PUE™: A COMPREHENSIVE EXAMINATION OF THE METRIC

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Executive Summary

Power usage effectiveness (PUE™) has become the industry-preferred metric for measuring infrastructure energy efficiency for data centers. The PUE metric is an end-user tool that helps boost energy efficiency in data center operations. It was developed by The Green Grid Association, a non-profit, open industry consortium of end users, policy makers, technology providers, facility architects, and utility companies working to improve the resource efficiency of information technology and data centers throughout the world. Since its original publication in 2007, PUE has been globally adopted by the industry. Over the past years, The Green Grid has continued to refine the metric measurement methodology with collaborative industry feedback. This collective work has been brought together here to simplify the absorption and use of the PUE metric. To produce this document, The Green Grid consolidated all its previously published material related to PUE and included new material as well. This document supersedes prior white papers and consolidates *all things* that The Green Grid has developed and published relating to PUE. As such, this document is recommended by The Green Grid to those implementing, using, and reporting PUE. Quick access to various levels of information is provided via the links embedded throughout the document. This document allows executives to gain a high level of understanding of the concepts surrounding PUE, while providing in-depth application knowledge and resources to those implementing and reporting data center metrics.

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I. Introduction

The Green Grid Association (TGG) works to improve the resource efficiency of information technology (IT) and data centers throughout the world. In 2007, The Green Grid published two “self-help” data center energy efficiency metrics for end users: power usage effectiveness (PUE™) and its inverse, data center infrastructure efficiency (DCiE™). Since the original publications, PUE has surpassed DCiE in industry adoption. In fact, PUE is currently viewed as the industry-preferred metric for measuring infrastructure energy efficiency in data centers.

In 2009, The Green Grid—in collaboration with organizations around the globe—began driving toward a set of metrics and indices that can be formally adopted by all participating organizations to improve worldwide data center energy efficiency. As a result, global agreement has been reached that affirms PUE as the industry’s preferred data center infrastructure efficiency metric. The following are the two task forces and supporting organizations[1] that have agreed on the PUE metric, measurement methodology, and reporting convention:

- Data Center Metrics Coordination Task Force (U.S. Regional Task Force)
  - 7x24 Exchange
  - The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE)
  - The Green Grid
  - Silicon Valley Leadership Group
  - Uptime Institute
  - U.S. Department of Energy Save Energy Now and Federal Energy Management Programs
  - U.S. Environmental Protection Agency’s ENERGY STAR Program
  - U.S. Green Building Council
- Global Harmonization of Data Center Efficiency Metrics Task Force (Global Task Force)
  - European Commission – Joint Research Centre Data Centers Code of Conduct
  - The Green Grid
  - Green IT Promotion Council, Japan
  - Ministry of Economy, Trade, and Industry, Japan

[1] For additional information on task force activities, see www.thegreengrid.org/Home/alliances/HarmonizationOfMetrics.aspx

- U.S. Department of Energy Save Energy Now and Federal Energy Management Programs
- U.S. Environmental Protection Agency's ENERGY STAR Program

PUE is an excellent metric for understanding how well a data center is delivering energy to its information technology equipment. The metric is best applied for looking at trends in an individual facility over time and measuring the effects of different design and operational decisions within a specific facility.

Therefore, comparing two data centers based on public reports of their PUE results was not initially recommended because many attributes of data center design, engineering, implementation, and operations affect PUE. However, since the original publications, the industry has globally adopted the PUE metric and begun to compare PUEs among data centers, raising further questions around how to interpret individual results, how to compare different results for the same data center, and how to compare results across different data centers. As there are various ways to calculate PUE, stakeholders in the industry have expressed concerns around the consistency and repeatability of publicly reported measurements. In response, The Green Grid has published a set of rules and guidelines regarding the process that organizations should follow when making public claims regarding their data centers' PUE measurements and has provided a free PUE reporting tool.[2] Section VI of this document outlines the PUE reporting requirements and also includes the definition of standard nomenclature that will enable individual claimants to communicate key information about their measurements.

Standardized PUE nomenclature, proper and transparent public reporting guidelines, and the availability of key information about reported results will enhance both the credibility and usefulness of the PUE metric. To further enable equitable comparison of PUE results among data centers, additional attributes, such as age, geographic location, capacity loading, size of facility, and the like, should be taken into consideration.

Provided the measurement guidelines, reporting guidelines, and the additional data attributes (as mentioned above) are obtained, The Green Grid believes PUE can be used to compare data center infrastructure efficiency.

[2] www.thegreengrid.org/register/pue-reporting-form.aspx

The PUE metric is associated with the data center infrastructure. PUE is not a data center productivity metric, nor is it a standalone, comprehensive efficiency metric. PUE measures the relationship between the total facility energy consumed and the IT equipment energy consumed. When viewed in the proper context, PUE provides strong guidance for and useful insight into the design of efficient power and cooling architectures, the deployment of equipment within those architectures, and the day-to-day operation of that equipment. Changes in PUE are most meaningful when they are seen as the data center's response to changes in infrastructure equipment or infrastructure operations. Studies investigating the effect on PUE of changes in infrastructure equipment or operations should ensure that any changes occurring to the IT load over the study's period of time are properly accounted.

This document provides guidelines for determining the PUE of a dedicated data center and that of a mixed-use facility or specialized facility, along with results, scalability analyses, and case studies. It also outlines the approach to reuse waste heat. Issues such as availability of equipment and the productivity of the data center require different metrics and different analyses.

Data centers are complex systems. Frequently, changing certain aspects of the facility (e.g., commissioning a new class of server) can produce apparent changes in PUE results for another aspect of the facility. The Green Grid advises data center owners and operators to take the greatest care around issues of availability. If an action or initiative taken to improve PUE has a negative effect on the availability of the IT equipment in the data center, owners and operators should review the potential impact on the data center and determine whether or not to proceed any further with that action or initiative.

In addition, PUE does not provide any guidance or insight into the operation or productivity of IT equipment. The Green Grid is currently investigating additional metrics and approaches to provide guidance and insight into these areas.[3] It is also possible, even likely, that changes in the deployment or operation of IT equipment will affect PUE results. For example, organizations implementing virtualization in their data centers may reduce overall IT load but see an increase in PUE. In these instances, the fixed overhead for power distribution and cooling has not changed, but the reduction in IT load delivers a seemingly poorer PUE result. PUE metric users

[3] The Green Grid, *Proxy Proposals For Measuring Data Center Productivity* White Paper #17 (2009) www.thegreengrid.org/Global/Content/white-papers/Proxy-Proposals-for-Measuring-Data-Center-Efficiency

should not become overly concerned when changes in one area affect results in another, but rather consider the factors that contributed to the PUE increase as further opportunities for improvements.

Source energy represents the total amount of raw fuel that is required to operate the data center and includes transmission, delivery, and production losses. A source energy–based PUE must be used when energy sources other than electricity are delivered to the data center. The Green Grid's recommended approach for measuring and calculating PUE by source energy will yield the same output as an all-electric data center calculating a site-based PUE. Please see section 4.9 for more information.

Numerous underlined internal references have been incorporated and linked throughout this document with a goal of maintaining an executive overview of each metric and key topic, while enabling end users and operators to obtain more detailed information, including implementation data, lessons learned, and best practices. This also allows those in particular verticals (e.g., government or healthcare) and business areas (e.g., executive management, marketing, or sales) to pull the level of information required in a quick and efficient manner. This is intended to enhance the use of this document and of PUE-related metrics.

II. Metric List and Intended Use

PUE for a dedicated building is the total facility energy divided by the IT equipment energy. PUE is an end-user metric used to help improve energy efficiency in data center operations. (Please see section 5.1 for more information.)

PUE for a data center in a mixed-use facility is highlighted in this document due to the need voiced throughout the industry to better define the contributions of data center total energy within a mixed-use facility. This refers to a data center that is located within a larger building that may support other functions. For example, a data center may occupy a single floor within a larger office building that contains some combination of non-IT operations, such as general administrative office space. A mixed-use facility may have its own dedicated infrastructure (including uninterruptible power supply [UPS] and cooling systems) or may have shared infrastructure. Because the majority of data centers are within mixed-use facilities, this section of the document provides practical guidelines on how to measure the PUE contribution of shared infrastructure resources. (Please see section 5.2 for a more in-depth discussion.)

Partial PUE (pPUE™) allows a data center manager to focus on the energy efficiency of a particular portion of the data center or mixed-use facility. This may be needed because some measurements of the total data center energy are unobtainable (because of a leasing arrangement, for example). Partial PUE is the total energy inside a boundary divided by the IT equipment energy inside the boundary. (Please see section VII for details.)

The PUE Scalability and statistical analysis metrics provide scalability metrics associated with changes in IT loads typically seen in the data center. PUE Scalability is used to show how well a data center's total energy consumption scales with changes in its IT equipment loads. (These metrics are described in section VIII.)

Data center infrastructure efficiency (DCiE) is the inverse of PUE: it is IT equipment energy divided by total facility energy. Since The Green Grid's introduction of these two metrics, PUE has surpassed DCiE in industry adoption. Moving forward, The Green Grid will use PUE and views it as the industry-preferred metric for measuring infrastructure energy efficiency in data centers.

III. An Overview of PUE

The Green Grid believes that metrics can help data center owners and operators better understand and improve the energy efficiency of their existing data centers, as well as help them make better decisions on new data center deployments. In addition, these metrics provide a dependable way to measure results against comparable IT organizations.

Why the need for greater energy efficiency? Because data center power and cooling are two of the biggest issues facing IT organizations today, and growing companies need a way to control these costs while enabling future expansion. Many traditional businesses are migrating their data to digital form and leveraging technology as a key business enabler. With more efficient data centers, IT organizations can better manage increased computing, network, and storage demands, cut energy costs, and reduce total cost of ownership (TCO)—all while remaining competitive and able to meet future business needs.[4]

The Green Grid recognizes the importance of establishing metrics for data center efficiency and offers guidance on technologies that claim to improve performance-per-watt. Ideally, these metrics, tools, and

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[4] Patterson, M.K., Costello, D., Grimm, P., Loeffler, M. "Data Center TCO; A Comparison of High-density and Low-density Spaces." THERMES 2007, Santa Fe, NM (2007)

associated processes will help organizations determine if an existing data center can be optimized before a new data center is needed.

3.1 PUE DEFINITION

PUE is defined as the ratio of total facilities energy to IT equipment energy, as shown in Equation 1 below.

Equation 1

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy}$$

Total facility energy is defined as the energy dedicated solely to the data center (e.g., the energy measured at the utility meter of a dedicated data center facility or at the meter for a data center or data room in a mixed-use facility). The IT equipment energy is defined as the energy consumed by equipment that is used to manage, process, store, or route data within the compute space.

It is important to understand the components for the energy in these measurements, which can be described as follows:

- **IT equipment energy** includes the energy associated with all of the IT equipment (e.g., compute, storage, and network equipment) along with supplemental equipment (e.g., KVM switches, monitors, and workstations/laptops used to monitor or otherwise control the data center).
- **Total facility energy** includes all IT equipment energy as described in the bullet above plus everything that supports the IT equipment using energy, such as:
  - Power delivery components, including UPS systems, switchgear, generators, power distribution units (PDUs), batteries, and distribution losses external to the IT equipment
  - Cooling system components, such as chillers, cooling towers, pumps, computer room air handling units (CRAHs), computer room air conditioning units (CRACs), and direct expansion air handler (DX) units
  - Other miscellaneous component loads, such as data center lighting

A more detailed component classification is provided in section 4.3.

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IV. More About PUE

PUE provides a way to determine:

- Opportunities to improve a data center's operational efficiency
- How a data center compares with similar data centers
- If the data center operators are improving the designs and processes over time
- Opportunities to repurpose energy for additional IT equipment
- A design target or goal for new data centers

PUE can be used to illustrate a data center's energy allocation. For example, a PUE of 3.0 indicates that the data center total energy usage is three times greater than the energy usage for the IT equipment alone. In addition, PUE can be used as a multiplier to help understand the real impact of an IT component's energy use.

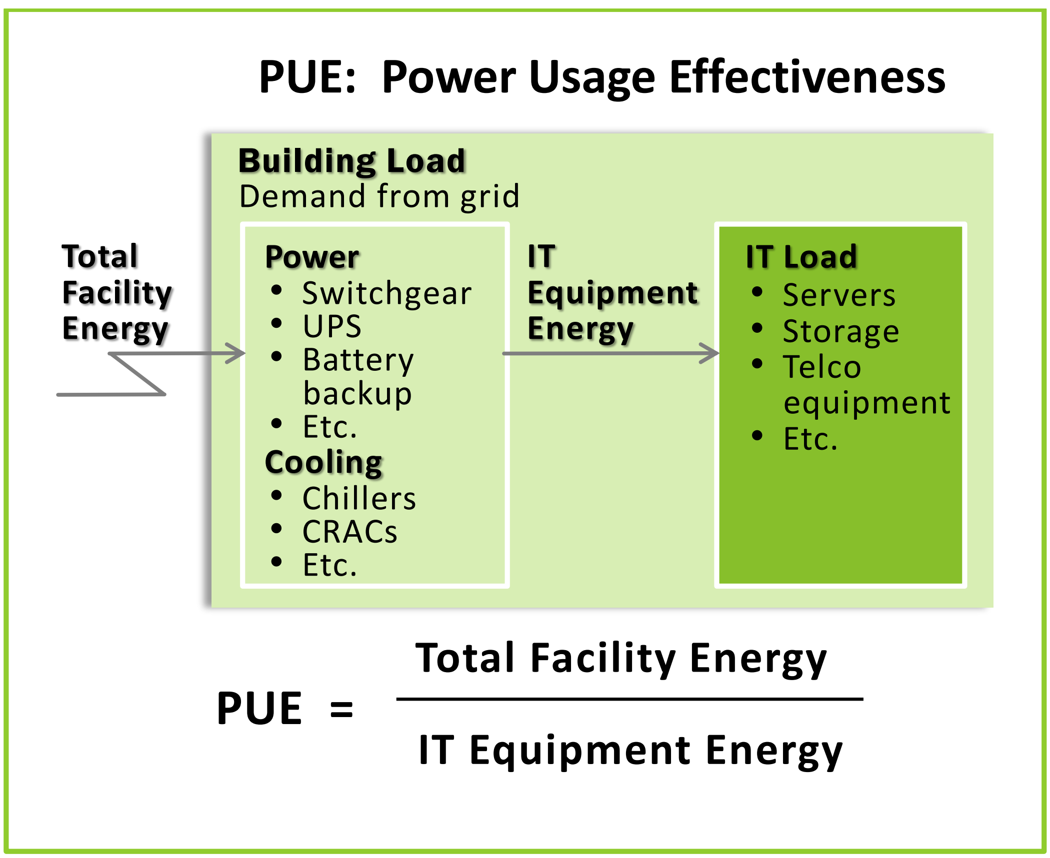

Figure 1. Illustration of how PUE would be calculated in a data center

In Figure 1, total facility energy is measured at or near the facility's utility meter(s) to accurately reflect the energy entering the data center. This measurement should represent the total energy used in the data center.

The data center–only portion of a facility's utility meter should be measured, since including in the calculation any energy that is not intended to be used in the data center would result in a faulty PUE metric. For example, if a data center resides in an office building, the total energy drawn from the utility will be the sum of the total facility energy for the data center and the total energy used by the non-data center offices in the building. In this case, the data center administrator could measure and subtract the amount of energy being used by the non-data center offices in order to calculate an accurate PUE.

IT equipment energy should be measured after all facility power conversion, switching, and conditioning is completed and before the energy is used by the IT equipment itself. The most likely measurement point is at the output of the computer room PDUs. This measurement should represent the total energy delivered to the compute equipment racks in the data center.

PUE values can range from 1.0 to infinity. Ideally, a PUE value approaching 1.0 would indicate 100% efficiency (i.e., all energy is used by IT equipment only). Currently, there is no comprehensive data set that shows the true spread of PUE for data centers. Some work indicates that many data centers may have a PUE of 3.0 or greater, but, with proper design, a PUE value of 1.6 (or better) should be achievable.[5] This is supported by measurements completed by Lawrence Berkeley National Labs,[6] which show that 22 data centers measured had PUE values in the 1.3 to 3.0 range.

4.1 PUE CALCULATION CONSIDERATIONS

A mixed-use building may house any number of functions, such as data center(s), labs, offices, etc. For mixed-use facilities, determining the energy usage of just the data center environment may be difficult. This is particularly true when the utility power grid enters the building through a single entrance point (e.g., a utility

[5] Belady, C., "Getting the Most Out of Your Data Center." AFCOM Data Center World presentation (March 2007) ftp://ftp.compaq.com/pub/products/servers/afcom-032607-final.pdf

[6] Greenberg, S., Mills, E., Tschudi, W., Rumsey, P., and Myatt, B., "Best Practices for Data Centers: Lessons Learned from Benchmarking 22 Data Centers." Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings (2006) http://hightech.lbl.gov/presentations/datacenter-2006aceee.ppt

room) and is then distributed to various building locations. These building configurations also make it difficult to determine the losses between the power entry into the building and its delivery to the data center.

To further complicate PUE calculation, some cooling technologies integrate cooling elements such as pumps, refrigeration, blowers, and heat exchangers within the IT equipment itself. These technologies blur what has traditionally been a clear delineation between facility equipment and IT equipment. However, equipment used to provide power and cooling to the data center must be accounted for in the metrics described in this document.

As part of its ongoing effort to promote continuous efficiency improvements in the data center, The Green Grid provides clearer distinctions between facility and IT equipment and recommends the use of energy measuring techniques throughout the data center, as well as for the equipment itself. This document covers these subjects in greater detail in the following sections.

4.2 PUE MEASUREMENT LEVELS

A three-level approach for measuring PUE, which includes basic, intermediate, and advanced levels of measurements is outlined in Table 1, below. The diagram (Figure 2) that follows the table shows a typical data center with measurement points identified for the proposed PUE measurement levels listed in Table 1. These points are indicated by meters in the diagram, which bear their associated Level 1 through Level 3 (L1 to L3) labels.

Table 1. High-level breakdown of The Green Grid's three-level approach to PUE measurement

	Level 1 (L1) **Basic**	**Level 2 (L2)** **Intermediate**	**Level 3 (L3)** **Advanced**
IT Equipment Energy	UPS Outputs	PDU Outputs	IT Equipment Input
Total Facility Energy	Utility Inputs	Utility Inputs	Utility Inputs
Measurement Interval	Monthly/Weekly	Daily/Hourly	Continuous (15 minutes or less)

Note: To report Level 1, Level 2, or Level 3, the required measurement location for that level must be used. For example, Level 2 must be measured at the PDU output and utility input. If measurements are made using power (versus energy), then the “measurement interval” is also required to report a certain level.

Additional measurement points are recommended to provide further insight into a data center infrastructure’s energy efficiency. Monitoring various components of the mechanical and electrical distribution will provide further insight as to the large energy consumers and where possible efficiency gains can be made (e.g., chillers, pumps, towers, PDUs, switchgear, etc.).

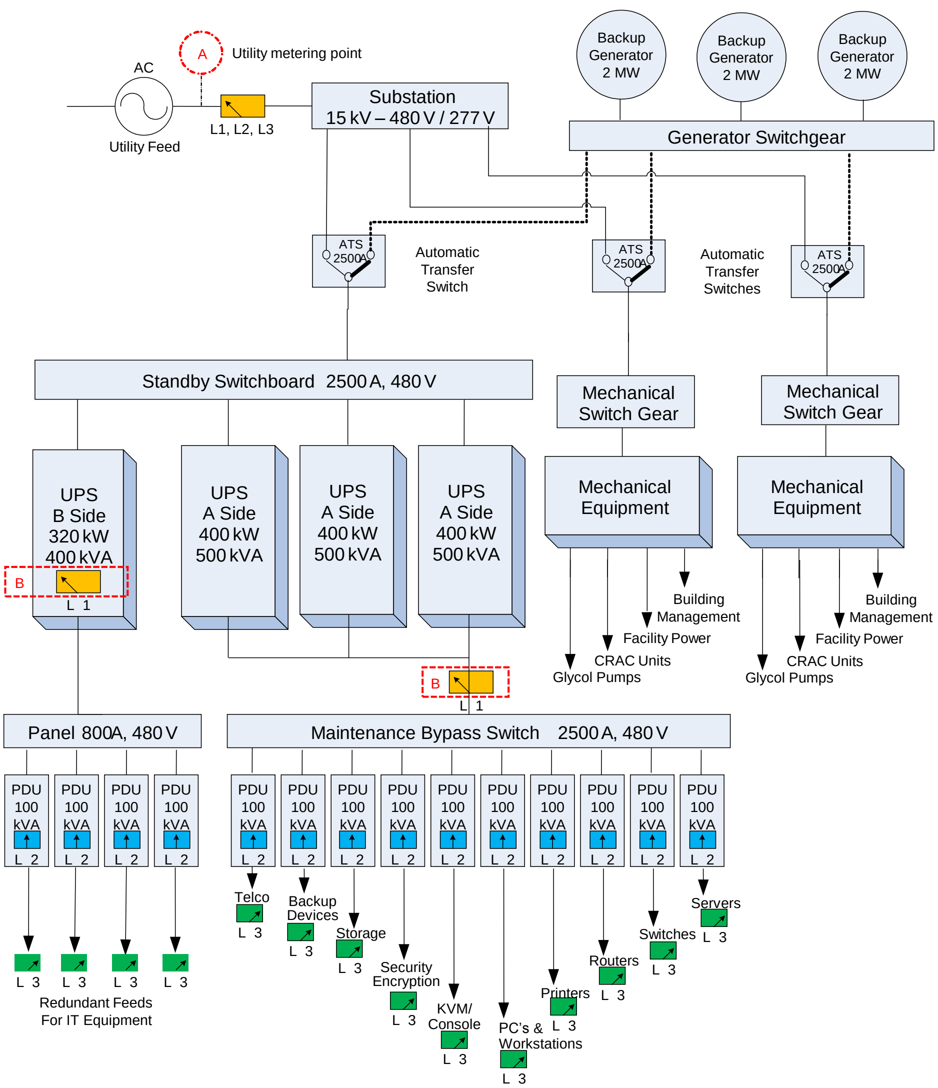

Figure 2. Graphical representation of the three PUE measurement levels for a typical data center

Level 1 Basic: The IT load is measured at the output of the UPS equipment and can be read from the UPS front panel, through a meter on the UPS output, or, in cases of multiple UPS modules, through a single meter on the common UPS output bus. The incoming energy is measured from the utility service entrance that feeds all of the electrical and mechanical equipment used to power, cool, and condition the data center. Basic monitoring requires, at a minimum, the collection of power measurements once a month; for energy measurements, that frequency is recommended. This typically involves some level of human activity to perform measurements.

Level 2 Intermediate: The IT load is measured at the output of the PDUs within the data center and can typically be read from the PDU front panel or through a meter on the secondary of the PDU transformer. Individual branch circuit measurement is also acceptable for Level 2. The incoming energy is measured from the utility service entrance that feeds all of the electrical and mechanical equipment used to power, cool, and condition the data center. Intermediate monitoring requires, at a minimum, the collection of power measurements once a day; for energy measurements, that frequency is recommended. This may require less human activity than Level 1 involves, as the data would be collected electronically through meters. For Level 2, it is expected that data will be logged in real-time with extensive trending possible.

Level 3 Advanced: The IT load is measured at each individual piece of IT equipment within the data center, either by metered rack PDUs (i.e., plug strips) that monitor at the strip or receptacle level or by the IT device itself. Note that non-IT loads must be excluded from these measurements. The incoming energy is measured from the utility service entrance that feeds all of the electrical and mechanical equipment used to power, cool, and condition the data center. Advanced monitoring requires, at a minimum, the collection of power measurements once every 15 minutes or less; for energy measurements, that frequency is recommended. Level 3 measurements should not require human activity to gather and record data; data will be collected by automated systems in real-time and should support extensive trending and analysis. The challenge is to collect the data in a simple format that serves various users' needs and ultimately to aggregate this data for a complete picture of the data center.

For the Level 1 and Level 2 measurement processes, it is recommended that measurements be taken at approximately the same time of day, when the loading in the data center is as consistent as possible with prior measurements. When making week-to-week comparisons, the day of the week should also be kept constant for comparable measurements.

The primary benefits of moving from Level 1 to 2 (Basic to Intermediate) or Level 2 to 3 (Intermediate to Advanced) are:

- **Measurement Period.** [7] Each level provides increased measurement frequency:
  - ***Basic*** = Monthly or weekly
  - ***Intermediate*** = Daily/hourly (same day/time)
  - ***Advanced*** = Continuous (e.g., 15-minute intervals or less)
- **Measurement Placement.** Each level provides a more accurate measurement of energy usage, as the measurements are taken closer to the devices that consume the energy. For example, for IT equipment, measurements are taken:
  - ***Basic*** = at UPS output (kilowatt-hour measurement taken either at the UPS display or through a meter on the UPS output; in cases of multiple UPS modules, a single meter on the common UPS output bus can be used)
  - ***Intermediate*** = at PDU output (kilowatt-hour measurement taken either at the PDU display or through a meter on the secondary of the PDU transformer)
  - ***Advanced*** = at IT equipment input (or rack PDU or smart plug)

It is important to note that The Green Grid discourages use of the PUE metric to compare different data centers without proper research and analysis. However, if the goal is to benchmark PUE against other data centers, it is critical to account for all devices that support the data center regardless of which PUE measurement level is chosen. A comprehensive list of devices is included in Table 2 in the following section.

4.3 COMPONENT CLASSIFICATION

In order for PUE to remain a global metric, there are two critical requirements that data center owners and operators must follow:

- Correctly classify each subcomponent that comprises the metric's two core contributors: IT equipment energy and total facility energy. (See Figure 3 for a subcomponent overview.)
- Use the same method to obtain the data inputs that create PUE's two core contributors (i.e., use a consistent method for data capture and always use actual measurements).

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[7] As described in *The Green Grid Metrics: Data Center Infrastructure Efficiency (DCiE) Detailed Analysis*, White Paper #14 from The Green Grid, a "Measurement Period" is the total interval of time over which many periodic samples are taken.

- A data center's network operations center (NOC) is a function of IT. Therefore, if the NOC supports the data center, the associated energy would be captured within the IT portion. If the NOC does not support the data center, then it is a separate function and the facility is mixed-use. (For specific information around mixed-use buildings, please see section 5.2.)

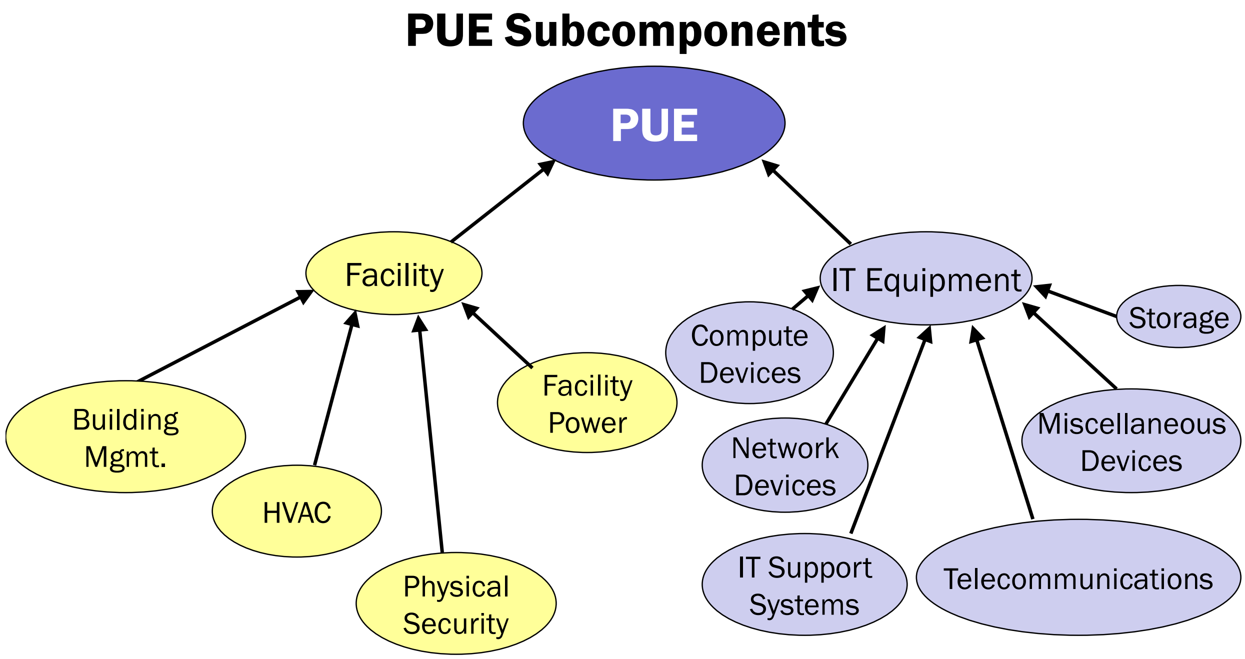

Figure 3. Overview of the subcomponents within a typical data center's facility and IT equipment

Table 2 below is designed to assist with correctly classifying each subcomponent.

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Table 2. Classification of subcomponents within IT and facility equipment categories in a typical data center

IT Equipment	
	Compute Devices
	Servers
	Network Devices
	Switches
	Routers
	IT Support Systems
	Printers
	PCs/workstations
	Remote management (KVM, consoles, etc.)
	Miscellaneous Devices
	Security encryption, appliances, etc.
	Storage
	Storage devices – switches, storage arrays, NAS systems
	Backup devices – media, libraries, virtual media libraries
	Telecommunications
	All telco (telecommunications company) devices
Facility Equipment	
	Power
	Automatic transfer switches (ATS)
	Switchgear
	UPS
	DC batteries/rectifiers (non UPS – telco nodes)
	Generators
	Transformers (step down)
	Static transfer switches (STS)
	Power distribution units (PDUs)
	Rack distribution units (RDUs)
	Breaker panels
	Distribution wiring
	Lighting
	Heating Ventilation and Air Conditioning (HVAC)
	Cooling towers

Facility Equipment	
	Condensers and condenser water pumps
	Chillers
	Heating Ventilation and Air Conditioning (HVAC)
	Chilled water pumps
	Water treatment systems
	Well pumps
	Computer room air conditioners (CRACs)
	Computer room air handlers (CRAHs)
	Dry coolers
	Air compressors
	Supply fans
	Return fans
	Air economizers
	Water-side economizers
	Dehumidifiers
	Humidifiers
	Heaters
	In-row and in-rack cooling solutions
	Condensate pumps
	Physical Security
	Fire suppression systems
	Water detection
	Physical security servers/devices
	Building Management System and Controls
	Servers/devices used to control/manage the data center
	Probes/sensors
	Plant controls

4.4 MEASURING ENERGY USAGE

4.4.1 Estimating Energy Usage for Data Center Design and Planning

Energy usage for the various components necessary to populate the PUE equation can be obtained using estimates such as efficiency curves and estimated loading conditions. The Green Grid envisions this method being used to estimate expected PUE and evaluate alternatives during the design and planning stages for future data centers. However, The Green Grid does not recommend this approach for operational data centers and strongly recommends measuring actual energy usage.

PUE values cannot be accurately calculated using name plate ratings for any of a data center's IT equipment *or* for any of its mechanical infrastructure components. Actual energy measurements must be collected in order for PUE to have any correlation to an operational data center.

4.4.2 Measuring Actual Energy Consumption

The Green Grid–recommended approach for obtaining the data necessary to calculate PUE is to measure actual energy usage for the entire data center and IT equipment. The Green Grid recognizes that obtaining actual measurements is not a trivial task, especially in existing data centers that do not have adequate instrumentation to collect the data. The minimum required measurement data would consist of two measurements one being total facility energy (Point A in Figure 2) and IT equipment energy (Point B in Figure 2). Although this would be adequate to calculate PUE, The Green Grid believes that more data is necessary to assess areas for potential improvements and evaluating changes intended to improve PUE within a data center.

4.4.3 Measurement Period

Hourly, daily, weekly, monthly, and seasonal variances affect PUE. Increasing the frequency of the measurement cycle provides a larger and more accurate data set to analyze. To truly understand and successfully manage a data center's efficiency, continuous real-time monitoring should be used so that historical trending and statistical analysis can be done to determine where efficiencies can be gained. Other benefits include early detection of unexpected variations that could indicate systems issues. In cases where continuous real-time monitoring is not practical or economically justifiable, some form of repeatable, defined process should be in place to capture PUE as often as possible for comparison purposes.

Measurements should not continue to be taken if maintenance is being performed within the data center or if other significant operational abnormalities are identified or present, any of which could have a negative impact and provide unrealistic PUE measurements.

Therefore, The Green Grid–recommended best practice is automated, real-time monitoring with data captured every 15 minutes or less. When reporting a PUE value, data center owners should use the average PUE measured over a one-year period. For data centers without real-time monitoring, PUE should be collected according to Table 1 per the intended level of implementation and reported using the guidelines set out in section VI (How to Report PUE) of this document.

4.4.4 Required and Recommended Measurement Points and Intervals

Table 3 adds to the PUE measurement levels outlined in Table 1, providing information about The Green Grid's additional recommended measurement points and intervals for the three levels.

Table 3. Guidance as to which measurement points and intervals are required and recommended for each PUE measurement level

Where do I measure? **How often do I measure?**		**Level 1 (L1)** **Basic**	**Level 2 (L2)** **Intermediate**	**Level 3 (L3)** **Advanced**
IT Equipment Energy	Required	UPS outputs	PDU outputs	IT equipment input
Total Facility Energy	Required	Utility inputs	Utility inputs	Utility inputs
	Additional recommended measurements*		**UPS inputs/outputs** **Mechanical inputs**	**PDU outputs** **UPS inputs/outputs** **Mechanical inputs**
Measurement Intervals	Required	Monthly	Daily	15 minutes
	Additional recommended measurements*	**Weekly**	**Hourly**	**15 minutes or less**

*Recommended measurements are in addition to the required measurements. The additional measurement points are recommended to provide further insight into the energy efficiency of the infrastructure.

The diagram in Figure 4 depicts the additional recommended measurement points from Table 3 for the three measurement levels. Figure 4 adds to the measurement points illustrated in Figure 2. Specifically, Level 2 measurement points have been added to the critical load ATS output and to the UPS input. The additional recommended measurement points are highlighted in yellow.

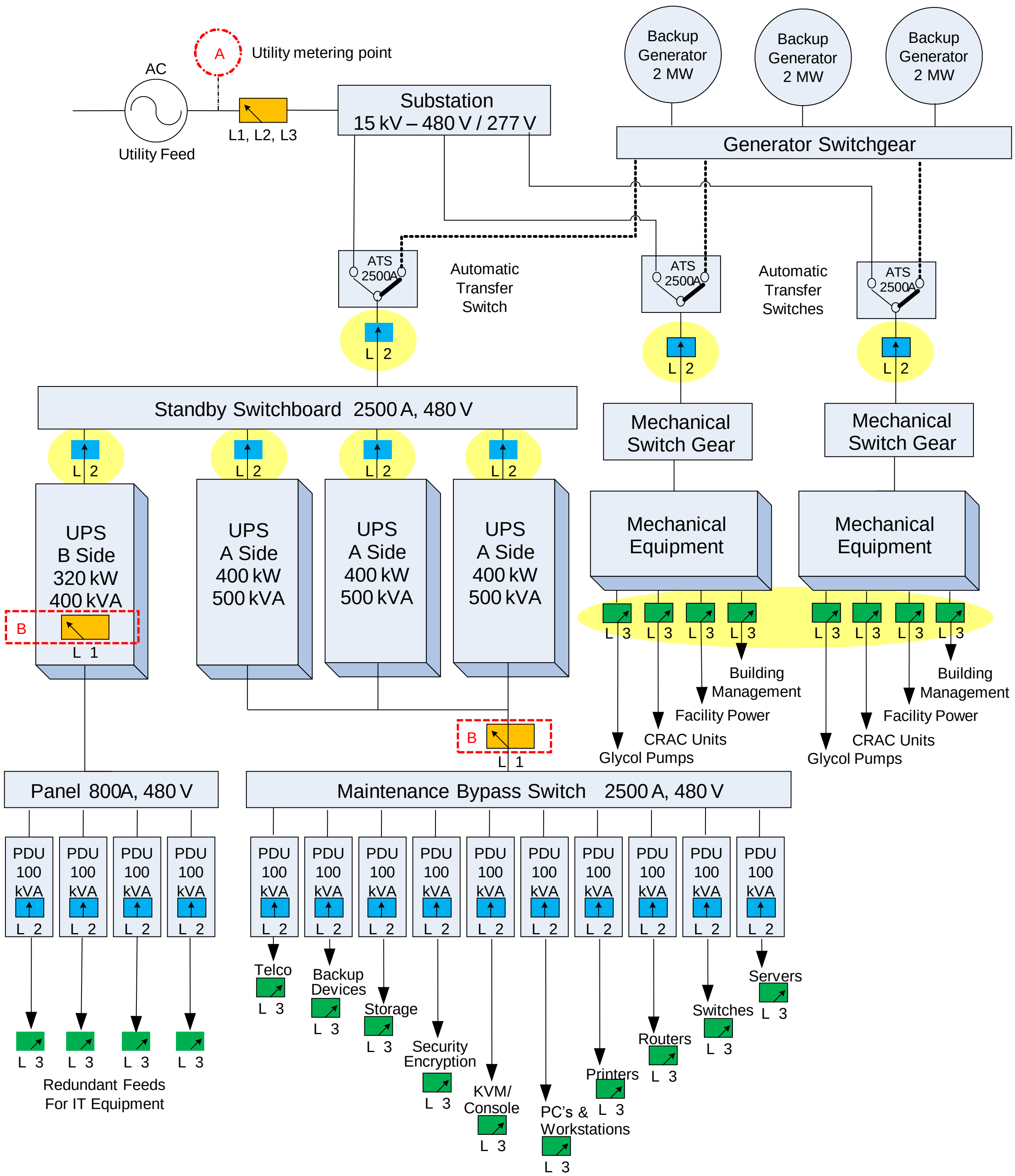

Figure 4. Monitoring and measurement points

4.4.5 Critical Power Path Measurement Points

Although monitoring energy usage at the service entrance and the critical loads for PUE data collection is a simple concept, the complexity of the critical power path can be overwhelming. Moving the monitoring location closer to the devices that are consuming the energy enables further isolation of distribution component losses. While this is preferred when measuring IT energy usage, distribution losses should be included in all other measurements, if possible.

The total critical power path can consist of many elements downstream from the utility meter, such as those shown in Figure 5 below. (For more detailed lists, see Table 2.)

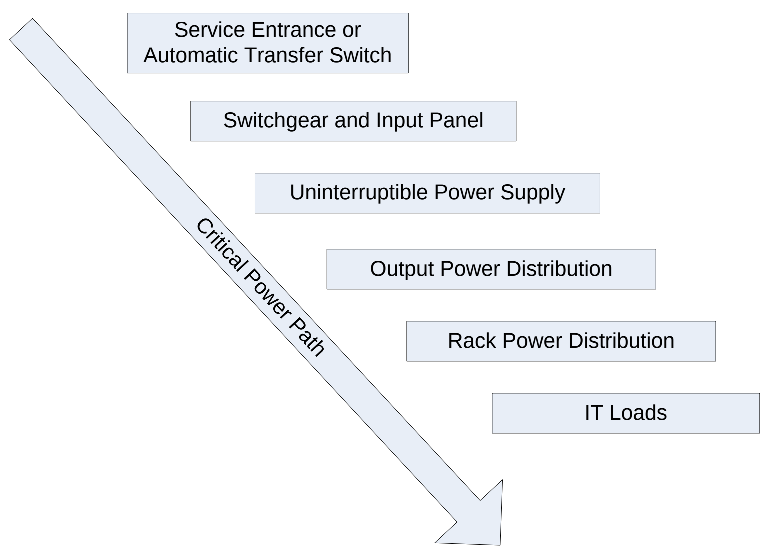

Figure 5. Hierarchy of critical power path measurement points

Monitoring energy usage within a critical power path involves many aspects that can prevent it from being easy and straightforward for the data center operator. Costs can be quite high to install measuring instruments at every point in the critical power path. Collecting, processing, and interpreting all the data also can be complex. Currently, there is no commercially available integrated measurement software solution, so the data center operator must deal with multiple data collection systems. Lastly, there is always some degree of error inherent in each of the meters measuring energy usage, which can affect results.

For a practical and achievable approach to monitoring, The Green Grid recommends that data center operators identify where it is most beneficial to measure, taking into account associated improvements in PUE accuracy.

4.4.6 Critical Mechanical-Path Measurement Points

Separating the mechanical system's loads can be even more challenging than dealing with the power path. The most useful data is obtained when equipment is grouped by system, which allows for energy comparisons with other systems. Efforts should be directed at determining the energy usage by system, including, but not limited to, the following examples:

- Cooling plant
  - Chillers
  - Towers
  - Pumps
  - Economizers
  - Thermal storage
  - Secondary chill water distribution systems
  - Computer room air handlers
- Lighting
- Fans (fresh air and exhaust)
- Security
- Fire suppression systems

While equipment can be divided into types, most often the electric energy that these loads use cannot be divided. Mechanical system configurations vary by philosophy and designer. In many instances, energy usage of different types are fed from the same source.

On a positive note, mechanical systems often include various monitoring information in order to manage themselves. Thus they provide ready sources of data that can be used, including building management systems, variable loads such as variable speed drives, equipment provided with metering, and fixed-speed loads such as some fans and pumps whose load profiles do not vary significantly.

4.4.7 Meter and Measurement Requirements

Most important to measuring the energy usage of equipment is requiring a suitable kilowatt-hour (kWh) meter that reports the "true" energy usage, via the simultaneous measurement of the voltage, current, and power factor over time. (Note that kilovolt-ampere [kVA]—the product of voltage and current alone—is not an accurate representation of the power, or kilowatts [kW], used in alternating current systems). Many watt meters also have the capability to report energy usage, which is the recommended measurement. For more in-depth guidance specific to energy measuring requirements, The Green Grid recommends ASHRAE Datacom Series Book #9, *Real-Time Energy Consumption Measurements in Data Centers*,[8] which was coauthored by The Green Grid and ASHRAE.

4.5 FACTORS AFFECTING PUE

The intent of PUE is to assist decision makers for data center operations, IT, and facilities in their efforts to improve data center efficiency. As with any data point, the PUE metric represents only one part of the entire data center picture. PUE is valuable for monitoring changes in a single data center at an aggregated level. It also can help identify large differences in Power Usage Effectiveness among similar data centers, although further investigation is required to understand why such variations exist. While measuring PUE is the first step in better understanding a data center's efficiency, subsequent investigation is required to determine the best approach for additional improvement.

4.5.1 Dynamic Nature of a Data Center

Data centers are in constant flux. Applications, as well as the IT equipment and infrastructure that support them, are continually evolving to better meet organizations' business needs. Therefore, the initial design of a data center is obsolete the day after the installation and commissioning is complete. Energy usage calculations are often based on a static design rather than on the dynamic data center configuration. The designed (static) versus actual (dynamic) nature of a data center must be considered. Improvements will come through incremental step changes in infrastructure over time. Also, it is important to keep in mind that as the load changes in a data center, the operating point of the subcomponents on their efficiency curves will change.

4.5.2 Type of Data Center

The type of processing done in a data center can greatly affect PUE values. Is the data center mainly used for testing, production, internal processes, networking, or something else? What is the primary business supported by the data center (e.g., financial services, healthcare, telecommunications, etc.)? What level of resiliency is required to support this business? Another aspect to consider is if the data center operations scheme includes disaster recovery, which would certainly affect efficiency.

[8] www.ashrae.org/publications/page/1900#9

Similarly, the physical attributes of the data center will have an impact on PUE. What temperature and humidity levels are typically maintained by the data center? What type of cooling system is used and does it include free cooling? How old is the data center and the subcomponents in it? Was the building intended to be a data center, or was it retrofitted to be used as one?

Many infrastructure subcomponents and some IT equipment currently support energy-reduction features—are these employed in the data center? Are they effective? Are dummy loads being run and, if so, why and when?

4.5.3 Climate and Location

A data center's location can have a significant impact on its PUE. The efficiency of identical mechanical systems can be drastically different depending on the climate in which the system operates. The local climate also affects the hours of free cooling available, as shown in Figure 6. (Note: Figure 6 is for illustrative purposes only, intended to convey the concept of free cooling; it does not capture all variances that could occur.) Free cooling implies the ability to provide cooling to IT equipment by leveraging local ambient conditions in order to reduce energy usage. Similarly, some mechanical systems are just not practical in some climates or locations. Location has a significant impact on utility rates and even energy availability.

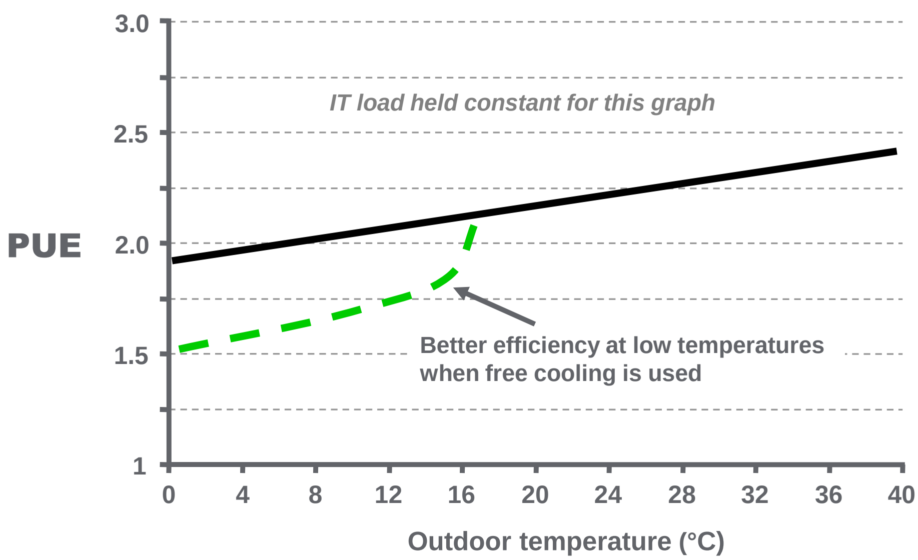

Figure 6. Sample illustration of the relationship between PUE and outdoor temperature

4.5.4 Data Center Design and Operation

The impact on PUE of a data center infrastructure's design cannot be underestimated. IT equipment density, power distribution architecture, cooling architectures, redundancy levels, and floor layouts—to name a few design elements—all have major impacts on efficiency. Many of these topics will be addressed in depth in other TGG white papers. Even the best design can result in poorer-than-designed efficiency as operation changes take place. For example, increasing the density in a single rack beyond the specified design value may result in air conditioners having to cool the new hot spot. As a result, the cooling system is no longer in balance and is less efficient.

4.6 SOMETIMES PUE SEEMS TO GO THE WRONG WAY

The common goal is to reduce energy usage, not manipulate a metric. In some real-world situations, the PUE metric may go up if the total energy provided to a data center is not adjusted accordingly to match a drop in IT energy. It is important to remember to reduce the infrastructure subcomponent energy consumption.

PUE needs to be considered with total data center energy usage in mind. A data center's total energy usage may go down, but its PUE may not reflect an improvement. Similarly, total energy costs may increase, but per-unit costs may decrease.

Unlike other measures, PUE awards no credits or percentage points for generating energy, recovering waste heat, etc. While important, these are not the focus of the PUE metric. The minimum PUE is 1.0, the maximum is infinity.

4.7 IMPROVING PUE

One of the chief reasons for collecting the necessary information and calculating a PUE is to determine the effectiveness of any changes made within a given data center. PUE provides an indication of how much energy is used by the facility infrastructure in order to distribute power to the IT equipment, deliver necessary cooling to the IT equipment, and maintain stability and redundancy in power delivery to the IT equipment.

A typical data center's PUE is likely to vary with the levels of its IT load. For a data center to improve its PUE and energy efficiency, it is necessary to make changes that affect the energy used by non-IT equipment in support of the IT equipment.

Implementing the Level 1 measurement points and intervals outlined in Table 3 is sufficient to derive the PUE of a facility and will provide the data necessary to determine the effectiveness of changes made to a data center. The added information obtained by implementing Levels 2 and 3 may be necessary, either all or in part, in order to identify those changes most likely to provide improvements.

Changes made to improve PUE should be made in the following order:

1. Follow best practices found in The Green Grid white papers and books
2. Increase granularity of measurements such that losses can be ranked by subsystems
3. Rank loss contributors by magnitude and investigate opportunities to make changes that will lower the energy used in subsystems while still supporting IT equipment requirements

The PUE metric provides a useful tool for evaluating and measuring the energy usage and efficiency of the infrastructure equipment that supports the IT equipment within a data center. Data center operators can use PUE results to address and reduce the energy usage related to the supporting infrastructure within their facilities. The Green Grid specifically tailored its Level 1 (Basic) PUE measurement approach to address the capabilities of existing equipment in data centers and give operators a means of measuring PUE with the minimum amount of changes to their existing data centers. Levels 2 and 3 (Intermediate and Advanced) provide additional insight into the data center so that operators can make continuous improvements in areas that will deliver the highest return on investment (ROI).

4.8 PARTICIPANTS IN AND INFLUENCES ON THE DEVELOPMENT OF PUE

In 2009, The Green Grid helped launch a collaborative effort to improve data center energy efficiency worldwide by developing metrics and indices for formal adoption by all participating organizations. As a result of this work with organizations around the world, PUE has been recognized globally as the industry's preferred infrastructure efficiency metric for data centers.

Two task forces—the Data Center Metrics Coordination Task Force[9] (U.S. Regional Task Force) and the Global Harmonization of Data Center Efficiency Metrics Task Force[10] (Global Task Force)—have affirmed PUE as the agreed-upon metric for measuring infrastructure energy efficiency in data centers. In a published memo,[11] The Data Center Metrics Coordination Task Force not only affirms agreement for PUE, it also provides recommended calculation and reporting guidelines for PUE. The U.S. Regional Task Force's session objectives include:

- Data center efficiency metrics: Develop common definitions for key metrics and seek consensus on guiding principles for metrics
- Measurement protocols: Define current status and gaps and coordinate plans for further development
- Tools: Review status and coordinate development

The Global Harmonization of Data Center Efficiency Metrics Task Force also published a memo[12] that affirms PUE and recommends PUE calculation and reporting guidelines. (See Table 4 below.) This task force's sessions focus on sharing global lessons and practices with an objective of arriving at a set of metrics, indices, and measurement protocols that can be formally endorsed or adopted by each participating organization to improve data center energy efficiency globally.

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9 Members include 7x24 Exchange, ASHRAE, The Green Grid, Silicon Valley Leadership Group, Uptime Institute, U.S. Department of Energy Save Energy Now and Federal Energy Management Programs, U.S. Environmental Protection Agency's ENERGY STAR Program, and the U.S. Green Building Council.

10 Members include European Commission – Joint Research Centre Data Centers Code of Conduct, The Green Grid, Green IT Promotion Council (Japan), Ministry of Economy, Trade, and Industry (Japan), U.S. Department of Energy Save Energy Now and Federal Energy Management Programs, and U.S. Environmental Protection Agency ENERGY STAR Program.

11 www.thegreengrid.org/Home/alliances/HarmonizationOfMetrics.aspx

12 www.thegreengrid.org/en/Global/Content/Reports/HarmonizingGlobalMetricsForDataCenterEnergyEfficiency

Table 4. Global Task Force recommendations for PUE measurement and reporting

PUE Level 2 Yearly Continuous	PUE_{L2YC}
Unit of measure	Energy
Frequency of measurement	Continuous
Averaging period of measurement	Annual
Data center location of measurement	Utility(ies) hand-off
Information Technology location of measurement	PDU output

In addition to contributing to the two task forces, The Green Grid has held many industry events, attended many industry events, and organized webcasts and working sessions with other industry organizations, end users, consultants, vendors, academics, and so on. These are ongoing efforts to collaborate and evolve PUE in a way that reflects the contributions of numerous and varied audiences.

4.9 SOURCE ENERGY

Both task forces' PUE recommendations are a subset of The Green Grid framework, as are their measurements and calculations for the metric. The primary difference between the two task forces is the source energy weighting factors used.

Source energy is a means of assessing the total primary energy usage or fuel consumption at a data center. The purpose of source energy is to ensure that data centers that purchase different forms of energy (e.g., electricity, natural gas, chilled water) can equitably compare their total energy usage. For example, if one data center purchases chilled water from a local utility company while another data center uses electricity to produce chilled water on-site, a factor is required to put the energy use in common units for comparison. This factor is called a source energy weighting factor, and it is a factor used to reflect a data center's total fuel consumption.

Because the majority of data centers operate with 100% electricity, source energy factors are weighted with respect to electricity. In other words, after a source factor is developed for each fuel, it is expressed relative to the source factor for electricity. This convention allows for any electricity purchases to be multiplied by a factor of one. Purchases of other fuels are multiplied by their respective factors before being added to the total. (See Equation 2.)

Equation 2

$$\textit{Weighted energy for each energy type} = (\textit{Annual energy use} * \textit{source energy weighting factor})$$

The source energy weighting factor is inherently a regional factor because the amount of fuel needed to produce one unit of electricity (or chilled water) will depend on the predominant method of electricity (or chilled water) generation in the specific country. Some countries have published values for these conversion factors (such as those provided by the Environmental Protection Agency's ENERGY STAR Program in the U.S.). However, to enable a fair comparison worldwide, standard, global factors should be applied. Global factors represent average values of factors from different regions. While the global factors are recommended for comparisons across different regions of the world, regional factors may be applied for greater accuracy of comparison within a specific region.

Table 5 shows the global source energy weighting factors harmonized by the Global Task Force. These factors should be used when trying to compare the PUE of a data center in the United States with the PUE of a data center in Japan or Europe.

Table 5. Global source energy weighting factors

Global Source Energy Weighting Factors	
Energy Type	**Weighting Factor**
Electricity	1.0
Natural gas	0.35
Fuel oil	0.35
Other fuels	0.35
District chilled water	0.4
District hot water	0.4
District steam	0.4

The U.S. Regional Task Force has a different set of source energy weighting factors. (See Table 6.) These are more accurate for calculating PUE in the United States and should be used when only comparing PUE values with those of similar data centers within the same region.

Table 6. U.S. source energy weighting factors[13]

U.S. Source Energy Weighting Factors	
Energy Type	**Weighting Factor**
Electricity	1.0
Natural gas	0.31
Fuel oil	0.30
Other fuels	0.30
District chilled water	0.31
District hot water	0.40
District steam	0.43
Condenser water	0.03

To express total source energy, each fuel should first be converted into a single common unit (kWh) and then multiplied by its weighting factor, after which the source energy for all fuels can be summed together.

For an example showing the use of source energy weighting factors, please see section 5.1.

4.10 ENERGY OR POWER

PUE can be computed using either energy (kilowatt-hour) or power (kilowatt) measurements. Energy measurements are more accurate, since power measurements only sample the energy flow at the exact time of the measurement, while energy measurements accumulate power flow over time. First-time PUE estimates often use power-based sampling, but energy-based sampling more accurately reflects long-term energy use and is now preferred by the industry. Most monitoring systems can be configured to report energy.

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13 The U.S. Environmental Protection Agency (EPA) source energy factor methodology for all energy types except condenser water is available at: www.energystar.gov/ia/business/evaluate_performance/site_source.pdf. The weighting factors presented in this document are obtained by dividing each EPA source factor by the reference source factor for electricity, 3.34. The factor for condenser water was calculated assuming 20 gpm/hp, 3 gpm/ton, and 1% line losses.

The original use of the term PUE was based upon the power drawn by the IT equipment, the power drawn by the cooling equipment, and the power losses in the electrical distribution system, hence the name "power usage effectiveness."

Power is generally assigned units in kilowatts, and it represents an instantaneous measurement or "snapshot in time" of the power use. Electrical energy (kWh) is an integral over time, the product of power (kW) times the duration that it is applied (hours), so the units of energy would typically be kilowatt-hours. If a group of servers with a power draw of 20 kW drew exactly that much power for an hour, it would have used 20 kWh of energy. The industry typically is more interested in energy, but both power and energy have an important function in the design and operation of any data center.

In the case of measuring PUE, a daily sample of power will only provide PUE at the time of the sample, but a daily sample of energy will provide an accumulated or averaged PUE over the entire day. These two methods provide different results for a data center where the day-night outdoor temperature or IT equipment use varies significantly and for a data center that employs economizer cooling modes.

The simplicity of the PUE metric actually allows the mathematics to be valid and consistent for either energy or power. However, The Green Grid's public reporting guidelines included in section VI of this document remove any ambiguity over the question because *PUE is defined as an energy metric*.

The use of energy when calculating PUE has also been endorsed by other industry groups, including the 7x24 Exchange, ASHRAE, Silicon Valley Leadership Group, U.S. Department of Energy, U.S. Environmental Protection Agency, U.S. Green Building Council, Uptime Institute, European Commission Joint Research Centre Data Centre Code of Conduct, Japan Ministry of Economy, Trade and Industry, and Japan's Green IT Promotion Council. Therefore, with the exception of PUE Scalability, the remainder of the examples in this document will use energy usage and not power.

V. Example Calculations—How to Measure PUE

Although PUE is a simple concept that has gained broad acceptance, correctly and accurately measuring PUE can be challenging. Many PUE claims seem too good to be true and cause others to wonder if they are incorrectly obtaining their PUE values.

The purpose of the following content is to educate data center operators on how to collect the necessary data and interpret the metric in order to drive a given facility to a higher level of effectiveness and efficiency, i.e., an improved PUE.

5.1 HOW TO MEASURE PUE IN A DEDICATED DATA CENTER FACILITY

This section provides information and guidelines necessary for end users to successfully apply PUE. Its recommendations are based upon a dedicated data center facility. If working with a mixed-use building (e.g., one that combines office space and data center space), please see section 5.2.

The Green Grid recommends monitoring PUE over a period of one year, taking ongoing measurements to compensate for peak and nominal loading changes that occur within the data center. If it is not possible to monitor energy consumption over a full year, select a period of time not less than one month and verify that the loading within the data center during that time is typical for that particular environment.

When beginning to measure PUE, first identify the primary motivation and intended outcomes of measuring PUE. If one is measuring PUE to compare data centers in different regions, PUE should be measured according to the Global Harmonization of Data Center Efficiency Metrics Task Force recommendations.[14] If one is measuring PUE to compare data centers within the United States region, PUE should be measured according to the recommendations of the Data Center Metrics Coordination Task Force.[15] Both the global and the U.S. regional task forces' recommendations are subsets of the original TGG recommendations. (The difference is the source energy weighting factors used in the calculation.)

If one is measuring PUE for internal energy efficiency improvements, begin measuring PUE according to the data center's existing capabilities (at least Level 1 energy usage) and advance through Level 2 or Level 3 energy measurements, depending on the organization's motivation and alignment with strategic objectives.

[14] www.thegreengrid.org/en/Global/Content/Reports/HarmonizingGlobalMetricsForDataCenterEnergyEfficiency

[15] www.thegreengrid.org/Home/alliances/HarmonizationOfMetrics.aspx

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The five data center examples below (Figure 7 through Figure 11) demonstrate how to calculate PUE for a Level 2 (Intermediate) measurement, using the global source weighting factors from the Global Harmonization of Data Center Efficiency Metrics Task Force in Table 5.

Recall the definition of PUE from Equation 1 (reproduced below for convenience):

$$\boldsymbol{PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy}}$$

Total energy should include all fuel sources. Equation 3 shows an example of how the PUE of a data center that purchases electricity and district chilled water can be expressed:

Equation 3

$$PUE = \frac{Electrical\ Energy\ * 1.0\ +\ Chilled\ Water\ Energy\ * 0.4}{IT\ Equipment\ Energy\ * 1.0}$$

Table 5 from above is reproduced here for convenience:

Global Source Energy Weighting Factors	
Energy Type	**Weighting Factor**
Electricity	1.0
Natural gas	0.35
Fuel oil	0.35
Other fuels	0.35
District chilled water	0.4
District hot water	0.4
District steam	0.4

DATA CENTER A – ALL ELECTRIC ENERGY PURCHASE

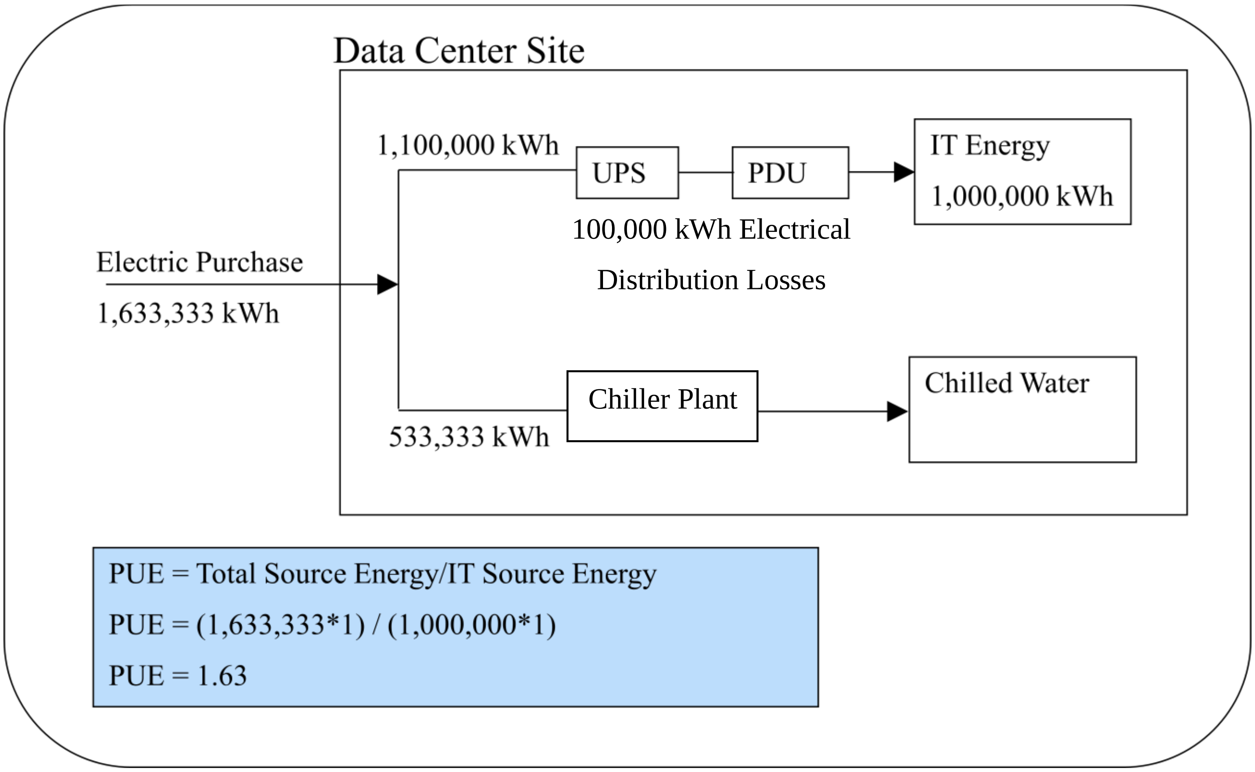


Figure 7. Example PUE calculation for a data center that purchases all electricity

DATA CENTER B – ELECTRIC & CHILLED WATER PURCHASE

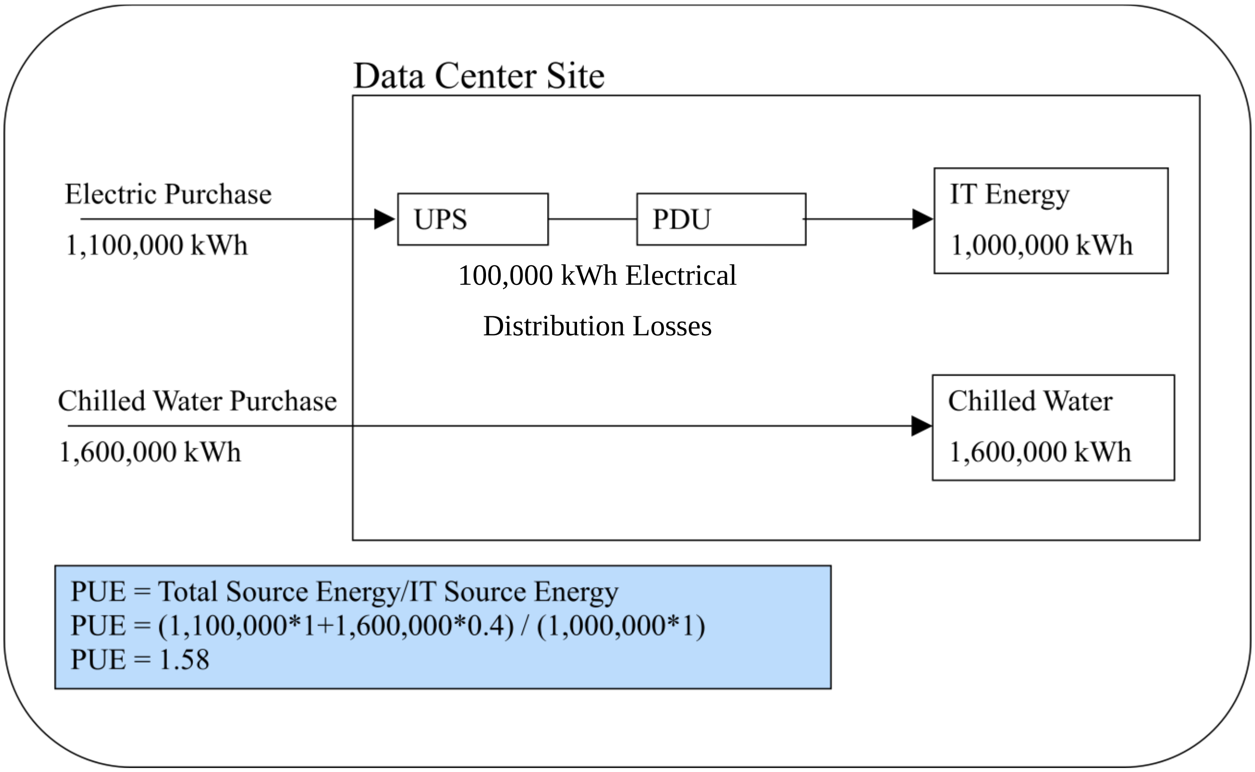
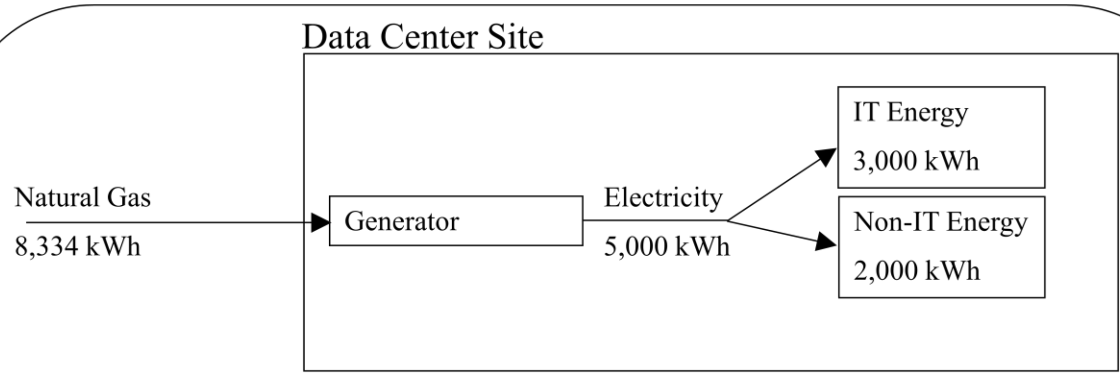


Figure 8. Example PUE calculation for a data center that purchases electricity and chilled water

DATA CENTER C – NATURAL GAS PURCHASE



Source conversion factor for IT Energy:

= Average factor for all electricity

= (Source Energy To Produce Electricity + Purchased Electricity)/(All Electricity At Site)

= (8,334*0.35+0*1)/(5,000) = 0.58

PUE = Total Source Energy/IT Source Energy

PUE = (8,334*0.35)/(3,000*0.58)

PUE = 1.67

Figure 9. Example PUE calculation for a data center that purchases natural gas

5.1.1 On-Site Electric Generation

To enable equitable PUE calculations in data center designs that operate on-site electric generation, two topics need to be explained: IT Source Energy Conversion Factor (immediately below) and Cogeneration Input Fuel Assumption (see Figure 11 and the bullet that comes after it).

- IT Source Energy Conversion Factor
  - To ensure the PUE calculations for a design including on-site electric generation and a design excluding on-site electric generation are equitable, the Global Harmonization of Data Center Efficiency Metrics Task Force has introduced the IT Source Energy Factor. The IT Source Energy Factor enables the data center owner/operator to include the efficiencies of generating chilled water (as in all calculations for PUE), but exclude the efficiencies of generating electricity (as in all calculations for PUE). PUE is not a metric to identify the efficiencies of how electricity is brought to the data center, it is a metric to identify how efficient the electricity is used from the data center control volume to the IT Equipment.

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DATA CENTER D – ELECTRIC & NATURAL GAS PURCHASE

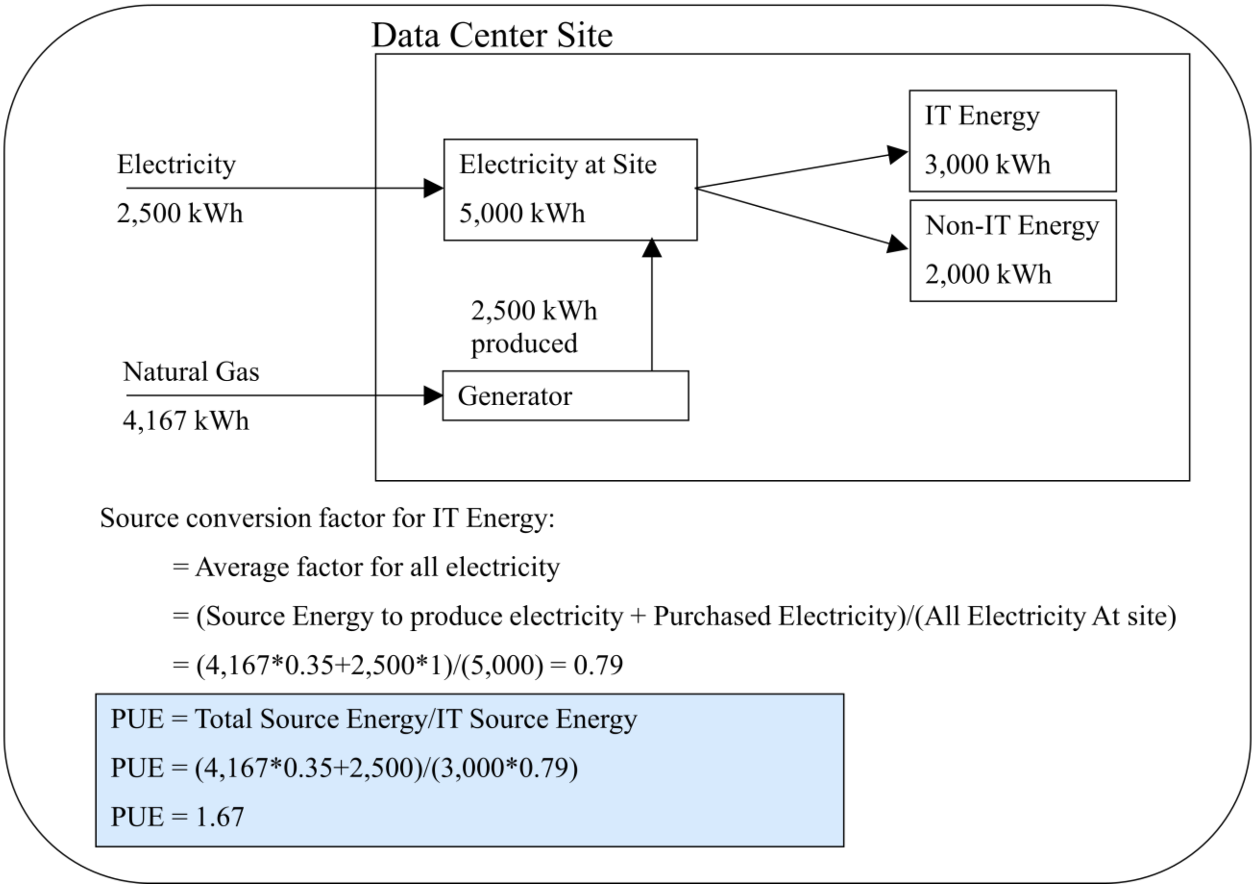

Figure 10. Example PUE calculation for a data center that purchases electricity and natural gas

DATA CENTER E – ELECTRIC & NATURAL GAS (COGENERATION) PURCHASE

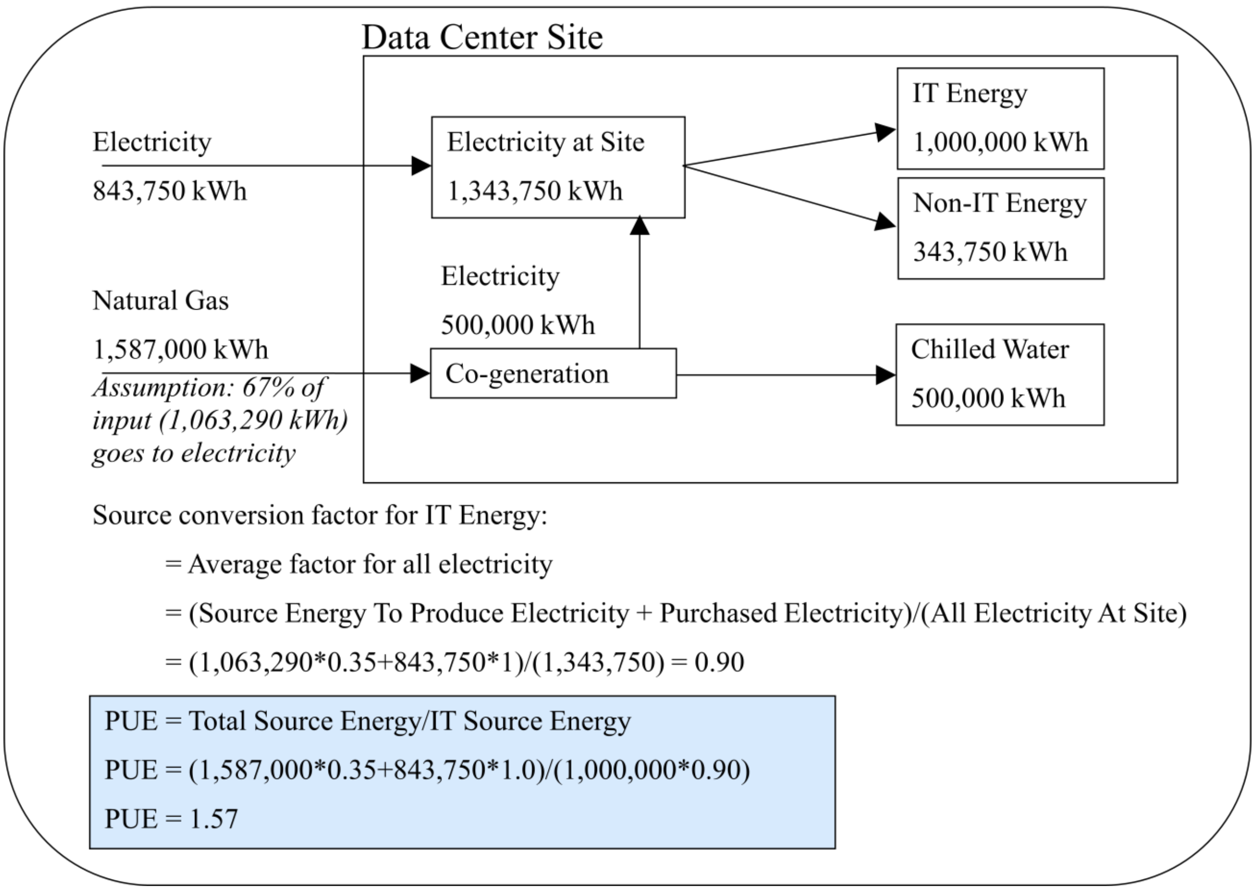

Figure 11. Example PUE calculation for a data center with electricity and natural gas cogeneration

- Cogeneration Input Fuel Assumption
  - The Global Harmonization of Data Center Efficiency Metrics Task Force has adopted the assumption that 67% of a cogeneration plant's input fuel is allocated to the primary form of generation (electricity in the provided example) and respectively 33% of the primary input fuel is allocated to the secondary form of generation (chilled water in the provided example).
  - This assumption is based on a similar steam based cogeneration study from the U.S. Environmental Protection Agency's Energy Star Program. Differences do exist between the two scenarios, but to solidify the methodology of calculating PUE and to drive consistent and equitable calculations for all design types, the Global Harmonization of Data Center Efficiency Metrics Task Force is proceeding with the recommendation to adopt this approach. As further

data specific to cogeneration examples are provided, the data will be taken into consideration. Provided there is a material change in calculations, the Global Task Force will consider updating the recommendations specific to this assumption.

– Stakeholder feedback is welcome and encouraged to continue the adoption, consistent communication, and equitable calculations for PUE in an effort to improve energy efficiency.

The PUE metric provides a very useful tool for evaluating and measuring the energy usage and efficiency of the infrastructure equipment supporting IT equipment within a data center. This allows data center operators to address and reduce the energy usage related to the supporting infrastructure within a data center.

5.2 HOW TO MEASURE PUE IN A MIXED-USE BUILDING

Most data centers around the world are not purpose-built, standalone buildings dedicated to processing information. They are tucked away inside much larger buildings, just one of several “tenants.” Facilities such as these are generally called mixed-use or multi-tenant buildings. Data centers in mixed-use buildings present unique challenges to their operators. The emphasis on PUE measurement for data centers has added yet another challenge—that of quantifying the proportion of total building energy required to operate the data center. Section 4.3 provides a guide to data center systems to help operators correctly account for all the systems in their particular data centers.

A data center in a mixed-use building typically shares systems such as lighting, security, various components of HVAC, and various components of electrical distribution. The challenge lies in determining how much of the building’s total energy is required to operate the data center. A common example is a chilled water plant that is shared by all the tenants in the building. Devices such as pumps, chillers, and cooling towers work to remove heat from the entire building. The data center is responsible for a portion of the energy used by these devices, which must be accounted for when calculating PUE. The Green Grid White Paper #14, *The Green Grid Metrics: Data Center Infrastructure Efficiency (DCiE) Detailed Analysis*, provided some high-level guidance on estimating data center efficiency in mixed-use buildings. The intent at the time was to give end users an easy method for driving energy efficiency improvements in their environment without fully instrumenting that environment. This has led to some confusion in the industry regarding communicated PUE numbers and the validity of the reported results. To drive consistent, equitable reporting of PUE, The Green Grid no longer recommends following the examples that used estimation. Instead, The Green Grid has provided a metric called partial PUE (pPUE) for end users who are unable to identify all the energy required to operate their data center but would like to compute the PUE of the environment that they control. (See section VII for more information.)

5.2.1 Shared Energy Sources

Calculating PUE in mixed-use buildings follows the same measurement methodology for calculating PUE in a dedicated data center, with a few noted exceptions. When measuring PUE in a dedicated data center, the total energy necessary to operate the data center is included. In a mixed-use building, the total energy consumption is also included, but when there are shared utilities (e.g., mechanical, electrical distribution, lighting, and other systems), calculating the total energy required to operate the data center can be more difficult. Additional monitoring points may be needed, but the measurement methodology is the same.

5.2.2 Cooling System

Quantifying energy usage in a data center that uses a dedicated air conditioning system is accomplished by directly measuring the associated electrical circuits. Data centers in mixed-use facilities can receive chilled water from a shared chiller plant. In such cases, the cooling system energy can be calculated the same way it is for a dedicated data center that purchases chilled water from the utility: by applying the factors discussed in section 4.9.

The control volume identified for calculating PUE in a dedicated data center is located at the utility hand-off of services. (See Figure 12 below.) The control volume identified for determining PUE in a mixed-use building is similar in that it is at the point of hand-off from the landlord or shared facilities team. The hand-off locations in Figure 13 are the points at which the facility chiller loop (Point A) and facility electrical feed (Point B) come into the data center control volume.

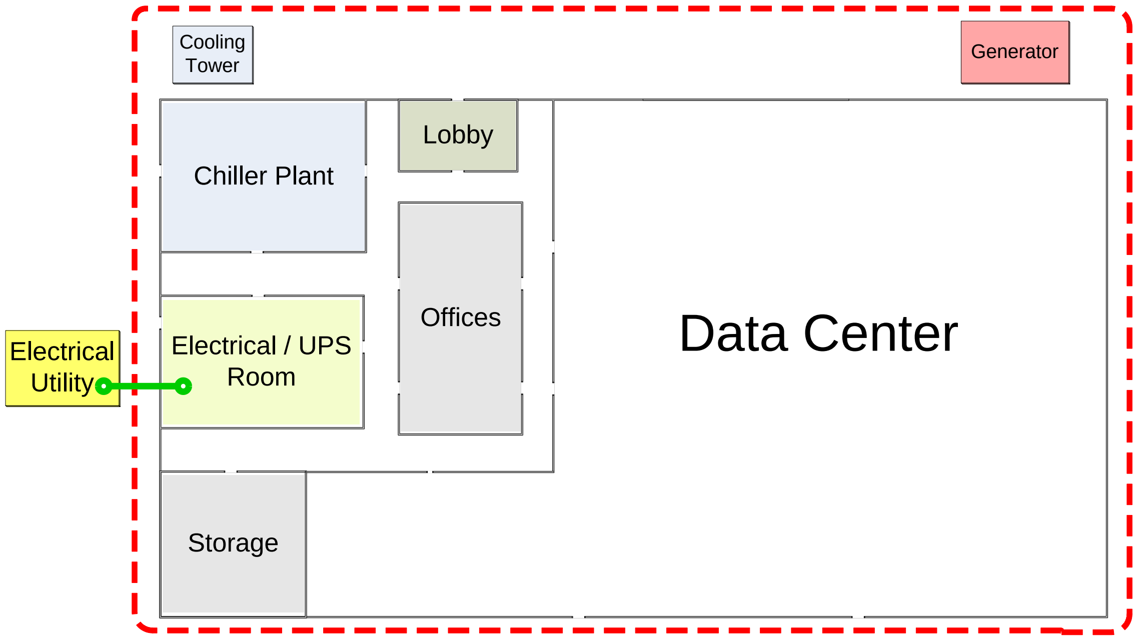

Figure 12. Control volume for a dedicated data center

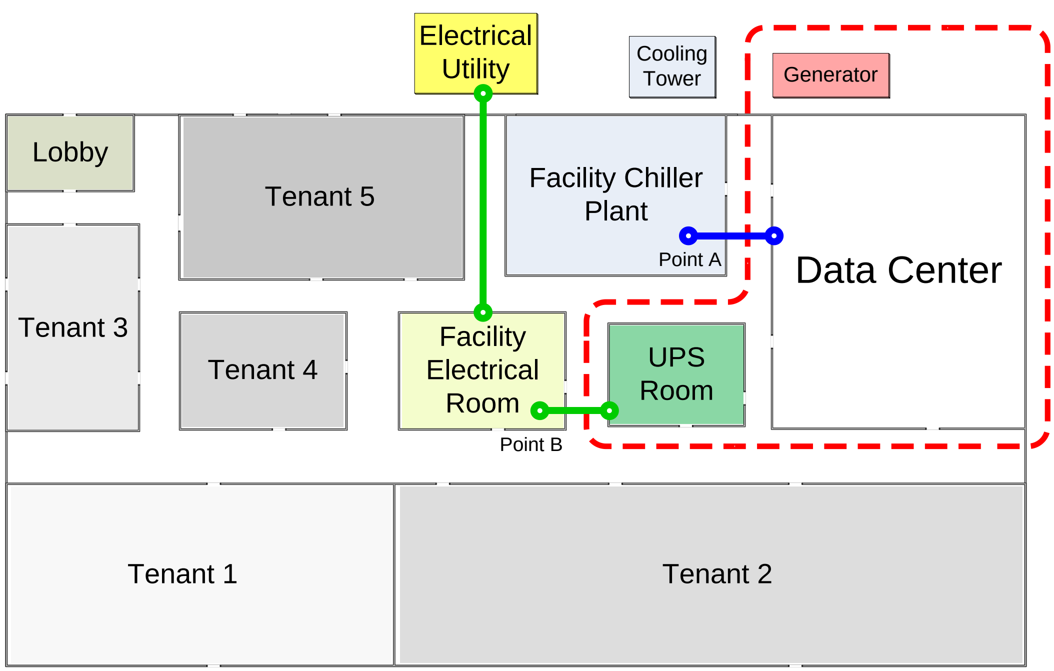

Figure 13. Control volume for a data center within a mixed-use building

Equation 4 illustrates how to quantify cooling system energy use, for a data center that has a shared chilled water plant. A flow meter must be installed in the chilled water supply pipe where it enters or in the return pipe leaving the data center. Temperature sensors must be installed in both the supply and return water pipes.

The flow and temperature data are used in Equation 4, which can be used to calculate the amount of energy removed by a chilled water plant.

Equation 4

$$Q = \frac{VHC \times Flow\ \ Rate \times \Delta T \times Time}{Energy\ \ Conversion}$$

Equation 5

$$VHC = Density\ of\ a\ fluid \times SpecificHeat\ of\ a\ fluid$$

For a shared chilled water example:

Q = energy from heat captured by chilled water, in megawatt-hours (MWh)

VHC = Volumetric Heat Capacity, a fluid property that is typically used in chilled water plants. VHC for any fluid mixture can be calculated by using Equation 5. Note that the VHC value for chilled water is different than the VHC value for water/glycol mixes, and fluid temperature affects the VHC value.

Flow Rate = chilled water flow rate (e.g., cubic meters per second (m^3/s) or gallons per minute (gpm))

ΔT = temperature difference between the chilled water supply and return (Kelvin for SI, Fahrenheit for English)

Time = period of time for energy measurement (using the same time base as the denominator of Flow Rate)

Energy Conversion = standard conversion necessary to change energy units from Joules or Btu to MWh

Example using chilled water and English units:

VHC = 8.34 lb/gallon x 1.0 Btu/(lb·°F)

VHC = 8.34 Btu/(gallon·°F)

Flow Rate = 47.55 gpm

ΔT = 9 °F

Time = 1 year = 525,600 minutes

Energy Conversion = 3,412,141 Btu/MWh

Q = 549.78 MWh

Example using chilled water and SI units:

VHC = 1,000 kg/m^3 x 4,184 J/(kg·°Kelvin)

VHC = 4,184,000 J/(m^3·°Kelvin)

Flow Rate = 0.003 m^3/s

ΔT = 5 °C = 5 °Kelvin

Time = 1 year = 31,536,000 seconds

Energy Conversion = 3,600,000,000 J/MWh

Q =549.78 MWh

Figure 14. Examples for calculating annual data center cooling energy with shared chilled water (equivalent examples in both English and SI units)

The data center cooling system energy (Q) must now be multiplied by the global or U.S. source energy weighting factor for chilled water. Equation 6 below uses the global value of 0.4 as the weighting factor for chilled water.

Equation 6 shows the formula for estimating shared chiller plant source energy consumption.

Equation 6

$$Chiller\ \ Plant\ \ Source\ \ Energy = Q \times 0.4$$

Where flow rates and temperatures cannot be measured, The Green Grid recommendation is to proceed with calculating a partial PUE. (See section VII.)

5.2.3 Power System

Most data centers use a dedicated UPS and power distribution system. However, for data centers that share these resources in a mixed-use building and where the data center operator is unable to measure the environment's energy consumption and efficiencies, the recommendation is to proceed with calculating a partial PUE. (See section VII.)

5.2.4 Other Shared Energy Resources

In most cases, data centers inside a mixed-use building do not use any shared energy resources other than chilled water and electricity. However, there may be times when shared energy such as steam, natural gas, fuel oil, etc. is used in the operation of a data center. In such cases, the energy use from a shared resource can be quantified by using the global or U.S. source energy weighting factors. (See Table 5 and Table 6.) As in the case of a shared chilled water plant, the shared resource energy consumed by the data center is measured and converted to either kWh or MWh, then multiplied by the weighting factor, as illustrated in Equation 7.

Equation 7 shows the formula for calculating source energy consumption from any shared energy resource.

Equation 7

$$Source\ Energy = Shared\ Resource\ Energy \times Weighting\ Factor$$

5.2.5 Shared Resources that may be Excluded

Indicated previously there are a few exceptions to the methodology for calculating PUE in a mixed-use building versus a dedicated data center. Due to the monitoring complexity and the small effect of some ancillary energy sources, The Green Grid states the following ancillary energy loads can be excluded from the PUE calculation in a mixed-use building.

The noted exceptions to calculating PUE in a mixed-use building are:

- Energy required for shared support spaces (ancillary energy loads):
  - Shared offices
  - Shared labs
  - Shared cubicles
  - Shared conference rooms
  - Shared elevators
  - Shared lobbies
  - Shared kitchens/break rooms

The shared elevator is one example to illustrate the rationale for the above noted exceptions. A data center can be a small portion of one floor located on one level of a multistory building. The data center is located on the 5th floor of a 10-story building. The 5th floor is also mixed-use with many business services and a data center. The effort to implement energy measurements on the shared elevator and the effort to try to quantify how much of that energy should be allocated to the data center traffic on the 5th floor is believed to be a point of diminishing returns. The proportional load for the elevator is insignificant in the PUE calculation. The primary reasons for The Green Grid's statement that these shared ancillary energy loads can be removed are as follows:

- The actual proportional load is insignificant in the PUE calculation
- A large effort (time, money, resource) is required to calculate these ancillary loads
- A large effort is required to ensure that each example across the globe is equitably calculated
- Point of diminishing returns

Energy consumption of all dedicated space is to be included. As an example, if there are offices or cubicles that are dedicated to the data center operations, the energy consumption should be included. Provided the above direction is followed, PUE reporting of data centers within mixed-use buildings follow the same nomenclature as PUE reporting of dedicated data centers.

VI. How to Report PUE

As the current infrastructure metrics promoted by The Green Grid have become more widely adopted, questions have arisen as to how to interpret individual results, compare different results for the same data center, and compare results across different data centers. Additionally, because there are various ways to calculate results, stakeholders in the industry have expressed concerns around the consistency and repeatability of publicly reported measurements. The Green Grid has published a set of PUE-related rules and guidelines and a required process that organizations should follow when making public claims as to their data centers' PUE measurements. This set includes the definition of standard nomenclature that will enable individual claimants to communicate key information about their measurements. With proper, transparent public reporting guidelines and the availability of key information about reported results, both the credibility and usefulness of The Green Grid metrics will be enhanced.

As more and more organizations report the performance of their data centers in terms of PUE, The Green Grid is seeing industry stakeholders and followers begin to compare and contrast different data centers. Each data center has individual characteristics, capabilities, and operational policies that affect its performance. Each data center also has different capabilities with respect to collecting and analyzing energy consumption data. Without additional information about the reported results, interpretations of data collected by different organizations using different approaches over different timeframes may be meaningless or misleading.

In addition to concerns about comparing different data centers' results, the industry also has expressed a desire for a certain amount of quality control. When an organization reports PUE data, industry followers and stakeholders want a degree of assurance that the information as presented is meaningful.

The following section addresses PUE reporting issues and provides a set of steps that organizations can follow should they wish to have The Green Grid acknowledge their publicly reported metric data, to register that data with The Green Grid, and/or to participate in any future data center performance awards programs or promotional activities as a result of their data centers' performance. These steps include submitting a report to The Green Grid that supports and describes specific claims. The Green Grid supports that process by providing means for organizations to submit and register their results for official recognition.

This section also provides nomenclature to enable an organization reporting results to communicate the manner in which, and over what timeframe, the data was collected. In addition, it discusses some common issues in calculating and reporting that make interpretation difficult and explains how to avoid those issues when reporting PUE results and making claims.

6.1 REQUIREMENTS FOR THE ACKNOWLEDGEMENT OR REGISTRATION OF PUE RESULTS

The following discussion considers only those data centers that are reporting measurements of their actual operating conditions. Many published PUE numbers are not measurements, but rather estimates made by engineers for hypothetical conditions, such as for data centers under construction or for IT loads other than the actual IT loads. These projections, while useful, are not considered measurements or results under The Green Grid guidelines. The Green Grid classifies publicly reported PUE results using four categories: Unrecognized, Reported, Registered, and Certified. Table 7 below provides descriptions of these categories, along with their expected benefits to reporting organizations.

Table 7. The Green Grid's classification of publicly reported metrics results

Classification	Description	Benefit to Reporting Organization
Unrecognized	A publicly reported result with no claims of following The Green Grid's guidelines. The Green Grid will not comment on Unrecognized results.	
Reported	A publicly reported result by a reporting organization that claims it followed The Green Grid's measurement recommendations and nomenclature guidelines. The Green Grid will not comment on Reported results.	The reporting organization can use standard materials from The Green Grid to explain its process and results to an audience.
Registered	A publicly reported result, with key contextual data provided to The Green Grid by the reporting organization, using The Green Grid's data center performance database.	Official registration of a reported result. Receipt of a registration number from The Green Grid. Link to public report data from The Green Grid's website.

Classification	Description	Benefit to Reporting Organization
Certified	A publicly reported result, with key additional data required for third-party validation or certification of results, provided to The Green Grid by the reporting organization.	All benefits applicable to Registered results, plus consideration of reported results in future TGG awards or recognition programs.

The Unrecognized classification consists of reported results where the reporting organization has not provided any additional detail as to how and for how long the data was collected or the granularity with which the result's individual data points were collected. While The Green Grid applauds any attempt to measure or calculate PUE, it will not comment on Unrecognized publicly reported figures. Accordingly, The Green Grid places no requirements on, nor has any specific recommendations for, Unrecognized results.

The second classification consists of those results where the reporting organization has reported using the nomenclature provided in this section and has self-certified that it has followed the measurement methodology for PUE defined by The Green Grid throughout this document. The Green Grid will not recognize Reported results and will not provide any additional comment on them. Reported results also will not be specifically referred to within The Green Grid's website.

The third classification consists of those results The Green Grid considers Registered. In order to register results with The Green Grid, the reporting organization must provide additional data to The Green Grid about the results being reported, in addition to providing those items required for The Green Grid to recognize the results. The additional data and items help set the context of the reported result as well as provide key information that The Green Grid will use in analyzing and commenting on overall industry performance and data center energy efficiency trends. Supporting Data Required for Reported, Registered, and Certified PUE (section 6.3) below provides initial examples of the data that The Green Grid is requesting; over time, The Green Grid expects to refine this data set. Please refer to The Green Grid website[16] for the most up-to-date

[16] www.thegreengrid.org/en/Global/Content/Tools/PUEReporting

information on specific data elements and also to register PUE results and data with The Green Grid. The Green Grid will provide the reporting organization with a registration number for those results that meet the registration requirements. Table 8 below summarizes The Green Grid's requirements for registration of results.) This registration number may be used in any public document to verify that the organization has met The Green Grid's requirements.

Table 8. Additional requirements for Registered results

Report measurement data and enter the required information (listed in section 6.3 of this document) into The Green Grid's Metrics Data Collection Database (www.thegreengrid.org/register/pue-reporting-form.aspx).
Agree to The Green Grid's metric public reporting consent form. (Please see www.thegreengrid.org for the most current version.)
Report to The Green Grid (email mailto:admin@lists.thegreengrid.org) any issues or difficulty in following The Green Grid's prescribed process and guidelines.

The last classification of results, Certified, has the most stringent data-reporting requirements. In addition to those items required for registration of a result, organizations wishing to qualify for inclusion in any program created by The Green Grid to award or recognize data center energy efficiency must meet further data requirements (such as those in Table 9 below). The Green Grid will also require copies of original source materials or publications necessary to validate the claim.

Table 9. Additional requirements for Certified results

If requesting a Certified Public Measurement Value, enter the extended data set information into The Green Grid's Metrics Data Collection Database (www.thegreengrid.org/register/pue-reporting-form.aspx).
If interested in co-promotion with The Green Grid, send the PUE registration number, along with a link to any original source material or publication, to The Green Grid at mailto:admin@lists.thegreengrid.org.

The Green Grid will provide information about proposed or active PUE recognition programs on an ongoing basis through its website, www.thegreengrid.org.

6.2 PUE NOMENCLATURE

6.2.1 Standard Construct for Communicating PUE Measurements

In order for a reported PUE to be meaningful, the reporting organization should provide additional information about the data collection process. This includes information about the manner in which the data was collected, the type of equipment from which the data was collected, the timeframe covered by the reported value, and the frequency with which individual data points were collected.

Organizations should provide this information by appending a subscript to the name of the metric being reported. For example, PUE would be reported and formatted as $PUE_{a,b}$ where "a" describes the measurement's metering placement level (see section 6.2.2) and "b" describes the measurement frequency and averaging period.

6.2.2 PUE Data Collection Metering Placement Methodology

Data collection metering placement is described as Level 1, Level 2, or Level 3, according to the definitions provided in Table 1 and Table 3. The appropriate level number should be included as part of the metric's subscript. For example, a PUE of 1.5 would be reported as 1.5 $PUE_{L1,\ b}$ if Level 1 (basic meter placement) were employed. The following section describes the "b" term, the averaging period and measurement frequency. Note: To report Level 1, Level 2, or Level 3, the required measurement location for that level must be used. For example, Level 2 must be measured at the PDU output and utility input. If measurements are made using power (versus energy), then the "measurement interval" is also required to report a certain level.

6.2.3 Reporting PUE Data Measurement Frequency and Averaging Period

The second subscript, "b," in a $PUE_{a,b}$ report describes the frequency with which individual data points were collected. The subscript is created by appending a character denoting the averaging period and a character denoting the data collection frequency onto the reported metric.

- The following choices for subscript nomenclature refer to the averaging period:
  - "Y" denotes a measurement averaged over a year
    - Measurement frequency must be "M" (monthly), "W" (weekly), "D" (daily), or "C" (continuous)
  - "M" denotes a measurement averaged over a month
    - Measurement frequency must be W, D, or C
  - "W" denotes a measurement averaged over a week
    - Measurement frequency must be D or C

- “D” denotes a measurement averaged over a day
    - Measurement frequency must be D or C
- The following choices for subscript nomenclature refer to the data collection frequency:
  - “M” denotes a measurement taken monthly
    - Averaging period must be yearly
  - “W” denotes a measurement taken weekly
    - Averaging period must be no less than monthly
  - “D” denotes a measurement taken daily
    - Averaging period must be no less than weekly
  - “C” denotes a measurement taken continuously (every 15 minutes or less)
  - “—“ denotes a single measurement (averaging period not used)

Except for measurements taken continuously, all measurements must be taken at roughly the same time of day. For example, a PUE of 1.5 would be reported as 1.5 $PUE_{a,WD}$ if daily measurements were taken and a weekly PUE average is being reported.

6.2.4 PUE Reporting Examples

Given the construct above, Table 10 provides examples of specific reports and their interpretation.

Table 10. PUE reporting examples

Sample PUE Report	Interpretation
2.25 $PUE_{L1,-}$	Single PUE measurement (2.25) taken using a Level 1 meter placement
1.95 $PUE_{L1,YM}$	Yearly average PUE (1.95), using data points gathered monthly with a Level 1 meter placement
1.6 $PUE_{L1,MW}$	Monthly average PUE (1.6) using data points gathered weekly with a Level 1 meter placement
2.43 $PUE_{L1,WD}$	Weekly average PUE (2.43), using data points gathered daily with a Level 1 meter placement

Sample PUE Report	Interpretation
1.8 PUE $_{L2,WC}$	Weekly average PUE using data points gathered continuously with a Level 2 meter placement
2.1 PUE $_{L3,YC}$	Yearly average PUE (2.1) using continuous measurements with a Level 3 meter placement

6.3 SUPPORTING DATA REQUIRED FOR REPORTED, REGISTERED, AND CERTIFIED PUE MEASUREMENTS

The Green Grid has developed a database for recording key data center information as well as measurement results and contextual information about those results. This section uses four lists to describe the kinds of information contained in that database. The first list (section 6.3.1) is The Green Grid's required data to support public PUE claims (Reported, Registered, and Certified). The second list (section 6.3.2) gives examples of required data for the Certified classification, which is necessary to qualify for TGG recognition awards. The third list, in section 6.3.3, gives examples of optional data that a reporting organization may choose to provide. The fourth list, in section 6.3.4, is The Green Grid's assessment of what will be publicly available for reported measurements. (The acknowledged measurements are referred to by The Green Grid registration number issued). For a current list of reporting requirements, visit www.thegreengrid.org/register/pue-reporting-form.aspx. The web page/site that captures this information will provide final details, as it is expected that data center owners and operators will provide inputs to the content and process to fine-tune them.

6.3.1 Examples of Data Required for a Publicly Reported, Registered, or Certified PUE Measurement

- Contact information
  - Note: Only the organization's name will be displayed in public inquiries.
- Data center location information (address)
  - Note: Only region or state information will be displayed in public inquiries.
- Measurement results: PUE with appropriate nomenclature
- Measurement methodology information (when, how, and result details)

6.3.2 Additional Data Required for Certified Results (optional for Reported or Registered measurements)

- Certification method used (contractor information and results)

6.3.3 Optional Data Examples

- Data center size (facility square footage)
- Total data center design load for the facility (e.g., 10.2 megawatt)
- Data center workload percentages (e.g., 20% web hosting, 80% email)
- Data center age
- Numbers of servers, routers, and storage devices
- Average server CPU utilization
- Percentage of servers using virtualization
- Average age of IT equipment by type
- Average age of facility equipment by type (cooling and power distribution equipment)
- Data center level of reliability
- Cooling and air-handling details

6.3.4 Publicly Viewable Data When a Registration Number is Researched on The Green Grid Site

- Registration number and issue date
- Organization's name and region or state
- Measurement results: PUE with appropriate nomenclature
- Date measurement(s) was completed
- Data center size (facility square footage if available)
- Link to additional user information if available (providing this is optional for the reporting organization)

For a current list of transparent data, visit www.thegreengrid.org/register/pue-reporting-form.aspx.

6.4 ADDITIONAL DETAILS ON THE PUE REPORTING GUIDELINES

6.4.1 Data Collection and Metrics Calculations

The Green Grid provides instructions throughout this document for several approaches to collecting energy consumption data and calculating PUE. Differentiated by their expected accuracy, these options are necessary to account for the different capabilities and maturity levels present in the industry's data centers. See Table 1 and Table 3 for descriptions of the Level 1 (L1), Level 2 (L2), and Level 3 (L3) approaches.

6.4.2 Reporting Result Timescale and Data Collection Details

Given that PUE incorporates data pertaining to both power distribution losses and the energy required by cooling equipment, PUE will vary over the course of a year, month, or even day. In order to be meaningful, public PUE reports must contain information as to the timeframe covered by the calculation, as well as the frequency with which data was collected. Timeframes can be a year, a month, a week, a day, or even a single measurement. Individual data points comprising the calculation should be collected either monthly, weekly, daily, or continuously.

Some combinations of data collection frequency and measurement level are not allowed. Level 1 calculations must be based on data collected no less frequently than monthly. Level 2 calculations require individual data points to be collected at least daily. Level 3 calculations require data to be collected continuously. (Note that "continuously" in this context is defined as data sets where individual data points are collected every 15 minutes or less.)

6.5 REPORTING RESULTS TO THE GREEN GRID

The Green Grid provides a portal[17] for organizations to record information about a specific PUE report and the data center about which the organization is making the claim. The initial data elements required for the report are listed in section 6.3. The Green Grid encourages the adoption of these standard methodologies for reporting and use as well as the submission of that data to The Green Grid's Metrics Data Collection Database. Background data about any reporting organization's results will, at its discretion, be kept anonymous. Benefits of submission include:

- Increased credibility for reported results
- Potential recognition of improvements made by the reporting organization to its PUE measurements
- Participation in an industry-driven process to improve these metrics and their associated measurement processes

6.6 COMMON ISSUES WITH REPORTING OR INTERPRETING PUE

As public and private discussions of PUE results have become more common, The Green Grid has seen a number of common misunderstandings with regard to the calculation and interpretation of PUE results. Professionals making claims should be aware of the following issues and ensure they are reporting valid numbers prior to making any public claims.

[17] www.thegreengrid.org/register/pue-reporting-form.aspx

6.6.1 Infrastructure Versus IT

A common problem with collecting and reporting data is determining how energy consumption should be allocated to the numerator or denominator of the PUE calculation. Each load in a data center must be designated as either an IT load, an infrastructure load, or not included in the calculation. Many data centers are in mixed-use buildings where there are significant office or other loads that are not related to the data center function; such buildings also may have shared systems such as cooling towers, switchgear, or ventilation systems. In these cases, it is necessary to explicitly describe how the loads have been incorporated into the calculation. The Green Grid has established standards and guidelines for PUE calculations, which enable meaningful comparison of results between data centers—dedicated and mixed-use facilities alike. For the purpose of improving a single, specific data center, what remains important is not the exact allocation of shared loads to the PUE calculation, but rather that the calculations be performed in a consistent manner.

6.6.2 Energy or Power

The Green Grid defines PUE as an *energy* metric and recommends that it be reported as such. For more on this, please see the discussion about energy and power in section 4.10 of this document.

6.6.3 "Better-than-Perfect" PUE Measurements

With the increased frequency of PUE reporting and discussion, The Green Grid has occasionally taken note of reported results that appear to be better than perfect, where PUE is less than 1.0. Since power distribution losses and cooling equipment energy consumption will always take positive values, PUE can never be less than 1.0.

The PUE metric incorporates three basic elements: energy delivered to IT equipment, energy lost in power distribution within the data center, and energy required by the cooling architecture. PUE does not receive a "credit" for waste heat repurposed within a larger facility. (See The Green Grid's White Paper #29, *ERE™: A Metric for Measuring the Benefit of Reuse Energy from a Data Center,* for more information on energy reuse effectiveness.[18]) Although energy reuse may be highly commendable, including those practices in the overall PUE calculation obfuscates results.

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[18] www.thegreengrid.org/~/media/WhitePapers/ERE_WP_101510_v2.ashx?lang=en

The Green Grid believes that issues such as cogeneration, waste heat reuse, and local generation of electricity should be considered in separate metrics. While important, these issues are outside the scope of improving the efficiency of the local power distribution and cooling architectures.

**** IN ANY OFFICIAL REPORTS TO THE GREEN GRID, PUE MEASUREMENTS LESS THAN 1.0 WILL AUTOMATICALLY BE REJECTED. ****

6.6.4 Comparing Results Calculated over Different Timeframes at Different Granularity Levels

Without some indication as to the time over which particular results were calculated or the frequency with which individual data points were collected, comparison of results is difficult. A yearly average of PUE measurements taken monthly with 12 data points has a different meaning than a single power reading collected during a data center's peak load on the coldest day of the year.

In general, the timeframe over which a particular result is calculated should correspond to the level of detail or the specific data center issues being studied. Yearly results are good for understanding infrastructure performance at a high level, but they will not be helpful in understanding how data center performance varies throughout the year. Monthly calculations are good for understanding how the data center varies over the course of a year, but they will not pick up behaviors occurring on a weekly basis. Daily or continuous measurements can provide useful insights as to how a data center handles short-term or rapid changes to various internal and external conditions.

In addition, the accuracy of a result will be partially determined by the frequency with which individual data points were collected and the number of individual data points in the result. A weekly result that is a rollup of power data collected daily will be different depending upon the time of day the data was collected. Daily variance issues can be addressed with more frequent individual measurements.

6.6.5 Comparing PUE Results Among Data Centers

As mentioned earlier in this document, PUE is an excellent metric for understanding how well a data center is delivering energy to its IT equipment, and the metric is best applied for looking at trends in an individual facility over time and measuring the effects of different design and operational decisions within a specific facility.

The Green Grid generally discourages comparisons of different data centers based only on public reports of PUE results. However, with standardized PUE nomenclature, proper and transparent public reporting guidelines, and the availability of key information about reported results, both the credibility and usefulness of the PUE metric will be enhanced. To further enable equitable comparison of PUE results among data centers, attributes, such as age, geographic location, capacity loading, size of facility, and the like, should be taken into consideration. Provided the measurement guidelines, reporting guidelines, and the additional data attributes (as mentioned above) are obtained, The Green Grid believes PUE can be used to compare data center infrastructure efficiency.

VII. Partial PUE

While PUE is a valuable tool, it can be used incorrectly. A common misuse is when an organization that calculates PUE only considers part of the overall PUE equation. Recall that PUE is formally defined as the total facility energy divided by the IT equipment energy. In this context, the total needs to take into account all uses of energy necessary to operate the IT equipment. Often, some elements of energy use are left out of a PUE calculation because of the focus on a particular portion of the facility, for marketing reasons, or simply because some aspects of facility energy use are difficult to measure. This is the situation for which The Green Grid designed the partial PUE (pPUE) metric.

One example of a scenario in which it is more appropriate to calculate pPUE than overall PUE is when considering a data center design that uses containerized/modular data center facilities (CMDFs). A CMDF might seem to be an all-in-one solution but is often missing some key facilities components. For example, a data center container may hold several hundred servers, a UPS, and several heat exchangers or in-row coolers. A PUE value that is calculated by dividing the total energy delivered to the container by the total IT energy used within the container will be missing the contributions made by components outside the container. These may include the energy required to deliver chilled water to the heat exchangers or the energy loss associated with external transformers and switchgear.

Another example of the misuse of the PUE metric can be seen when an organization evaluates only a portion of its data center facility, such as just the cooling infrastructure. In many data centers, the energy required to deliver cooling is the major infrastructure cost and is subject to the closest scrutiny by management. It can be tempting to compute the PUE metric by taking into account only the IT energy load and the energy associated with the cooling—in order to gain management visibility into the cost of that cooling—while ignoring other components of the total energy that are considered to be overhead, such as lighting, UPS losses, transformer losses, etc. Although it is worthwhile to pay attention to the efficiency of the cooling, that is not a formally correct use of the PUE metric.

In certain cases, despite the best intentions, it might not be possible to calculate a correct PUE because some necessary data is unavailable. This can be common in a mixed-use or colocation facility where cooling may be provided by chilled air that is also supplying other tenants or other cooling purposes in the building. Similarly, power distribution in a mixed-use facility may preclude the sub-metering necessary for a full, accurate measurement of the energy use for the data center facility and IT components.

The Green Grid developed the pPUE metric to prevent the misuse of the PUE metric but still allow the use of PUE-style calculations when they are useful. By using pPUE, rather than PUE, facility designers, managers, and others can take advantage of PUE-style calculations even when all facility components are not included in the calculations.

Note that pPUE should not be considered a substitute for a complete PUE evaluation. It is always best to develop a comprehensive PUE model in order to fully understand a facility and manage it with complete knowledge of all components. Furthermore, as with PUE, pPUE is a metric best used as a tool for management, rather than for making comparisons with other facilities.

7.1 DEFINITION OF PARTIAL PUE

The definition of pPUE is intuitive for anyone who is familiar with PUE. Whereas the PUE metric includes all energy-using components within a ***facility,*** pPUE includes all energy-using components within a ***boundary.*** A boundary can be a physical designation such as a container, room, modular pod, or building. It also can be a logical boundary such as equipment owned by a department or a customer, owned versus leased equipment, or any other boundary that makes sense for the management of the assets. For the sake of discussion below, the area enclosed by a boundary is referred to as a ***zone***.

It should be noted that a PUE calculation uses the IT energy as the denominator in a fraction and is thus undefined if the IT energy in a zone is zero. Since the reason for a pPUE calculation is to provide a metric of the efficiency of delivering energy and cooling to IT equipment, pPUE has no meaning for a zone that contains no IT equipment. Such a zone would more appropriately be accounted for as overhead.

Figure 15 below shows a sample data center zoning configuration for purposes of discussing pPUE and its relationship to PUE.

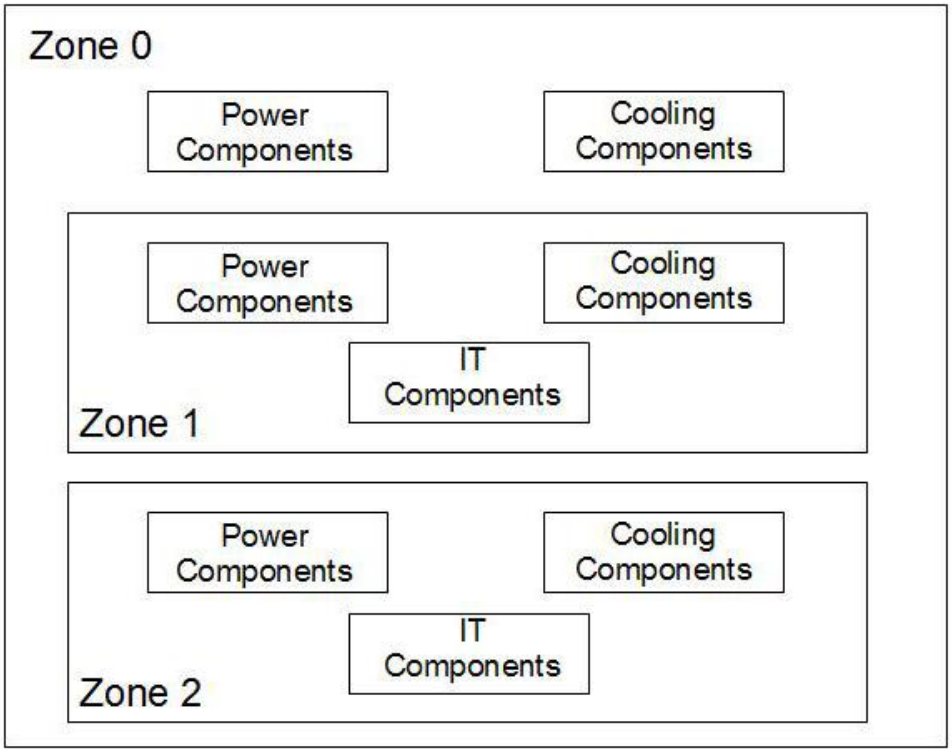

Figure 15. Boundaries and zones in a sample data center facility

Equation 8 shows how inside each boundary that contains IT equipment, pPUE is defined as:

Equation 8

$$pPUE = \frac{Total\ energy\ inside\ the\ boundary}{Total\ IT\ equipment\ energy\ inside\ the\ boundary}$$

In the example of Figure 15, the pPUE of Zone 1 will be calculated based only on the components contained in that zone. If some notations are defined as follows in Equation 9 and Equation 10:

Equation 9

$$I_i = The\ total\ IT\ equipment\ energy\ inside\ Zone\ i$$

Equation 10

$$N_i = The\,total\ non\text{-}IT\ equipment\ energy\ inside\ Zone\ i$$

Then Figure 15 turns into Figure 16:

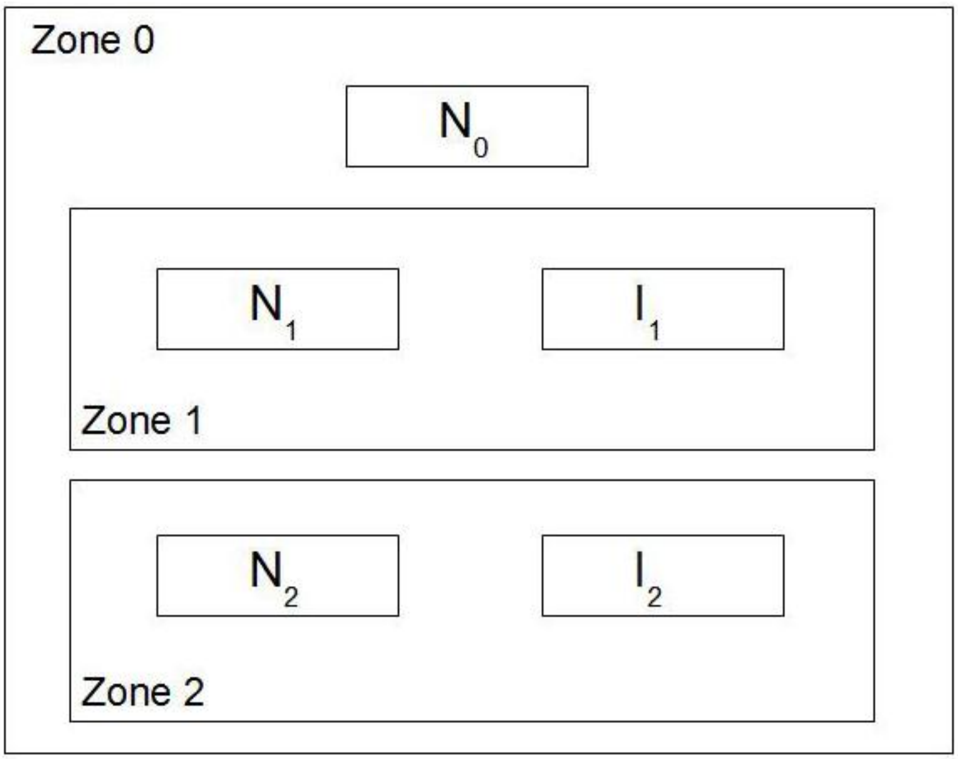

Figure 16. IT and non-IT energy in example zones

The pPUE calculations for Zones 1 and 2, as shown in Equation 11, would be:

Equation 11

$$pPUE_1 = \frac{N_1 + I_1}{I_1} \quad \text{and} \quad pPUE_2 = \frac{N_2 + I_2}{I_2}$$

7.2 MATHEMATICAL RELATIONSHIP TO PUE

To understand the relationship of PUE to pPUE, the PUE for the example in Figure 16 can be manipulated into a different form. The total facility PUE, shown in Equation 12, would be:

Equation 12

$$PUE = \frac{N_0 + N_1 + N_2 + I_1 + I_2}{I_1 + I_2}$$

Regrouping terms yields Equation 13:

Equation 13

$$PUE = \frac{N_0}{I_1 + I_2} + \frac{N_1 + I_1}{I_1 + I_2} + \frac{N_2 + I_2}{I_1 + I_2}$$

Shown in Equation 14, the pPUEs for Zones 1 and 2 are:

Equation 14

$$pPUE_1 = \frac{N_1 + I_1}{I_1} \quad and \quad pPUE_2 = \frac{N_2 + I_2}{I_2}$$

Multiplying each of these equations by their denominators yields Equation 15:

Equation 15

$$I_1 * pPUE_1 = N_1 + I_1 \quad and \quad I_2 * pPUE_2 = N_2 + I_2$$

Substituting Equation 15 into Equation 13 yields Equation 16:

Equation 16

$$PUE = \frac{N_0}{I_1 + I_2} + \frac{I_1 * pPUE_1}{I_1 + I_2} + \frac{I_2 * pPUE_2}{I_1 + I_2}$$

Equation 17 shows that if a ratio of the IT energy in Zone i is defined as a proportion of the total IT energy, then:

Equation 17

$$r_i = \frac{I_i}{I_1 + I_2}$$

Substituting that into Equation 16 yields Equation 18:

Equation 18

$$PUE = \frac{N_0}{I_1 + I_2} + r_1 * pPUE_1 + r_2 * pPUE_2$$

The way to understand Equation 18 is that PUE is the overhead seen by all zones, plus the pPUE of each zone, times the percentage of that zone's contribution to the overall IT load. This understanding allows facilities managers to use the pPUE of each zone as a contributor to the overall PUE. Although this mathematical derivation may seem obscure, it provides a helpful way of using pPUE to manage facilities.

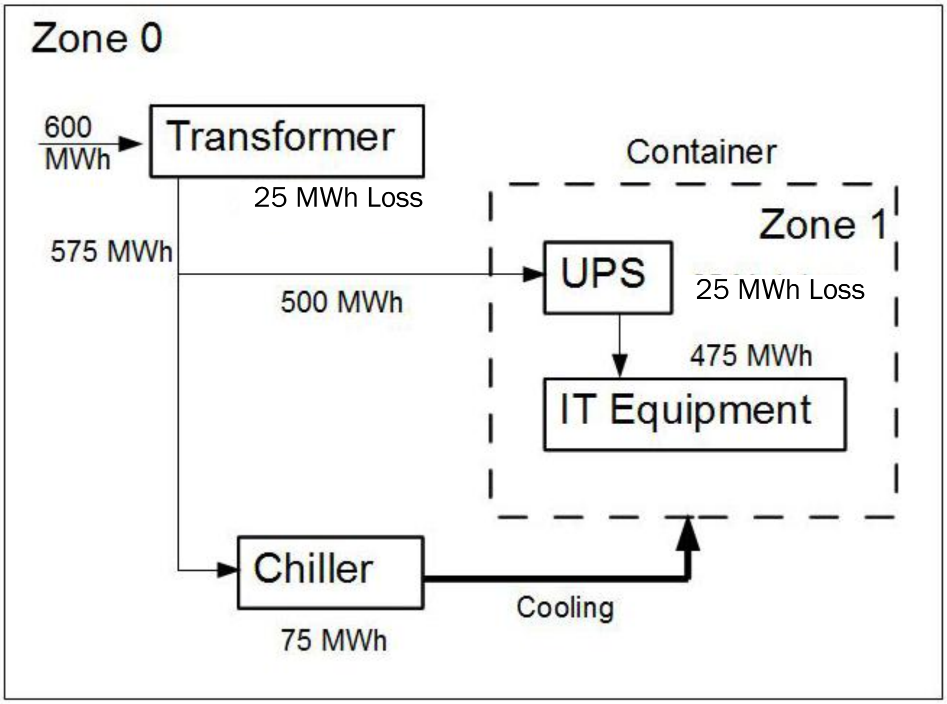

Figure 17. Partial PUE Usage Example 1

Figure 17 shows a simple example in which Zone 1 is a containerized data center and includes a UPS that is 95% efficient. Zone 0 represents the surrounding infrastructure necessary to support the containerized data center and includes a transformer and a chiller. The chiller uses 75 megawatt-hours (MWh) of energy per year to cool the equipment in the container, which uses 500 MWh of energy. The total energy delivered to the transformer is 600 MWh. The transformer is approximately 96% efficient. There is no Zone 2 in this example.

As in Figure 16, Figure 17's energy usage can be grouped such that:

N_0 = 25 (transformer) + 75 (chiller) = 100

N_1 = 25 (UPS)

I_1 = 475 (IT)

Using Equation 11, the pPUE of Zone 1 ($pPUE_1$) would be = (25 + 475) / 475 = 1.05. Using Equation 12, the PUE in this example would be = (100 + 25 + 475) / 475 = 600 / 475 = 1.26. This example is a practical one to keep in mind when hearing quotes for PUE in the range of 1.05 or a similarly small number. It is often the case that what is really being presented is the partial PUE of a particular zone such as a containerized data center.

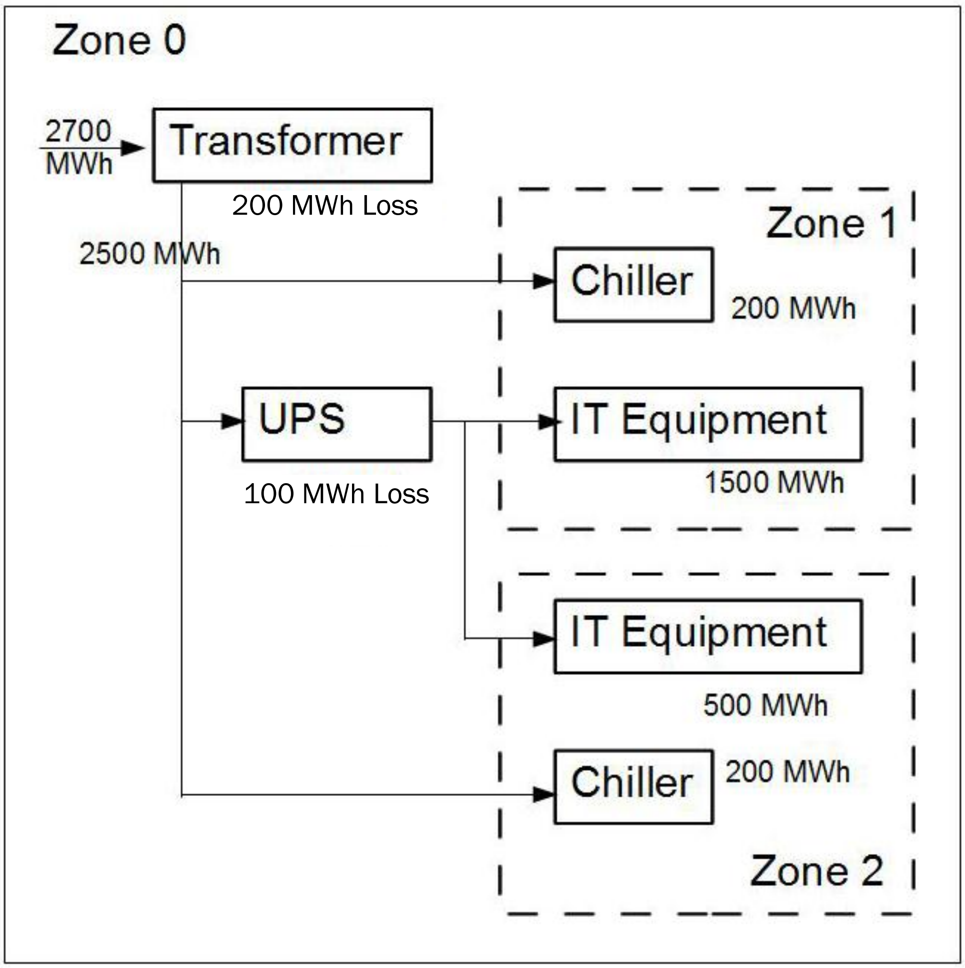

Figure 18. Partial PUE Usage Example 2

The example in Figure 18 shows Zones 1 and 2 as being two separate server rooms. Zone 1 contains IT equipment that consumes 1,500 MWh per year and a chiller that consumes 200 MWh per year. Zone 2 contains only 500 MWh of IT load but has the same chiller as Zone 1, which is providing too much cooling and is wasteful. The UPS is approximately 95% efficient and consumes 100 MWh while delivering power that is split among the IT loads in Zones 1 and 2. Zone 0 has a transformer that is approximately 93% efficient.

The usage in Figure 18 can be grouped similarly to Figure 16:

N_0 = 200 (transformer) + 100 (UPS) = 300

N_1 = 200 (chiller)

I_1 = 1500 (IT)

N_2 = 200 (chiller)

I_2 = 500 (IT)

Using Equation 11, Equation 12, and Equation 17 yields the following:

PUE = (300 + 200 + 200 + 1500 + 500) / (1500 + 500) = 2700 / 2000 = 1.35

$pPUE_1$ = (200+ 1500) / 1500 = 1.13

$pPUE_2$ = (200 + 500) / 500 = 1.40

r_1 = 1500 / (1500 + 500) = 0.75

r_2 = 500 / (1500 + 500) = 0.25

In the Figure 18 example, there is major inefficiency due to over-cooling in Zone 2, which is clear from the higher pPUE for Zone 2 relative to Zone 1.

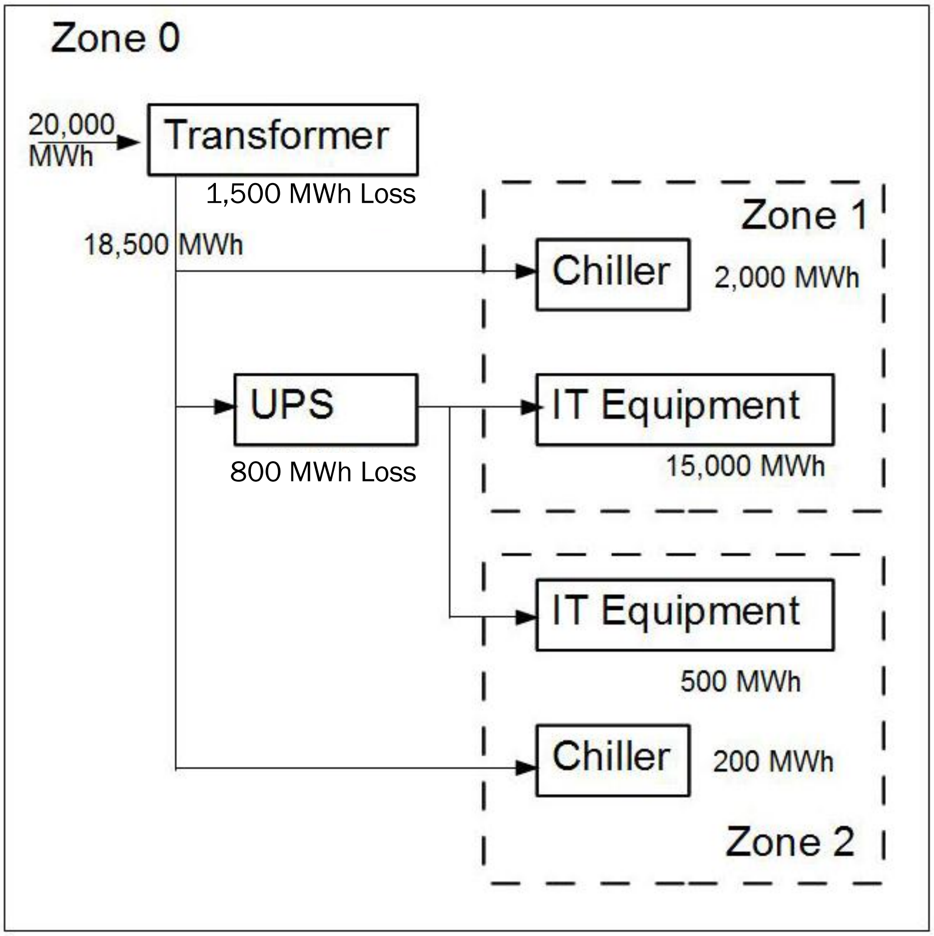

Figure 19. Partial PUE Usage Example 3

The example in Figure 19 is similar to the one in Figure 18 except that the load from the IT and chiller equipment in Figure 19's Zone 1 has been increased by a factor of 10. Zone 2 is unchanged in this example, and the equipment in Zone 0 has been appropriately scaled to the same efficiency as in Figure 18.

The power usage in Figure 19 can be grouped similarly to Figure 16:

N_0 = 1,500 (transformer) + 800 (UPS) = 2,300

N_1 = 2,000 (chiller)

I_1 = 15,000 (IT)

N_2 = 200 (chiller)

I_2 = 500 (IT)

Using Equation 11, Equation 12, and Equation 17 yields the following:

PUE = (2,300 + 2,000 + 200 + 15,000 + 500) / (15,000 + 500) = 20,000 / 15,500 = 1.29

$pPUE_1$ = (2,000 + 15,000) / 15,000 = 1.13

$pPUE_2$ = (200 + 500) / 500 = 1.40

r_1 = 15,000 / (15,000 + 500) = 0.97

r_2 = 500 / (15,000 + 500) = 0.03

In this Figure 19 example, the partial PUEs are the same for Zones 1 and 2 as they are in the previous Figure 18 example, and it is still true that the cooling is less efficient in Zone 2. But, because the difference in r1 and r2 is so dramatic, it may make more sense to work on efficiency issues in Zone 1 to achieve a better overall PUE.

The examples here are by no means a complete set of examples; it is possible to construct many examples to demonstrate the concept of pPUE. The included examples have been chosen for simplicity and clarity in describing how to calculate and understand pPUE.

VIII. PUE Scalability and Statistical Analyses

Trends in data centers toward increased virtualization and power management of information technology equipment (such as servers, network, and storage)—along with continuous growth in storage, network, and compute capacities—mean that power loads for IT devices in data centers may be very dynamic during the life of a data center. Facilities with infrastructures that are highly scalable should be able to proportionally reduce total energy consumption when the critical IT load is low and proportionally ramp up cooling capacity and total power consumption as IT load increases. Yet many data centers are designed so that cooling capacity and infrastructure energy consumption remain about the same, regardless of IT load. The PUE metric is highly useful for measuring a data center's long-term energy efficiency. However, to better assess how well a facility's infrastructure handles dynamic changes in IT power loads, a data center needs to understand how well its total energy consumption scales with changes in IT power load. This section explains how to leverage energy consumption data collection to enhance the results of PUE with additional statistical analyses, and it describes a metric called PUE Scalability, which provides a more detailed view of infrastructure energy efficiency in data centers.

While energy measurements are the recommended means for sampling power and energy consumption, this section's statistics require energy to be divided by the period of time in the sample interval, so the units of analysis are watts of average power for the time interval.

8.1 PROPORTIONAL DATA CENTER POWER SCALABILITY

Ideally, a data center's total facility power ($Power_{total}$) would scale linearly to zero as the IT equipment power ($Power_{IT}$) scales to zero. The dotted lines in Figure 20 are not asymptotes, but are ideal linearity for how $Power_{total}$ would optimally scale if $Power_{total}$ scaled proportionally to changes in $Power_{IT}$.

Figure 20 shows four examples of ideal PUE scalability for hypothetical data centers with different mean PUE values. This section uses mean PUE for the PUE value, rather than assuming an annual PUE, because its statistics and analyses are intended to be useful throughout the year both to help data center owners and operators view instantaneous results and govern operations.

All linear equations are in the form y=mx+b. To describe proportional scalability, $Power_{total}$ is the dependent variable on the "y" axis, $Power_{IT}$ is the independent variable on the "x" axis. The "y" intercept point ("b") is zero in this ideal case. The slope term "m" is called m_{PUE}, shown below in Equation 19.

Equation 19

$$Power_{total} = m_{PUE} * Power_{IT} + 0$$

$$m_{PUE} = \frac{Power_{total}}{Power_{IT}} = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} = PUE$$

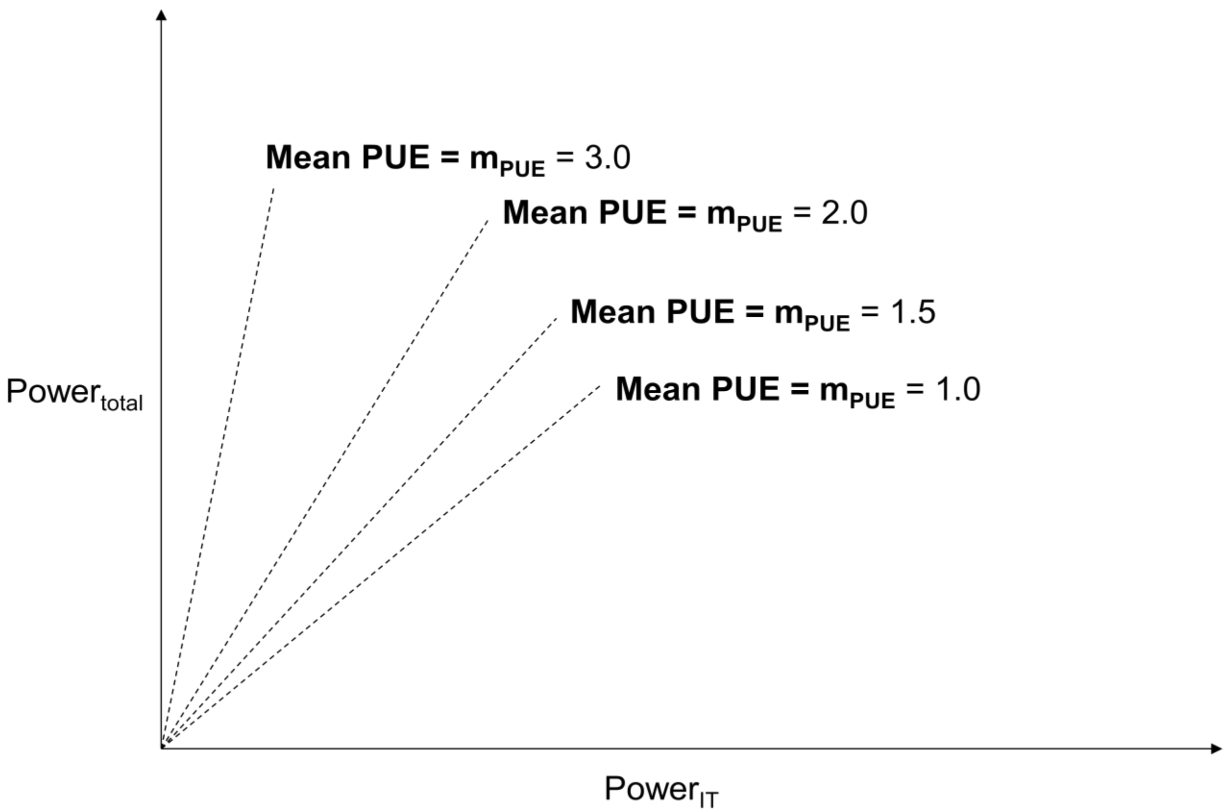

Figure 20. Proportional data center power scalabilities at several PUE values

8.2 DETERMINING ACTUAL PUE SCALABILITY

8.2.1 Periodic Measurements

To determine a data center's Actual PUE Scalability value, a Measurement Period needs to be established, during which continuous periodic measurements (e.g., every 15 minutes or less) should be taken and data stored for IT equipment power average load ($Power_{IT}$) and total facility power average load ($Power_{total}$). Collection of the accumulated periodic values enables data center operators to compute statistical analyses, such as mean values and standard deviations for $Power_{total}$ and $Power_{IT}$. Statistical mean values during the Measurement Period for $Power_{total}$ and $Power_{IT}$ should correlate to simpler derivations of average $Power_{total}$ and average $Power_{IT}$. To calculate these derivations, data center operators can either divide long-term energy use (e.g., kilowatt-hours) during the Measurement Period by the elapsed time of the Measurement Period (in hours), or they can keep a running average of power measurements during the Measurement Period.

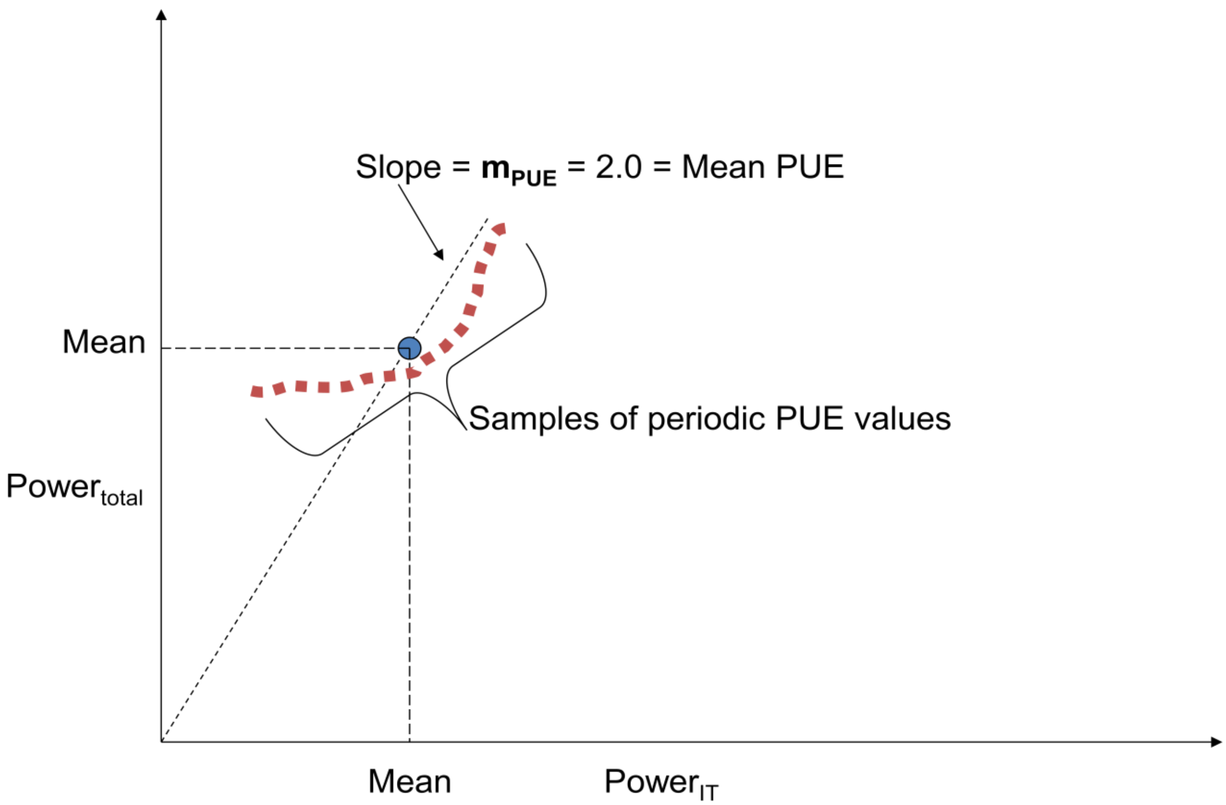

Figure 21. Proportional power scaling in a data center with mean PUE = 2.0

Figure 21 shows an example with periodic $Power_{IT}$ and $Power_{total}$ samples. Since proportional scalability of daily PUE measurements should follow a line through the origin (0,0), the linear slope of proportional scalability is equal to mean PUE, regardless of the value of mean PUE. As shown in Figure 21, actual periodic PUE values are likely to deviate from the linear slope of proportional scalability.

8.2.2 Periodic $Power_{IT}$(i)

$Power_{IT}$(i) is the average IT load power (in kilowatts) measured during the most recent sample period. $Power_{IT}$(i) can be measured as shown in Equation 20:

Equation 20

$$Power_{IT}(i) = \frac{IT\ Equipment\ Energy\ use\ (during\ sample\ period)}{sample\ period}\ watts$$

8.2.3 Periodic Power$_{total}$(i)

Power$_{total}$(i) is the average data center total power (in kilowatts) measured during the most recent sample period, or alternatively, as seen in Equation 21:

Equation 21

$$Power_{total}(i) = \frac{Total\ Facility\ Energy\ use\ (during\ sample\ period)}{sample\ period} watts$$

8.3 STATISTICAL ANALYSES OF DATA

Periodic sampling of Power$_{total}$ and Power$_{IT}$ (shown above) should be done at regular intervals (e.g., every 15 minutes or less). N samples of each will be taken during a Measurement Period.

The statistical analyses in the subsections below can either be performed on a complete data set or accumulated and updated after each sample.

8.3.1 Mean Power$_{IT}$

Equation 22 shows the formula for Mean Power$_{IT}$:

Equation 22

$$Mean\ Power_{IT} = \frac{1}{N}\sum_{i=1}^{N} Power_{IT}(i)$$

8.3.2 Standard Deviation of Power$_{IT}$

If the sampled data follows a Gaussian distribution, there is a 68.27% probability that Power$_{IT}$ samples will be within the range: Mean Power$_{IT}$ ± σ_{IT}. Chebyshev's inequality also specifies that, regardless of a random variable's distribution, at least 75% of samples will fall within Mean Power$_{IT}$ ±2σ_{IT}.

σ_{IT} = StdDev(Power$_{IT}$) = Standard Deviation of Power$_{IT}$. (See Equation 23.)

Equation 23

$$\sigma_{IT} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(Power_{IT}(i) - Mean(Power_{IT})\right)^2}$$

8.3.3 Dynamic Range of Power$_{IT}$

A statistical range of Power$_{IT}$ samples shows the total change (maximum minus minimum) of the power consumption of all IT equipment during the Measurement Period. The Dynamic Range of Power$_{IT}$ is the difference between the largest and smallest values for Power$_{IT}$, normalized by the Mean of Power$_{IT}$. The dynamic range of total IT power also may be referred to as: Dynamic Range of Power$_{IT}$ = Range(Power$_{IT}$). (See Equation 24.)

Equation 24

$$Range(Power_{IT}) = \frac{Max(Power_{IT}(i)) - Min(Power_{IT}(i))}{Mean(Power_{IT})} * 100\%$$

8.3.4 Mean Power$_{total}$

Equation 25 shows the formula for Mean Power$_{total}$:

Equation 25

$$Mean\ Power_{total} = \frac{1}{N}\sum_{i=1}^{N} Power_{total}\ (i)$$

8.3.5 Standard Deviation of Power$_{total}$ (σ_{total})

If the sampled data follows a Gaussian distribution, there is a 68.27% probability that Power$_{total}$ samples will be within the range: Mean Power$_{total}$ ± σ_{total}. Chebyshev's inequality also specifies that, regardless of a random variable's distribution, at least 75% of samples will fall within Mean Power$_{total}$ ±2σ_{total}.

σ_{total} = StdDev(Power$_{total}$) = Standard Deviation of Power$_{total}$. (See Equation 26.)

Equation 26

$$\sigma_{total} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(Power_{total}(i) - Mean(Power_{total})\right)^2}$$

8.3.6 Dynamic Range of Power$_{total}$

A statistical range of Power$_{total}$ samples shows the total change (maximum minus minimum) of the total power consumption of the data center during the Measurement Period. The Dynamic Range of Power$_{total}$ is the difference between the largest and smallest values for Power$_{total}$ normalized by the Mean of Power$_{total}$. The dynamic range of total facility power also may be referred to as: Dynamic Range of $Power_{total}$ = Range($Power_{total}$). (See Equation 27.)

Equation 27

$$Range(Power_{total}) = \frac{Max(Power_{total}(i)) - Min(Power_{total}(i))}{Mean(Power_{total})} * 100\%$$

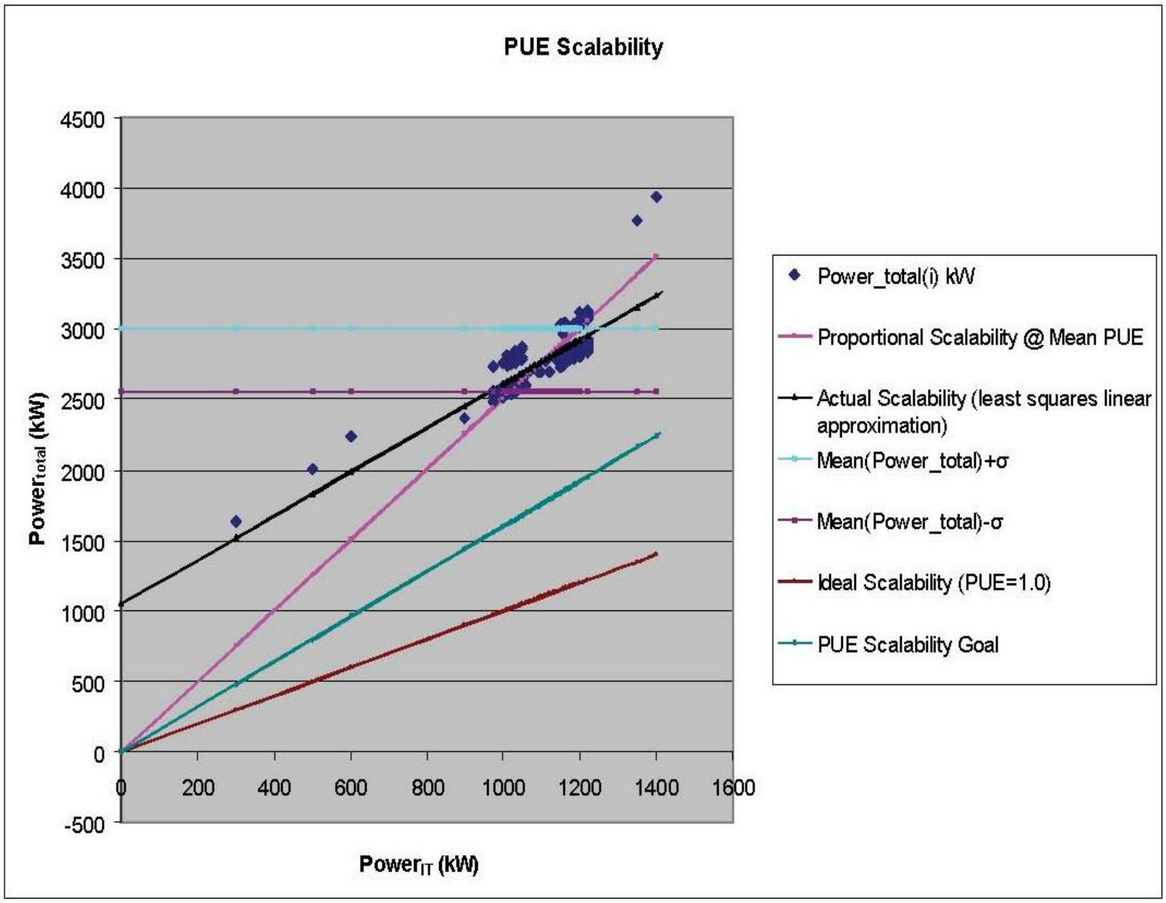

Figure 22. $Power_{total}$ variations versus $Power_{IT}$

The examples illustrated in Figure 21 and Figure 22 show data center infrastructures that do not scale their total power consumption proportionally to IT power fluctuations. These examples show an infrastructure with limited ability to scale $Power_{total}$, as $Power_{IT}$ deviates from its mean.

8.4 PUE SCALABILITY

8.4.1 Slopes of Scalability

In addition to statistical analysis of data captured during the Measurement Period for periodic $Power_{total}(i)$ and $Power_{IT}(i)$ measurements, the scalability of a data center's infrastructure should be assessed.

As illustrated in Figure 21, proportional PUE scalability at the Mean PUE is represented by a line intersecting the origin that has a slope = m_{PUE}. (See Equation 28.)

Equation 28

$$Slope\ of\ Proportional\ PUE\ scalability = m_{PUE} = \frac{Mean(Power_{total}) - 0}{Mean(Power_{IT}) - 0} = Mean\ PUE$$

As illustrated in Figure 22, the slope of the line that represents Actual Scalability is represented by analyzing the sampled $Power_{IT}(i)$ and $Power_{total}(i)$ data to calculate the linear approximation of the data using the least squares[19] method. (See Equation 29.)

Equation 29

$$Slope\ of\ Actual\ PUE\ Scalability$$
$$= m_{Actual} = \frac{\left(N * \sum_{i=1}^{N}(Power_{IT}(i) * Power_{total}(i))\right) - \left(\left(\sum_{i=1}^{N} Power_{IT}(i)\right) * \left(\sum_{i=1}^{N} Power_{total}(i)\right)\right)}{\left(N * \sum_{i=1}^{N}(Power_{IT}(i))^2\right) - \left(\sum_{i=1}^{N} Power_{IT}(i)\right)^2}$$

8.4.2 PUE Scalability Metric

Because a data center infrastructure should (ideally) proportionally scale total power with changes in IT power loads, the PUE Scalability metric rewards any infrastructure that is able to equate the slope of actual power scalability (m_{Actual}) with the slope of proportional scalability (m_{PUE}). A PUE Scalability score of 100% thus occurs when $m_{Actual} = m_{PUE}$, and PUE Scalability will be a quotient of those two parameters.

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[19] CRC Press, *CRC Standard Mathematical Tables, 26th Edition*, pp509 (1981)

Non-proportional scalability indicates an inability of the infrastructure to scale up or scale down one or more of its parts when the IT load scales. (See Equation 30.)

Equation 30

$$PUE\ Scalability = \frac{m_{Actual}}{m_{PUE}} * 100\%$$

(PUE Scalability values >100% are invalid and would indicate an inadequate number of samples.)

For the example shown in Figure 22:
m_{Actual} = 1.57, m_{PUE}= 2.51, and PUE Scalability = 62.5%

[m_{Actual} is also equal to the trigonometric tangent of the angle between a horizontal line representing Mean($Power_{total}$) and a line representing Actual PUE Scalability.]

8.4.3 Predicted Chronic Load

As illustrated in Figure 23, a line can be drawn that has slope m_{Actual} and intersects the point where Mean $Power_{IT}$ meets Mean $Power_{total}$. Using large data sets, the point where the line of Actual PUE Scalability intersects the $Power_{total}$ axis ("y" axis) is a useful approximation of the constant minimum infrastructure load. Predicted Chronic Load is only valid if the infrastructure has not been substantially modified during the Measurement Period and $m_{PUE} > m_{Actual}$. (See Equation 31 and Equation 32.)

Equation 31

$$Predicted\ Chronic\ Load = Mean(Power_{total}) - [m_{Actual} * Mean(Power_{IT})]\ watts$$

Equation 32

$$Chronic\ Annual\ Energy\ Waste\ (kWh) = Predicted\ Chronic\ Load(kW) * 8766\ hours\ kWh$$

8.4.4 Actual PUE Scalability

Using the Slope of Actual PUE Scalability (m_{Actual}) and the Predicted Chronic Load from the sections above, a line can be drawn that illustrates an approximation of the Actual Scalability in the form of y=mx+b. Examples of the predicted linearity are shown in Figure 22 and Figure 23, and Equation 33 is the equation for that linear prediction:

Equation 33

$$Actual\ PUE\ Scalability(i) = (m_{Actual} *\ Power_{IT}(i)) + Predicted\ Chronic\ Load$$

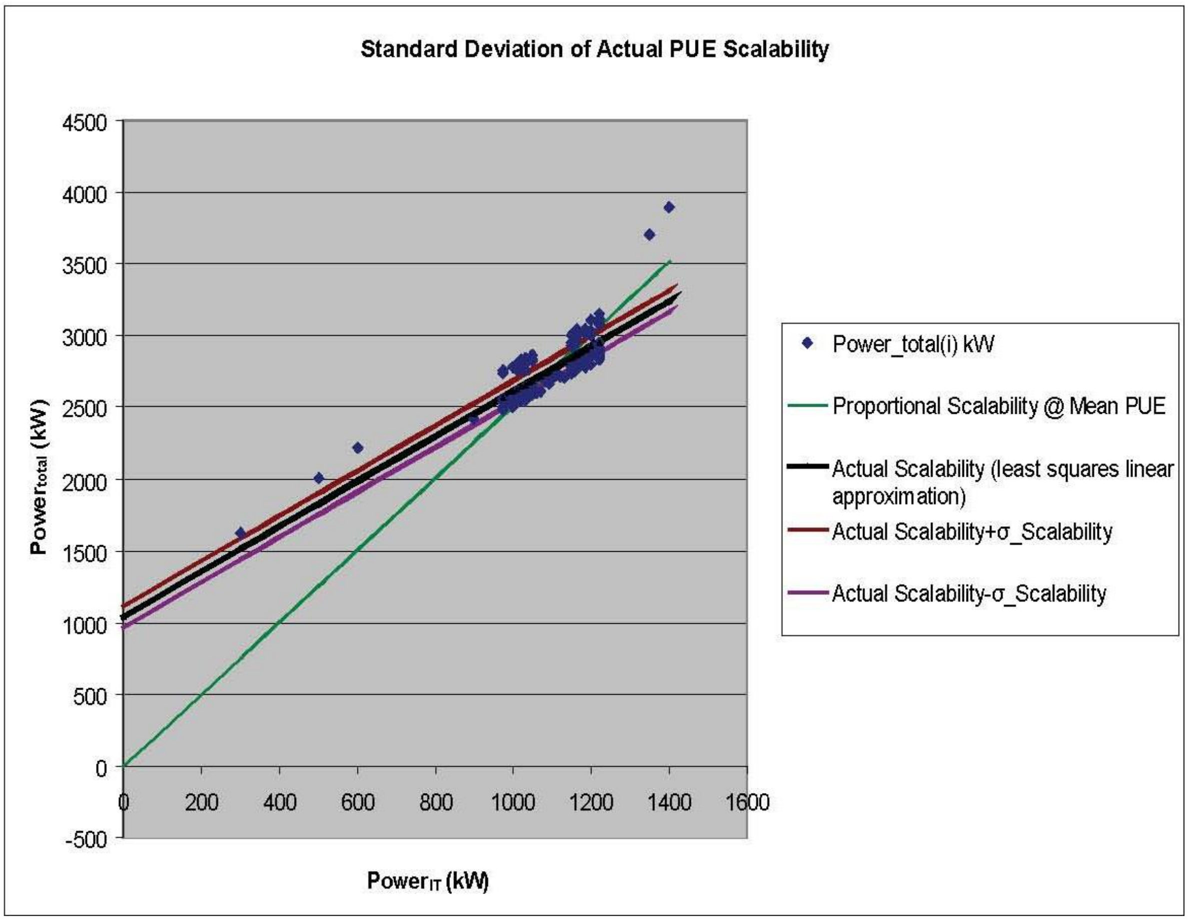

Figure 23. Actual PUE Scalability and standard deviation of Actual PUE Scalability

8.4.5 Standard Deviation of Actual PUE Scalability ($\sigma_{Scalability}$)

Since the Actual PUE Scalability equation creates a least squares linear approximation by using the actual data samples for $Power_{total}$ and $Power_{IT}$, some assessment of the standard deviation of that linearity is appropriate.

A standard deviation equation usually takes the root mean square of the differences of samples versus a mean value, but, in this instance, the “mean” value used is the predicted value from the linear equation for Actual

PUE Scalability. Therefore, the standard deviation must be calculated perpendicular to the Actual PUE Scalability line. This is accomplished by taking the root mean square of the $Power_{total}(i)$ differences from the calculated Actual PUE Scalability for the corresponding $Power_{IT}(i)$ value for that sample, and then, as shown in Equation 34, Equation 35, and Equation 36:

Equation 34

$$\sigma_{Scalability} = StdDev(Actual\ Scalability) = Standard\ Deviation\ of\ Actual\ PUE\ Scalability$$

Equation 35

$$\sigma_{Scalability} = Cos[ArcTan(m_{Actual})]$$

Equation 36

$$\sigma_{Scalability} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(Power_{total}(i) - Actual\ PUE\ Scalability(i)\right)^2}$$

8.5 INTERPRETING PUE SCALABILITY

No single metric is able to illustrate the complete picture of data center energy efficiency. Implementing regular, periodic sampling of data center energy consumption is the first step in achieving a comprehensive understanding of energy efficiency. The statistical analyses and metrics in this section complement raw energy-use data, and they add depth and understanding to the PUE metric.

The previous section describes how to calculate the mean $Power_{IT}$ and $Power_{total}$ values necessary for calculating long-term PUE metrics. It also provides a means for viewing instantaneous and cumulative results without waiting until the end of an annual PUE certification period. Statistics for standard deviation and range also illuminate the details in data sets captured during the process of validating a PUE measurement in a data center.

PUE Scalability informs data center operators about how well their infrastructure scales total facility power ($Power_{total}$) to accommodate changes in IT equipment power ($Power_{IT}$) loads. An extremely well-designed data center infrastructure scales $Power_{total}$ consumption proportionally with changes in $Power_{IT}$. PUE Scalability shows how closely a data center approaches the proportional scalability goal, using the set of actual power measurements in the Measurement Period. The Standard Deviation of PUE Scalability provides a statistic for how wide the distribution of data is around the linear approximation of Actual PUE Scalability.

Statistical analyses of $Power_{IT}$ and $Power_{total}$ samples provide valuable insights into the variability of the $Power_{IT}$ and $Power_{total}$ loads during the Measurement Period. Small standard deviations would indicate that workloads are fairly constant and investments in scalable infrastructure may provide less ROI, while large standard deviations and dynamic ranges indicate that a higher ROI is possible when deploying a dynamically scalable infrastructure.

When evaluating long-term data sets, the Predicted Chronic Load value shows the theoretical estimate of how much power the infrastructure would draw if $Power_{IT} = 0$. Identifying the chronic use of power helps to quantify opportunities for cost savings that are made possible by investing in a more dynamically scalable infrastructure.

Real-time monitors can numerically or graphically display all of the statistics, metrics, measurements, and derivations described above. The graphical display of data, statistics, and metrics helps to identify scalability problems, short-term aberrations, and chronic power drawn by the infrastructure.

IX. Conclusion

The definition and methodology for calculating PUE is complete. PUE has been globally accepted and is widely used across the data center industry and across many different data center types. Moving forward, The Green Grid expects PUE to be used to continually drive efficiency improvements throughout the data center.

The Green Grid has provided a great deal of information concerning PUE in this document, with the goal of driving further, more consistent use of the metric. The definition and measurement guidelines included here have been harmonized globally, with a primary focus on energy.

While PUE is a *key* metric, it is not the *only* metric that should be relied upon for data center operational and business decisions. PUE is great for its intended use, but it needs to be used in conjunction with additional data, metrics, and business policy in order to drive correct decision making. PUE is a tool that should be used with a goal of reducing energy consumption and considered with total data center energy consumption in mind.

Resiliency is a key data center attribute. An organization should consider the resiliency and maintainability requirements of its data center, along with an evaluation of the business performance requirements of the data center, when making decisions about improving PUE. It should also know the financial impacts of potential changes, both in terms of TCO and ROI.

PUE should be used with additional efficiency and effectiveness metrics, many of which have been or are being developed by The Green Grid. For example, the carbon usage effectiveness (CUE™) metric, addresses carbon emissions associated with data centers and includes grid-based energy sources. The Green Grid's metric for water usage effectiveness, WUE™, focuses on the environmental impact and sustainability of the data center in conjunction with its water usage.

The metrics that The Green Grid develops further its vision of enabling data centers to have meters, monitors, and analysis tools available to guide their managers' decisions when optimizing facility designs for energy efficiency. The Green Grid expects that other xUE metrics may be developed with a goal of helping the data center community better manage the issues of energy, sustainability, and compliance—along with environmental and societal aspects—associated with building, commissioning, operating, and decommissioning data centers.

In addition to developing this document about PUE, The Green Grid will pursue a variety of efforts to give equipment manufacturers, data center owners and operators, and others in the industry the insight and instruments they need to enhance their resource efficiency.

This document supersedes prior white papers and consolidates *all things* that The Green Grid has developed and published relating to PUE. The Green Grid will continually review and revise PUE as advancements are made in technology and data center design. The Green Grid assumes that things will change, and it will continue to update the PUE metric to reflect those changes.

All prior PUE-related white papers will continue to be available and are archived on The Green Grid website at www.thegreengrid.org.

X. References

1. ASHRAE Datacom Series Book #9, *Real-Time Energy Consumption Measurements in Data Centers* (2010) www.ashrae.org/publications/page/1900#9.
2. Belady, C., "Getting the Most Out of Your Data Center." AFCOM Data Center World presentation (March 2007) ftp://ftp.compaq.com/pub/products/servers/afcom-032607-final.pdf.
3. CRC Press, *CRC Standard Mathematical Tables, 26th Edition*, pp509 (1981).
4. Global Harmonization of Data Center Efficiency Metrics Task Force, "Global Taskforce Reaches Agreement on Measurement Protocols for PUE – Continues Discussion of Additional Energy Efficiency Metrics" (February 2011) www.thegreengrid.org/en/Global/Content/Reports/HarmonizingGlobalMetricsForDataCenterEnergyEfficiency.
5. Greenberg, S., Mills, E., Tschudi, W., Rumsey, P., and Myatt, B., "Best Practices for Data Centers: Lessons Learned from Benchmarking 22 Data Centers." Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings (2006) http://hightech.lbl.gov/presentations/datacenter-2006aceee.ppt.
6. Patterson, M.K., Costello, D., Grimm, P., Loeffler, M. "Data Center TCO; A Comparison of High-density and Low-density Spaces." THERMES 2007, Santa Fe, NM (2007).
7. The Green Grid, *ERE: A Metric for Measuring the Benefit of Reuse Energy from a Data Center* White Paper #29 (2010) www.thegreengrid.org/en/Global/Content/white-papers/ERE.
8. The Green Grid, *Usage and Public Reporting Guidelines for The Green Grid's Infrastructure Metrics (PUE/DCiE)* White Paper #22 (2009) www.thegreengrid.org/en/Global/Content/white-papers/Usage%20and%20Public%20Reporting%20Guidelines%20for%20PUE%20DCiE.
9. The Green Grid, *PUE Scalability Metric and Statistical Analyses* White Paper #20 (2009) www.thegreengrid.org/Global/Content/white-papers/PUE%20Scalability%20Metric%20and%20Statistical%20Analyses.
10. The Green Grid, *Proxy Proposals For Measuring Data Center Productivity* White Paper #17 (2009) www.thegreengrid.org/Global/Content/white-papers/Proxy-Proposals-for-Measuring-Data-Center-Efficiency.
11. The Green Grid, *The Green Grid Metrics: Data Center Infrastructure Efficiency (DCiE) Detailed Analysis* White Paper #14 (2008) www.thegreengrid.org/Global/Content/white-papers/DCiE-Detailed-Analysis.
12. The Green Grid, *The Green Grid Data Center Power Efficiency Metrics: PUE and DCiE* White Paper #6 (2007) www.thegreengrid.org/Global/Content/white-papers/The-Green-Grid-Data-Center-Power-Efficiency-Metrics-PUE-and-DCiE.

13. The Green Grid, *Global Harmonization of Data Center Energy Efficiency Metrics* (2009) www.thegreengrid.org/Home/alliances/HarmonizationOfMetrics.aspx.
14. The Green Grid, *PUE™ Reporting* (2009) www.thegreengrid.org/en/Global/Content/Tools/PUEReporting.
15. U.S. Data Center Industry: Data Center Metrics Coordination Task Force, *Recommendations for Measuring and Reporting Overall Data Center Efficiency* (May 2011) www.thegreengrid.org/Home/alliances/~/media/WhitePapers/Data%20Center%20Metrics%20Task%20Force%20Recommendations%20V2%205-17-2011.ashx.
16. U.S. Environmental Protection Agency and the U.S. Department of Energy, *ENERGY STAR Performance Ratings Methodology for Incorporating Source Energy Use* (March 2011) www.energystar.gov/ia/business/evaluate_performance/site_source.pdf.

XI. About The Green Grid

The Green Grid Association is a non-profit, open industry consortium of end users, policy makers, technology providers, facility architects, and utility companies that works to improve the resource efficiency of information technology and data centers throughout the world. With its member organizations around the world, The Green Grid seeks to unite global industry efforts, create a common set of metrics, and develop technical resources and educational tools to further its goals. Additional information is available at www.thegreengrid.org.