Juho Kaivosoja

Green Data Centers: Evaluating Efficiency

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 19.9.2016

Thesis supervisor:

Prof. Jukka Manner

Thesis advisor:

Lic.Sc. (Tech.) Markus Peuhkuri

Aalto University
School of Electrical
Engineering

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE
MASTER'S THESIS

Author: Juho Kaivosoja

Title: Green Data Centers: Evaluating Efficiency

Date: 19.9.2016 Language: English Number of pages: 7+57

Department of Communications and Networking

Professorship: Networking Technology Code: S-38

Supervisor: Prof. Jukka Manner

Advisor: Lic.Sc. (Tech.) Markus Peuhkuri

Due to a number of reasons, data centers have become ubiquitous in our society. Energy costs are a significant portion of a data center's total lifetime costs, so it makes financial sense for data center operators to keep energy costs low. Additionally, cutting energy consumption makes data centers more environmentally friendly. In this thesis, some metrics for comparing the "greenness" of data centers are considered.

This thesis also explores ways of improving a data center's energy efficiency and briefly introduces a few ultra-efficient data centers. Some measurements from a data center environment as well as the outside environment were collected, and it was observed that using outside air directly for cooling can – in this data center – save about 25 % of energy used for cooling.

Keywords: Data Center, Energy Consumption, Energy Efficiency, Energy Reuse, Metric

AALTO-YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Juho Kaivosoja

Työn nimi: Green Data Centers: Evaluating Efficiency

Päivämäärä: 19.9.2016 Kieli: Englanti Sivumäärä: 7+57

Tietoliikenne- ja tietoverkkotekniikan laitos

Professuuri: Tietoverkot Koodi: S-38

Työn valvoja: Prof. Jukka Manner

Työn ohjaaja: TkL Markus Peuhkuri

Palvelinkeskukset ovat yhteiskunnassamme läsnä kaikkialla. Energiakustannukset ovat suuri osa palvelinkeskuksen elinkaaren aikaisista kuluista, joten on palvelinkeskusten ylläpitäjille taloudellisesti järkevää pitää energiakustannukset matalina. Lisäksi energiankulutuksen vähentäminen tekee palvelinkeskuksista ympäristöystävällisempiä. Tässä opinnäytetyössä tutustutaan joihinkin palvelinkeskusten ”vihreyden” mittareihin.
Tässä opinnäytetyössä pohditaan myös tapoja parantaa palvelinkeskuksen energiatehokkuutta, ja esitellään lyhyesti muutama ultratehokas palvelinkeskus. Joitakin mittaustuloksia kerättiin palvelinkeskusympäristöstä ja ulkoa, ja todettiin, että jäähdyttäminen suoraan ulkoilmalla säästäisi – tässä palvelinkeskuksessa – noin 25 % jäähdytykseen kuluvasta energiasta.

Avainsanat: Palvelinkeskus, energiankulutus, energiatehokkuus, energian uudelleenkäyttö, mittari

Preface

Writing this thesis was a long and interesting process – as were my studies overall. I would like to think that all this time spent would have led to a deep understanding of the whole field, but this remains to be seen.

I would like to thank my advisor, Markus Peuhkuri, and my supervisor, professor Jukka Manner, for their support and seemingly never-ending patience with my slow-but-mostly-steady progress. My thanks also to all my co-workers at Comnet, especially Risto Järvinen for his invaluable advice.

I'd also like to thank my parents and siblings for their support and comments on my work, especially my brother Mikko for checking not only the contents but the language as well.

Espoo, 19.9.2016

Juho Kaivosoja

Contents

Abbreviations

AC	Alternating Current
CRAC	Computer Room Air Conditioner
DC	Direct Current
DCeP	Data Center Energy Productivity
DCiE	Data Center Infrastructure Efficiency
ERE	Energy Reuse Effectiveness
ERF	Energy Reuse Factor
FLOPS	Floating Point Operations Per Second
HVDC	High-Voltage Direct Current
ICT	Information and Communications Technology
IT	Information Technology
LAN	Local Area Network
MED	Multiple Effect Distillation
PDU	Power Distribution Unit
PF	Power Factor
PFC	Power Factor Correction
pPUE	Partial Power Usage Effectiveness
PSU	Power Supply Unit
PUE	Power Usage Effectiveness
SMPS	Switched-Mode Power Supply
TIA	Telecommunications Industry Association
UPS	Uninterruptible Power Supply

1 Introduction

Data centers are rooms or buildings that house server computers and networking equipment. Small data centers can fit in rooms of bigger buildings, while bigger data centers are buildings themselves. Important data centers housing services on a global scale may take up a complete industrial lot. Typically, a data center's control room is also on-site. The computing and networking equipment need cooling (and, in harsh climates, heating in the winter), the office space needs heating and cooling, and there are usually some security measures. To top it all off, everything needs to be powered, and in some cases, the power systems duplicated.

Historically, data centers appeared with the first computers in the 1940s and 1950s. The computers were big and complex, with enough parts and interconnections to warrant a separate – often big – room for them. In the 1970s and 1980s microcomputers began to be deployed to users' offices everywhere, and the need for server computers diminished. At the same time, server computers became smaller and less demanding of the environment, which led to normal rooms or even closets being used to house servers and a further decline of data centers.

In the late 1990s, during the dot-com bubble, data centers again gained popularity owing at least partially to the advent of Linux and the proliferation of open-source server software as well as the need to better regulate the environment of server computers. With the growth of cloud services in the 2000s data centers are now more popular – and more important – than ever. Many companies would need to practically shut down their operations at least temporarily if a data center outage occurred.

One would expect the computing and networking equipment in a data center to age quickly and be replaced periodically. It turns out, that also the data center infrastructure ages, albeit not as quickly. A Gartner study suggests that a data center older than seven years of age is obsolete, but the average age of a data center hovers around 12 years (in the US) or nine years (worldwide). This probably is at least partially due to the sudden increase in need for data center facilities during the dot-com bubble. [1, 2]

Depending on the importance of data centers, their availability requirements differ. Organizations such as Telecommunications Industry Association (TIA) and Uptime Institute, have defined different tiers of data centers. Uptime Institute defines four tiers, whose availability requirements range from Tier 1's 99.671 % to Tier 4's 99.995 %. Although the differences seem minute, this means that a Tier 1 data center can have a little over 28 hours of downtime a year, whereas a Tier 4 data center can only have about 26 minutes of downtime a year. In practice, this means that there needs to be some redundancy in the power supply system as well. In some countries, notably the United States, a Tier 4 data center would need on-site backup power as well, whereas in Finland the power grid is stable enough in itself (over 99.99998 % uptime since 1998). [3, 4]

Those not familiar with data centers and their significance in the modern world might expect a data center being down to affect the systems of one company, but in reality, a lot of data centers host different systems for different companies. One data center being down might mean that the websites of a hundred companies go down, but on the other hand, other systems of those same companies might still be up.

Data centers consume significantly more energy than normal office buildings. The actual energy consumption increases roughly linearly with data center size, ranging from a few kilowatts for a rack of servers up to a hundred megawatts for a very large facility. In addition to the Information and Communications Technology (ICT) equipment, which includes computing and storage devices and networking equipment, power is also needed to keep the ICT equipment cooled. Depending on the importance of the data center, there is probably some redundancy in the computing, networking, power supply, and cooling equipment.

It was observed that directly using outside air in cooling the data center can save around 25 % of the energy used for cooling, which is on the order of 6 % of the total energy consumption of a data center. In Finland the outdoors environment is almost always suitable for direct cooling. It also turns out that it is possible to detect instances of direct cooling from temperature data.

Measuring the energy consumption is of course important, as are metrics for comparing the energy consumption and efficiency of either one data center over time, or two or more data centers to each other. This thesis briefly explains the operations of a data center, explores the problems in selecting a suitable metric, discusses some data centers, and explores measurement data from one data center.

Section 2 deals with how data centers operate, while Section 3 deals with the different metrics used in the industry for comparisons of data center energy consumption and efficiency. Section 4 explains ways to make a data center more environmentally friendly, or “green”, and briefly introduces some ultra-efficient data centers.

Section 5 describes the various environmental (e.g. indoors and outdoors air temperature and humidity) and operational (e.g. cooling liquid flow rate, cooling fan operational time) measurements taken in the Aalto University Department of Communications and Networking (Comnet) data center. The section also explores some of the findings in the measurement data.

2 Data Center Operations

Data centers today are omnipresent in the sense that they are involved in many of the things we do in our daily lives. This chapter deals with the history of data centers, the growing need for them, and the basic structure of a data center. The need for changes in the future is also discussed.

2.1 Need for Data Centers

The need for modern data centers began to arise in the late 1990s with the dot-com bubble. Companies ran into the need to rapidly build up their on-line services (and to rapidly tear them down, when no longer needed). Thus, it was no longer feasible for every single company to operate their own data centers, and companies based on the business model of renting out space or server computers in data centers began to crop up.

Some of the most common services running in data centers are different web services. These have grown more complicated over time as storage space and computing power of the servers have grown. The average web page size has historically grown ten-fold in about ten years – the average page is now more than a hundred times bigger than it was twenty years ago. Figure 1 illustrates the growth on a logarithmic scale. [5]

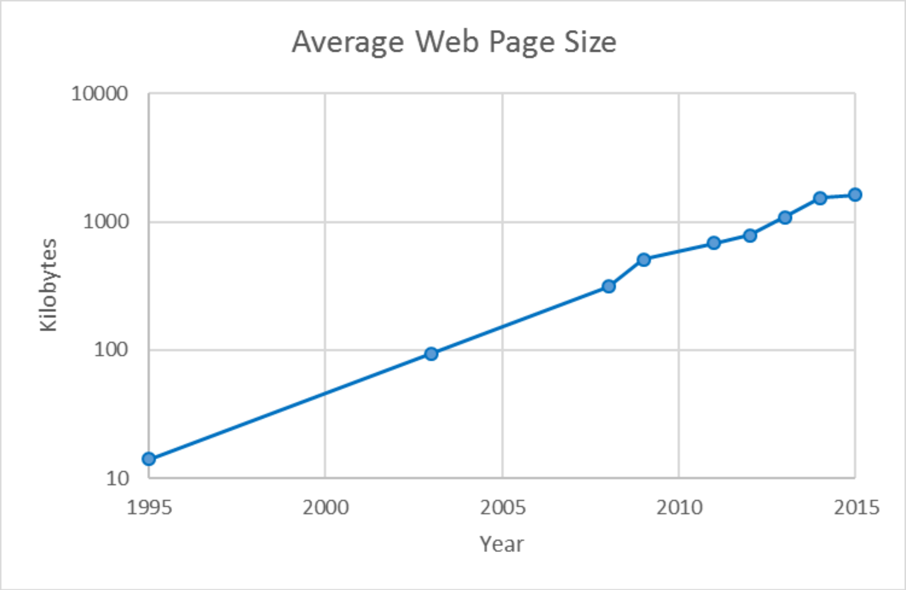

Figure 1: Average web page size has grown ten-fold in size in a little less than ten years. Scale is logarithmic. [5]

As the storage space per device increases, the price per megabyte decreases. From 1995 to 2011, the price of a megabyte of hard drive storage fell by about a third to two thirds per year, and from 2012 to 2015 by about a fifth per year [6]. Figure 2 illustrates the falling price of hard drive and solid state drive storage on a logarithmic scale. The bump in 2012 and the subsequent slowing of the price dropping in hard drive storage price can to some extent be explained by the November 2011 floods in Thailand (and, to a lesser amount, by the tsunami and earthquake in Japan earlier in the year) [7].

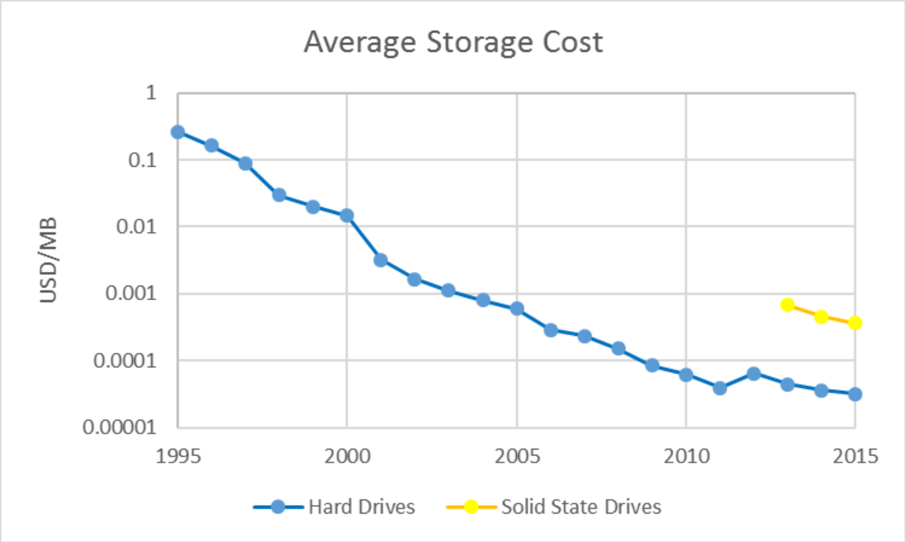

Figure 2: The average price of a megabyte of hard drive storage (blue line, in United States Dollars) has fallen to 1/8000th in twenty years. The price of solid state drive storage (yellow line) is higher, but similarly in decline. Scale is logarithmic. [6]

As shown in Figure 3, the average price of storage fell more quickly than the average size of a web page grew until 2011. From 2012 to 2015 the average storage cost of an average web page was relatively stable. Of course, web pages are nowadays rarely stored as files or even as a separate set of data – dynamically collecting information from databases seems to be the norm – but the average size serves as a proxy for the storage space needs of a data center.

Storage space on mobile devices is more expensive. Virtually all mobile devices have flash-based non-volatile solid-state mass memory, which is more expensive per byte than hard drives. Additionally, the size and energy consumption demands of mobile devices are much more stringent than those of server computers. Despite the constraints, the storage capacities of mobile devices continue to climb. Figure 4 illustrates the maximum smartphone storage capacities for the years 2004–2015. At the same time, prices for flash memory drop every year.

Figure 5 illustrates on a logarithmic scale the falling average price per gigabyte. As Figure 6 shows, the cost of a high-end smartphone's internal storage – discounting the clear outliers – tends to hover around 60 USD.

Despite the growing storage capacity and computing power of mobile devices, it is not feasible to do heavy calculations or store vast amounts of data on mobile devices. This introduces the need for cloud services – which are housed in data centers. As data centers and their users need to be well-connected, the data centers offering cloud services need to have good network connections with the mobile networks' switching

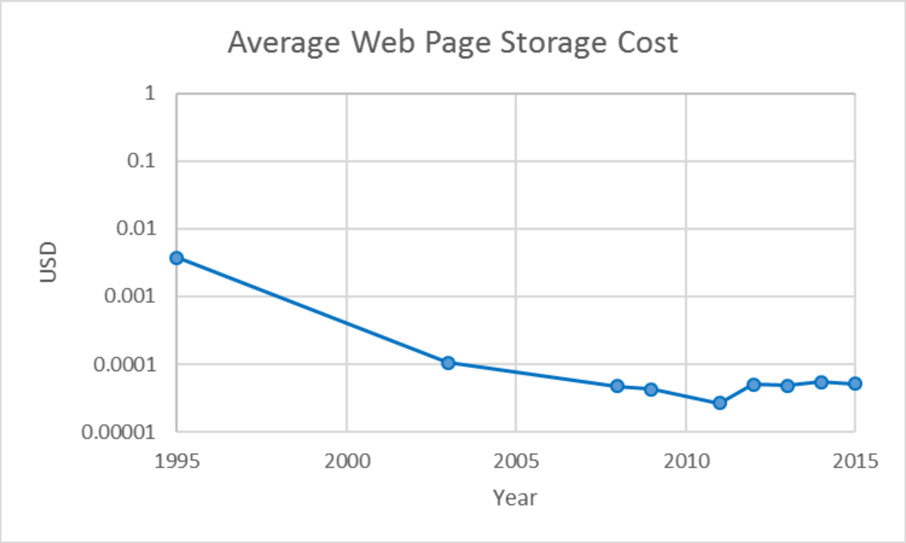

Figure 3: The average storage cost of an average web page over twenty years. Scale is logarithmic.

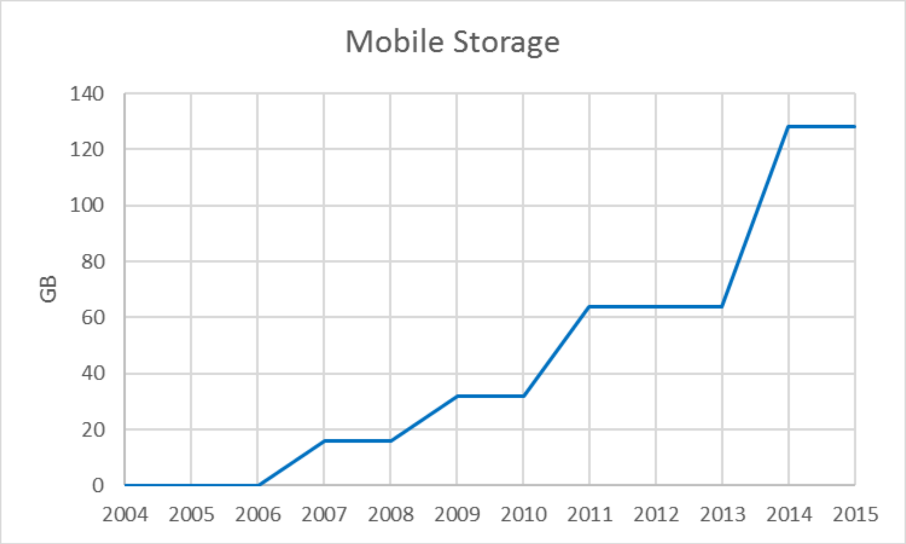

Figure 4: Maximum mobile phone flash storage capacities for the years 2004 to 2015. Only internal storage is counted.

centers. Some cloud service operators even place some of their equipment inside the switching centers. Information sharing (including photos, videos etc.) is not feasibly done in a peer-to-peer fashion with mobile devices, introducing the need to use cloud services to facilitate the sharing – the social media services.

The number of people using these cloud services is not insignificant. In 2015, 25 % of EU citizens used cloud storage to store at least some files (35 % of Finnish citizens) [8]. This is equivalent to 127 million people in the EU alone (and 1.9 million in Finland) [9]. Smartphone usage in Western Europe surpassed 50 % in 2014, and is almost 55 % in 2015 [10].

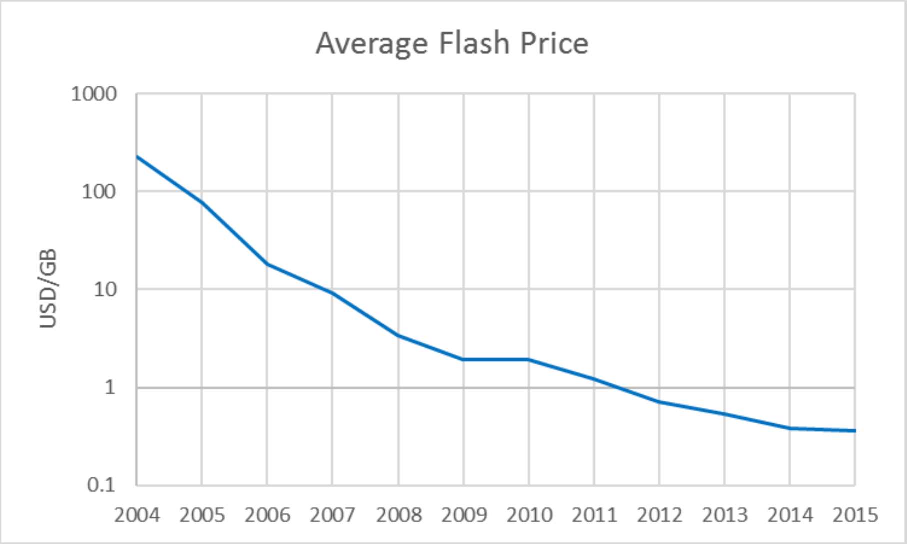

Figure 5: Average flash storage prices for the years 2004 to 2015 [6]. Scale is logarithmic.

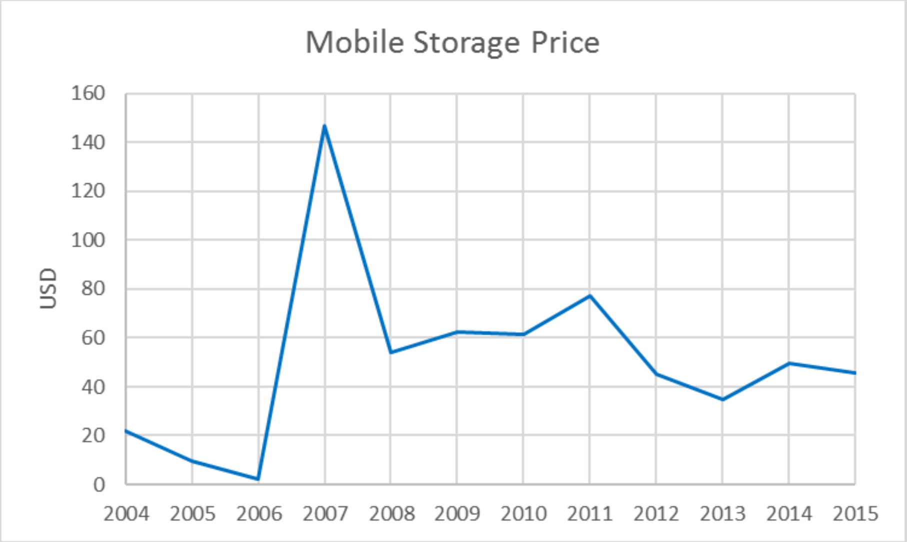

Figure 6: Average prices for high-end mobile phone storage for the years 2004 to 2015.

2.2 Data Center Design

Data centers range in size from a room in a building to a multi-building facility. Regardless of the size, the basic components are mostly the same:

- The Building
    - Building Security
- ICT Equipment

  - Server Computers
  - Data Storage Equipment
  - Networking Equipment
- Electrical Infrastructure
  - Power Supply Equipment
  - UPS
  - Backup Power
- Mechanical Infrastructure
  - Air Conditioning Equipment
  - Cooling Equipment
  - Humidity Control Equipment

Apart from the cooling and air conditioning equipment, most equipment is usually housed in uniformly sized racks. These racks are usually 482.6 mm (19 inches) wide, lined on both sides with mounting strips complete with holes for mounting the equipment. The holes are arranged in groups of three, with the height of one group being 44.45 mm (1.75 inches). This height is also known as a height unit, or U. Other rack standards also exist, including ones based on SI units.

Many, if not most, data centers have raised floors and lowered ceilings. Both the space below the floor and above the ceiling can be used for cabling, and the under-floor space is also used to bring cold air to the equipment. The space above the ceiling is often used for collecting hot air from the room. Figure 7 shows an example of an equipment rack in a data center, with power supply units, network switches, servers, and data storage equipment.

A single-room data center might look something like Figure 8. Racks are usually arranged in rows, so that there are walkable aisles between the rows of racks. Other equipment, such as cooling, air conditioning, and backup power equipment, might be placed along the walls or in a suitable location in the room – or outside.

2.3 Data Center Power Supply

A power supply system in a data center is a bit more complicated than simply plugging a computer into a wall outlet. Typically a data center hosts a significant number of server computers in racks, requiring dozens or even hundreds of times more power per unit of area than a normal office building [11, 12]. This power needs to be uninterruptible, for which uninterruptible power supplies (UPS) are used. As voltages in power grids are not always stable, most UPSs also filter out any spikes. A UPS, however, can only power computers from its batteries for so long, and many data centers require also backup power in the form of fuel-powered generators, duplicate connections to the power grid, or both.

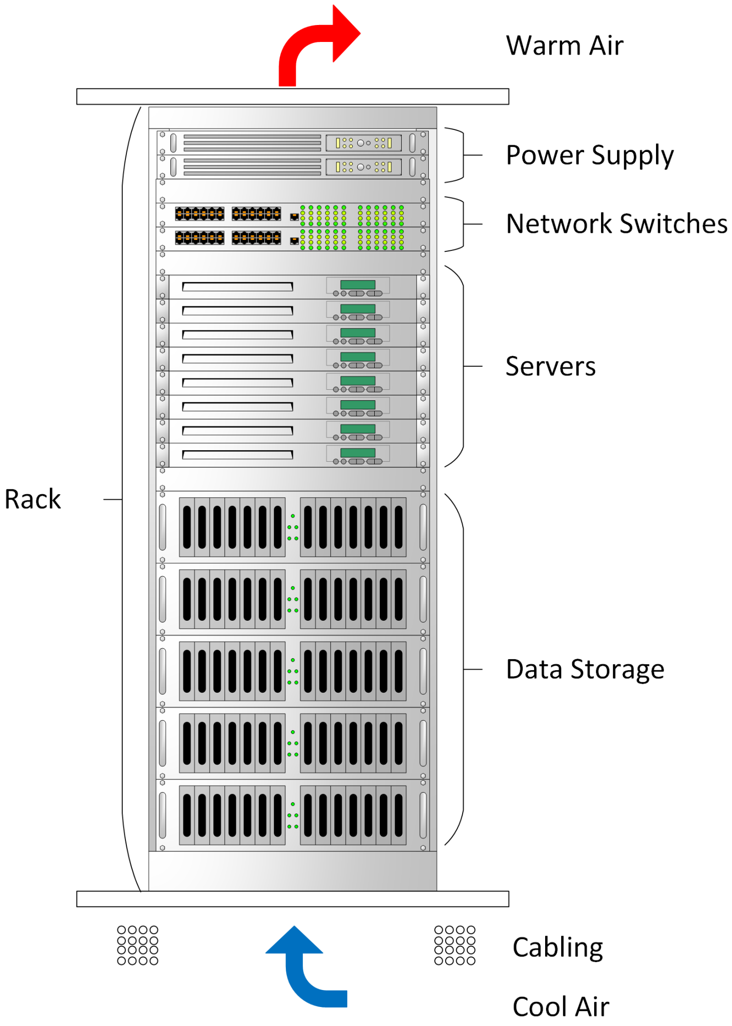

Figure 7: A simplified example of a rack in a data center. Real-life racks might not have all types of equipment in the same rack.

Building a power supply infrastructure capable of powering a data center is not cheap; the building costs can be comparable to the lifetime energy costs of the data center. Not only does the power system need to be capable of powering all ICT and other equipment, it needs to do this while running not quite at maximum power. Additionally, the system needs to be redundant to a desired level, meaning surplus capacity while everything is running normally. While the energy consumption of a data center's ICT equipment varies slightly with the ICT load, the costs of building a power supply facility depend only on the desired maximum capacity. [13]

Typically, a highly resilient power distribution system in a data center would have all of its components doubled, including connections to the power grid (utility company). Figure 9 illustrates a highly simplified model, with two independent power paths. A real system would have interconnections between the two paths (replacing the vertical arrows with a mesh of vertical and diagonal arrows), further increasing the system's resilience but also making it more complicated.

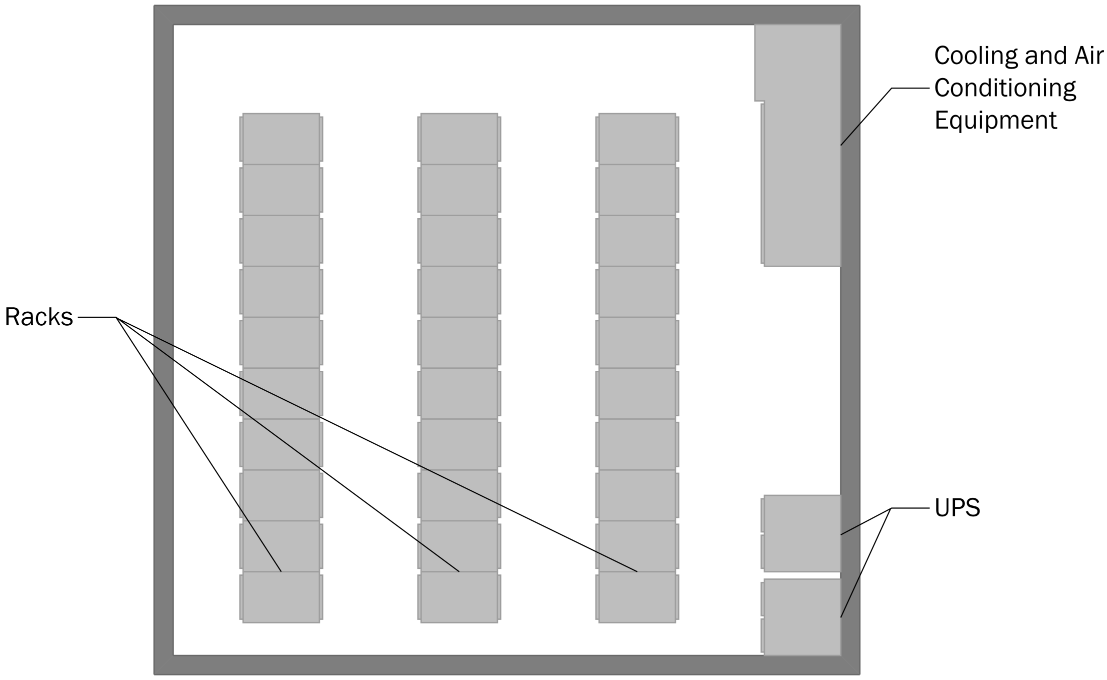

Figure 8: A simplified example of a single-room data center.

The energy consumption of servers in the United States doubled between 2000 and 2005, and in 2005 the total energy consumption of data centers in the US was estimated to be around 1.2 % of the total energy consumption, comparable to the energy consumption of color televisions. By 2013, the figure had risen to more than 2 % [14]. Worldwide, the total power draw of data centers was estimated to be about 14 GW, powering an estimated total of about 27 million servers. [15]

According to Pelley et al., the subsystems that contribute most to a data center's power consumption are servers and storage systems (56 %), cooling and humidification systems (30 %), power conditioning equipment (8 %), networking equipment (5 %), and lighting and physical security (1 %) [16].

Almost all of the energy a data center consumes is turned into waste heat [16]. The data center facility and the equipment must thus be cooled and the heat either dumped outside or reused in some manner (see section 4.1).

2.3.1 Power Factor

Alternating current has a (usually) sinusoidal waveform, where both voltage and current oscillate between negative and positive. In a circuit with only resistive load, these waves have the same phase, and the power consumed by the load (real power) equals the power transported from the power source (apparent power). However, reactive (capacitive or inductive) loads cause a phase difference between voltage and current, causing the load to alternatingly consume more power than a purely resistive load and actually feeding power back into the circuit. The reactive load may be, on average, consuming the same amount of power as a purely resistive load, but the maximum power transported from the source is greater. The relationship between

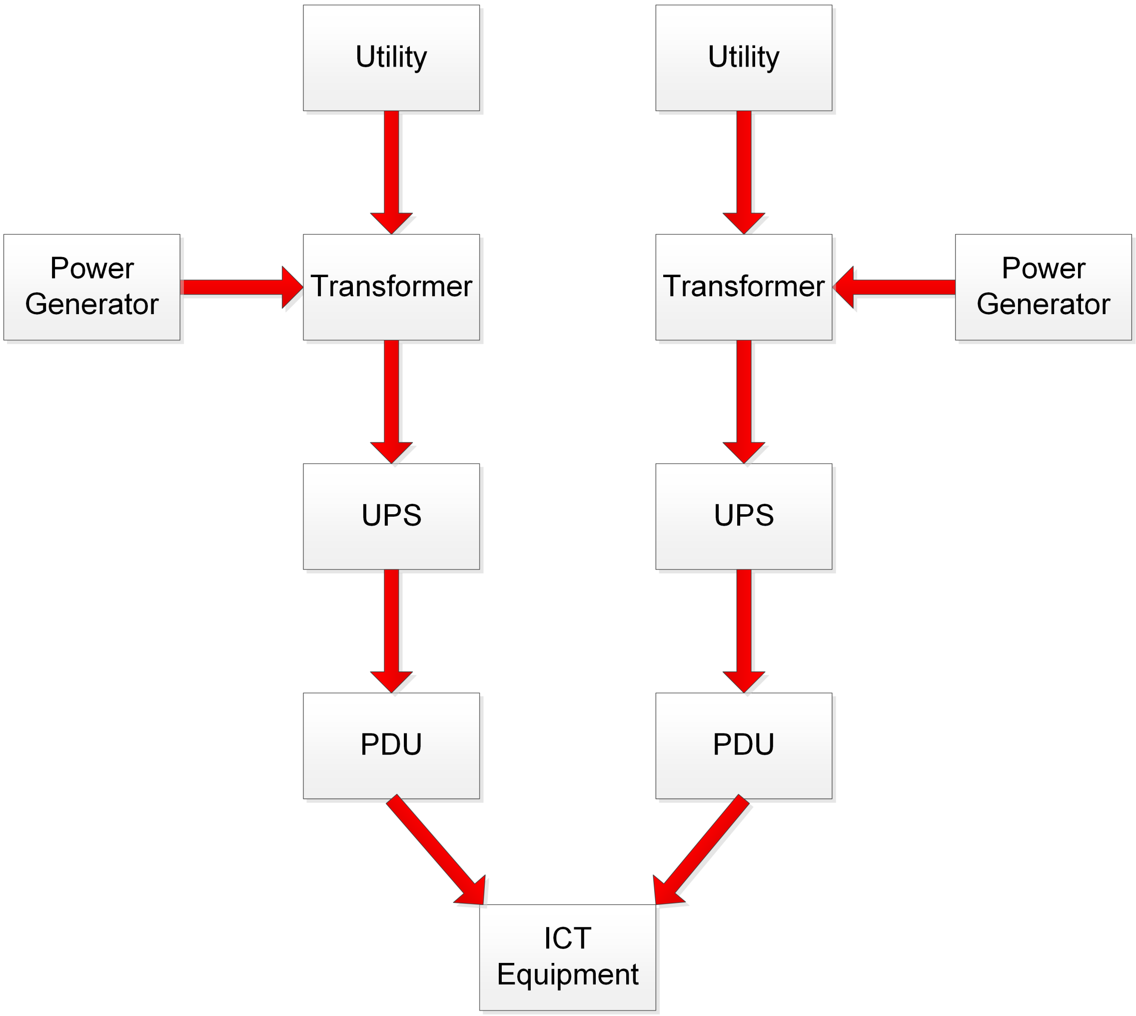

Figure 9: A greatly simplified example of a highly resilient power distribution system in a data center.

real power and apparent power is called the power factor (PF).

Power factor can be defined as

$$PF = \frac{P}{S} \tag{1}$$

where P is the real power and S is the apparent power of the circuit. Power factor is dimensionless.

The most common power supplies in computers are switched-mode power supplies (SMPS), which historically have had a low power factor. Due to regulation on the subject, modern SMPSs include power factor correction (PFC) equipment which can increase the power factor to values up to 0.99 [17].

2.4 Data Center Air Conditioning and Cooling

Device placement in a data center is a factor as well. The servers and racks need to have enough space, cooling and power. Additionally, the servers need to be replaceable and easily accessed for maintenance. With increasing power densities in servers and other ICT equipment, care needs to be taken in planning the power supply and cooling systems. [12, 18]

Operating and investment costs can be reduced by carefully designing the airflows in a data center. Cool air must not bypass racks or equipment, and similarly, hot air needs to be directed to air return ports, not towards other equipment. This is usually most easily achieved by placing rack rows in an alternating pattern, so that a rack's front is always facing another rack's front and a rack's back is conversely always facing another rack's back. This way, there are alternating "hot aisles" and "cool aisles" between the racks. In this arrangement, cool air is normally fed to the data center from below a raised floor through vents between equipment racks (in the so-called "cool" aisles), it passes through the racks and is collected through vents in the ceiling (in the so-called "hot" aisles). This arrangement is depicted in Figure 10. [12]

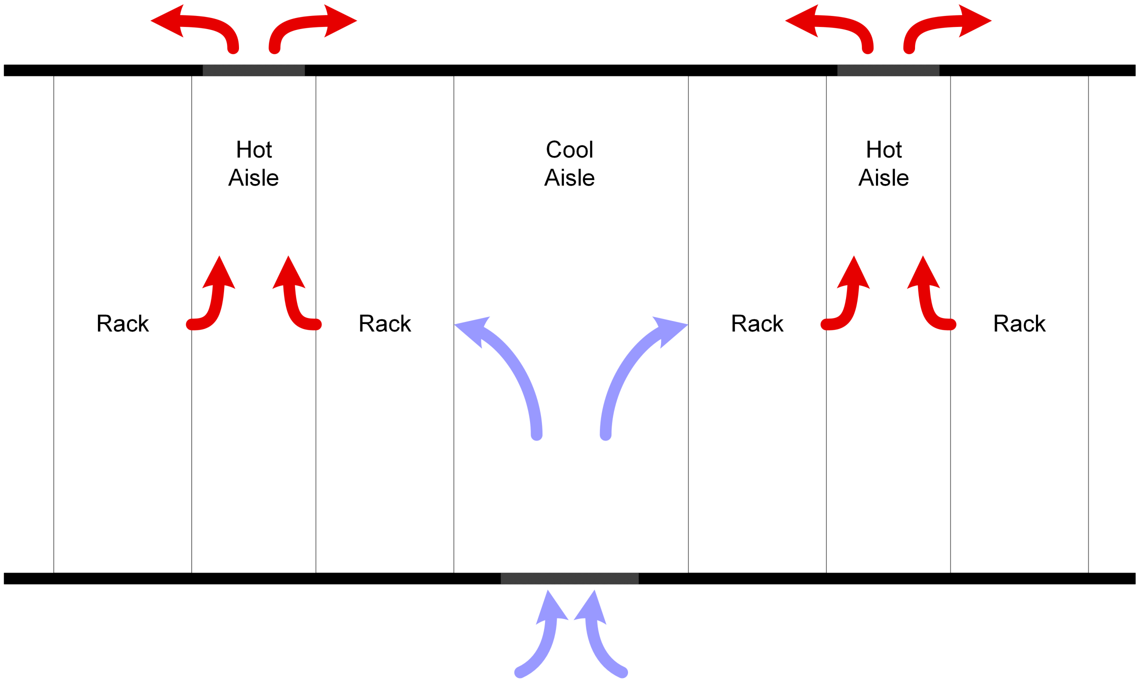

Figure 10: Air flows in a data center with a hot-and-cool-aisles arrangement. [11, 19]

In some cases, though, what is considered "used" hot air by one device, can still be "fresh" cool air to another device with more permitting requirements for an operating environment. In these cases, maximum savings can be achieved when no device gets "too good" air. [12]

For example, Intel has demonstrated cooling servers with outside air at temperatures up to 32 °C [20]. Dell has servers and networking equipment that can utilize intake air of up to 45 °C. This greatly expands the temperature range of outside air that can be directly used to cool the equipment and reduces the need to use water in the cooling process.

While cooling the equipment is something that needs to be done everywhere, it can be done much more energy efficiently in colder climates. Dumping the excess heat requires less energy the lower the outside temperature is, and if the outside temperature is acceptable, it can be used directly to cool the equipment. Figure 11 shows a simplified view of energy and cooling flows in a data center.

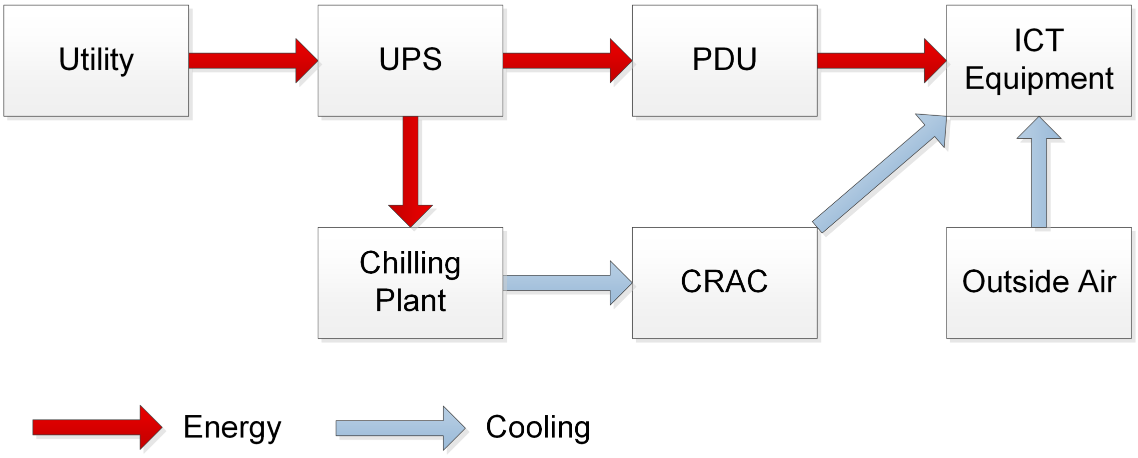

Figure 11: A simplified example of energy and cooling flows in a data center. [21]

Traditionally, most of the air in a data center is circulated over and over, cooling the equipment and getting cooled in the air conditioning unit alternately. Figure 12 shows a simplified cooling flow in a data center facility. While "cooling" (blueish arrows) is the desired "product" here, thermal energy (reddish arrows) is the actual transported "trash".

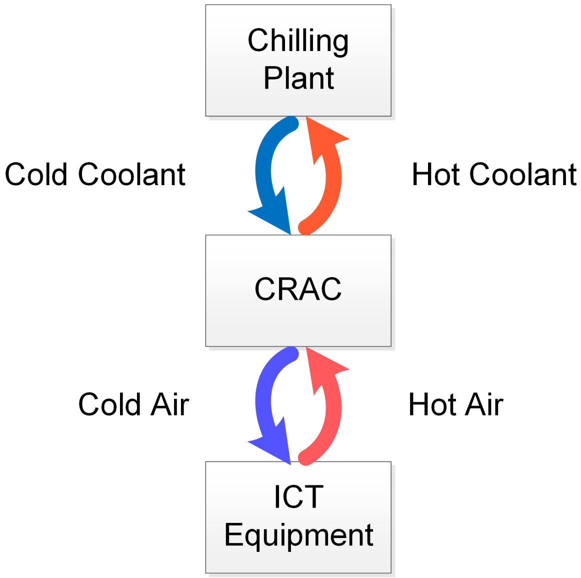

Figure 12: A simplified example of cooling flows in a data center.

When it's colder than about 25 °C outside, it takes less energy to cool the outside air (rather than the inside air) to be used inside the data center. Below about 18

°C, outside air can be used directly (after filtration) and warm air dumped outside. Below about 15 °C, some (or all) of the warm air from the inside can be used to pre-heat the outside air. While normally a data center has to "pay" for cooling in the form of spent energy, in places where outside air can be used at least some of the time for equipment cooling, a data center can thus get some of its cooling for "free", that is to say by spending far less energy. Figure 11 shows how outside air is brought into the mix. [4, 22]

2.5 Data Center Humidity Control

Humidity requirements for a data center environment are traditionally very strict, with 45 % to 55 % having been the recommended range of relative humidity [23]. This made sense with tape storage systems, but nowadays the requirements could be relaxed in most environments. Too tight requirements can lead to inadvertent simultaneous humidifying and dehumidifying of the atmosphere by different pieces of equipment, especially in bigger data centers. [11]

Nowadays, a relative humidity of between 40 % and 60 % is often recommended. Depending on the climate, a humidity control system might not be absolutely necessary, but most data centers include at least a dehumidifier within the temperature control system. If drier environments were allowed, even more data centers could directly use outside air for cooling. At some point static electricity becomes a problem, though. Too humid air leads to water condensation in unwanted places and ultimately corrosion of the equipment and infrastructure.

Measuring the dew point instead of relative humidity would possibly be beneficial in at least some situations. While relative humidity changes relative to temperature, the dew point (the temperature at which water starts to condense) stays the same for a given air mass with a given mass of water vapor. Required humidity values for a data center environment would perhaps be still better if given as absolute humidity (the mass of water in an air mass divided by the mass of the air mass). A suitable absolute humidity operating range would be from 0.006 to 0.011 (0.6 % to 1.1 %). [23]

2.6 Need for Change

The ICT world is fast-paced and constantly evolving. Anybody who wants to stay competitive in the market of new technologies needs to be able to significantly alter their operations in a relatively short timeframe. Significantly expanding or downsizing a data center is neither fast nor cheap, which has led to a lot of companies outsourcing their data centers. Data centers with multiple users are less vulnerable to the changing environment, but planning for future is of essence.

Self-contained containers that only use outside power (and sometimes cooling) are a popular way of providing easy expandability. Using containers makes a data center somewhat modular, and modules of known properties can be added or removed. Another way to provide changeability in a facility are expandable power distribution systems, which can be modified without disruption of operations. Cooling and ventilation systems tend to be more difficult to modularize or modify.

Computers are getting more powerful all the time, which leads to not only more computing power in the same space, but (usually) also more energy consumption and thus heat output in the same space. A real world example: A cluster that in 2010 consisted of 20 desktop computers was later replaced by a 10U rack enclosure and still later by a 2U rack enclosure. At the same time, its computing power has gone from 1 200 to 6 400 to 3 600 billion floating point operations per second (gigaflops).

One key requirement of planning expansions and future operations is knowing the present state of a facility. Monitoring the power consumption of different parts of a data center facility is central to this. Some metrics for data center energy efficiency are discussed in section 3. A case study of a data center measurement system is presented in section 5.

2.7 Summary

The need for new data centers grew rapidly during the dot-com boom in the late nineties. The proliferation of cloud services ensures a growing need for data center capabilities for the foreseeable future, although data center space requirements do not grow quite as quickly, owing to the growing capabilities of single servers.

Power densities in data centers are on the rise, which leads to pressures on the power grid. Sufficiently reliable power grids also reduce the need for on-site backup power (which usually uses fossil fuels). Although energy costs can be as much as a third of a data center's lifetime costs, building a facility is a big investment. Most of the building costs lay in building the power supply chain and air conditioning and cooling systems. Energy costs can be significantly reduced by using outside air for cooling, especially so in colder climates.

Outsourcing data center operations completely, as well as using modular data centers have emerged as ways of coping with rapidly changing data center capacity needs.

3 Energy Efficiency in ICT

While comparing different things people tend to reduce the complex differences to a single metric, which may or may not reflect the actual properties of the thing being compared. Much the same applies to data centers; reducing the “betterness” or “greenness” of a data center to a single metric is tempting, but can be very misleading. This chapter deals with energy efficiency and different metrics for measuring it, as well as the problem of selecting a suitable metric for the task at hand.

3.1 Selecting a Metric

Given the importance of data centers in today’s society, it’s no wonder they are ubiquitous. Although computing performance per unit of consumed energy has increased, the energy consumption has increased as well. Add to that the computers becoming smaller and smaller and thus more heat per unit of volume, and you can see that cooling the data centers becomes more and more important as well, requiring more energy. As the price of energy is projected to go up, it is important to measure the efficiency of data centers. [21]

The energy density of a data center can be a hundred or two hundred times that of a typical office environment. More than half of the energy consumption can be the ICT equipment, so an obvious way to reduce energy costs would be to look into more energy efficient ICT equipment. Most server computers run at a maximum of 20 to 30 % utilization most of the time, meaning that hardware that can partially power itself down during low-usage moments can lead to some savings in energy costs, both directly and in cooling costs. Data storage and network equipment can similarly take advantage of the low average usage. [12, 24]

By using bigger power supplies to power entire racks instead of individual servers, savings can be made not only due to a generally better efficiency of bigger units, but also due to the fact that not all server computers experience their peak loads at the same time (although certain “peak hours” are usually evident). Supplying DC power instead of AC in the data center infrastructure leads to a better efficiency and a smaller thermal load. [12, 25]

Locating equipment with similar heat load densities and environmental requirements together allows for the cooling system and other environmental systems to be more finely-tuned to the most energy efficient settings for each environment. Some isolation might be needed between differently served areas, but the costs are quickly offset by the savings. [12]

Historically there has been several different metrics to measure the efficiency of data centers, and more are being developed seemingly every day [26]. Partly this is probably due to the fact that data centers are an easy target for anyone demanding efficient usage of energy, especially as the price of energy is rising [26]. Estimates of data center energy costs vary from as little as 15 % [27] to as much as a third [13] of the total costs of a data center. Measuring the energy usage in data centers is by no means trivial, and selecting a metric depends on a lot of things. [28]

Besides the obvious savings in energy costs, energy efficiency metrics can have other goals as well. Comparisons can be made to other data centers within the same company, geographical area, climate, or service profile to find how other variables affect energy consumption. Comparing different data centers can also lead to better information in site selection and design as well as operational decisions. When making outsourcing decisions, metrics of the potential hosts are also vital. [21]

3.2 Power Usage Effectiveness

One of the most popular if not the most popular metrics seems to be Power Usage Effectiveness (PUE) [26, 28, 29, 30]. PUE can be calculated with Equation 2, where P_{in} is the total energy consumption of the facility, P_{loss} is all the lost energy and P_{ICT} is the energy consumed by the ICT equipment.

$$PUE = \frac{P_{in}}{P_{ICT}} = \frac{P_{ICT} + P_{loss}}{P_{ICT}} = 1 + \frac{P_{loss}}{P_{ICT}} \tag{2}$$

P_{loss} includes all the losses in the facility: Losses in transformers, PDUs, PSUs, and other electrical equipment, plus all of the energy consumed by auxiliary operations: Cooling, ventilation, heating, lighting etc. [31]

Per Equation 2, a PUE of exactly 1 would mean a data center where all the power consumed is used by the servers, routers, and other ICT equipment.

Generally, cooling and ventilation consume around 25 to 55 % of the total energy, whereas losses in uninterruptible power supplies (UPS) are usually around 12 to 15 % [29]. In high-voltage direct current (HVDC) data center environments, modern DC/DC converters can reach 95 % efficiency [32]. These numbers would correspond to an overall PUE of about 1.3 to 2.6. The worldwide average PUE is estimated to be 2.5 [33]. However, Google claim the average PUE of their data centers is 1.12 [31].

Strictly speaking, the definition of PUE calls for an annual average, and also for the energy consumption to be measured at the energy source. In most cases, an instantaneous PUE measurement is accurate enough and can actually offer more information about the current environment and functioning of the data center. Additionally, measuring energy consumption at the source can be difficult and only offers more information than on-site measuring in cases where different locations of data centers are being compared. [21]

One problem with PUE is its behavior with ITC equipment refreshes. As new, more energy efficient ICT equipment is brought in, the total ICT energy consumption of the facility decreases. If the supporting infrastructure is kept as-is, its energy consumption will be more or less the same, leading to a decreasing share of the total energy consumption being ICT. This, in turn, would mean a *rising* PUE, making updating the ICT equipment seem like a bad decision.

Figure 13 shows examples of PUE values (yellow lines) and total energy consumption (blue lines) of a data center that was upgraded twice. In this example. the data center was built in 2000, and all its servers were replaced in 2005 and 2010. The auxiliary equipment was left as-is. Figure 13 shows two possible paths of upgrade: One where the number of computers stays the same (solid lines), and one where the total computing power of the data center stays the same but the number of computers drops (dashed lines). The calculations are shown in Appendix A.

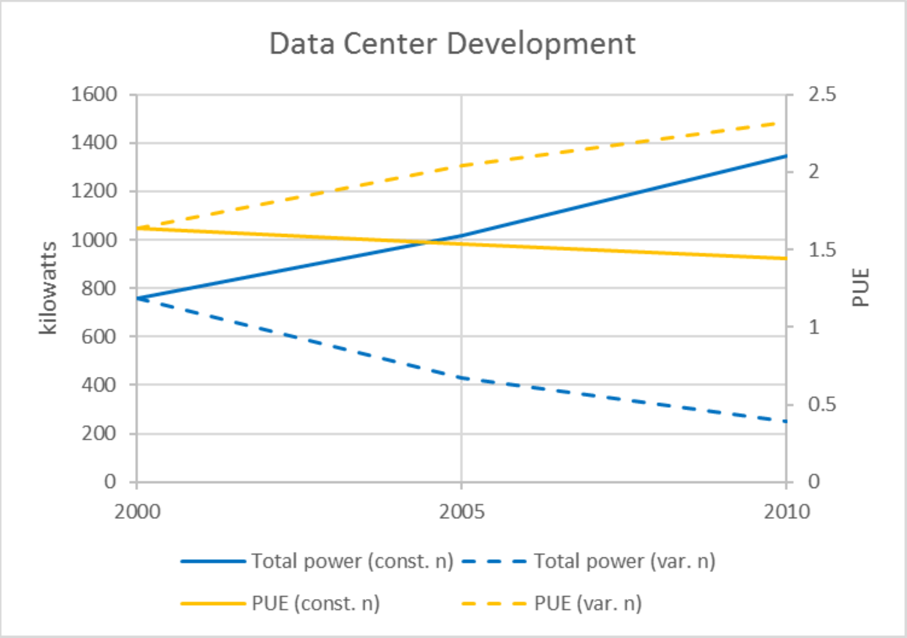

Figure 13: The change of PUE values (yellow lines) and total energy consumption (blue lines) during two possible upgrade paths of an example data center; one where the number of servers stays constant (solid lines), and one where the total computing power of the data center stays constant (dashed lines).

3.2.1 Partial Power Usage Effectiveness

Sometimes data centers consist of one or more self-contained containers. These containers typically have all the computing and networking equipment, power distribution, and cooling equipment needed to operate a small data center. All the containers need are networking, power and sometimes cooling connections. At some point it may be beneficial to measure the "PUE" of these containers, but doing so might be difficult, especially if the containers use some site-wide resources (for example, using centrally chilled water). For this reason, Partial Power Usage Effectiveness (pPUE) has been defined as the PUE of a specific area in a data center, not including site-wide facilities. An area can be either physical or logical. [21, 34]

3.3 Data Center Infrastructure Efficiency

Data center infrastructure efficiency (DCiE), the reciprocal of PUE, is another popular metric. It is the fraction of total power consumption of a data center that is used by ICT equipment. DCiE can be calculated with Equation 3. [26, 30]

$$DCiE = \frac{P_{ICT}}{P_{in}} = \frac{P_{ICT}}{P_{ICT} + P_{loss}} = \frac{1}{1 + \frac{P_{loss}}{P_{ICT}}} \tag{3}$$

As DCiE cannot be above 1, it is usually expressed as a percentage.

Even though DCiE was defined at the same time as PUE, it has since fallen out of favor. So much so, that Green Grid, who originally defined both, hardly mentions DCiE anymore. [21]

3.4 Energy Reuse Effectiveness

As mentioned before, PUE values below 1 are impossible. Such values, however, have been reported, due to a misunderstanding how PUE works. To counter this, Green Grid have come up with yet another metric, Energy Reuse Effectiveness (ERE). Denoting waste energy from the data center that was used elsewhere as P_{reuse}, ERE can be defined like in Equation 4. [21, 34]

$$ERE = \frac{P_{in} - P_{reuse}}{P_{ICT}} = \frac{P_{in}}{P_{ICT}} - \frac{P_{reuse}}{P_{ICT}} = PUE - \frac{P_{reuse}}{P_{ICT}} \tag{4}$$

Energy Reuse Factor (ERF) is defined as

$$ERF = \frac{P_{reuse}}{P_{in}}, \tag{5}$$

leading to another definition for ERE.

$$ERE = (1 - ERF) * PUE \tag{6}$$

While using just ERE instead of PUE and ERE might seem reasonable, it would make it more difficult to tell apart data centers with a bad PUE and a bad ERF. [21, 34]

3.5 Energy Consumption

In cloud computing systems, the average workload of the whole system is often below 30 % [33]. Although this number varies between different services, it can be expected that single-service data centers would be running practically idle at least some of the time. Combining different services in data centers would help, as the services would be expected to have their peak traffic hours at different times. Partially this can be achieved by running services aimed at both office and home users, as these services typically experience their peaks at different times of the day. They do, however, have some overlap in the early evening and times of low usage occur at night in both kinds of services.

In practice, data center operators have been overselling their capacity, much like airlines, for a long time. This is done to help minimize the time data centers run idle, but can also lead to problems if all customers happen to want maximum capacity at the same time. In cases where one entity runs critical services in multiple data centers, some of the capacity is usually reserved for failovers in case a data center or its network connection fails completely. This can lead to up to two thirds of capacity wasted, although Google developed a system where multiple services run in multiple data centers all the time, bringing the wasted capacity down to around 40 % [35].

Workload variations happen mostly in patterns with the length of one week, and on weekdays (Monday to Friday) a strong daily pattern is also observable [36]. Finding and combining services whose workload patterns' sum is smooth would be ideal, as that would give the opportunity to run a data center at close to maximum capacity all the time. Unfortunately, most services experience their peaks during daylight hours and their lows during nighttime. Combining services – even the same service – from different time zones would seem to solve that, but this would run against the trend of placing data centers near the users. Data centers are normally placed near the end users to reduce latencies to a minimum. The proposed maximum latency for fifth-generation (5G) mobile networks is one millisecond, a time in which light travels slightly less than 300 kilometers.

Measuring the total energy consumption of a facility naturally gives valuable information, and keeping track of energy consumption over time provides insight into the trends going on in a specific facility. However, there are a lot of different things that can greatly affect the total energy consumption of a data center, thus diminishing the validity of total energy consumption as a metric. Some of these variables are the environment, weather, and refreshes in ICT or infrastructure equipment.

Additionally, the total energy consumption is always unique to that particular data center, and thus it cannot be used to compare one data center to another. To unify the power consumption metric between facilities, we need to measure energy consumption per something.

3.5.1 Data Center Energy Productivity

Data Center energy Productivity (DCeP) was The Green Grid's first attempt at a data center efficiency metric. In its simplicity, it's defined as

$$DCeP = \frac{U}{P_{in}}, \tag{7}$$

where U is the total utility or useful work produced in a data center. Finding a useful measure of U is nontrivial, which has caused The Green Grid to look into proxy measures. Another problem with DCeP is that for it to remain a useful metric for a single data center, its purpose and use should remain consistent. [21]

3.5.2 Energy Consumption per Unit of Area

Different-sized data centers can be (roughly) compared by dividing their total energy consumption by the total floor area in the data center. Although this provides useful information for estimations in future plans, it doesn't really tell anything about how "good" or "bad" a data center is. Room height can have a significant impact on air flows, thus impacting the efficiency of air conditioning, and some data centers might be packed more densely than others.

3.5.3 Energy Consumption per Rack or Server

Server racks are fairly uniform in size, so dividing a data centers total energy consumption by the number of server racks gives a pretty good estimate for how much energy the whole facility is using per server. Of course, this doesn't account for different-sized servers or empty spaces in racks, but one would expect there to not be too much empty space. Energy consumption per rack, while historically as low as 3 kW, can nowadays be up to 40 kW.

A better average can be calculated by dividing the energy consumption by the number of servers. However, as server form factors and processor core numbers vary wildly, these numbers are still far from describing the energy costs of actually doing something useful. Energy consumption per server has also multiplied over the years.

While consuming more energy, modern computers are also vastly more capable than their historical counterparts. Thus, the energy cost of a calculation has decreased while energy density has gone up. Increased energy density does require more in terms of spot cooling from the cooling system of a facility, but this does not necessarily mean it would consume more energy.

3.5.4 Energy Consumption per Hour of Entertainment

To measure the actual usefulness of energy consumed, it might be a good idea to measure how much energy it takes to entertain a consumer for one hour. Of course, any precise measurements are impossible, but estimates based on the average amount of users, service type, etc. would probably give a somewhat usable number.

For example, for a YouTube-type video service, it can probably be said that there is, on average, one person watching for every second of video downloaded. This would make it very straight-forward to measure the lengths of the videos served and the energy consumed and deduce the energy consumption per hour of entertainment. Interestingly enough, Netflix has measured in 2014 this number to be 1.3 Watt-hours (Wh) in their data centers [37]. This is remarkably little, and any devices people use to watch the videos are likely to consume far more. For an online game the measurement would likewise be easy.

A data center serving, for example, downloadable games, would have to make some more guesses as to the usage of the games before arriving at a usable number. In a data center hosting multiple types of services on the same computers this number might be very hard or downright impossible to measure.

As a lot of corporate software nowadays runs on servers, an hour of "entertainment" from a data center can also mean an hour of work. In cases where a user's actions are visible on the server side, energy consumption per hour of work can also be measured. Cases like email may not be totally straightforward to measure, as on the server side it is pretty much impossible to tell if a user is reading an email or if the email is visible on the user's screen while the user is out having coffee.

3.6 Carbon and Water Usage Effectiveness

Carbon Usage Effectiveness (CUE) is measured by dividing the total CO_2 emissions caused by the total energy consumption of the data center facility by the energy consumed by the IT equipment. Likewise, Water Usage Effectiveness (WUE) is measured by dividing the total water consumption of the data center facility by the energy consumed by the IT equipment. Unlike PUE, CUE and WUE are not dimensionless. The unit of CUE is kilograms of carbon dioxide per kilowatt-hour ($kgCO_2eq/kWh$) and the unit of WUE is liters per kilowatt-hour (l/kWh). [22, 38, 39]

CUE and WUE as such are not strictly related to the energy efficiency of a data center facility; however, they do have value in showing the environmental friendliness and sustainability of a facility. Like always, these values may not be directly comparable across the globe, as consuming a liter of water has a different impact on the environment in different climates. [22, 38, 39]

3.7 Measuring the Metrics

Measurements can generally be done either continuously or instantaneously. Usually, an "instantaneous" measurement is still actually an average, most often over the time of one hour. Continuous measurement gives a real-time glimpse into the energy consumption and efficiency of a data center, but in some cases momentary measurements can be done more thoroughly. Total power consumption of a data center tends to be cyclic regardless of the current ICT load. There are several cycles: Powering cycles of the cooling and ventilation equipment, daily cycles, weekly cycles, yearly cycles. Overall, one can get the best picture of power consumption by taking an average over a long time – for example, a year – but in the fast-paced world of ICT it may be hard to find a data center that stays stable for a year. [26, 28]

Rasmussen argues that due to the problems in obtaining representative measurements, it would be at least beneficial if not outright necessary to complement the measurements with a mathematical model of the data center. If the model is precise enough, it might be possible to reduce the number of points in which it is necessary to measure energy consumption. However, creating the model necessitates precise measurements in different circumstances and conditions. After the initial measurements, continuous measurement requires fewer data points. [28]

Typically the energy consumption of a data center does not vary very much with varying ICT loads. This means that the amount of energy needed to provide a certain amount of ICT services varies wildly; the more demand for ICT services, the more efficient they are to provide. [25, 26, 28]

As efficiency gets better when ICT load goes higher, there is an incentive to measure energy consumption at the maximum ICT load to get the best PUE (or DCiE). Data centers, however, rarely run for any length of time at their maximum load – this is in fact seen as a failure of capacity estimations. On the other hand, if the reporting metric is the energy consumption of the data center (either ICT energy consumption or total energy consumption), there is an incentive to measure energy consumption with an ICT load level as low as possible. Not having a standard for the level of ICT load at which energy consumption should be measured presents a problem when comparing different metrics and different data centers, especially those operated by different operators. [26]

Gaming the measurements and fudging the metrics can be done on many levels. To make PUE look better, a data center might temporarily run some extraneous services on (some) servers to make the ICT energy consumption bigger (and thus bigger in comparison to the amount of energy "wasted" in support functions). The same effect could be achieved with unnecessary network operations, making the network equipment consume more energy. Figure 14 illustrates how different metrics can be gamed by arbitrarily choosing the ICT load level at which the energy consumption measurements are made. PUE can be made to look best by measuring at 100 % ICT load level; total energy consumption looks best when measured at a very low ICT load level.

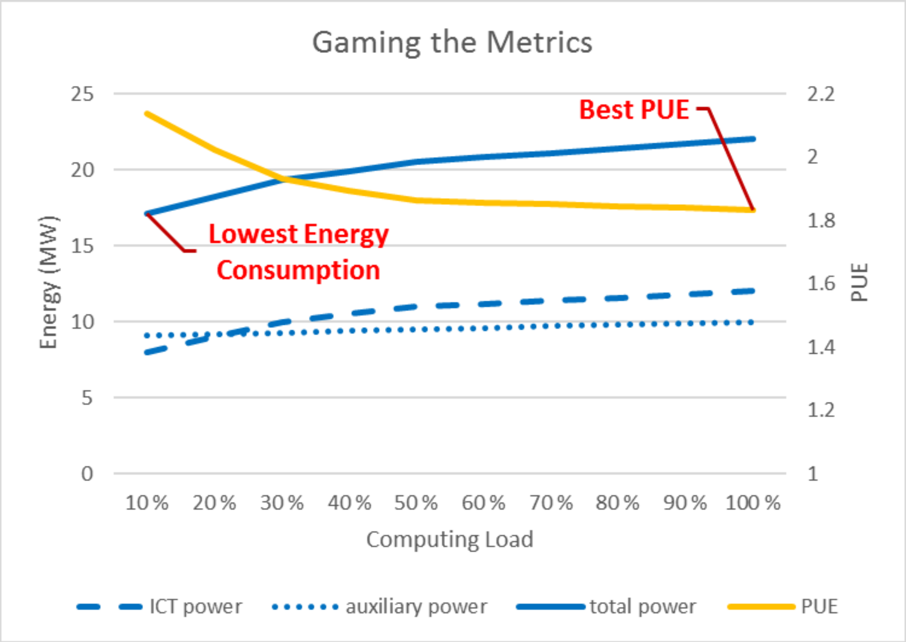

Figure 14: How metrics can be gamed by arbitrarily choosing the ICT load level at which to measure energy consumption. The numbers are an example.

On the other hand, the gaming can be done more "honestly" by reducing the amount of energy consumed by the facility's support functions (UPSs, power distribution, air conditioning, cooling). This would be more "honest" in the sense that it would also lower the total energy consumption of the facility, although it would be possible to cheat here as well by, for example, letting the data center temporarily get hotter than recommended.

Depending on who is doing the measurements and what the metrics are going to be used for, the measuring time period needs to be long enough to make cheating infeasible. Unfortunately, this likely means the loss of many interesting granularities.

3.8 Goals and Problems

Generally the goal of defining metrics and keeping track of measurements is to improve whatever it is that one is measuring. However, to not end up improving only the *metric*, one needs to make sure the metric is suitable for its purpose and that improving the metric brings measurable gains in operations as well. It must also be possible to improve the metric – if we can't do anything about what we are measuring, the measurements will have been a waste of time and resources. Even if it *is* possible to improve the metric, we need to make sure that the measurements do not cost more than can be gained. [21]

For example: Let's presume a server consumes 1250 Watts (at maximum capacity) and that electricity costs 0.10 €/kWh. Now, running a server a whole year like this would cost

$$365\ days * 24\frac{h}{day} * 1\ 250\ W * 0.10\ \frac{€}{kWh} = 1\ 095\ €.$$

Similarly, let's assume a rack of 32 servers. Its energy consumption would be

$$32 * 1250\ W = 40\ kW$$

and yearly running cost

$$32 * 1095\ € = 35\ 040\ €.$$

Likewise, a data center with 300 racks of servers would need

$$300 * 40\ kW = 12\ MW$$

of power to run them, which would cost

$$300 * 35\ 040\ € = 10\ 512\ 000\ €$$

annually. If we assume that energy savings of 10 % are possible, we can calculate that the cost of electricity measuring per power supply (assuming two per server) needs to be less than

$$10\% * \frac{1\ 095\ €}{2} = 54.75\ €$$

per year.

Assuming the same 10 % power savings can also happen in the auxiliary equipment, the savings naturally increase. With a PUE of 2.5, the auxiliary equipment would use 1.5 times as much energy as the ICT equipment, and the total savings would be

$$10\% * 2.5 * 10\ 512\ 000\ € = 2\ 628\ 000\ €$$

annually. On the other hand, with a PUE of 1.12, the savings would be

$$10\% * 1.12 * 10\ 512\ 000\ € = 1\ 177\ 344\ €$$

annually.

To make any improvements over time, we need to – depending on the metric we are using – make sure that the environment and processes stay constant. If we use metrics that are hardware-dependent, we need to be using hardware compatible with the metric – often it makes more sense to select a better metric than to voluntarily lock in to specific hardware. A good metric also can't easily be gamed by a vendor or staff, and the necessary measurements need to be possible to be taken without disrupting operations in the data center. [21]

3.9 Summary

The energy density and energy cost of a data center are both high, and energy efficiency is a desired trait. How to measure energy efficiency is not very simple – one needs to know the purpose of the comparison to know what exactly to measure, and how. Some metrics, like Power Usage Effectiveness and Data Center Infrastructure Efficiency, can be pretty easily gamed to get a more favourable result.

Measuring the raw energy consumption is probably the most reliable way to go, but it unfortunately limits any comparisons to the same data center in the same configuration at different times. To counter that, one can divide the energy consumed by some other value: Number of servers, data center area, or, perhaps optimally, hours of entertainment produced.

4 Improving Data Center Efficiency

As energy costs are a major part of the overall costs of running data centers, data center operators tend to want to curb the energy consumption, which also has the side effect of making the data center greener. Besides improving the energy efficiency of a facility, energy reuse has also emerged as a way of making a data center greener – often while also saving money.

This chapter deals with different ways of reusing energy as well as ways of improving energy efficiency. A couple of ultra-efficient data centers are also discussed.

4.1 Energy Reuse

One way of reducing the net energy consumption of a data center facility is to reuse some of the waste energy produced. As waste energy in a data center usually means waste heat, thermal energy reuse seems like an obvious choice for energy reuse. Several techniques for this have been researched, including using the waste heat for district heating. As district heating is already quite popular in Finland, this coupled with a cool climate would seem to indicate a favorable location for data centers.

Several uses for the waste heat can be found; it can be used as a source of electricity, or a source of power in a chemical process. It can even be used for refrigeration. The simplest, and by far most efficient [40], way is to use waste heat for space heating nearby.

While water cooling is already much more efficient than forced-air cooling, hot-water cooling can be even more efficient. Zimmermann et al. have shown that temperatures as high as 60 °C are efficient in cooling microprocessors. This effectively eliminates the need for a chilling unit, saving in investment and energy costs. Using hot water as a coolant also makes it easier to reuse the waste heat. [41]

4.1.1 Reuse Heat as Heat

In Finland, almost all towns and cities have at least some kind of a district heating system. In the whole country, about 46 % of all buildings are heated with district heating, and in larger cities over 90 % [42]. According to Malkamäki and Ovaska's estimate, domestic heating in Finland could take up to 12 GW of continuous power during the coldest month, which means that there is ample demand for waste heat from data centers [43]. However, when the weather is at its coldest, the water used for district heating needs to be at its hottest, somewhat reducing the efficiency of heat reuse.

In 2014, the Russian search engine company Yandex built a data center outside Mäntsälä, and its waste heat heats a part of the town of Mäntsälä, replacing natural gas as an energy source [44]. In Espoo, some 50 gigawatt-hours of energy from two data centers is reused in district heating annually [45], making one of the two one of Wired magazine's greenest data centers of 2011 [46]. A 2 MW data center in a disused air-raid shelter has provided district heating in central Helsinki since 2010 [47].

The water used in district heating systems may be as hot as 110 °C, especially during the winter. Water this hot is not usually available as waste heat at data centers, but, using heat pumps, the temperature may be raised. Heat pumps themselves need energy in the form of electricity, but up to 80 % of the combined energy in the electricity and waste heat can be converted to heat of a higher temperature. Also, during summer, some systems circulate water at 65 °C, which is much more suitable for waste heat reuse. If there are suitable buildings nearby, it might be possible to transfer the waste heat to these buildings directly (without using heat pumps and temperatures suitable for district heating) to be used for heating domestic water or in under-floor heating. [48]

Sports centers and especially swimming pools might be some of the potential heat consumers for a data center. Swimming water needs to be heated to around room temperature, which is certainly cool enough to be done by excess heat from a data center, even if the heat has to be transported for some distance and heat losses occur.

So-called data furnaces, where individual servers are sited in homes or apartment buildings, could prove useful in places where district heating is not the norm. Data furnaces could provide savings of up to $300 per server annually in the United States by reducing land, building, and air conditioning utility costs. Another, perhaps a little harder to measure financially, perk is that servers placed closer to the users present shorter latencies in network connections. However, hardware maintenance would be more cumbersome and security could be an issue. Waste heat temperature requirements are less stringent in data furnaces than in district heating. [14]

4.1.2 Reuse Heat as Electricity

Waste heat can be used to pre-heat the water in a thermal Rankine cycle or directly as the evaporator in an organic Rankine cycle, recovering some of the energy lost in waste heat as electricity. Both of these require the data center to be essentially at the power plant, leading this to be feasible only with purpose-built water-cooled facilities. [14]

Most thermal energy reuse systems require the waste heat to be of at least some temperature, or in a specific temperature range. Liquid-cooled systems can meet the temperature requirements more easily than air-cooled systems. Heat pumps can in some circumstances be utilized to condense waste heat to a higher temperature. One problem with waste heat reuse is that the reusing needs to be done close to the data center facility, as heat does not transport too well. [14]

Piezo-electric generation can be used to recover waste energy directly from the turbulent airflows in a data center. This technique doesn't require much from the quality of the waste heat, but the resulting power is tiny, on the order of milliwatts. Using the thermo-electric principle, electricity can be obtained from semiconductors subjected to a temperature difference. The required temperature difference means that the thermo-electric modules need to be situated close to the heat-producing components, and the efficiency of the process is also very low. [14]

4.1.3 Reuse Heat as a Power Source

A multiple-effect distillation (MED) system is a method of removing salt from seawater. The MED process can use waste heat from a water-cooled data center facility as an energy source. Depending on the number of stages in the MED process, almost all of the waste heat can be reused. The limit in the number of stages is money; the stages are expensive. If there are enough stages, it can be possible to completely omit the chiller unit from the data center coolant cycle, thus saving not only in energy but also capital costs. In most data center locations, however, fresh water is not in short supply, making the profitability of this scheme a little questionable. [14]

4.2 Improving Efficiency

As stated before, not all metrics seem to improve every time an improvement in a data center is made, even if the improvement is big enough to show up in measurements. Some ways of improving efficiency in one part of a data center may make the efficiency in some other parts (either physical areas or logical segments of the facility) worse. Some of these relations are presented in Figure 15.

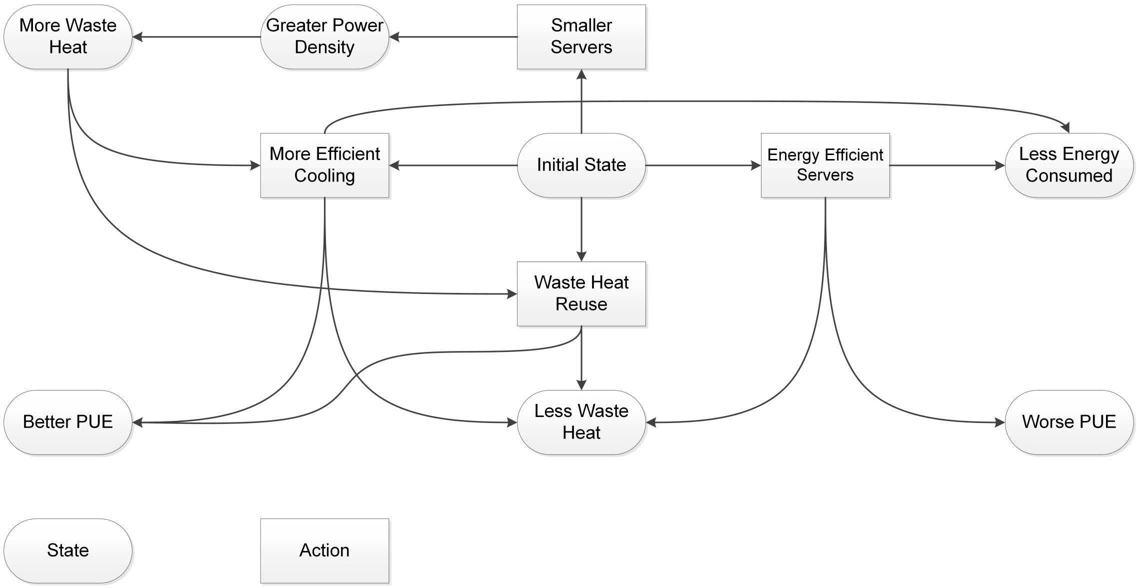

Figure 15: A model of some of the complex relations between different data center improvement methods and outcomes.

4.2.1 Operations Efficiency

Energy can be saved by running the ICT equipment in a data center at close to maximum capacity. Servers do consume less energy when not using all of their processor power, but the savings in energy are less than the excess capacity, i.e. a server running at 50 % processor capacity will still consume considerably more than 50 % of the energy it consumes when running at 100 % of processor capacity. Traditional load-balancing works against this by trying to share the workload equally between computers. [33]

In practice, the maximum sensible load level is around 70 %. Although usage levels can in many cases be anticipated based on history, short-term high-frequency fluctuations combined with higher loads would lead to queue lengths growing quickly.

More energy can be saved running some servers at close to capacity and letting the extra servers sleep, as a server in the sleeping state consumes far less energy than an idle server. This, however, presents the problem of ramping up capacity, because transitioning from sleep to idle takes some time – on the order of seconds. Knowing the nature of the services run in the data center and predicting the usage rate in the future become essential, although it would still be necessary to run at least some servers at idle or not at maximum capacity all the time. Depending on the type of service run in the data center, reducing the number of servers performing the same task might not have a big impact on user experience [49]. Usage of the networking equipment needs also to be considered, meaning, basically, that the servers running at maximum capacity should not be located next to each other. [33, 50]

Somewhat depending on the type of services run on the servers, virtualization environments matter as well. While hypervisor-based virtualization basically recreates the underlying hardware for the quest operating system, container-based virtualization more or less creates sandboxes within the operating system for processes to run in. In processor-intensive tasks the type of virtualization has little to no effect on energy consumption, but, interestingly, in network-intensive tasks the container-based virtualization environments consume 10 to 15 % less energy. [51]

There are essentially four different levels on which data center optimization can happen:

1. Infrastructure
2. Server hardware
3. Operating system and software
4. Software architectures

Optimizations on the infrastructure level would include things like airflow management and power path design. Selecting optimal server hardware means considering the energy consumption, heat output, computing power, cooling method, and physical size. Optimization on the operating system level can mean for example selecting an operating system that allows idle computers to sleep.

4.2.2 Liquid Cooling

Liquid cooling for computers has a better efficiency than air cooling. This comes from no longer needing to cool the whole room to the computers' air intake temperature and greater efficiency in moving the heat away from the components. Air cooling requires a greater temperature differential between a chip and the coolant than liquid.

A differential as low as 15 °C is possible with liquid cooling, whereas air cooling needs a differential of some 35 °C [40]. Also, if the facility is equipped with waste heat reuse, that can be done more efficiently if the computer equipment is liquid-cooled.

Traditional liquid cooling circulates a coolant in tubes between heat exchangers that are in contact with the heat-inducing components on one hand and outside air on the other. In liquid immersion cooling the heat-inducing components are completely immersed in the coolant, which is then either circulated to allow heat to dissipate, or let to evaporate at the components and again condensing in a tank. Liquid immersion cooling is especially efficient; it uses as little as one percent of the energy needed by traditional air cooling. Liquid immersion cooling necessitates a dielectric coolant, while the coolant for traditional liquid cooling can be chosen more freely. Appropriate care needs to be taken to ensure minimal disturbance to services in cases of leakage.

On the other hand, liquid cooling systems are expensive due to the greater complexity and relatively low sales volumes. Liquid cooling also makes the infrastructure in a data center more complex. Moving computers from one place to another becomes more difficult, which reduces the flexibility of the facility. However, most data centers are relatively stable in terms of server computer lifespans, so the savings made in energy costs can mitigate the losses of greater infrastructure building costs and reduced flexibility.

4.3 Ultra-efficient Data Centers

The average PUE worldwide is around 2.5 [33], with many if not most data centers sporting numbers in the 2 to 3 range. Some of the most energy-efficient data centers in the world advertise PUEs as low as 1.05 to 1.2, making them ultra-efficient. A PUE of 1.05 in this context does not necessarily mean that all the support functions in the data center facility consume only 5 % of the power consumed by the ICT equipment; usually in these cases any waste energy that is reused is subtracted from the energy used by the support functions. Strictly speaking, this number is not PUE but ERE, Energy Reuse Effectiveness. Energy obtained directly from nature by e.g. “free” cooling or solar panels is usually not counted as energy used.

There are two relatively new, very efficient data centers in Finland. One in Hamina, on the southern coast, operated by Google, and another in Kajaani, near the eastern border, operated by CSC and IBM. Both of these data centers are not only very efficient in their operation; their infrastructure was built very efficiently as well; both of the data centers are built in a defunct paper mill. While placing a data center in a former paper mill might sound surprising, they do have some requirements in common. A paper mill needs a steady supply of energy and water, big production facilities and usually also storage facilities. A data center can usually directly use the energy supply and after minor modifications the water supply system and production and storage facilities of paper mills. [4]

4.3.1 Google, Hamina

In Hamina, Google utilized the existing primary power supply system – capable of delivering the 900 GWh the paper plant needed annually – but built a new backup for it. Likewise, they used the existing water pipelines to dump warm exhaust water into the sea, but decided to build a new pipeline for water intake deeper in the sea. This facility was the first data center in the world to use sea water for cooling. Sea water – although the water in the Gulf of Finland is considered to be brackish rather than saline water – can be used directly year round, as temperatures deeper below the surface stay below 5 °C even in the summer [52, 53]. Unlike many other paper mills, hydroelectric power is not available at this site, leading to Google building an array of diesel-powered generators. This has, however, been criticized as unnecessary, as the electricity grid itself is much more reliable in Finland than in the United States. Since 1998, the electric grid in Finland has been unavailable less than 0,00002 % of the time, corresponding to around six seconds of unavailability a year. [4, 54]

Google outright bought the former paper mill and surrounding lands in Hamina for around 40 million euros. As Google has since spent an estimated 150 million euros in renovating the site and plans to spend another 150 million euros, it can safely be said that the initial buying price is not the biggest deciding factor in these kinds of deals. [4, 54]

4.3.2 CSC and IBM, Kajaani

In Kajaani, CSC and IBM decided to use the existing primary power system, capable of delivering 2 TWh annually. Near the paper mill there is a 10 MW hydroelectric power plant, but it could not be used to power the data center because the data center only needs about a fifth of the plant's power. The facilities included water pipelines suitable for water cooling, but it was found that the water temperatures in the nearby river would climb too high during the summer months, leading to a need for a specialty intermediate cooling stage. This was deemed too expensive and inefficient. However, outside air in the region is cold enough year round to be directly used for free-air cooling, and the overall PUE of the data center is as low as 1.06. A power plant on paper mill premises also provides district heating for the town of Kajaani. The original plans called for several tenants with data centers to be housed in the production facilities, but these plans fell through after Facebook built its data center in Sweden. It was decided that the production facilities are much too big for a smallish data center, and the CSC/IBM data center is now housed in the main cold storage warehouse, of which it occupies about half. CSC uses around four times as much space as IBM. [4, 55]

CSC's plan for the Kajaani data center is for it to replace some 160 small (and mostly inefficient) data centers in Finnish institutions of higher education. With today's data networks, additional latencies from locating one's servers a few hundred kilometers away are more than offset by the increased efficiency in power usage. [4, 55, 56]

Unlike the site in Hamina, the site in Kajaani is ultimately still owned by the same corporation, which now rents facilities and services to several tenants on long-term leases. [4]

4.3.3 Elsewhere

Large-scale operations can of course better utilize the lower availability requirements of some aspects of their data. Facebook, a global (and popular) provider of a social network, already owns some of the most efficient data centers in the world with PUE values of 1.05 to 1.1 [46]. In addition to this, Facebook found savings by re-thinking the immediate availability of their users' photos. Since most photos are seldom accessed, they do not need to be replicated in all of their front-line data centers. Instead, they store the photos in very few places in the "live" network, and designed and built two data centers to house the backup copies of these photos. The photos are stored in servers that only power up when needed, and all the redundant power supply systems were left out of the data centers. This way, the two data centers in the United States are expected to consume less than one-sixth of the power a data center of that size normally would. [57]

Energy reuse, especially reusing waste heat to heat other spaces, is a big factor in bringing the overall PUE down in many data centers. Cooling with outside air – or outside water – are some of the other factors. Something as simple as air flow management – preventing cold air mixing with hot air – can make a difference in efficiency, and is surprisingly seldom well-organized. [46]

Overall, ultra-efficient data centers are apparently still seen as a gimmick of sorts. Using a way of saving or reusing energy is seen as newsworthy. Combining these efficiency tricks should not be impossible – save as much energy as you can, and reuse what little waste you have – but it seems to be impossible to find a data center that does this.

4.4 Summary

Reusing the waste energy of a data center seems like a good candidate for improving the energy efficiency. Using waste heat in district heating systems is already being done in Finland, and keeping the reuse in mind while selecting a data center location would make it possible also in places where district heating has not been deployed.

Moving waste heat over longer distances is not really feasible, so the heat needs to be converted to some other form of energy – usually electricity – for transport. Processes to do exactly that do exist, but require specialized equipment near the data center.

A data center's efficiency can also be improved by making sure it runs at as close to maximum capacity as possible, by for example "over-booking" its capacity. On the other hand, powering down equipment that is temporarily not needed, can also make significant improvements in efficiency.

The most energy-efficient data centers in the world usually employ multiple ways of improving their efficiency. In addition to efficient operational practices and energy reuse, they may produce some of the energy they need on-site with for example solar panels.

5 Comnet Data Center

To know how much energy a data center uses, its energy consumption needs to be monitored. Other measurements, such as indoor and outdoor temperatures and cooling power can also be utilized to help run a data center efficiently. Aalto University Department of Communications and Networking (Comnet) has a small data center, where some measurements were collected over seventeen months.

This chapter discusses the energy consumption metering system and other measurement data collected, as well as some observations made from the data either directly or after some calculations.

5.1 Monitoring a Data Center

Monitoring large-scale data center facilities with maybe thousands of server computers and all the other equipment that comes with that is a daunting task. Although many energy consumption metrics call for a long-term measurement, monitoring all functions of a data center effectively requires real-time data. Numerous pieces of software of varying quality and price exist to make this task manageable.

For long-term operation of a data center it is also important to gather data of many kinds. In addition to energy consumption, one needs to monitor room temperatures (in different areas, on different heights), equipment temperatures, air humidity, airflows and workloads. The most oft-used models for operation planning follow the MAPE (Monitor, Analyze, Plan, Execute) approach. [58]

5.2 Electricity Metering Setup

The power consumption metering system in the Comnet test data center consists of twelve Carlo Gavazzi EM24-DIN energy analyzers, eleven of which are in use at the time of writing. The analyzers are connected in series to a two-wire RS-485 (also known as TIA-485-A, TIA/EIA-485 and ANSI/TIA/EIA-485) bus terminated at a Moxa NPort 5150 serial port server. The NPort is also connected to the internal LAN in the data center, and there is a management computer in the data center as well. The management computer can be accessed remotely and all the meters in the energy analyzers can thus be read remotely.

A two-wire RS-485 bus requires two data wires and additionally a ground reference, which, in this case, was arranged with a common ground wire. The two data wires (white and brown) and the ground wire (yellow-green) can be seen emerging from a protective sleeve in Figure 16.

The maximum length of a RS-485 bus is about 1200 m, at which length it can still offer communications at up to 100 bits/s. While this length is quite enough in the test data center (where the actual bus length is between 10 and 20 m), it might not be enough in a very large-scale facility. The maximum device number can also be an issue; however, repeaters can be used to extend the network. In large-scale environments it might also be beneficial to set up several separate buses.

Figure 16: The two data wires and ground wire of an RS-485 bus, with another set of RS-485 wires and a Carlo Gavazzi EM24-DIN energy analyzer in the background.

Ideally, the RS-485 bus would be tested before switching on the mains power – simply using a light bulb and a battery would suffice in a pinch. As it happened, the RS-485 bus in this case was in fact insufficiently connected in several places, including before the very first analyzer and before the second analyzer. In the Carlo Gavazzi EM24-DIN energy analyzers the low-voltage RS-485 bus and the high-voltage mains power are, as illustrated in Figure 17, partly located under the same protective plastic plate. This meant that getting to the RS-485 bus required exposing (but not touching) some high-voltage connections.

In addition to the plastic covers of the EM24-DIN energy analyzers, the live electrical connections are normally behind an additional plastic plate, through which only the display and control switches of the energy analyzers protrude.

When trying to make the RS-485 bus work, it was repeatedly cut in different places to isolate possible short circuits (of which there were none) and bad connections. For testing purposes, some analyzers were temporarily bypassed to make sure a faulty analyzer was not hampering the operation of an otherwise working bus. As illustrated in Figure 18, this was done by pressing the respective bus wires to and from the analyzer together with plastic clamps – the kind used by photographers. By using plastic clamps, it was easy to prevent any unintended cross-connections between the RS-485 bus wires.

In the end, none of the energy analyzers proved faulty, and all faults in the bus were discovered to be inadequate connections between the bus wires and an analyzer. In some places the bus wires, plugged into the same connector on an analyzer, had sufficient connection with each other to create a continuous bus with a seemingly

Figure 17: A Carlo Gavazzi EM24-DIN energy analyzer with the RS485 and some of the high voltage connections exposed.

Figure 18: Bypassing a suspected faulty energy analyzer with photographers' clamps.

faulty analyzer in between.

A common fault of the bus is illustrated in Figure 19. The left-most white wire hangs a little lower than the other wires, and looking carefully, one can see that the copper head has not been flattened like the other copper heads. Clearly, it had not been fully inserted into the connector.

In the end, the RS-485 bus was essentially rebuilt by disconnecting all energy analyzers and then adding them back one by one, starting from the one closest to

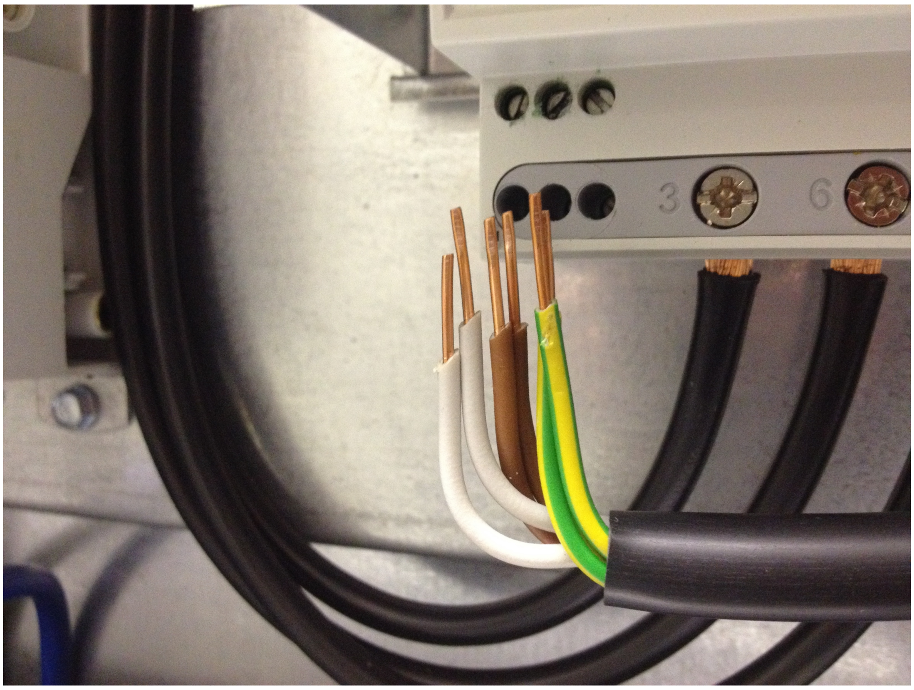

Figure 19: A close-up of the RS-485 bus wires, freshly out of the energy analyzer. Note the white wire with a pristine copper head.

the serial port server. Testing was done after each analyzer was connected to ensure all faults were discovered immediately. As the management computer could *only* be used remotely, testing the bus meant leaving the data center every time.

The Moxa NPort 5150 serial port server is normally managed with Moxa's NPort Administrator software and can also be managed via a web interface. The Carlo Gavazzi EM24-DIN energy analyzers can be read in bulk by Carlo Gavazzi software, or individual analyzers can be communicated with using any serial port software. Not only will the analyzers tell all their measurements this way, they can be – to an extent – configured this way. Automating energy analysis using an automated serial port software to gather the data should be at least possible if not downright easy.

In RS-485, the same wires are used both to issue commands and to receive replies. This requires that the serial port driver and software can rapidly switch between read (receive reply) and write (issue command) modes. Using the Carlo Gavazzi software this seemed to be easily done, but the software lacks all automation features. RealTerm, a serial port terminal program, should be easy to automate. For some reason, only individual values from individual analyzers could be read at a time; all automation proved impossible. It seems that the issue was with timely mode-switching, but it remains unclear whether the issue has to do with RealTerm, the Moxa serial port server, or a virtual serial port driver in Microsoft Windows on the management computer.

5.3 Environmental Monitoring

There are several different types of environment monitors in the data center. Indoor temperature is monitored in total by eight different meters, seven of which form a column ranging from the under-floor crawl space to the ceiling. Relative humidity is also monitored, as well as dew point and humidity and heat indices. Cooling pump flow rates, operating times, and temperature differences are also monitored, as well as the operation of compressors and condensers. This data is all collected once per minute and stored in databases.

Environmental data from outdoors is obtained from Finnish Meteorological Institute. Their closest point of measurement is located some two kilometers away from the data center. From there, weather information such as air temperature, wind speed, wind direction, relative humidity, dew point, air pressure, amount of rain, snow thickness and visibility data is collected every ten minutes.

As different variables had different resolutions, it was necessary to do some calculations. To make the amount of data more easily usable, it was decided to average all variables to the resolution of once per hour. Also, because some variables had different collection periods, all data was truncated to equal the shortest. The end result was 11 666 rows – sixteen months – of data in 68 columns. Un-truncated data was also kept for comparisons between variables that had longer collection periods.

The interior measurements are done mainly in one spot only, and can thus be easily affected by the conditions inside the test data center. Very short-term effects – like a person standing next to a temperature meter – are mostly wiped away with the averaging, but long-term small changes – like moving a piece of furniture and thus redirecting air flows – would still be visible (but undetectable) in the final temperature data.

As Figure 20 shows, the condenser fan operating time closely follows the outside temperature. This is hardly a surprise; in cool temperatures the condenser can work pretty much by itself, but in hot temperatures it needs to be actively fanned. A scatter plot in Figure 21 confirms the linear relationship. This seems to nicely confirm the validity of the data collecting and processing procedures.

5.4 Partial Direct Cooling

Exact data on how often and when direct (or “free”) cooling was used in the data center does not exist, but it is known that it has been done seldom and generally not for long periods of time. Points where free cooling was possibly used – points where the indoor temperature suddenly drops – are pointed out in long-term temperature data in Figure 22.

All sudden drops might not necessarily be instances of free cooling, however. Instances where forced cooling was the root cause for the temperature drop should differ from actual free cooling instances if the total power of forced cooling is taken into account. For this comparison, the total forced cooling power in the test data center was calculated from flow rates and temperature differences in two cooling systems in the test data center.

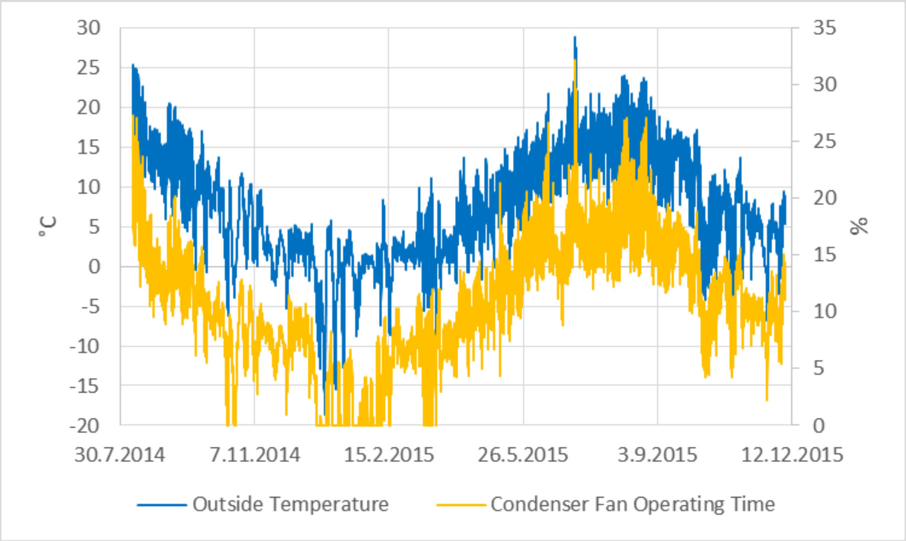

Figure 20: Outside temperature and condenser fan operating time from July 2014 to December 2015.

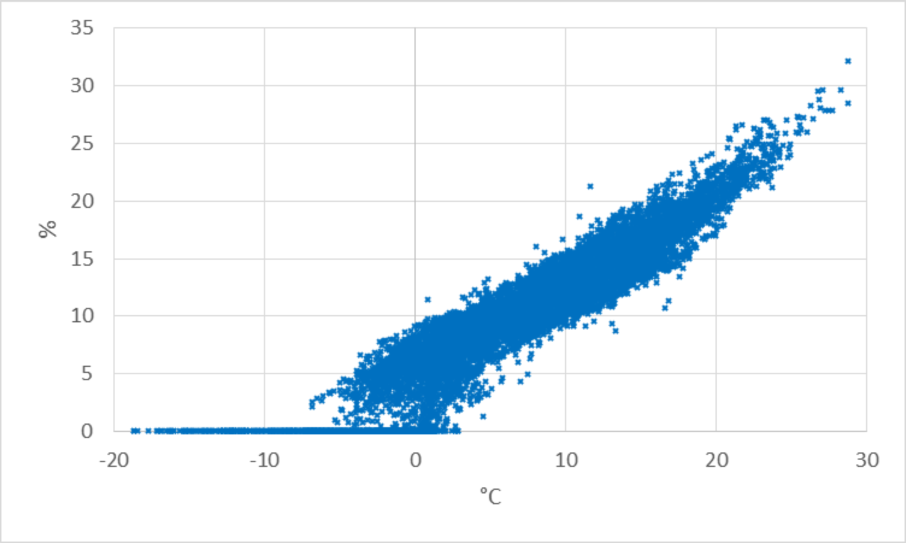

Figure 21: Outside temperature and condenser fan operating time from July 2014 to December 2015, in a scatter plot. Vertical axis is condenser fan operating time, horizontal axis is outside temperature.

Cooling power can be calculated with the formula

$$P = \frac{Q}{t} = \frac{c_P * m * \Delta T}{t} = \frac{c_P * V * \rho * \Delta T}{t} = c_P * \frac{V}{t} * \rho * \Delta T = c_P * \dot{V} * \rho * \Delta T, \quad (8)$$

where c_P is the specific heat capacity of the cooling liquid (in this case, water), $\dot{V}$ is the flow rate of the cooling liquid, ρ is the volumetric mass density of the cooling liquid, and ΔT is the temperature difference in the cooling liquid (before and after cooling the ICT equipment).

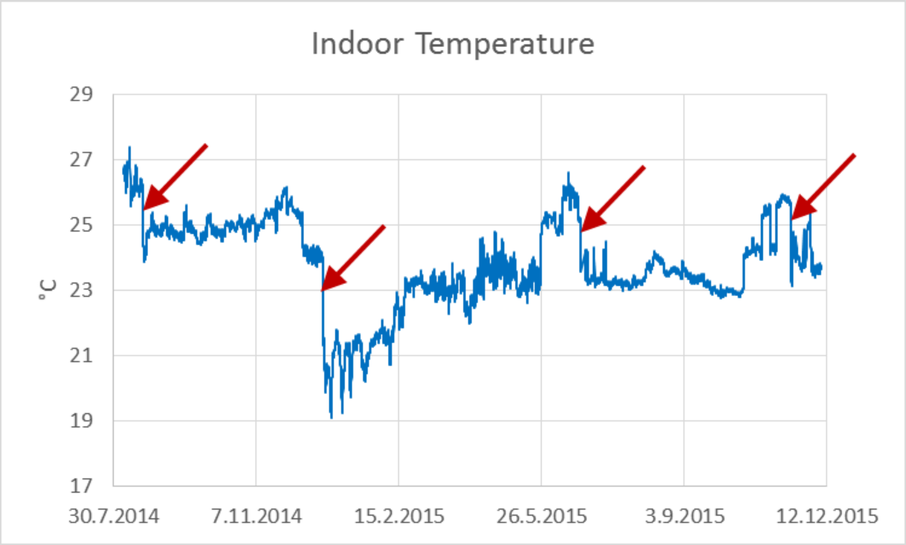

Figure 22: Indoor temperature data from the Comnet test data center over 17 months. The red arrows point out times where free cooling was possibly used.

As Figures 23 and 24 show, in two instances the cooling power drops simultaneously with the indoor temperature, while in two other instances the cooling power spikes when the indoor temperature starts to drop. Figure 23 shows situations where the drop in temperature was likely caused by free cooling, whereas Figure 24 shows situations where the drop in temperature was likely caused by the increase in cooling power.

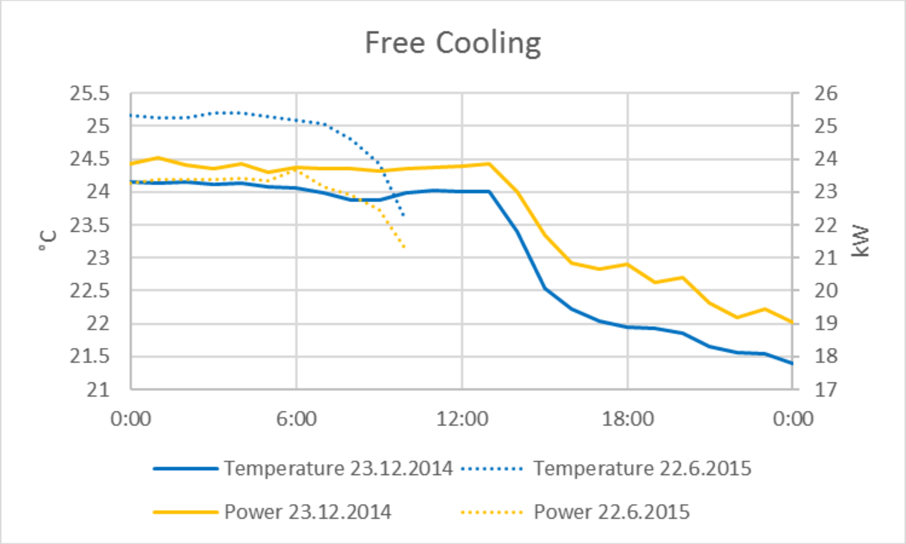

Figure 23: Indoor temperature (blue lines) and cooling power (yellow lines) data from December 23, 2014 (solid lines) and June 22, 2015 (dotted lines). The data for June 22, 2015 is incomplete.

Figure 25 has the rapid temperature drops of Figure 22 marked with differently

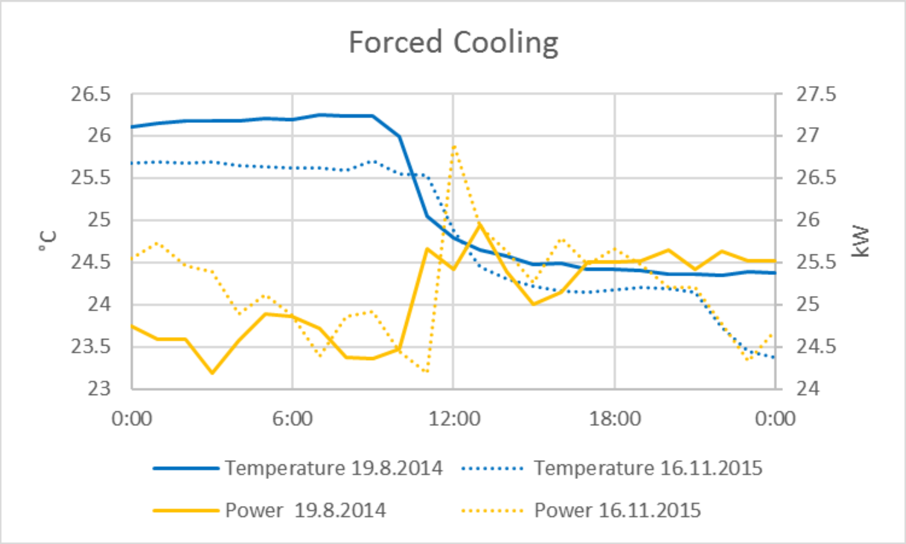

Figure 24: Indoor temperature (blue lines) and cooling power (yellow lines) data from August 19, 2014 (solid lines) and November 11, 2015 (dotted lines).

colored arrows. The green arrows point to instances where the rapid temperature drop looks like the result of free cooling, while the red arrows point to instances where upon closer inspection it looks like the rapid temperature drop was the result of forced cooling.

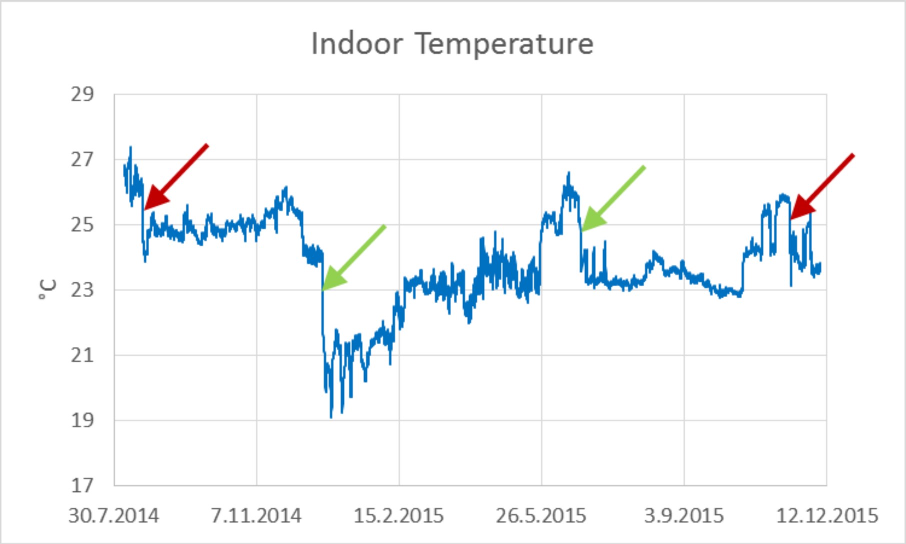

Figure 25: Indoor temperature data from the Comnet test data center over 17 months. The two light green arrows in the middle point out times where free cooling was likely used, and the red arrows point out times where the rapid temperature drop was likely the result of forced cooling.

As is predictable, cooling power is somewhat dependent on the temperature in a data center. While the condenser fan's operation is mostly dependent on outdoor temperature, the cooling power is mostly independent of outdoor temperature. Figures 26 and 27 show the relationship between cooling power and temperatures. In Figure 26 the horizontal axis is the indoor temperature, while in Figure 27 the horizontal axis is the outdoor temperature.

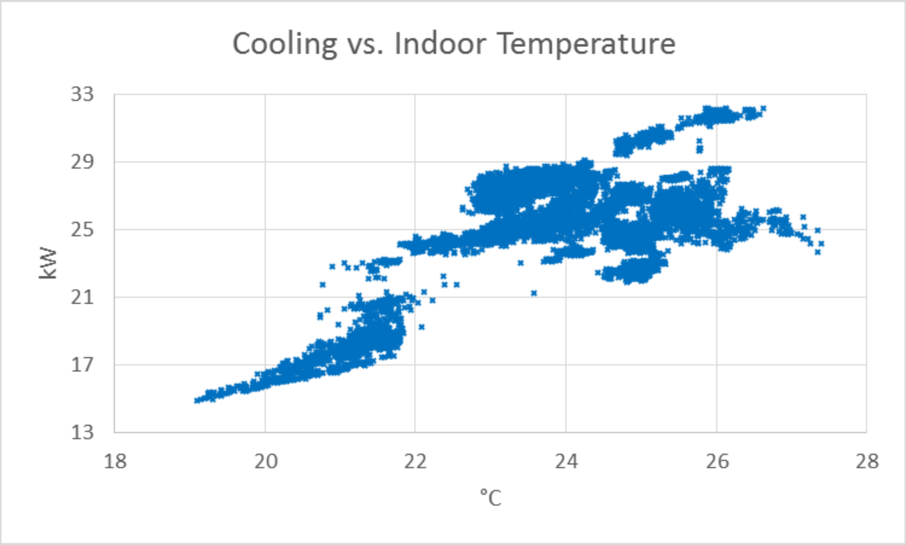

Figure 26: Cooling power (vertical axis) versus indoor temperature (horizontal axis) in a scatter plot.

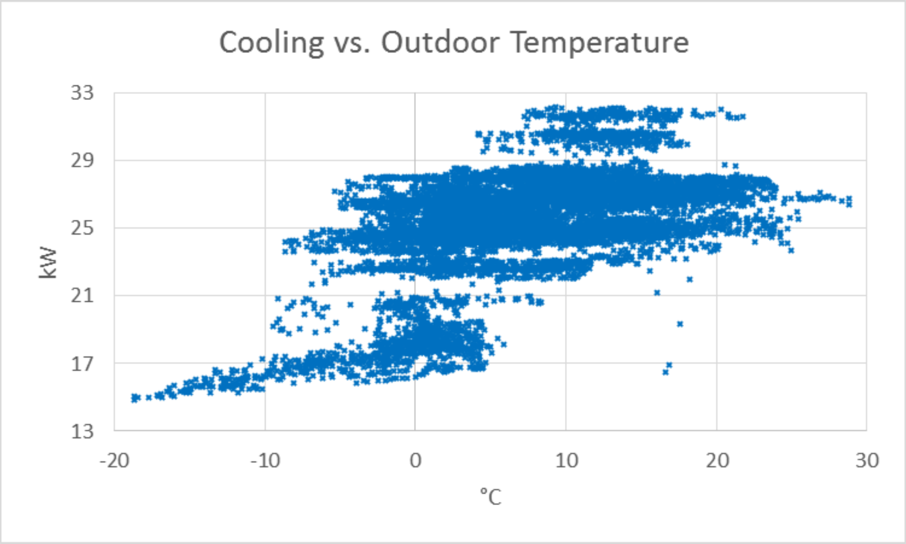

Figure 27: Cooling power (vertical axis) versus outdoor temperature (horizontal axis) in a scatter plot.

The cooling power follows the same daily rhythm as indoor temperature, including the somewhat fuzzy periods of Saturdays and Sundays. Figure 28 shows the average weekly cycle of indoor temperature and cooling power. Cooling power seems to follow indoor temperature with a slight lag.

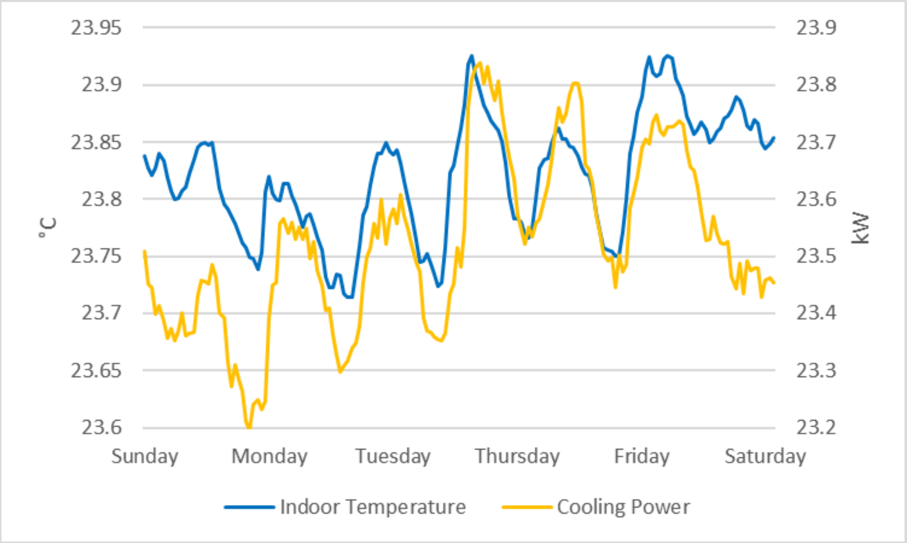

Figure 28: Average inside temperature and cooling power for each hour of the week.

Taking a look at Figures 26 and 27, one can see a distinct “tail” in both graphs. In Figure 26 it’s pretty well defined as the corner where the cooling power is less than 21 kilowatts and the indoor temperature less than 22 °C; in Figure 27 it’s a little less well defined but has the same distinct shape. The time period this happens in is roughly December 23, 2014 to February 11, 2015. In Figures 29 and 30 it is clearly evident that during this time the indoor temperature in the test data center is heavily dependent on the outdoor temperature. Based on this and the fact that the cooling power was abnormally low during the same period, it’s probably safe to say that free cooling was in use for the whole period.

During free cooling outside air is pumped in essentially raw, and the same amount of inside air escapes. To know whether free cooling adequately explains the drop in cooling power, it is possible to solve Equation 8 for a different variable:

$$\dot{V} = \frac{P}{c_P * \rho * \Delta T} \tag{9}$$

Here, $\dot{V}$ is the volumetric flow ($\frac{m^3}{s}$) of air that needs to be displaced to satisfy the deviation in cooling power, P is (the negative of) the deviation in cooling power, c_P is the specific heat capacity of air, ρ is the volumetric mass density of air, and ΔT is the temperature difference between inside and outside air. Figure 31 shows the cooling power deviation and the required displacement air flow for the period. The required air flow stays nicely below 500 liters per second (0.5 $\frac{m^3}{s}$). This happens to also be the capacity of the air conditioning equipment in the test data center, further suggesting that this was indeed a period of free cooling.

5.5 Humidity and Temperature

Outdoor temperature generally follows a daily cycle where the afternoon is warmest and the early morning coldest. Conversely, relative humidity is at its highest in the

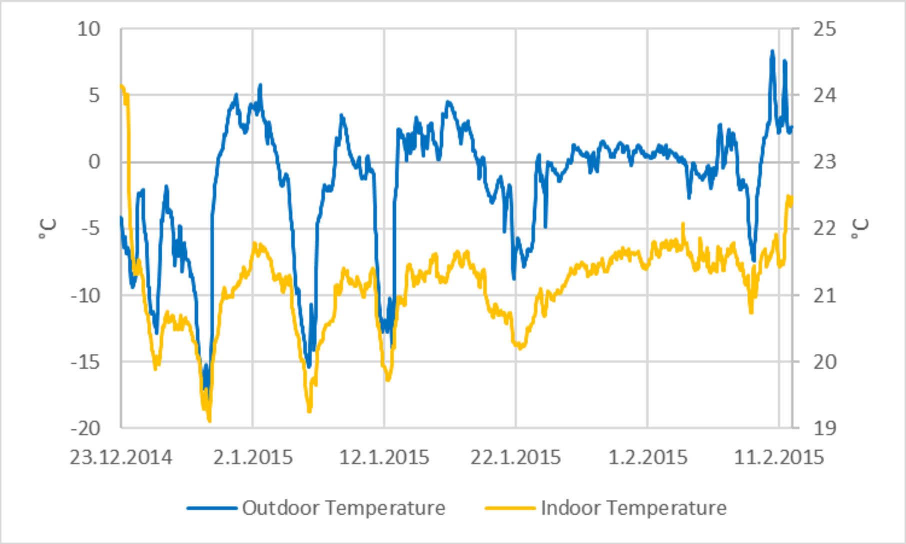

Figure 29: Outdoor temperature (blue line, scale on the left) and indoor temperature (yellow line, scale on the right) between December 23, 2014 and February 11, 2015. The indoor temperature is actually much higher than the outdoor temperature; the two lines have different scales.

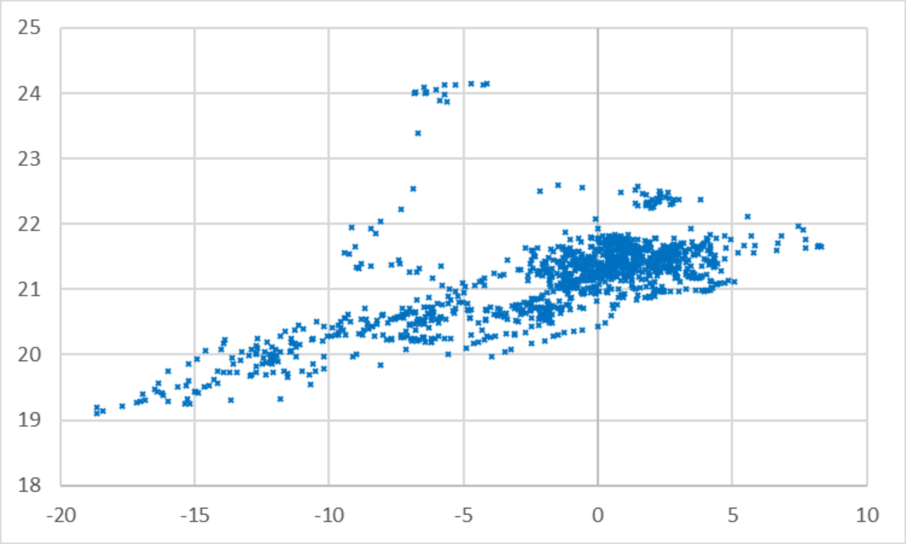

Figure 30: Outdoor temperature (horizontal axis) and indoor temperature (vertical axis) between December 23, 2014 and February 11, 2015 in a scatter plot. The linear relationship between the two variables is evident.

early morning hours and lowest in the afternoon. This cycle is evident in Figure 32.

Funnily enough, the inside temperature and relative humidity seem to follow each other, without the phase difference, as is evident in Figure 33. The temporal differences in temperature and relative humidity indoors are very minute compared to those outdoors, though.

There is no humidity control in the data center, so the humidity in outside air gets

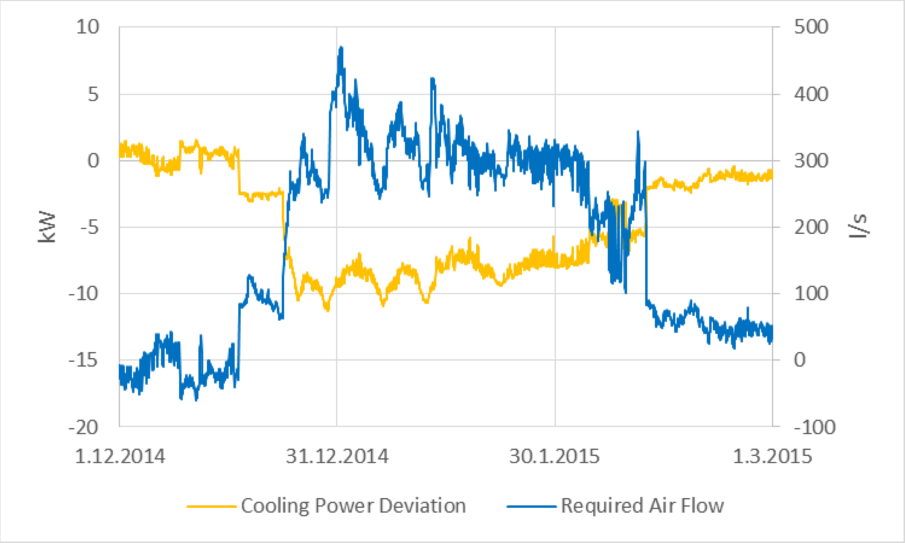

Figure 31: Cooling power deviation (yellow line) and required air flow (blue line) between December 23, 2014 and February 11, 2015.

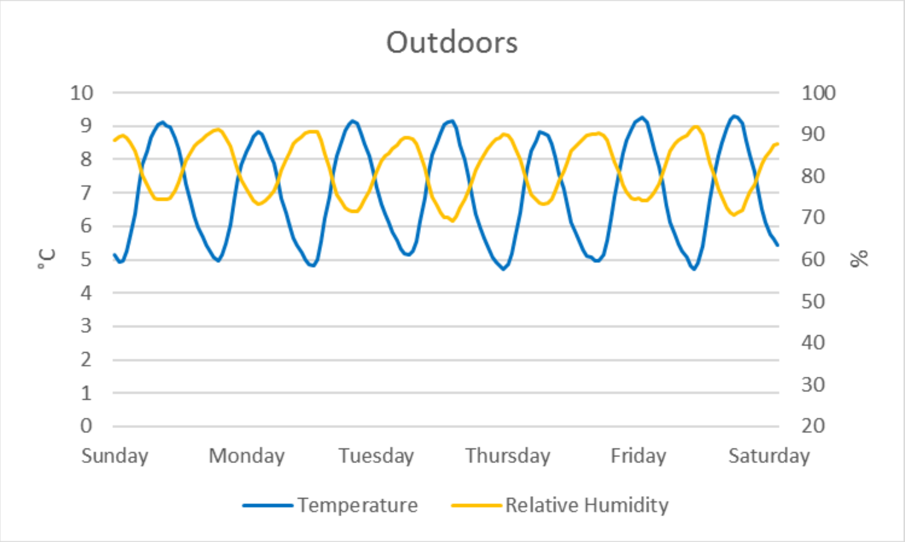

Figure 32: Average outside temperature and relative humidity for each hour of the week.

transported indoors as it is; either directly when using direct cooling or pre-cooled if the outside air is too hot. As Figure 34 shows, while the outdoor and indoor relative humidities have relatively little in common, both the dew points are nearly equal all the time. This is because the dew point is dependent on the actual amount of water in the air, whereas relative humidity is dependent not only on the amount of water in the air but also air temperature. Being located near the Baltic Sea, the outdoor relative humidity hovers most of the time near 100 % (50 % of time the relative humidity was more than 88 %), but as the outdoor temperature varies wildly and is generally much colder than the indoor temperature, the indoor relative humidity is

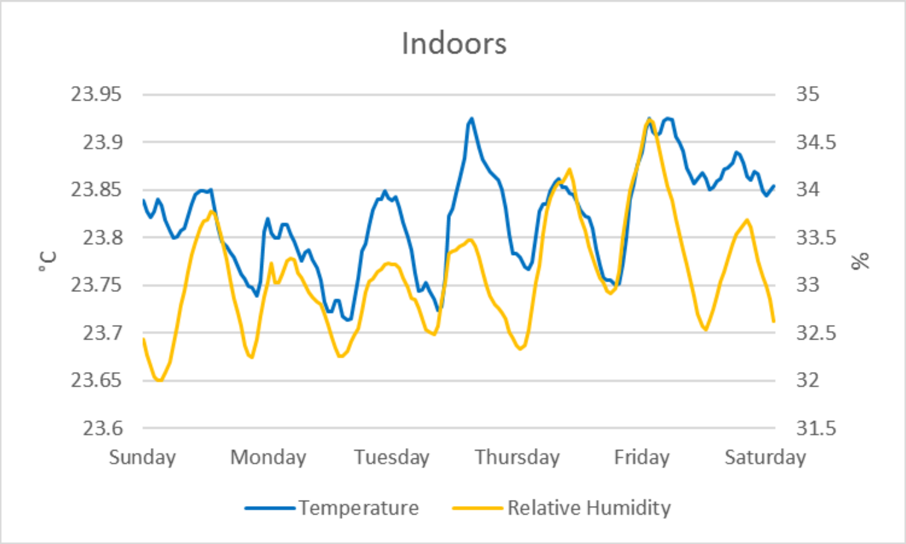

Figure 33: Average inside temperature and relative humidity for each hour of the week. There is a distinct daily pattern, but the overall differences in temperature and relative humidity are very minute.

significantly drier. As can be seen in Figure 35, the actual amount of water in the air both outdoors and in the data center are very near each other all the time.

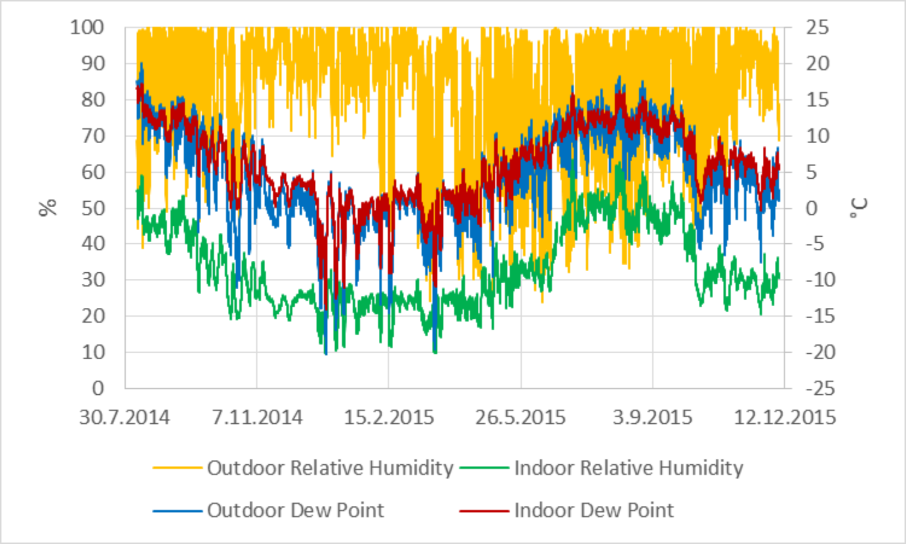

Figure 34: Outdoor (yellow line) and indoor (green line) relative humidities and outdoor (blue line) and indoor (red line) dew points from August 2014 to December 2015.

A particularly high dew point in outside air during free cooling could prove problematic, as water could start condensing on some of the colder surfaces in the data center. For example, even if the inside air in the data center might temporarily be warmer, some of the colder surfaces might be around 20 °C. If the dew point was

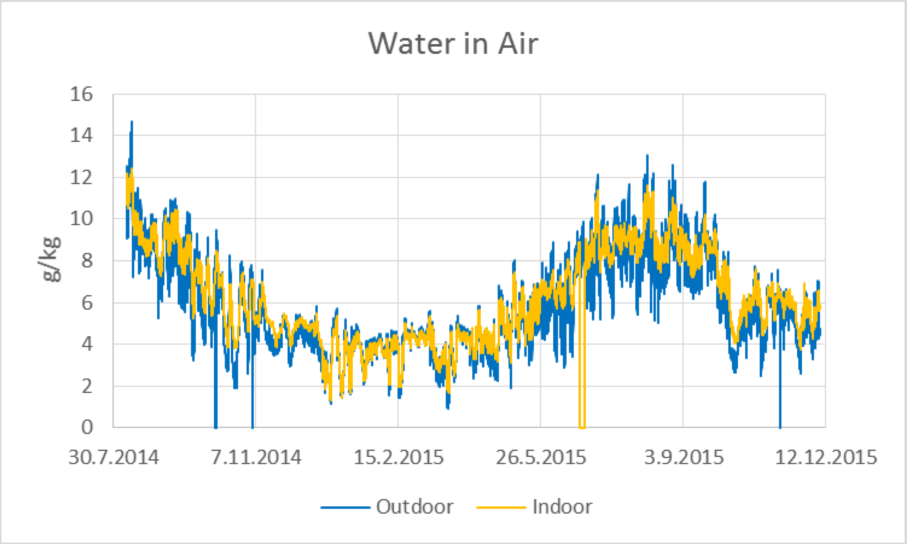

Figure 35: Amount of water in outdoor (blue line) and indoor (yellow line) air from August 2014 to December 2015.

higher than that, condensation would start to occur. However, as Figure 36 shows, only once did the outside dew point spike over 20 °C (with the outdoor relative humidity over 95 %), and at that point the indoor temperature had been above 25 °C for days. At a minimum, the indoor temperature was 5.6 °C above the dew point.

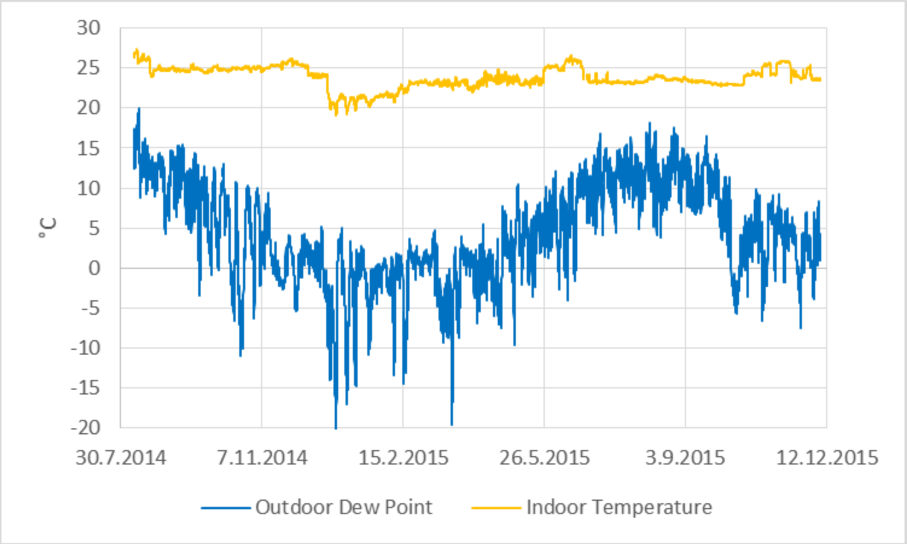

Figure 36: Outdoor dew point (blue line) and indoor temperature (yellow line) from August 2014 to December 2015.

5.6 Summary

The use of direct cooling seems to save about 6 kilowatts or around 25 % of the power used for cooling. During the sixteen months of measurements, 99.79 % of the time it was colder than 25 °C outside. Even if only situations where the outside temperature is at least 10 °C colder than the inside are accepted as suitable for direct cooling, that still happened 80.44 % of the time. This seems to suggest that the use of direct cooling could save on the order of 20 % of energy spent in cooling or around 6 % of total energy in the Comnet data center (or a similar data center in a similar climate). Although this may not sound like much, it is still a potential of real savings and could justify an investment on the order of maybe one to three per cent of building costs.

One of the concerns with using direct cooling in data center facilities without proper humidity control equipment is the resulting humidity of the inside air. As direct cooling is generally used when it's cold outside, even a high relative humidity in the outside air translates to a significantly lower relative humidity in the warmer inside air. During the measurement period it was observed that the minimum relative humidity was slightly less than 10 % (at the same time, the outdoor relative humidity was 88 % and the outdoor temperature was almost 38 °C colder than the indoor temperature). Although 10 % relative humidity is drier than most recommendations, it does not seem to have caused any problems in this data center.

6 Conclusions

Energy costs are a sizable chunk of a data center's total lifetime costs, and it is thus in the interests of a data center operator to reduce these costs. Measuring the energy consumption as well as having a useful metric to compare data centers' performances over time are of utmost importance. Many metrics call for a long-term average measurement of energy consumption, but although the systems to collect the data do in most cases exist, a data center's configuration may not stay stable enough for a long time, thus requiring short-term averages to be used.

Selecting metrics for both self-comparisons over time and for comparison to other data centers is not a trivial task. The industry standard for comparison of data centers seems to be PUE, Power Usage Effectiveness, although misuse of it is common. Perhaps the ultimate metric would be energy consumption per hour of entertainment produced – "entertainment", here, meaning both actual entertainment and work – but this requires many assumptions to be made.

There are a lot of ways to save energy, ranging from easy and cheap to difficult and expensive. Some of the energy saving aspects are easy to implement if they are taken into account already in the planning stages but potentially costly to implement later – such as the hot-and-cool-aisles arrangement. Depending on the availability requirements, redundant power systems may be necessary, making saving energy more complicated.

Low energy consumption is also environmentally friendly, although this is more of a nice bonus than a driving force. This might change in the future, as more and more consumers demand environmentally responsible behavior of companies. As energy produced on-site is not usually counted as energy consumed, building solar or wind farms in conjunction with a data center, these environmentally friendly options also make a data center good in the light of numbers like PUE.

Reusing energy, while not saving it, is also an environmentally friendly option, as well as an economically good option. Energy reuse usually requires some special circumstances either around the data center – such as a sports center to be heated – or in the data center itself – such as servers that are cooled with hot water that is then used in district heating. Energy reuse does not, strictly speaking, affect the PUE of a data center, but a similar number, ERE, Energy Reuse Effectiveness.

It seems to be possible to recognize the use of direct cooling from the temperature and cooling power data afterwards, but this result needs to be verified by carefully recording when and how direct cooling is used. Using direct cooling does save money, but the savings vary with data center configurations. Getting exact data on the effects of direct cooling would require operating a data center both with and without direct cooling for a period of time, with the exact same configuration, workload, and weather conditions. Conceivably, this could be done by dividing one data center into two identical halves, one with direct cooling in the appropriate conditions and one without, with load balancing making sure the workloads stay identical.

Further research could be done on how well the results from the Comnet data center are generalizable among similar data centers in similar climates, as well as what are the effects of the climate and data center configuration. Automating data collection from the energy analyzers would give the possibility to directly compare energy consumption with other variables. Monitoring the usage of services – if at all possible – might give insight as to how much time people spend using the services, thus shedding light on the hours of entertainment produced.

References

[1] IBM Global Technology Services. *Extending the life of your existing data centers.* URL: `https://www-935.ibm.com/services/nl/cio/pdf/extending_the_life_of_your_existing_data_centers.pdf` (visited on 11/12/2014).

[2] Ed Sperling. *Next-Generation Data Centers.* URL: `http://www.forbes.com/2010/03/12/cloud-computing-ibm-technology-cio-network-data-centers.html` (visited on 11/13/2014).

[3] Uptime Institute, LLC. *Data Center Site Infrastructure Tier Standard: Topology.* URL: `http://uptimeinstitute.org/index.php?option=com_docman&task=doc_download&gid=82` (visited on 11/11/2014).

[4] Päivi Hanna Maria Aaltonen and Pertti Aaltonen. *Reusing old infrastructure to host datacenters: Eco-innovation as an exaptation process.* URL: `http://druid8.sit.aau.dk/acc_papers/sdkni07008042i1ecadcjv2g07nc.pdf` (visited on 09/29/2015).

[5] LLC Website Optimization. *Average Web Page Breaks 1600K.* URL: `http://www.websiteoptimization.com/speed/tweak/average-web-page/` (visited on 11/18/2015).

[6] John C. McCallum. *Disk Drive Prices (1955-2015).* URL: `http://www.jcmit.com/diskprice.htm` (visited on 11/19/2015).

[7] Thomas Fuller. *Thailand Flooding Cripples Hard-Drive Suppliers.* URL: `http://www.nytimes.com/2011/11/07/business/global/07iht-floods07.html` (visited on 02/04/2016).

[8] Eurostat. *Information society statistics - households and individuals.* URL: `http://ec.europa.eu/eurostat/statistics-explained/index.php/Information_society_statistics_-_households_and_individuals` (visited on 02/02/2016).

[9] Eurostat. *Population and population change statistics.* URL: `http://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics` (visited on 02/02/2016).

[10] Statista. *Smartphone user penetration as percentage of total population in Western Europe from 2011 to 2018.* URL: `http://www.statista.com/statistics/203722/smartphone-penetration-per-capita-in-western-europe-since-2000/` (visited on 02/02/2016).

[11] Steve Greenberg et al. “Best practices for data centers: Lessons learned from benchmarking 22 data centers”. In: *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings in Asilomar, CA.* vol. 3 (2006), pp. 76–87.

[12] Otto VanGeet, W Lintner, and B Tschudi. *FEMP best practices guide for energy-efficient data center design.* 2011. URL: `http://www.ccrasa.com/library_1/29010%20-%20Best%20Practices%20Guide%20for%20Energy-Efficient%20Data%20Center%20Design.pdf` (visited on 06/05/2015).

[13] Xiaobo Fan, Wolf-Dietrich Weber, and Luiz Andre Barroso. "Power Provisioning for a Warehouse-sized Computer". In: *SIGARCH Comput. Archit. News* 35.2 (June 2007), pp. 13–23. ISSN: 0163-5964. DOI: `10.1145/1273440.1250665`. URL: `http://doi.acm.org/10.1145/1273440.1250665`.

[14] Khosrow Ebrahimi, Gerard F. Jones, and Amy S. Fleischer. "A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities". In: *Renewable and Sustainable Energy Reviews* 31.0 (2014), pp. 622 –638. ISSN: 1364-0321. DOI: `http://dx.doi.org/10.1016/j.rser.2013.12.007`. URL: `http://www.sciencedirect.com/science/article/pii/S1364032113008216`.

[15] Jonathan G. Koomey. *Estimating Total Power Consumption by Servers in the U.S. and the World.* URL: `http://hightech.lbl.gov/documents/DATA_CENTERS/svrpwrusecompletefinal.pdf` (visited on 11/05/2014).

[16] Steven Pelley et al. "Understanding and abstracting total data center power". In: *Workshop on Energy-Efficient Design.* System Energy Efficiency Lab, UCSD, 2009.

[17] Yasunobu Suzuki et al. "Experimental studies on active and passive PFC circuits". In: *INTELEC 97., 19th International Telecommunications Energy Conference.* IEEE. 1997, pp. 571–578. DOI: `10.1109/INTLEC.1997.646051`.

[18] Prajesh Bhattacharya. "Data Center Monitoring". In: *Energy Efficient Thermal Management of Data Centers.* Springer, 2012, pp. 199–236.

[19] Roger R Schmidt, EE Cruz, and Madhusudan K Iyengar. "Challenges of data center thermal management". In: *IBM Journal of Research and Development* 49.4.5 (2005), pp. 709–723.

[20] Don Atwood and John G. Miner. *Reducing Data Center Cost with an Air Economizer.* URL: `http://www.intel.com/content/www/us/en/data-center-efficiency/data-center-efficiency-xeon-reducing-data-center-cost-with-air-economizer-brief.html` (visited on 06/15/2015).

[21] Michael K. Patterson. "Energy Efficiency Metrics". In: *Energy Efficient Thermal Management of Data Centers.* Springer, 2012, pp. 237–271.

[22] Timo Kontturi. "Working for a sustainable world". University lecture. URL: `https://noppa.aalto.fi/noppa/kurssi/elec-a7900/luennot/ELEC-A7900_slides.pdf`.

[23] Jeff Clark. *Humidity in the Data Center: Do We Still Need to Sweat It?* URL: `http://www.datacenterjournal.com/humidity-in-the-data-center-do-we-still-need-to-sweat-it/` (visited on 11/03/2015).

[24] Jie Liu et al. "Challenges towards elastic power management in internet data centers". In: *Distributed Computing Systems Workshops, 2009. ICDCS Workshops' 09. 29th IEEE International Conference on.* IEEE. 2009, pp. 65–72.

[25] Markus Peuhkuri et al. *Datacenters – Energy Hogs or Helping to Optimize Energy Consumption.* URL: `http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6642387` (visited on 08/22/2014).

[26] Liam Newcombe. *Data centre energy efficiency metrics: Existing and proposed metrics to provide effective understanding and reporting of data centre energy.* URL: `http://www.bcs.org/upload/pdf/data-centre-energy.pdf` (visited on 10/14/2014).

[27] Albert Greenberg et al. "The Cost of a Cloud: Research Problems in Data Center Networks". In: *SIGCOMM Comput. Commun. Rev.* 39.1 (Dec. 2008), pp. 68–73. ISSN: 0146-4833. DOI: `10.1145/1496091.1496103`. URL: `http://doi.acm.org/10.1145/1496091.1496103`.

[28] Neil Rasmussen. *Electrical Efficiency Measurement for Data Centers.* URL: `http://www.apcmedia.com/salestools/nran-72754v/nran-72754v_r2_en.pdf` (visited on 10/20/2014).

[29] Grant Sauls. *Measurement of data centre power consumption.* URL: `https://learningnetwork.cisco.com/servlet/JiveServlet/previewBody/3736-102-1-10478/measurement%20of%20data%20centre%20power%20consumption.pdf` (visited on 10/21/2014).

[30] George Spafford. *Greening the Data Center: A Pocket Guide.* IT Governance, 2009.

[31] Google. *Efficiency: How we do it.* URL: `http://www.google.com/about/datacenters/efficiency/internal/` (visited on 10/21/2014).

[32] Rejeki Simanjorang et al. "High-efficiency high-power dc-dc converter for energy and space saving of power-supply system in a data center". In: *Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE.* IEEE, Mar. 2011, pp. 600–605. DOI: `10.1109/APEC.2011.5744657`.

[33] Dzmitry Kliazovich et al. "Energy consumption optimization in cloud data centers". In: *Cloud Services, Networking and Management.* Ed. by Nelson L. S. da Fonseca and Raouf Boutaba. Wiley, 2015.

[34] Dan Azevedo et al. *Data Center Efficiency Metrics.* URL: `http://www.thegreengrid.org/~/media/TechForumPresentations2011/Data_Center_Efficiency_Metrics_2011.pdf` (visited on 03/10/2015).

[35] Ashish Gupta and Jeff Shute. *High-Availability at Massive Scale: Building Google's Data Infrastructure for Ads.* URL: `https://static.googleusercontent.com/media/research.google.com/en//pubs/archive/44686.pdf` (visited on 03/01/2016).

[36] Daniel Gmach et al. "Workload analysis and demand prediction of enterprise data center applications". In: *Workload Characterization, 2007. IISWC 2007. IEEE 10th International Symposium on.* IEEE. 2007, pp. 171–180.

[37] Neil Hunt. *Netflix Streaming - More Energy Efficient than Breathing.* URL: `http://techblog.netflix.com/2015/05/netflix-streaming-more-energy-efficient.html` (visited on 11/24/2015).

[38] Christian Belady et al. *Carbon usage effectiveness (CUE): a Green Grid data center sustainability metric.* Tech. rep. The Green Grid, 2010.

[39] Michael Patterson et al. *Water usage effectiveness (WUE): a Green Grid data center sustainability metric.* Tech. rep. The Green Grid, 2011.

[40] Severin Zimmermann et al. "Aquasar: A hot water cooled data center with direct energy reuse". In: *Energy* 43.1 (2012), pp. 237–245.

[41] Severin Zimmermann et al. "Hot water cooled electronics: Exergy analysis and waste heat reuse feasibility". In: *International Journal of Heat and Mass Transfer* 55.23 (2012), pp. 6391–6399.

[42] Energiateollisuus ry. *Kaukolämmitys.* URL: `http://energia.fi/koti-ja-lammitys/kaukolammitys` (visited on 06/05/2015).

[43] Tuomo Malkamäki and Seppo J Ovaska. "Data centers and energy balance in Finland". In: *International Green Computing Conference (IGCC)*. IEEE. 2012, pp. 1–6.

[44] Jukka Sinervä. *Datakeskuksen hukkalämpö lämmittää jopa koko Mäntsälän.* URL: `http://yle.fi/uutiset/datakeskuksen_hukkalampo_lammittaa_jopa_koko_mantsalan/7550739` (visited on 06/05/2015).

[45] Susanna Huuskonen. *Nyt kodit lämpiävät myös nettivideoilla.* URL: `http://www.fortum.com/countries/fi/yksityisasiakkaat/kaukolampo/tutustu-kaukolampoon/tulevaisuuden-lampo/palvelinkeskus/pages/default.aspx` (visited on 06/05/2015).

[46] Eric Smalley. *2011: The Year Data Centers Turned Green.* URL: `http://www.wired.com/2011/12/green-data-centers-of-2011/` (visited on 11/12/2015).

[47] Justin Vela. *Helsinki data centre to heat homes.* URL: `http://www.theguardian.com/environment/2010/jul/20/helsinki-data-centre-heat-homes` (visited on 06/05/2015).

[48] Ilkka Maaskola and Matti Kataikko. *Ylijäämälämmön taloudellinen hyödyntäminen. Lämpöpumppu- ja ORC-sovellukset.* URL: `http://www.motiva.fi/files/10217/Ylijaamalammon_taloudellinen_hyodyntaminen_Lampopumppu-_ja_ORC-sovellukset.pdf` (visited on 11/09/2015).

[49] Riku Lääkkölä. "Data Center Degrowth - an Experimental Study; Palvelinkeskusten kasvun purku - kokeellinen tutkielma". MA thesis. 2015. URL: `http://urn.fi/URN:NBN:fi:aalto-201505272920`.

[50] Qiang Huang et al. "Power consumption of virtual machine live migration in clouds". In: *Third International Conference on Communications and Mobile Computing (CMC)*. IEEE. 2011, pp. 122–125.

[51] Roberto Morabito. “Power Consumption of Virtualization Technologies: an Empirical Investigation”. In: *2015 IEEE/ACM 8th International Conference on Utility and Cloud Computing (UCC)*. IEEE. 2015, pp. 522–527.

[52] Jan Thulin and Andris Andrushaitis. “The Baltic Sea: its past, present and future”. In: *the proceedings of the Religion, Science & the Environment Symposium V on the Baltic Sea.* 2003.

[53] Hannu Grönvall. “Finnish Operational Oceanographical Service”. In: *Operational Oceanography. The Challenges for European Co-operation.* Ed. by J. H. Stel. Elsevier, 1997.

[54] Google. *Google Data Centers: Hamina, Finland.* URL: `http://www.google.com/about/datacenters/inside/locations/hamina/index.html` (visited on 10/09/2015).

[55] CSC. *One of the world’s most energy efficient datacenters in Kajaani has been extended.* URL: `https://www.csc.fi/-/maailman-ekotehokkaimpiin-kuuluva-konesali-kajaanissa-laajennettu` (visited on 10/09/2015).

[56] NDBS News. *Centralised server room in Kajaani to serve all Finnish HEIs.* URL: `http://www.ndbsevents.com/centralised-server-room-in-kajaani-to-serve-all-finnish-heis/` (visited on 10/13/2015).

[57] Krish Bandaru and Kestutis Patiejunas. *Under the hood: Facebook’s cold storage system.* URL: `https://code.facebook.com/posts/1433093613662262/-under-the-hood-facebook-s-cold-storage-system-/` (visited on 07/10/2015).

[58] Justin Moore et al. “Data center workload monitoring, analysis, and emulation”. In: *Eighth Workshop on Computer Architecture Evaluation using Commercial Workloads.* 2005.

[59] Jonathan Koomey. *Growth in data center electricity use 2005 to 2010.* URL: `http://www.analyticspress.com/datacenters.html` (visited on 09/11/2015).

[60] John L. Hennessy and David A. Patterson. *Computer architecture: a quantitative approach.* Elsevier, 2011.

A Power Usage Effectiveness Calculations

Let's assume a data center of 1 000 typical servers in the year 2000. Each server consumes 424 Watts of energy [15]. Power consumption distribution is assumed to be that of a typical data center [16]. The wattages for other categories are extrapolated from the server consumption and distribution percentages in Table A1.

Table A1: Distribution of energy consumption in 2000.

Category	**% of total power**	**W**
IT equipment	56	424 000
Network equipment	5	37 857
ICT total	**61**	**461 857**
Cooling	30	227 143
Power Supply	8	60 571
Security	1	7 571
Aux total	**39**	**295 285**
Total	**100**	**757 143**

A.1 Upgrade Using the Same Number of Servers

Now let's upgrade the data center twice, in 2005 and 2010. Both times, we will upgrade all 1 000 servers with 1 000 typical new servers. Total IT energy consumption of the data center is calculated in Table A2, taking into account the energy consumption of a typical server each year [15, 59].

Table A2: IT energy consumption 2000–2010. W_s is power consumption per server in watts, and W_t is the total energy consumption of 1 000 servers in watts.

Year	W_s	W_t
2000	424	424 000
2005	625	625 000
2010	895	895 000

If nothing is done to the other systems in the data center, auxiliary systems' energy consumption is going to be mostly constant. 30 % of the cooling energy consumption is assumed to be linearly dependent on the total IT energy consumption, as well as 100 % of the PSU energy consumption. The energy consumptions for network equipment and physical security are presumed to be totally constant.

The energy consumption of the UPSs for the years 2005 and 2010 are calculated with the equations

$$W_{PSU}(2005) = \frac{W_{IT}(2005)}{W_{IT}(2000)} * W_{PSU}(2000) \tag{A1}$$

and

$$\begin{aligned} W_{PSU}(2010) &= \frac{W_{IT}(2010)}{W_{IT}(2005)} * W_{PSU}(2005) \\ &= \frac{W_{IT}(2010)}{W_{IT}(2005)} * \frac{W_{IT}(2005)}{W_{IT}(2000)} * W_{PSU}(2000) \\ &= \frac{W_{IT}(2010)}{W_{IT}(2000)} * W_{PSU}(2000). \end{aligned} \tag{A2}$$

Similarly, the cooling energy consumptions for the years 2005 and 2010 are calculated with the equations

$$W_{Cool}(2005) = 0.7 * W_{Cool}(2000) + 0.3 * \frac{W_{IT}(2005)}{W_{IT}(2000)} * W_{Cool}(2000) \tag{A3}$$

and

$$W_{Cool}(2005) = 0.7 * W_{Cool}(2000) + 0.3 * \frac{W_{IT}(2010)}{W_{IT}(2000)} * W_{Cool}(2000). \tag{A4}$$

The data center's energy consumption numbers by category for the years 2005 and 2010 are presented in Table A3.

Table A3: Distribution of energy consumption in 2005 and 2010.

Category	**W (2005)**	**W (2010)**
IT equipment	625 000	895 000
Network equipment	37 857	37 857
ICT total	**662 857**	**932 857**
Cooling	259 446	302 839
Power Supply	89 286	127 857
Security	7 571	7 571
Aux total	**356 304**	**438 268**
Total	**1 019 161**	**1 371 125**

As the IT energy consumption goes up, so does the auxiliary systems' energy consumption, but not as quickly. This leads to the PUE number going down. At the same time, the data centers' total computing power increases. The PUE numbers for the years 2000–2010 are shown in Table A4.

Table A4: Power Usage Effectiveness numbers in 2000–2010.

Year	PUE
2000	1.639
2005	1.538
2010	1.470

A.2 Upgrade Preserving Computing Power

Let's try a different kind of upgrade. We'll again update the data center twice, in 2005 and 2010. This time, we will use the minimum (integer) number of servers that can achieve the same total computing power as the previous setup (i.e. the total computing power in 2010 is equal to or greater than the total computing power in 2005, not 2000). The comparison of computing power is done using SPECint benchmark scores [60]. The benchmark scores for a typical computer as well as the number of servers used and their energy consumption are shown in Table A5.

Strictly speaking, the energy consumption numbers and benchmark scores are not necessarily for the same computer. In this example, however, it doesn't really matter since the calculations are dependent on how the numbers change, not so much on the numbers themselves. The rate of change is very likely to be similar across the industry.

Table A5: Typical computing power, server number, and IT energy consumption 2000–2010. n is the number of computers used, W is the total energy consumption of n servers.

Year	score	n	W
2000	1 779	1 000	424 000
2005	6 505	276	172 500
2010	24 129	78	69 810

Similarly to Chapter A.1, auxiliary systems' energy consumption is going to be mostly constant. The variable energy consumptions for the PSUs and cooling equipment for the years 2005 and 2010 are again calculated with Equations A1, A2, A3, and A4. The data center's energy consumption numbers by category for the years 2005 and 2010 are presented in Table A6.

As the IT energy consumption goes down, so does the auxiliary systems' energy consumption, but again not as quickly. This leads to a worsening PUE number. The PUE numbers for the years 2000–2010 are shown in Table A7.

Although the data center is capable of doing the same job with a dramatically (over sixty percent) dropping total energy consumption, the PUE number for it becomes progressively worse. The reason is that even though the auxiliary systems' power

Table A6: Distribution of energy consumption in 2005 and 2010.

Category	**W (2005)**	**W (2010)**
IT equipment	172 000	69 810
Network equipment	37 857	37 857
ICT total	**210 357**	**107 667**
Cooling	186 723	170 219
Power Supply	24 643	9 973
Security	7 571	7 571
Aux total	**218 938**	**187 764**
Total	**429 295**	**295 430**

Table A7: Power Usage Effectiveness numbers in 2000–2010.

Year	**PUE**
2000	1.639
2005	2.041
2010	2.322

consumption drops quite a lot as well, their share of the total energy consumption rises.