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Effectiveness  
and Its Use as Data Center  
Energy Sustainability Metrics

By

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# **A critical analysis of Power Usage Effectiveness and its use as data center energy sustainability metric**

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## **Abstract**

*Data centers represent an increasingly popular construction project type, supported by the continued growth in internet-based services. These facilities can, however, consume large amounts of electricity and—especially if growth trends continue—put strain on utility grids and energy resources. Many metrics have been proposed to evaluate and communicate energy use in data centers. In many cases, the goal is that these metrics will be used to develop energy conscious behavior and perhaps data center sustainability ratings or building codes to reduce average energy use. In this paper, we examine one of the more popular metrics, Power Usage Effectiveness (PUE), and discuss its shortcomings toward effectively communicating energy sustainability. Our inference is that PUE is an instantaneous representation of electrical energy consumption that encourages operators to report the minimum observed values of PUE. Hence, PUE only conveys an understanding of the minimum possible energy use. Instead we propose the use of energy-based metrics or average PUE over a significant time period—e.g., a year—to better understand the energy efficiency of a data center and to develop sustainability rating/ranking systems and energy codes.*

**Keywords**-Data centers; energy efficiency metrics; sustainability standards; Power Usage Effectiveness

## **1. Introduction**

Human influences on global climatic change (Karl, 2003) and threat of fossil fuel depletion (Shafiee, 2009) have increased sociological movements toward adopting more energy-efficient and ecologically-friendly lifestyles during the past three decades. With regard to the built environment, the building energy codes in many

countries have evolved to reduce energy usage in new construction projects (Geller, 2006). In addition, a number of voluntary building rating systems and construction guidelines continue to be developed that aggressively push environmentalism (e.g., Leadership in Energy and Environmental Design or “LEED” rating systems).

Coinciding with the ramping movements in sustainable building design is the rapid growth of data center construction. Data centers can be very power-hungry—a matter that is discussed later in this paper. Although data centers are treated as building projects in most jurisdictions, most of the power-consuming elements of the facilities are not (and are difficult to) curb using conventional building energy codes. Furthermore, the utility-value seen through adopting voluntary rating systems in other building projects may not translate well for data centers.

Many metrics have been proposed to evaluate and communicate energy efficiency in data centers. In many cases, the hope is that these metrics can be used to develop behavior, sustainability ratings, and/or building codes to reduce average data center energy use. In this paper, we discuss some of these metrics, focusing on one of the more popular metrics, i.e., Power Usage Effectiveness (PUE). We illustrate a few of the issues involved with using PUE to communicate energy usage and what can be done to address some of these issues. Before continuing our examination into data centers, PUE, and related metrics, we first present some of the building codes and other systems that promote energy reduction and sustainability in the built environment. This discussion should develop an understanding of the effectiveness and concepts behind these building energy codes and systems in order to support analyses presented later in this paper.

## **2. Building energy codes and sustainability rating systems**

Building energy codes typically allocate maximum power allowances to certain energy consuming building subsystems—such as lighting and heating/cooling—thereby providing guidelines for the associated engineering efforts in a construction project. These power allowances convey the maximum potential energy

consumptions of the associated building subsystem and provide a general idea of the actual energy consumption, when factoring in utilization rates. Building energy codes help limit electricity use in new construction to an amount found suitable by the relevant governmental jurisdiction(s), since meeting or surpassing building codes is mandatory to complete the construction initiative. Building-plan-checkers review engineering designs and analyses against the corresponding building energy codes in order to determine if the construction project is fit for realization.

To develop an understanding of building energy code provisions we can look at their development and application in the U.S. construction industry. Two primary baseline energy standards govern building construction in the U.S. (U.S. DOE, 2010): (1) The International Energy Conservation Code (IECC), and (2) the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1 (ASHRAE, 2010). These standards are adopted and—in some cases—expanded upon by states and local ordinances to create building energy codes. Perhaps one of the most notable building energy codes in the U.S. is the California Energy Code or “Title 24,” which since its first release in 1974, has aggressively pushed energy reduction in lighting and mechanical subsystems beyond IECC and ASHRAE prescriptions in its tri-annual updates. Like ASHRAE, Title24 allocates maximum power allowances to building types or spaces based on the type of use and expected occupancy. For example, office building lighting power densities have to be less than  $0.85 \text{ W/ft}^2$  as per the 2010 version of Title 24 (CBSC, 2010); this translates to a maximum potential lighting energy consumption of approximately  $26.8 \text{ MJ/ft}^2/\text{year}$  or  $7.45 \text{ kWh/ft}^2/\text{year}$  assuming that lights are never switched off.

Although building codes have been effective channels for building energy reduction, they can be ineffective at developing energy conscious behavior. Often such codes are treated as an exhaustive set of technical requirements (Gann, 1998), therefore limiting innovational thinking toward further reducing energy consumption and other considerations. The codes can take many years to be updated and, as a result, often become regulations late in the lifecycle of energy reducing technologies. Also, building energy codes often do not cover all of the

energy consuming elements of a building, e.g., no power allowances are placed on plug-loads in the dominant building energy codes in the U.S. Voluntary rating systems such as LEED and 'EnergyStar' attempt to address the voids and limitations in building energy codes. Most of these rating systems allocate "points" to the extent of reduction beyond the governing energy standards and use these points to compare buildings or communicate energy efficiencies to investors or end-users of a building project. Essentially, these systems attempt to use societal demand for more sustainable buildings to create a utility for points, rankings, or certifications in the promise of increased building occupancy or occupant happiness. Unfortunately, although this can work well for typical commercial (and maybe residential) buildings, this may not work as well to curb energy use in data centers since the primary purpose of these facilities is not to house humans.

### **3. Data centers**

Data centers can be defined as any space whose main function is to house servers (Bailey, 2007; Koomey, 2008) or computing devices that are in-use, i.e., are powered on and performing functions. Although a small computing room within a multipurpose building can be considered as a data center, the term is conventionally used to describe buildings whose sole purpose is to house these servers. In this conventional sense, human occupancy is limited to small Information Technology (IT) support groups who may have office space within the building—these office spaces are small relative to the total size of the building. These facilities differ greatly from most buildings from a construction perspective. For example, mechanical and electrical systems account for 70% of construction costs in data centers, in contrast to only 15% of costs in commercial buildings (Turner, 2008).

Today's data centers are mainly used for internet or network-based activities. They contain servers that store and process electronic data, communicate with other computer networks, and/or manage user interactions with server-based software tools and web portals. Quite often, data centers are used to manage data and operations that are considered to be sensitive or important, such as email

correspondences and company/government databases. As a result, reliability—i.e., its ability for the servers to be functioning properly and not lose data—is a critical concern for many data centers. This reliability is strongly linked not only to the characteristics of the servers used but also to that of the data center data center “infrastructure”, which includes the power distribution and mechanical—i.e., Heating Ventilation and Air Conditioning (HVAC)--systems. That is, the servers need a constant supply of electricity and are less susceptible to hardware breakdown when operating below a certain temperature. (It is important to note that the servers can generate substantial amount of heat and, as a result, data centers often have large cooling loads (ASHRAE, 2005)). Therefore, in addition to having redundant computing setups, most facilities use redundant power distribution networks, Uninterruptable Power Supply (UPS) and Automatic Transfer Switch (ATS) devices, and specialized mechanical cooling systems in order to minimize the probability of server failures. The extent of redundancy in the power distribution network and mechanical systems are often used to rank and compare the reliability of data centers. This is referred to as the data center ‘Tier level’ (Nixcraft, 2008) where higher Tier levels represent greater redundancy.

Achieving reliability through power/cooling redundancy and the use of UPS and ATS devices increase the electrical energy used by a data center. In contrast, other buildings typically do not need such redundancies and devices. In addition, data center operators often try to optimize floor space usage by maximizing the number of servers that they can fit in the facility. Therefore, data centers tend to have high power densities, sometimes greater than 100 W/ft<sup>2</sup> (Rasmussen, 2008), in comparison to the 7-10 W/ft<sup>2</sup> seen in typical office buildings (Mitchell-Jackson, 2001). As a result, although there are far fewer data centers than other buildings and energy loads, data centers accounted for approximately 1.1% to 1.5% of global electricity usage in 2010 (Koomey, 2011).

As the use of internet-based services grows, data center construction has increased. During the period 2000 to 2010, the annual construction of data centers (in terms of money spent) increased over 300%, from approximately \$15 billion

USD to \$50 billion USD (Belady, 2011). Some of this increased spending is attributable to more data centers being built per year, while others is attributable to increased redundancy in the newer data centers. That is, a ‘Tier 4’ data center can cost \$22 million USD/MW in comparison to \$10 million USD/MW for a ‘Tier 1’ facility (Belady, 2011). With focus and spending placed on ensuring reliability, matters related to energy consumption and efficiency are often secondary or tertiary considerations in construction and operation. Data center energy use grew by 16.7% per year globally between 2000 and 2005 (Koomey, 2008) and 56% over the five years 2005 to 2010 (Koomey, 2011), or 11.6% per year. Over this entire ten-year period, the project size and power densities of data centers have increased. Therefore the slight difference in the rate at which energy use increase between 2000-2005 and 2005-2010 is likely a result of the use of more energy efficient components or building systems as developers push for greater energy efficiencies.

### ***3.1 Energy efficiency and sustainability in data centers***

As stated, data centers can consume large amounts of electricity, strain utility grids, and accrue significant electrical bills to facility operators. With increasing societal movements toward energy sustainability, poor economic climates, etc., there has been a push in the data center industry to better evaluate and communicate the energy usage with the general hope of increasing energy efficiencies. Many researchers and industrialists have discussed methods to benchmark and optimize data center designs for energy considerations (e.g., Greenberg, 2006). And research organizations, such as the 7x24 Exchange, The Uptime Institute, and Data Center Dynamics have been formed that focus on data centers. These organizations track and report data center energy use, hold conferences and release publications that address data center energy considerations. In addition, some organizations have also proposed adjusted sustainability rating systems—such as LEED—that focus explicitly on data centers (e.g., LBNL, 2008).

Many metrics have been introduced to develop an understanding and comparison of energy use and efficiency in data centers. Two popular metrics are:



- IT productivity Per Embedded Watt (IT-PEW), which captures the power efficiency of the servers and is a metric that operators should want to maximize (Brill, 2007); and
- PUE, which is analogous to Data Center infrastructure Efficiency (DCiE) (Verdun, 2008) and Site Infrastructure Energy Efficiency (SI-EER) (Kooimey, 2007); all three of which attempt to quantify the power efficiency of the infrastructure systems and are metrics operators should want to minimize.

PUE is considerably the most popular metric used in sustainability discussions. Operators often brag about their PUE when making statements regarding the energy efficiency of their data centers. Organizations such as the Uptime Institute track and report the average PUE of data centers using surveys. PUE has also been proposed as a method to rate and rank data center sustainability (Microsoft Corporation, 2011). However, as we convey in the next section, PUE can be problematic when trying to understand the complete energy profile of a data center.

#### **4. Power Usage Effectiveness (PUE)**

PUE is a representation of the ratio between the total power consumed by a data center  $P_t$  and the power used by the computer servers  $P_s$  (Rasmussen, 2005), i.e.,

$$PUE = \frac{P_t}{P_s}. \quad (1)$$

The non-computing—i.e. infrastructure—systems in a data center account for the difference between  $P_t$  and  $P_s$ . This includes the power consumed by HVAC systems and power losses due to the electrical resistance of current carrying conductors, and the inefficiency of components in the electrical distribution system, which typically includes transformers, switchboards, and Power Distribution Units (PDU) in addition to ATS and UPS devices. Figure 1 conveys an example power flow diagram for a data center to better convey power transformations and sources for losses and inefficiencies. A PUE of 1 means that the power consumed by the servers account for all of the power delivered to a data center. Since the purpose of a data center is to

house these servers, a PUE of 1 is taken to represent a 100% efficient data center from a power usage perspective. Also, it is impossible to have a PUE less than 1.

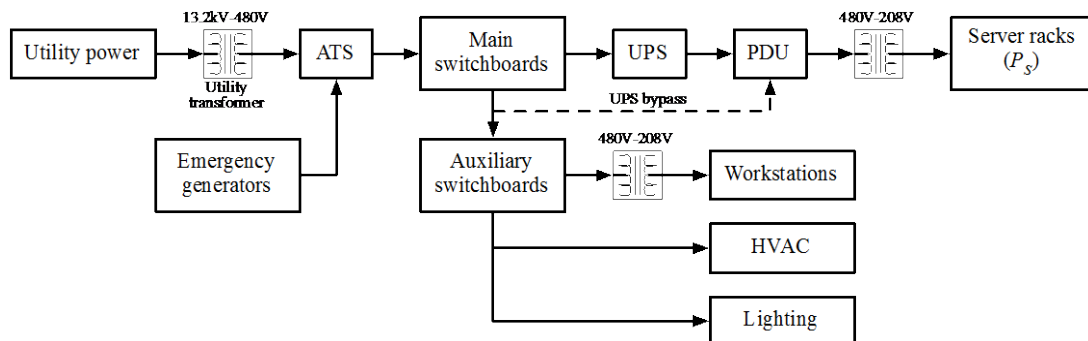


Figure 1. An example power flow diagram for a data center

Data from Uptime Institute surveys suggests that average PUE of today's data centers is between 1.8 and 1.89. This is further supported by data center power consumption breakdown studies (e.g., Pelley, 2009), which indicate that approximately 56% of total data center power is consumed by servers, 30% by cooling systems, 13% by power networks and conditioning devices, and 1% for lighting, resulting in a PUE of 1.79. Many things can be done to improve PUE in the construction phase of a project, such as use more energy efficient infrastructure systems. However, what happens when/if the lights are turned off during operation or if lighting loads are not considered in the PUE calculation? In this case, the difference is subtle and the new "PUE" is 1.77; however, an inconsistency such as this is one of the issues with current PUE determinations and reporting.

#### 4.1 Issues with PUE determinations

There are several issues or challenges associated with PUE determinations and using the metric and a means of comparing data center facilities. One of the more fundamental problems is inconsistency when determining what infrastructure components constitutes  $P_t$ . Some consider  $P_t$  to represent the "useful" power entering a data center that specifically supports the continued operation of the computer servers (Rasmussen, 2005). Based on this perspective, systems such as lighting, security, or even certain mechanical devices—that are not always needed to cool server spaces—may not be considered as constituents of  $P_t$ , hence resulting in

better PUE values. There may also be some confusion as to how to treat power that is generated on site (The Green Grid, 2011). A closely related issue is identifying a node in the power flow diagram to define  $P_t$ . For example, given the power flow diagram shown in Figure 1, if  $P_t$  was defined as being at the input of the utility transformer then the PUE of the data center would be worse than if it were defined at the output of that transformer, or at the output of the ATS or main switchboard. Complications with identifying a  $P_t$  node may be further exacerbated for data centers in multipurpose buildings where the power path to the servers is shared with other building systems. Several recommendations have been proposed to streamline the factors should be considered in PUE determinations (e.g., The Green Grid, 2011). In addition, “Partial PUE” (pPUE) metrics have been proposed to help address the problem by defining spatial and electrical zones in the data center (e.g., the server floor zone) and determining a pPUE for each zone (Azevedo, 2011). Unfortunately, although pPUE may work for rooms in a multipurpose building, the sum of the pPUE for each zone may not represent the overall PUE of the facility.

PUE estimates made during the engineering phase of a data center construction project can be severely inaccurate unless detailed considerations are made. Engineers often use the full-load nameplate ratings of infrastructure components to determine their inefficiencies and resultant power losses in their designs (Rasmussen, 2005). However, power system and HVAC devices are typically designed for worst-case conditions—as to conform to most building codes—and, therefore, are often over-sized and under-loaded during operation. When under-loaded, the efficiencies of these devices tend to decrease below their full-load nameplate ratings. As a result, full-load engineering estimates likely exaggerate the efficiency of the data center and results in higher PUE values than achievable in the actual system. To address this, engineers may need to acquire manufacturing specifications that relate operating load to efficiency and develop precise loading estimates for these for all critical devices. Further complicating matters is that the heat produced by infrastructure components, e.g., heat emitted from wiring in cooled spaces, have to be modeled and accounted for when estimating HVAC

operation conditions (Rasmussen, 2005). In addition it can be difficult to match engineering estimates with power readings acquired during operation. Power sensors can be very inaccurate when not operating near full-load conditions. Since many are likely to be over-sized, this can result in uncontrollable variances in power metering data and resulting PUE calculation.

There are several other issues associated with PUE. For instance, IT specialists may choose to implement virtualization during data center operation as a means off reducing total power consumption via decreased server utilization (Niles, 2008). Such activities, however, reduce  $P_s$  and therefore increases PUE, since the power used by the infrastructure components likely do not decrease proportionally with  $P_s$  (Longbottom, 2012). In addition, infrastructure devices may perform less efficiently because they are under-loaded further worsening PUE. Unless the metric is adjusted to include server utilization factors (Longbottom, 2012), situations like these make PUE less informative in sustainability discussions than simply communicating the total data center power use or power densities. These situations can also confuse system managers who base their energy related decisions on minimizing PUE. However, perhaps the most critical issue with PUE for the purpose of this sustainability discussion is that PUE is a power and not (directly) an energy metric. In addition, the behaviors associated with PUE reporting can dramatically misinform the energy efficiency of data centers.

#### ***4.2 Problem with using PUE as a sustainability driving metric***

By definition, power is the rate at which energy is used. A non-time averaged power value represents an instantaneous point in an energy profile and may not be completely communicative of overall energy use. Just the same, a PUE value represents the energy efficiency of a data center infrastructure at a specific point in time. The power characteristics of infrastructure systems are susceptible to changes in the environment, such as ambient temperature variation. As a result, the energy efficiency of a data center is function of temperature (Patterson, 2008) and, by association, is a function of time when considering weather or climatic changes

(Verdun, 2008). Hence, the PUE of a data center can vary based on time-of-day and time-of-year, especially in climates that have extreme daily or seasonal temperature variances. For example, imagine two identical data centers were built in the U.S., one in a relatively mild climate such as San Francisco and the other in Chicago, which has significantly colder winters and hotter summers. Figure 2 illustrates potential PUE values for these data centers over a one-year period. Supposing that the data centers attempt to take advantage of free-air cooling, the facility in Chicago has a PUE advantage during the winter through reduced HVAC loads. In addition, power system components are most times more efficient at lower temperatures, i.e., resistive power losses in wiring decreases, etc. However, in the summer the HVAC systems in the Chicago data center have to work harder to cool the facility because of higher outside air temperatures.

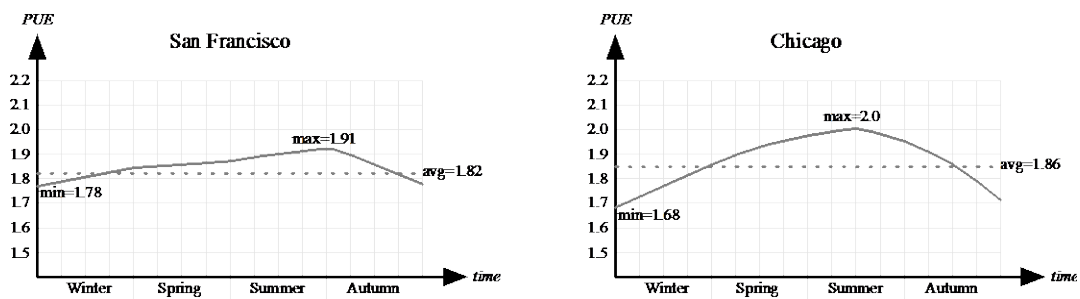


Figure 2. Hypothetical PUE for identical data centers in different geographical locations

The impact of location on building performance, energy efficiency, and—by association—PUE is well known. The issue lies in what typical PUE reports actually represent. Facility operators or engineers are likely to report the lowest PUE observed or estimated over a time period or facility lifecycle. In the case of the illustration given in Figure 2, this means that PUE values of 1.78 and 1.68 are likely to be reported for the respective data centers, suggesting that the Chicago data center is more “energy efficient”. However, such inferences are incorrect. Being that the Chicago data center has a higher average yearly PUE—1.86 in comparison to the 1.82 for the San Francisco facility—the Chicago facility consumes more energy per year than the San Francisco facility and therefore is less energy efficient.

## **5. Recommendations for rating systems and codes**

PUE is a convenient metric. It can neatly capture the power overheads of infrastructure systems in a data center, especially if strict rules are set as to what factors into PUE calculations and if server utilization rates are considered. From a communications perspective, it may be better to share the PUE obtained from metered data during operations than that derived from engineering estimates, unless detail equipment-load characterizations are performed in those analyses. This may mean, however, the use of more efficient power sensors or increased metering systems, both of which can increase construction costs.

Unfortunately, typical PUE reports communicate the minimum data center infrastructure power use and therefore can only be used to determine the minimum potential energy usage of the corresponding facility. From the perspective of energy sustainability, we believe that understanding maximum energy use is more important therefore making a power allowance approach to data center energy use more effective. That is, power allowances in building energy codes dictate and communicate the maximum potential energy used by the associated building subsystems. Unfortunately, the majority of power used by data centers is in the form of plug-loads or similar constructs, which are currently not limited to power allowances in building energy codes. Furthermore, enforcing such power allowances may be difficult since the power requirements of such loads can vary largely and it is difficult to predict for future equipment.

For PUE to be effective at capturing energy use or sustainability it has to be adjusted to communicate the influence of time. This can be done via enforcing that PUE reports have to represent time-averaged observed or estimated PUE for a significant time period, e.g., at least one year, to account for seasonal changes. This recommendation is similar to those made by other researchers and industrialists to adjust PUE communications to account for inefficiency peaks (e.g., Verdun, 2008). Continuous observation or engineering analysis for PUE over a significant time period may also help in identifying opportunities to improve energy usage.

To further avoid potential for confusion as to the difference between power and energy or to avoid discrepancy in sustainability reports, we propose an adjustment of PUE that is based on energy readings or estimates. This adjusted metric: “Energy Usage Effectiveness” (EUE) compares the total electrical energy consumed by the data center  $E_t$  with the energy consumed by the servers  $E_s$ , i.e.,

$$EUE = \frac{E_t}{E_s}. \quad (2)$$

$E_t$  and  $E_s$  can be determined from energy metering or estimations or from  $P_t$  and  $P_s$  and during the time of evaluation  $t_1$  to  $t_2$ , i.e.,

$$E_t = \int_{t_1}^{t_2} P_t, \quad (3)$$

$$E_s = \int_{t_1}^{t_2} P_s. \quad (4)$$

The efficiency ratios obtained using EUE should be similar to that obtained using time averaged PUE. Like averaged PUE, EUE should be determined over a significant time period, such as at least one year. However, the nomenclature illustrates that EUE is directly communicating energy efficiencies. Also, it may be possible to determine EUE directly for electrical bills (which conveys energy use in kWh), at least when determining  $E_t$  for single-purpose data center facilities.

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