the CRAC units is at 16 ~ 20°C, which leads to cold aisle temperature of 18 ~ 22°C [21]. The warm coolant then returns to a chiller.

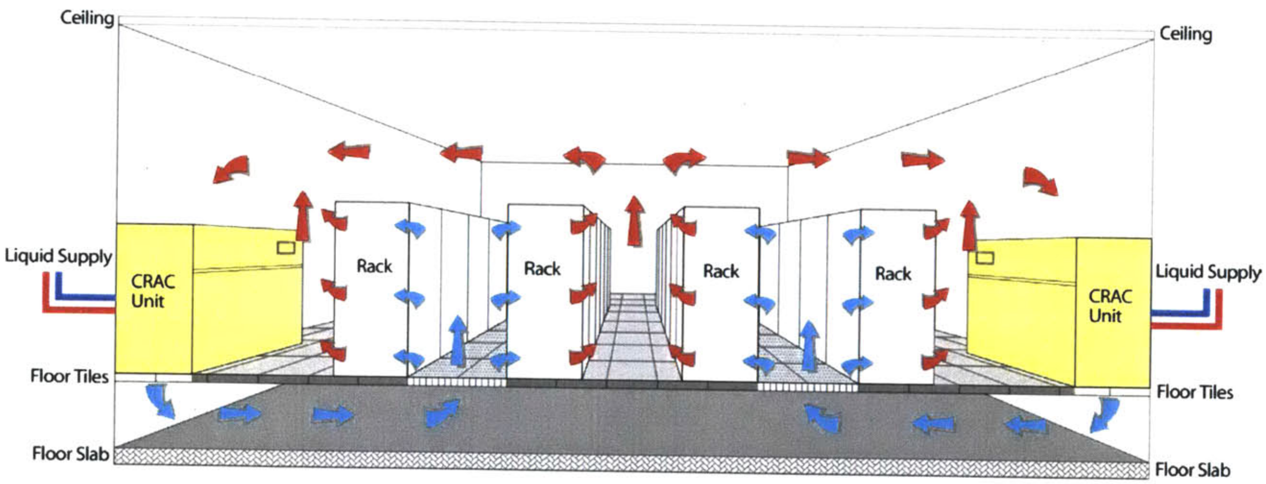

Figure 13. Raised Floor Datacenter with Hot-Cold Aisle Setup [22]

Based on this cooling process, the CRAC units draw electrical power as well as the cooling load of the chiller. The chiller unit generates the primary cooling capacity used by the CRAC. The conventional chillers are water-cooled and have a supply of cooling water from the cooling tower. The cooling tower uses ambient air to cool down the incoming water and uses commercial utility water for make-up losses due to evaporation. In reality, there are various combinations of ambient and electrical cooling, and they are used to meet the cooling load.

4.4. The Chiller Plant Unit

In large, air-conditioned datacenters, the chiller plant is one of the main energy consumers. The energy consumption of auxiliary chiller plant components includes: the cooling tower, the chilled-water pump, and the condenser water pump. The chiller types are water-cooled, air-cooled or evaporative-cooled. In Figure 14, the typical chilled-water systems feature separate central chillers and air handlers, with a network of pipes and pumps to connect them. Chillers use one of four types of compressor: reciprocating, scroll, screw or centrifugal. Reciprocating chillers are the least efficient. Screw and scroll compressors are typically used in applications needing up to 300 tons of cooling capacity. Centrifugal compressors traditionally provide larger capacities, although a new type of centrifugal compressor that employs magnetic bearings breaks this mold to serve the under-300-ton market [23].

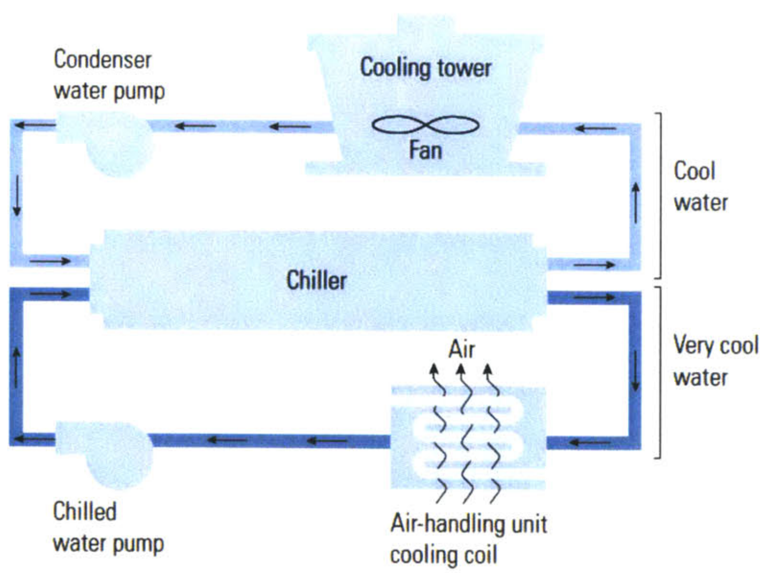

Figure 14. Typical Water-Cooled Chiller System[4]

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[4] EPA, http://www.energystar.gov/index.cfm?c=business.EPA_BUM_CH9_HVAC#F_9_2

The evaporator is located remotely from the condensing section on air-cooled units in order to allow the chilled water loop to remain inside the building envelope when using an outdoor chiller. In case of freezing conditions, the chiller system keeps the chilled water loop inside the building to prevent the need for some form of antifreeze. The chilled water flows through the evaporator of the chiller. The evaporator is a heat exchanger where the chilled water gives up its sensible heat and transfers the heat to the refrigerant as latent energy [24].

5. APPLYING THE MODEL: A CASE STUDY.

5.1. Minimization of Datacenter Power Consumption

In order to maximize the datacenter energy efficiency, this paper will consider the effect of the different parameters' efficiency. The PUE metric calculation based on the example profile of the datacenter also could be used as the design of the next generation datacenter. To demonstrate the optimization model, this paper considers the power requirements of a hypothetical datacenter. The optimization model was tested for a typical air-cooled datacenter with a 1000 kW of IT load. Typical values were assumed for model parameters and system characteristics, as given in Table 6.

Table 6. Assumptions Used in the Analysis

Total Average Cooling Load	0.35
Chiller Load (%)	50
Chiller COP Increase per 1°C (%)	3.6
PSU Load (%)	90
Initial Rack Power (kW)	1,000.00
Initial Total Power (kW)	2,100.00
Initial PUE	2.10
Number of Servers	900
Number of Fans	6
Initial Fan Power (W)	10
Utilization (%)	50
Server Peak Power (W)	300
Server Idle Power (W)	200
Ram Power (W)	100
CPU Resistance (Ω)	5
CPU Electrical Current (Amps)	3
Coefficient of Resistance	0.0040
Cost per kWh (NJ) ($)	0.1491

The example datacenter has 900 servers and 250 racks. The datacenter uses a standard rack (approximately 1.8 inches) holding roughly four 1U servers. This paper assumes that a single rack of four 1U servers each with two 300W processors. This paper assumes that the datacenter consumes 2,100 kW of the annual average total power use and 1,000 kW of the annual average IT power use. The power consumption of the cooling system is:

$$P_{cooling} = 2{,}100\text{ kW} \times 0.35$$

$$= 735\text{ kW}$$

$$P_{chiller} = 735\text{ kW} / 2$$

$$= 367.5\text{ kW}$$

Thus, the COP of the chiller is given by:

$$COP_{chiller} = \frac{heat\ removed}{P_{chiller}}$$

$$= \frac{(P_{datacenter} - P_{chiller})}{P_{chiller}}$$

$$= (2100\text{ kW} - 367.5\text{ kW}) / 367.5\text{ kW}$$

$$= 4.72$$

Figure 15 shows how COP improves with increasing chilled water temperature, for a typical chiller. The graph indicates that the 10°C rise will increase the COP of the chiller system by about 36% [25]. That is, the chiller COP can be improved by about 2% by increasing chilled water temperatures 1 °F.

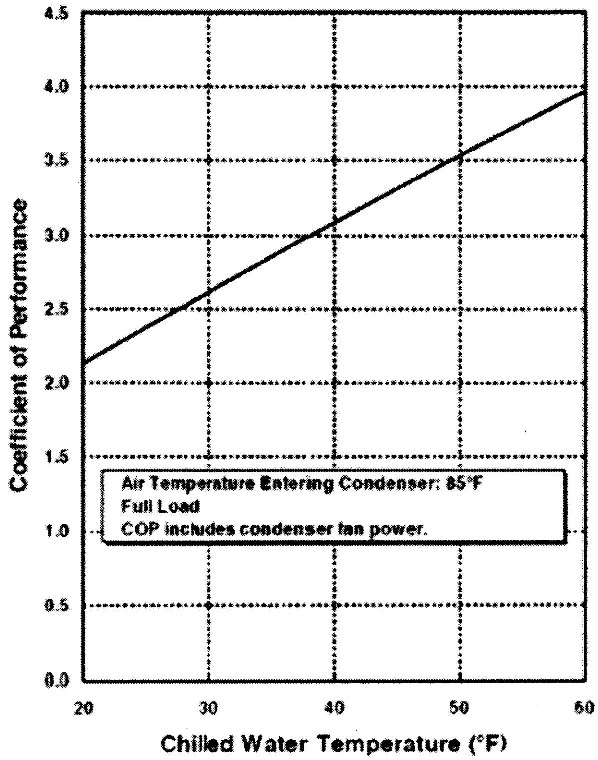

Figure 15. Dramatic Improvement of Chiller COP by Raising the Chilled Water Temperature

Based on the correlation between the Chiller COP and the room temperature, increasing the room temperature by 10°C would be the COP chiller of 6.41.

The new chiller power can be derived by the following equation:

$$COP_{chiller} = \frac{(P_{datacenter} - P_{chiller\_new})}{P_{chiller\_new}} = 6.41$$

$$\frac{(2{,}100\ \text{kW} - P_{chiller\_new})}{P_{chiller\_new}} = 6.41$$

$$P_{chiller\_new} = 2{,}100\ kW/7.41$$

$$= 283.4\ \text{kW}$$

Thus, by increasing the inlet temperature by 10°C, the cooling power consumption can be calculated as:

$$P_{cooling\_new} = 283.4\ kW \times 2$$

$$= 566.8\ \text{kW}$$

In addition, this paper considers the increased fan power with an increase in inlet air temperature from 20°C to 30°C. This paper assumes a power supply (PSU) efficiency of 80%. In order to calculate the power of fan, this paper will apply the fan laws with power changes being related to flow changes to the 3rd power:

$$\left(\frac{P_{new}}{P_{old}}\right)_{fan} \propto \left(\frac{v_{fnew}}{v_{fold}}\right)^3$$

$$\left(\frac{P_{new}}{P_{old}}\right)_{fan} = k\left(\frac{v_{fnew}}{v_{fold}}\right)^3$$

Where:

P = power,

V = volume,

T = temperature,

k = coefficient of fan power.

The model assumes P_{peak} at 32°C and $P_{low-end}$ at 20°C:

$$P_{peak} = 40\ \text{W}$$

$$P_{low-end} = 10\ \text{W}$$

According to the fan laws, power consumption increases to the 3rd power. That is, fan power is the largest temperature dependent power use in the platform.

$$P_{new} = P_{old} \times \left(\frac{T_{new}}{T_{old}}\right)^3$$

$$= 10W \times \left(\frac{30°C}{20°C}\right)^3$$

$$= 33.75 \text{ W}$$

$$P_{increase} = P_{new} - P_{old}$$

$$= 33.75 \text{ W} - 10 \text{ W}$$

$$= 23.75 \text{ W}$$

In addition, the increased power should consider the power supply (PSU) efficiency of 90%, and this paper assumes the 1U server has six 10W fans at 20°C.

$$P_{fan} = 23.75 \text{ W} \times 1.1$$

$$= 26.13 \text{ W}$$

The power consumption of the rack is given by:

$$P_{rack} = Initial\ rack\ power + P_{fan} \times number\ of\ fans \times \frac{Number\ of\ servers}{1000}$$

$$= 1000\ kW + 26.13\ W \times 6 \times \frac{900}{1000}$$

$$= 1{,}141 \text{ kW}$$

In addition, the power consumption should include the static power consumption of CPU. For a static power dissipation of 5W CPU, operating at 1.5 volts and 5 ohm consumes 3.3 amperes, and the static power at 30°C is:

$$P = I^2 \left[R_{ref} * \left[1 + \alpha * (T - T_{ref})\right]\right]$$

$$= 3.3^2 \times \left[5 * [1 + 0.0040 * (30 - 20)]\right]$$

$$= 56.63\, W$$

The static power dissipation of the same CPU above at 20°C is:

$$P = I^2 \left[R_{ref} * \left[1 + \alpha * (T - T_{ref})\right]\right]$$

$$= 3.3^2 \times \left[5 * [1 + 0.0040 * (20 - 20)]\right]$$

$$= 54.45\, W$$

Thus, increasing inlet temperature by 10°C, the total static power dissipation of the 5W CPU operating at 1.5 volts and 5 ohm is increased by:

$$P_{CPU_{30}°C} - P_{CPU_{20}°C} = 56.63W - 54.45\, W$$

$$= 2.18\, W$$

Consequently, based on the fan power use, the datacenter power use can be corrected:

$$P_{datacenter} = P_{chiller\_new} + P_{cooling\_new} + P_{rack} + P_{CPU}$$

$$=283.4 \text{ kW} + 566.8 \text{ kW} + 1{,}141.08 \text{ kW} + 2.18 \text{ W}$$

$$= 1{,}993 \text{ kW}$$

As a result of increasing inlet temperature by 10°C, the total datacenter power is decreased by 55.78 kW. Also, this would increase the datacenter efficiency:

$$PUE = 1 + \frac{P_L}{P_{IT}}$$

$$= 1 + \frac{(P_{cooling\_new} + P_{chiller\_new})}{P_{datacenter} - (P_{cooling\_new} + P_{chiller\_new})}$$

= 1 + (566.8 kW + 283.4 kW) / (1,993 kW – (566.8 kW + 283.4 kW))

= 1 + 850 kW / 1,143 kW

= 1.74

Figure 16 illustrates how an optimal temperature for a given power consumption is chosen. The minimal power loss is at an optimal temperature at 30°C (86°F). As the cooling technology advances, the total power loss at the optimal point reduces and the cooling cost is reduced, allowing for better performance and lower cost.

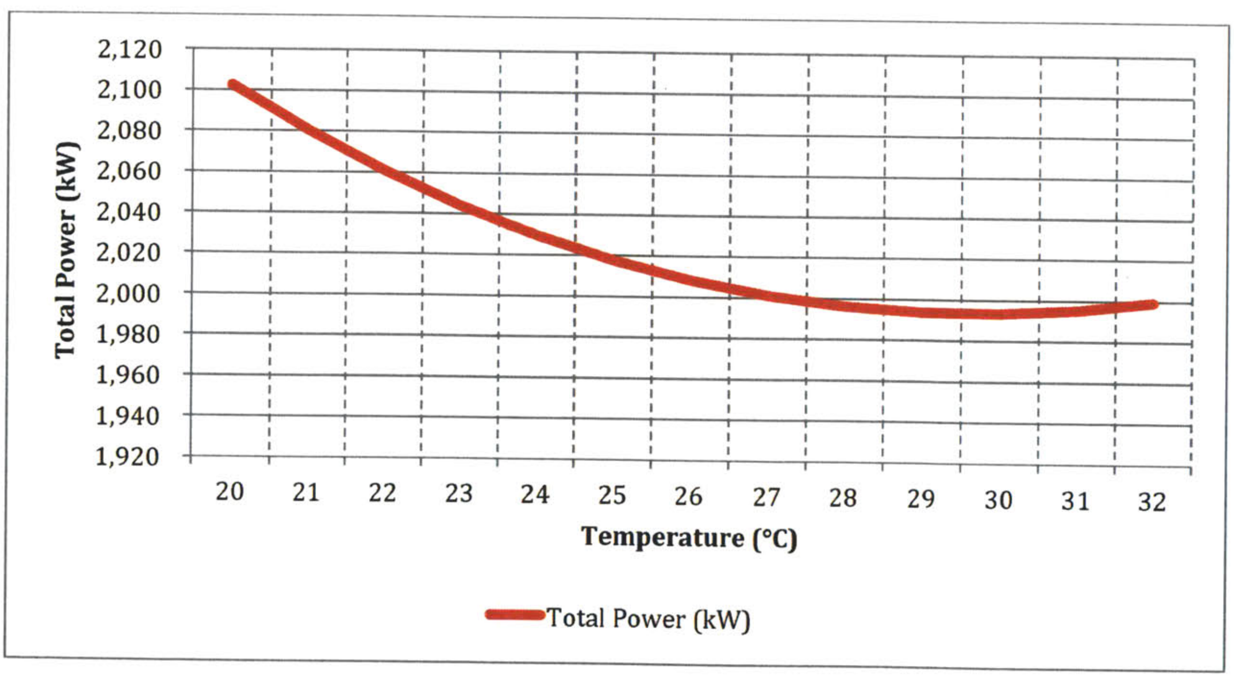

Figure 16. The Total Power Decreased by Raising Inlet Temperature Setpoint

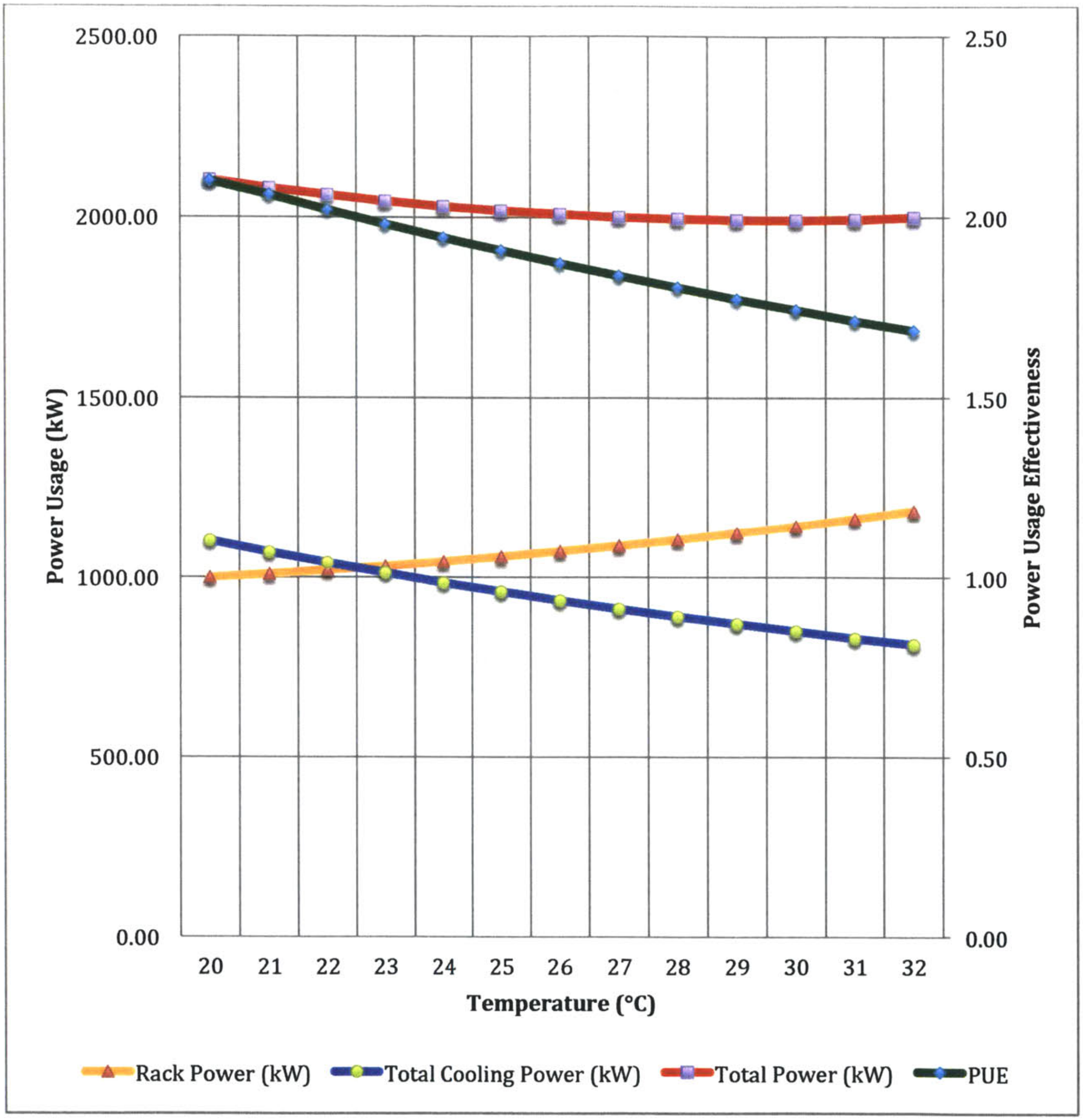

Figure 17. Optimization Results

Based on the equations above, this paper calculated the increased fan power and rack power energy consumption. The result is presented in the Table 9 (see Appendix). In Figure 17, the graph presents energy consumption as datacenter temperature increased. The graph illustrates the cooling energy consumption (BLUE), the IT energy consumption (ORANGE), total combined

(IT + cooling) energy consumption (RED), and PUE (GREEN) for the datacenter. The COP for chiller continued to improve the total energy for the chiller and, along with the rack power, increased as a function of increasing server airflow and power. That is, more energy per unit of time is required for the cooling at higher temperatures. While the point of cooling system energy increase lagged the point of increase for total combined (IT + cooling) energy increase the net effect results in an increase at about 30°C (86°F) for total combined energy. The combined effect of cooling energy needed, combined with increasing IT energy needed, gives a minimal energy rate at 30°C (86°F). This suggests that total energy required would not continue to improve as a function of increased datacenter temperature setpoint, beyond this optimal temperature for this particular system.

6. ECONOMIC ASSESSMENT OF THE OPTIMIZATION MODEL

6.1. Methodology

The sensitivity analysis will be applied to the case study datacenter to demonstrate how sensitivity information can influence business decisions to improve datacenter efficiency. This analysis aims to describe how much model output values are affected by changes in model input values. Moreover, this method scrutinizes the significance of inaccuracy or uncertainty in model inputs in a decision-making process. The importance and interactions among model inputs can be used not only to interpret model outcomes, but also to recognize where our efforts to improve models and individual parameters should be directed. There are many techniques that have been developed to determine how sensitive model results are to changes in model inputs. This analysis considers either the effects of changes in a single model inputs or parameter value, assuming no changes in all the other parameter values. The optimization model runs with the following steps to evaluate the impact of cost drivers in a datacenter:

1) identify key cost drivers and assumptions for sensitivity test;
2) select the parameters to be monitored:
3) set the range of each input parameter:
4) define inputs to describe the possible values to test:
5) simulate the model using the selected inputs:
6) determine the relative significance of each input:
7) evaluate the results to determine which parameters affect the cost most:

6.2. Sensitivity Analysis

The cost of ownership of a datacenter can be summarized as follows:

$$\text{Cost}_{\text{total}} = \text{Cost}_{\text{rack}} + \text{Cost}_{\text{cooling}} + \text{Cost}_{\text{facility}} + \text{Cost}_{\text{operation}}$$

The cost associated with the IT load and the cooling infrastructure is predominantly power consumption when the inlet temperature increases in a datacenter. For this reason the analysis considers both how the cost of rack changes and how the cost of cooling changes at various operating temperatures in a datacenter. Based on the cost of ownership, the analysis used the following formulae to estimate a value of the sensitivity of the optimization model. The variables in the various formulae from the previous chapter are defined in Table 7.

$$P_{fan} = T_{ref} \times \left(\frac{T}{T_{ref}}\right)^3$$

$$P_{cpu} = I_{cpu}{}^2 \times (R_{cpu} \times (1 + \alpha(T - T_{ref})))$$

$$P_{rack} = P_{init\_rack} + P_{fan} \times (1 + L_{psu})) \times N_{fans} \times \frac{N_{servers}}{1000} + P_{cpu}$$

$$COP_{chiller} = COP_{init\_chiller} \times (1 + (T - T_{ref}) \times L_{chiller}$$

$$P_{chiller\_new} = P_{init\_dc} / (1 + COP_{chiller})$$

$$P_{cooling\_new} = 2 \times P_{chiller\_new}$$

$$P_{dc} = P_{chiller\_new} + P_{cooling\_new} + P_{rack} + P_{CPU}$$

Table 7. Description of Variables Used in the Sensitivity Analysis

Variable	Description
P_{fan}	Fan power
T_{ref}	Reference temperature of 20°C
T	Increased temperature
P_{cpu}	CPU power
I_{cpu}	Electric current of CPU
R_{cpu}	Conductor resistance at temperature T
α	Temperature coefficient of resistance
P_{rack}	Rack power
P_{init_rack}	Initial rack power
N_{fans}	Number of fans
$N_{servers}$	Number of servers
$COP_{chiller\_new}$	Coefficient of performance for chiller at temperature T
$COP_{init\_chiller}$	Initial coefficient of performance for chiller
$L_{chiller}$	Chiller load
$P_{chiller\_new}$	Chiller power at temperature T
$P_{cooling\_new}$	Cooling power at temperature T
P_{dc}	Total power of the datacenter at temperature T

The range used for each parameter to be evaluated is presented in Table 8 for the optimal model, and the base values corresponding to the parameters are also in Table 8. The base parameters are based on the result of the optimization in Table 9 (see Appendix). The parameter sets of the optimal model are presented in Table 10 (see Appendix).

Table 8. Base and Range of Parameter Used in the Sensitivity Analysis

Parameter	Base	Range
Temperature	26	20 ~ 32 [°C]
Fan Power	21.97	10 ~ 40 [W]
CPU Power	55.76	54 ~ 58 [W]
Increased PSU Power	13.17	0 ~ 35 [W]
Cooling Power (kW)	623.81	540 ~ 735 [kW]
COP of Chiller	5.74	4.7 ~ 6.8
Chiller Power (kW)	311.90	270 ~ 370 [kW]

6.2.1. Results

The observed values used in this analysis are obtained from a simulation using the base value for each parameter. In Figure 18, the tornado diagram shows the range of the output variables representing the mean of annual power cost saving for high and low values of each of the parameter sets.

In Figure 19, the percent change graph illustrates the relationships between model output describing the mean of annual power cost saving and variations in each of the parameter sets, expressed as a percentage deviation from their nominal values. In the plot below, the horizontal dashed line displays the mean of the annual power cost saving as a reference (in this case about $2,654,561). The vertical range that is covered with an input line shows the degree of sensitivity of statistic results. When the increased PSU power (Yellow) lies in it -100% ~ -50% range, the mean of the annual power cost saving is approximately $2,550,000, and when the increased PSU power (Yellow) lies in its 122% ~ 166% range, the mean of the annual power cost saving is approximately 2,750,000 – a range of 200,000. By using this percent change graph, the sensitivity analysis shows that the output mean is most sensitive to the chiller power and the COP of chiller, and the mean output is least sensitive to the increased PSU Power.

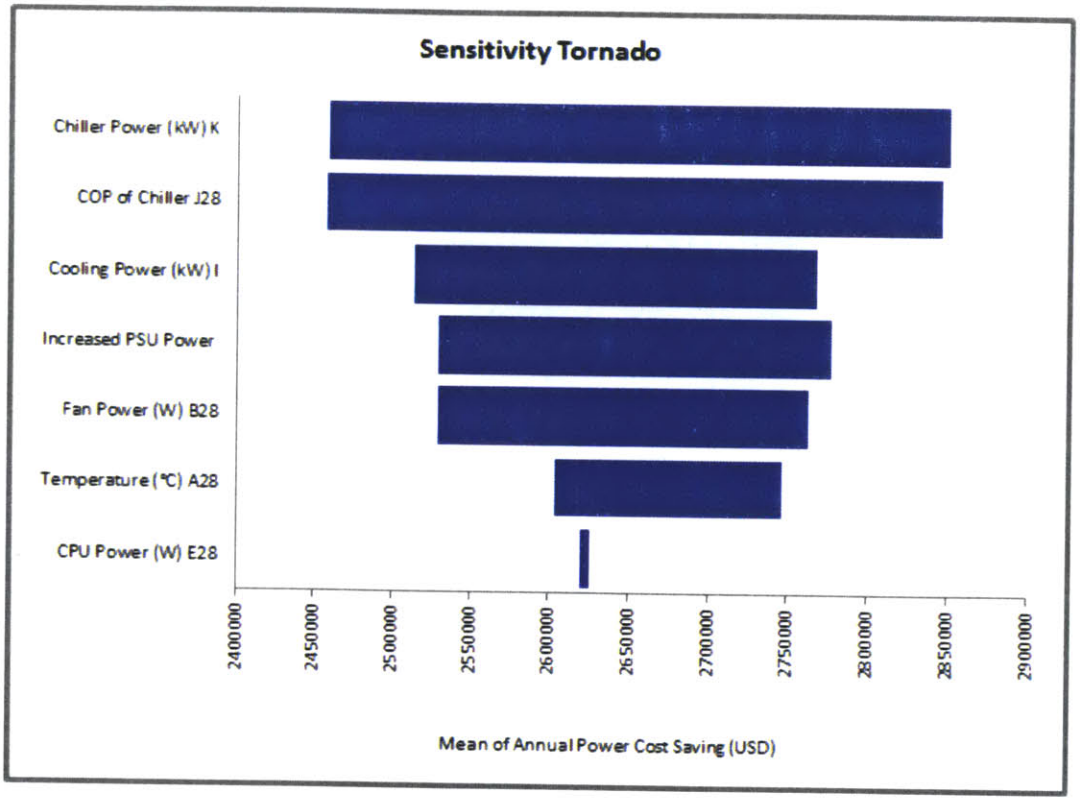

Figure 18. Tornado Chart

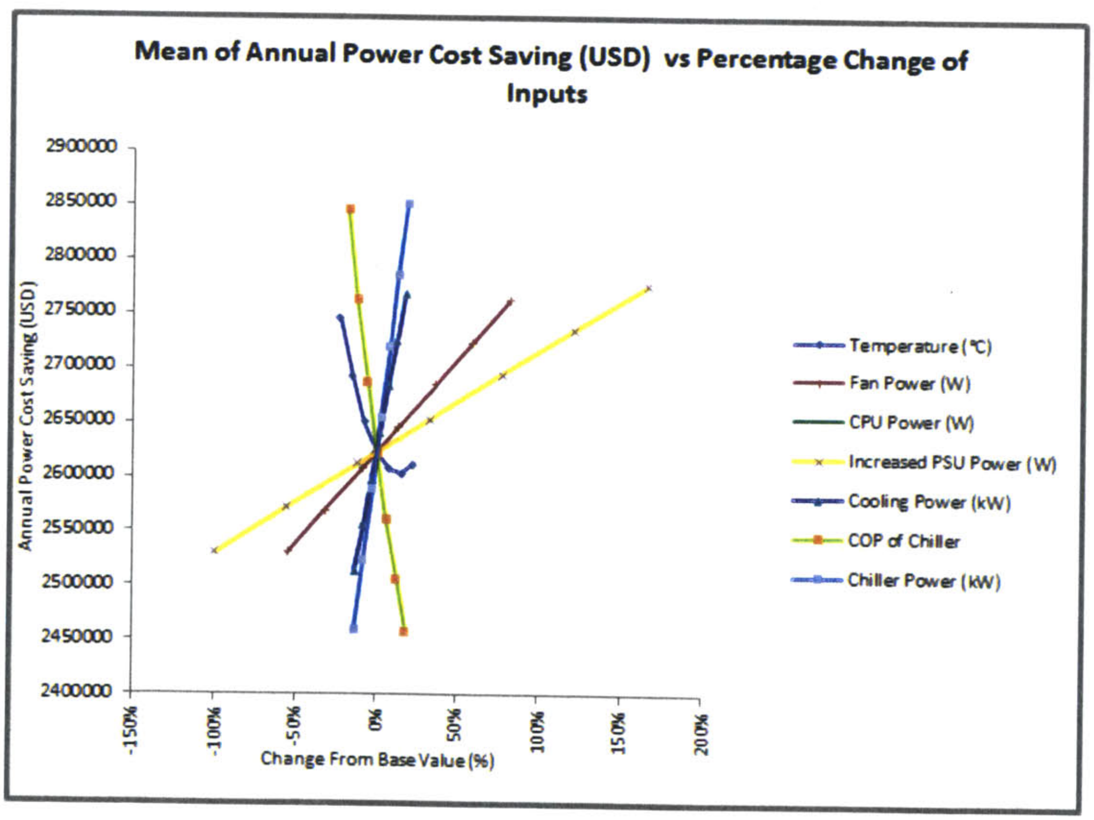

Figure 19. Percent Change Graph

7. CONCLUSION

From the calculation of optimizing the datacenter temperature the ideal operating temperature is at 30°C (86°F). This calculation and analysis focus on the inlet air temperature to the IT equipment, and there are some assumptions such as the total average cooling load, the chiller load, the fan power usage, and the power supply (PSU) efficiency. Also, the sensitivity analysis shows that the mean of annual power cost savings is most sensitive to both the chiller power and the COP of chiller. It is important that the key driver of the chiller power and the cooling system is the inlet temperature set point. This result supports that chillers consume more than 50% of the electrical energy during seasonal periods of in datacenter use [26]. In addition, according to DOE survey, more than 120,000 chillers in the U.S. are expending more than 30% in additional energy through operational inefficiencies. In order to improve datacenter energy efficiency, reducing energy consumption of the chiller and improving cooling efficiency is becoming a fundamental requirement for most firms both to contain operating costs and to support growth.

This paper does not include precise details regarding the energy consumption in the datacenter. The outcome, however, includes considerations for the correlation between temperature and energy efficiency in the datacenter by using the example data from the Somerset datacenter and the calculation of optimizing its temperature set point. The best cooling solution with raising temperature is related to both consideration of the implications to IT equipment and measurement of PUE within the datacenter.

This paper shows that the datacenter would conserve the most energy when running at 30°C (86°F). With improvements in IT equipment design, the set point may have shifted a few degrees higher. This paper focuses on raising the datacenter set point and finding out the optimal temperature in the datacenter. To optimize the datacenter's cooling system efficiency requires setting up a cooling monitoring system. Since the datacenter's temperature is the essential metric, we should carefully decide where and at how many points we measure temperatures. As ASHRAE recommended, many datacenters measure temperature at various points per cabinet face of the rack as well as lower, middle, and top of the rack. However, the points of measurement do not provide us with detailed information of optimizing the datacenter power consumption. Each type of cooling system in the datacenter is different. However, the measurement should include all components such as fans, chillers, pumps, and so on. Also, the system we are measuring should be able to consider energy use over time as well as other useful information including CPU power use and its leakage, server cooling fans, and other IT subsystems.

Although raising the datacenter temperature reduces datacenter cooling efficiency, the datacenter owners should consider the impact cautiously before increasing temperature set point in the datacenter due to the possibility of correlation between temperature and reliability of IT equipment. If raising the datacenter temperature has an influence on an IT equipment failure, or if the cooling system fails in that case, this raising temperature can be a serious factor during the cases. Before we increase the datacenter temperature, we should consider the redundancy and recovery time of the cooling systems. In addition, to take advantage of the energy advantages of increased temperature operation, the datacenter may have to consider selecting the type of cooling system or airflow management techniques.

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9. APPENDIX

Table 9. Rack Energy Consumption as the Datacenter Temperature Increased

Temperature (°C)	Fan Power (W)	Increased Fan Power (W)	Server Power (W)	CPU Power (W)	Increased CPU Power (W)	Increased PSU Power (W)	Rack Power (kW)
20	10.00	-	225,000	54.45	-	-	1000.00
21	11.58	1.58	225,000	54.67	0.22	1.73	1009.58
22	13.31	3.31	225,000	54.89	0.44	3.64	1020.10
23	15.21	5.21	225,000	55.10	0.65	5.73	1031.59
24	17.28	7.28	225,000	55.32	0.87	8.01	1044.11
25	19.53	9.53	225,000	55.54	1.09	10.48	1057.70
26	21.97	11.97	225,000	55.76	1.31	13.17	1072.41
27	24.60	14.60	225,000	55.97	1.52	16.06	1088.27
28	27.44	17.44	225,000	56.19	1.74	19.18	1105.34
29	30.49	20.49	225,000	56.41	1.96	22.53	1123.65
30	33.75	23.75	225,000	56.63	2.18	26.13	1143.25
31	37.24	27.24	225,000	56.85	2.40	29.96	1164.19
32	40.96	30.96	225,000	57.06	2.61	34.06	1186.52

Table 10. Cooling Energy Consumption as the Datacenter Temperature Increased

Temperature (°C)	Cooling Power (kW)	COP of Chiller	Chiller Power (kW)	Total Cooling Power (kW)	Total Power (kW)	PUE
20	735.00	4.72	367.50	1102.50	2,102.50	2.10
21	713.79	4.89	356.90	1070.69	2,080.27	2.06
22	693.78	5.06	346.89	1040.67	2,060.77	2.02
23	674.86	5.23	337.43	1012.28	2,043.88	1.98
24	656.94	5.40	328.47	985.40	2,029.52	1.94
25	639.94	5.57	319.97	959.92	2,017.62	1.91
26	623.81	5.74	311.90	935.71	2,008.12	1.87
27	608.47	5.91	304.23	912.70	2,000.97	1.84
28	593.86	6.08	296.93	890.79	1,996.13	1.81
29	579.94	6.25	289.97	869.91	1,993.56	1.77
30	566.66	6.42	283.33	849.99	1,993.24	1.74
31	553.97	6.59	276.99	830.96	1,995.15	1.71
32	541.84	6.76	270.92	812.76	1,999.28	1.68

Table 11. Parameter Used in the Sensitivity Analysis

Parameter Name	Output: Annual Power Cost Saving (USD)							
	Value	Mean	Min	Max	Mode	Median	5%	95%
Temperature (°C)	20	2746108.9	2746108.9	2746108.9	2746108.9	2746108.9	2746108.9	2746108.9
	22	2691599.0	2691599.0	2691599.0	2691599.0	2691599.0	2691599.0	2691599.0
	24	2650787.0	2650787.0	2650787.0	2650787.0	2650787.0	2650787.0	2650787.0
	26	2622840.7	2622840.7	2622840.7	2622840.7	2622840.7	2622840.7	2622840.7
	28	2607177.3	2607177.3	2607177.3	2607177.3	2607177.3	2607177.3	2607177.3
	30	2603405.9	2603405.9	2603405.9	2603405.9	2603405.9	2603405.9	2603405.9
	32	2611285.7	2611285.7	2611285.7	2611285.7	2611285.7	2611285.7	2611285.7
Fan Power (W)	10	2529973.5	2529973.5	2529973.5	2529973.5	2529973.5	2529973.5	2529973.5
	15	2568765.2	2568765.2	2568765.2	2568765.2	2568765.2	2568765.2	2568765.2
	20	2607556.8	2607556.8	2607556.8	2607556.8	2607556.8	2607556.8	2607556.8
	25	2646348.5	2646348.5	2646348.5	2646348.5	2646348.5	2646348.5	2646348.5
	30	2685140.1	2685140.1	2685140.1	2685140.1	2685140.1	2685140.1	2685140.1
	35	2723931.8	2723931.8	2723931.8	2723931.8	2723931.8	2723931.8	2723931.8
	40	2762723.4	2762723.4	2762723.4	2762723.4	2762723.4	2762723.4	2762723.4
CPU Power (W)	54.00	2620546.1	2620546.1	2620546.1	2620546.1	2620546.1	2620546.1	2620546.1
	54.67	2621416.9	2621416.9	2621416.9	2621416.9	2621416.9	2621416.9	2621416.9
	55.33	2622287.6	2622287.6	2622287.6	2622287.6	2622287.6	2622287.6	2622287.6
	56.00	2623158.4	2623158.4	2623158.4	2623158.4	2623158.4	2623158.4	2623158.4
	56.67	2624029.1	2624029.1	2624029.1	2624029.1	2624029.1	2624029.1	2624029.1
	57.33	2624899.9	2624899.9	2624899.9	2624899.9	2624899.9	2624899.9	2624899.9
	58.00	2625770.6	2625770.6	2625770.6	2625770.6	2625770.6	2625770.6	2625770.6
Increased PSU Power (W)	0	2529973.5	2529973.5	2529973.5	2529973.5	2529973.5	2529973.5	2529973.5
	5.83	2571116.2	2571116.2	2571116.2	2571116.2	2571116.2	2571116.2	2571116.2
	11.67	2612258.8	2612258.8	2612258.8	2612258.8	2612258.8	2612258.8	2612258.8
	17.50	2653401.5	2653401.5	2653401.5	2653401.5	2653401.5	2653401.5	2653401.5
	23.33	2694544.2	2694544.2	2694544.2	2694544.2	2694544.2	2694544.2	2694544.2
	29.17	2735686.8	2735686.8	2735686.8	2735686.8	2735686.8	2735686.8	2735686.8
	35	2776829.5	2776829.5	2776829.5	2776829.5	2776829.5	2776829.5	2776829.5
Cooling Power (kW)	540.00	2513376.2	2513376.2	2513376.2	2513376.2	2513376.2	2513376.2	2513376.2
	572.50	2555825.0	2555825.0	2555825.0	2555825.0	2555825.0	2555825.0	2555825.0
	605.00	2598273.8	2598273.8	2598273.8	2598273.8	2598273.8	2598273.8	2598273.8
	637.50	2640722.5	2640722.5	2640722.5	2640722.5	2640722.5	2640722.5	2640722.5

	670.00	2683171.3	2683171.3	2683171.3	2683171.3	2683171.3	2683171.3	2683171.3
	702.50	2725620.1	2725620.1	2725620.1	2725620.1	2725620.1	2725620.1	2725620.1
	735.00	2768068.9	2768068.9	2768068.9	2768068.9	2768068.9	2768068.9	2768068.9
COP of Chiller	4.70	2846010.5	2846010.5	2846010.5	2846010.5	2846010.5	2846010.5	2846010.5
	5.05	2762396.9	2762396.9	2762396.9	2762396.9	2762396.9	2762396.9	2762396.9
	5.40	2687928.6	2687928.6	2687928.6	2687928.6	2687928.6	2687928.6	2687928.6
	5.75	2621182.9	2621182.9	2621182.9	2621182.9	2621182.9	2621182.9	2621182.9
	6.10	2561017.7	2561017.7	2561017.7	2561017.7	2561017.7	2561017.7	2561017.7
	6.45	2506505.7	2506505.7	2506505.7	2506505.7	2506505.7	2506505.7	2506505.7
	6.80	2456885.8	2456885.8	2456885.8	2456885.8	2456885.8	2456885.8	2456885.8
Chiller Power (kW)	270.00	2458644.0	2458644.0	2458644.0	2458644.0	2458644.0	2458644.0	2458644.0
	286.67	2523949.8	2523949.8	2523949.8	2523949.8	2523949.8	2523949.8	2523949.8
	303.33	2589255.6	2589255.6	2589255.6	2589255.6	2589255.6	2589255.6	2589255.6
	320.00	2654561.4	2654561.4	2654561.4	2654561.4	2654561.4	2654561.4	2654561.4
	336.67	2719867.2	2719867.2	2719867.2	2719867.2	2719867.2	2719867.2	2719867.2
	353.33	2785173.0	2785173.0	2785173.0	2785173.0	2785173.0	2785173.0	2785173.0
	370.00	2850478.8	2850478.8	2850478.8	2850478.8	2850478.8	2850478.8	2850478.8