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Edge and Core Facilities Energy Metrics

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Table of Contents

Title **Page Number**

NOTICE 2
1. Scope 5
2. Normative References 5
3. Informative References 5
   3.1. SCTE References 5
   3.2. Standards from other Organizations 5
   3.3. Published Materials 5
4. Compliance Notation 6
5. Abbreviations and Definitions 6
   5.1. Abbreviations 6
   5.2. Definitions 7
6. Critical Facility Power 8
   6.1. Definition of Total Facility Energy 8
   6.2. Determining P_{TF} for a Critical Facility 8
7. Subscription 11
   7.1. Subscribers 11
8. Critical Facility Data Throughput 12
   8.1. Definition of Consumed Bit 12
   8.2. Determining Consumed Bits/Bytes 12
   8.3. Measurement Example: Calculating C_{BR} and C_{BYTE} for a Critical Facility 14
9. Critical Facility Productivity Metric (DCeP) 14
   9.1. Per Subscriber Critical Facility Productivity Metrics 15
   9.2. Critical Facility Productivity Metric (DCeP) using Data Throughput 16
10. IT Equipment Power 17
   10.1. Definition of IT Equipment Power P_{IT} 17
   10.2. Determining P_{IT} for a Critical Facility 19
11. Critical Facility Efficiency Metric - PUE 23
   11.1. Definition of PUE 23
   11.2. Determining PUE 23
   11.3. Frequency of Measurement 23
   11.4. Sample PUE Calculation 24
   11.5. Use of PUE 25
12. DCeP Measurements Using IT Equipment Power 25
   12.1. Per Subscriber Critical Facility Productivity Metrics using IT Equipment Power 26
   12.2. Data Throughput Critical Facility Productivity Metrics using IT Equipment Power 27
13. Using PUE and DCeP together to characterize facilities 28

List of Figures

Title **Page Number**

FIGURE 1 - EXAMPLE MEASUREMENT POINTS FOR P_{TF} & P_{IT} 22

FIGURE 2 - PUE VS DCEP QUADRANT GRID 29

List of Tables

Title	Page Number
TABLE 1 - IT EQUIPMENT VS. FACILITY EQUIPMENT	19
TABLE 2 - THREE LEVELS OF FACILITY AND IT EQUIPMENT POWER	21

1. Scope

This document provides a metric to help operators measure how effective changes in the service impact energy consumption from both a high level and functional work perspective.

The metric *should* help:

- Drive the energy strategy and direction of the organization
- Provide a focus of energy for an operator
- Help make decisions regarding energy
- Drive performance operationally, financially and environmentally
- Measure energy change and within the organization
- Produce good internal and external public relations regarding energy impact

The scope of the energy metric standard includes edge and core network facilities servicing the customers. Excluded from this standard are labs and testing facilities, people space, parking lots, parking garages, warehouses, and Customer Premise Equipment (CPE). Please refer to SCTE 211 2015, Energy Metrics for Cable Operator Access Networks, for similar metrics for the access portion of the network.

2. Normative References

The following documents contain provisions, which, through reference in this text, constitute provisions of the standard. At the time of Subcommittee approval, the editions indicated were valid. All standards are subject to revision; and while parties to any agreement based on this standard are encouraged to investigate the possibility of applying the most recent editions of the documents listed below, they are reminded that newer editions of those documents may not be compatible with the referenced version.

- No references are applicable

3. Informative References

The following documents may provide valuable information to the reader but are not required when complying with this standard.

3.1. SCTE References

[i1] SCTE 184 2015, SCTE Recommended Practices for Cable Facilities

[i2] SCTE 211 2015, Energy Metrics for Cable Operator Access Networks

[i3] SCTE 210 2015, Performance Metrics for Energy Efficiency & Functional Density of Cable Data Generation, Storage, Routing, and Transport Equipment

3.2. Standards from other Organizations

[i4] ETSI ES 205 200-2-1 ATTM Energy management; Global KPIs;, Operational infrastructures;, Part 2: Specific requirements;, Sub-part 1: Data centres

3.3. Published Materials

[i5] "PUE^{TM}: A Comprehensive Examination of the Metric", ASHRAE Datacom Series Book 11

[i6] "Harmonizing Global Metrics for Data Center Energy Efficiency", Joint Statement of The Green Grid Taskforce, March 13, 2014

4. Compliance Notation

shall	This word or the adjective "***required***" means that the item is an absolute requirement of this specification.
shall not	This phrase means that the item is an absolute prohibition of this specification.
should	This word or the adjective "*recommended*" means that there may exist valid reasons in particular circumstances to ignore this item, but the full implications should be understood and the case carefully weighted before choosing a different course.
should not	This phrase means that there may exist valid reasons in particular circumstances when the listed behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.
may	This word or the adjective "*optional*" means that this item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because it enhances the product, for example; another vendor may omit the same item.

5. Abbreviations and Definitions

5.1. Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineer
ATS	automatic transfer switch
ATTM	access, terminals, transmission and multiplexing
BDFB	battery distribution fuse bay
CATV	cable television
CB	consumed bytes
CMTS	cable modem termination system
CPE	customer premises equipment
CRAC	computer room air conditioner
CRAH	computer room air handler
DC	direct current
DCeP	data center energy productivity
DX	direct expansion [air handler unit]
e.g.	for example (*exempli gratia*)
EMS	[SCTE] Energy Management Subcommittee
ES	ETSI Standard
ETSI	European Telecommunications Standards Institute
FEC	forward error correction
GB	gigabyte
Gbps	gigabits per second
hr	hour
HVAC	heating, ventilation, and air conditioning
i.e.	that is (*id est*)

IT	information technology
KPI	key performance indicator
kV	kilovolt
kVA	kilovolt ampere
KVM	keyboard-video-mouse
kWh	kilowatt hour
kW	kilowatt
Mbps	megabits per second
MHz	megahertz
MPEG	Moving Picture Experts Group
MSO	multiple system operator
MW	megawatt
PC	personal computer
PDU	power distribution unit
PUE	power usage effectiveness
RDU	rack distribution unit
SCTE	Society of Cable Telecommunications Engineers
STS	static transfer switch
TB	terabyte
TGG	The Green Grid
TS	transport stream (?? see usage on page 12. My interpretation is that TS is transport stream)
UPS	uninterruptible power supply
V	volt

5.2. Definitions

Core Facility	Structures responsible for backbone traffic and edge to edge connectivity of services to large pools of customers
Critical Facility	Any structure that if non-functional, impacts customer experience and would generate greater than 250 calls to call centers
Critical Load	Equipment, if turned off or not operable, greatly impacting customer experience
Customer	Invoiced/complimentary consumer of network service(s)
DC Power Plant	Batteries, rectifiers, charge controllers, power bays, primary and secondary distribution equipment (BDFB/fuses), converters and inverters supporting load.
Downstream	Information flowing from the hub to the user
Edge Facility	Structures servicing neighborhoods where an outage would be contained to a specific pool of customers and not impact greater customer base
Meter	Equipment able to measure amount of energy in kWh or power in kW consumed over time
Metric	Mathematical calculation aiding in the intelligent decision making process
Outside Plant	Section of the cable network responsible for connecting facilities to customers as well as facilities to facilities
People Space	Building whose primary function is to enable people to perform activities such as meetings, calls, computer work, and all other non-critical facility activities
Power Distribution	Moving of power in a controlled manner from utility service entry to load

Uninterruptable Power Supply (UPS)	Power protection device helping to prevent equipment power down during primary source of power failure
Upstream	Information flowing from the user to the hub

6. Critical Facility Power

6.1. Definition of Total Facility Energy

Critical facilities are responsible for the housing of the equipment required to deliver the products to the cable subscribers. Equipment is typically staged in racks. Equipment requires proper power, airflow management, and backup power to support everyday operations. Total critical facility energy is defined as the energy dedicated solely to the facility (e.g., the energy measured at the utility meter of a dedicated facility or at the meter for a facility or equipment room in a mixed-use facility). Total facility energy includes all IT equipment energy, plus everything that supports the IT equipment-using energy, such as the following:

- 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

The energy provided to the critical facility by all sources is consumed by all the elements of a critical facility. As such, total critical facility energy P_{TF} can be expressed as:

$$\boldsymbol{P_{TF} = P_{IT} + P_{HVAC} + P_L + P_{Dist}} \qquad \textbf{Equation 1}$$

Where

$P_{IT} = Power\ consumed\ by\ IT\ Equipment$

$P_{HVAC} = Power\ consumed\ by\ HVAC\ and\ Cooling\ of\ facility$

$P_L = Power\ consumed\ by\ Lighting\ and\ Convenience\ outlets\ in\ facility$

$P_{Dist} = Power\ consumed\ for\ IR^2\ losses\ , rectifier/UPS\ ineffiencies, etc.$

6.2. Determining P_{TF} for a Critical Facility

1) For all critical facility locations, total critical facility power ($\boldsymbol{P_{TF}}$) ***shall*** be measured.
2) $\boldsymbol{P_{TF}}$ ***shall*** be measured from the utility service entrance that feeds all of the electrical and mechanical equipment used to power, cool, and condition the critical facility.
3) In the event a facility is fed by multiple sources, $\boldsymbol{P_{TF}}$ is the sum of the measurement from all the sources feeding the critical facility. Mathematically, this is represented by the following equation:

$$P_{TF} = \sum_1^n P_{TF(n)} \qquad \textbf{Equation 2}$$

Where
n = Total Number of Power Sources

$P_{TF(n)}$ = Power Measured at n^{th} source

6.2.1. Although the majority of critical facilities are fed with 100% electricity, energy to power the facility does occasionally emanate from a source other than direct electricity (e.g., natural gas, purchase of chilled water for HVAC, etc.). When this happens, source energy weighting factors should be used to determine $P_{TF(n)}$ for those sources. TGG and ASHRAE TC9.9 detail the use of source energy weighting in Section 4.9 of [i5] – please refer to it for how to treat energy sources other than electricity in determining P_{TF}

6.2.2. A number of options exist for operators to use to measure and/or calculate P_{TF} for a critical facility. These include but are not limited to

a) Use of utility bill information from grid/source provider. Because this method relies entirely on third party data and reporting, and is not available in real time, but only at best in the month following the measurement, it is not preferred. But in many cases, as it *may* be the simplest and most practical way for an operator to attain P_{TF}, it is deemed an acceptable way for the purpose of the metrics defined in this standard. Output of this measurement would be in kWh, and time period Δt_p as extracted from the utility bill.

b) *Should* they be accessible to operator personnel, periodic reading of utility meters placed at the critical facility by the grid/source supplier manually can also be used. As utility meters typically measure in kWh, meter readings must be taken over a period of time. Output of this measurement would be in kWh, and time period Δt_p.

c) Automated power monitoring systems. These systems place power monitoring/measurement capability in the appropriate location in the critical facility, storing and/or transporting power data automatically as instructed by the operator. Systems such as these are preferred as they automate the data collection process, as well as allow for continuous measurement of data *should* that be required for a metric. Regardless of how the measurement detail is taken by the automated system, the measurement *should* be reported in kWh and time period Δt_p.

It is up to the operator to select and use a method and/or combination of methods to measure/calculate P_{TF} for all of its electricity sources feeding a critical facility.

6.2.3. Frequency of Measurement

a) If utility bill information is used, the frequency of measurement *should* be monthly (i.e. totaled across a whole month), with P_{TF} being provided in kWh over the billing period. Utility bills are typically monthly, so this *should* be possible for large majority of sites.
b) If manual readings from utility meters are used, measurement period *should* be at least once a month, preferably the first day of the month, providing a total kWh measurement for the previous month.

c) For Automated Systems, measurement *should* be at a minimum recorded and stored at least daily, measured at the same time each day. In the event continuous measurement of P_{TF} is required for a metric, TGG recommendation [i5] is to measure at a minimum every 15 minutes. But this frequency of measurement *should* only be performed if continuous measurement is a requirement.

6.2.4. Converting kWh to average kW in an hour and different time period Δt_p

In some cases, metrics *may* require that P_{TF} be converted to a different time period Δt_p from what is provided. To do this, first the kWh measurement is converted to an average kWh per hour (i.e. kWh if Δt_p= 1 hour) using the following equation:

$$\boldsymbol{P_{TFkW} = \frac{P_{TF}}{\Delta t_p}} \textbf{ kWh per hour average} \qquad \textbf{Equation 3}$$

Where

P_{TFkW} = Average Total Facility Energy in kWh per hour

P_{TF} = Total Facility Energy as defined in Section 6.2., in kWh over period Δt

Δt_p= Time period P_{TF} is measured across in hours

It *should* be noted that P_{TFkW} is also equal what the average kW draw of the facility would be. P_{TFkW} is sometimes shortened, then, to have the unit of kW, and is used in metrics where time and or Δt is not relevant and/or required.

In the event P_{TF} needs to be calculated for a new/different Δt, this is done by simply multiplying P_{TFAVE} by the new timeframe in hours.

$$\boldsymbol{New\ P_{TF} = P_{TFAVE} * New\ \Delta t_p.} \qquad \textbf{Equation 4}$$

Sample calculation is below:

Assumptions (from Utility Bills):

Critical Energy Usage: 114,398 kWh (from utility bill)
Billing Days in the Month: 33 (from utility bill)
New P_{TF} timeframe needed for metric: 7 days (1 week)

First calculate P_{TFAVE} using Equation 3

$$P_{TFAVE} = \frac{P_{TF}}{\Delta t_p.} = \frac{114{,}889\ kWh}{33 * 24\ hours} = 145.2\frac{kWh}{hour}$$

To find P_{TF} for the new 7-day period needed for the metric, using Equation 4

$$New\ P_{TF} = P_{TFkW} * New\ \Delta t_p. = 145.2\ \frac{kWh}{hr} * \ 24\frac{hr}{day} * 7\ days$$

$= 24{,}394\ kWh$ for 7 days

7. Subscription

7.1. Subscribers

The equipment in the critical facility is deployed to service the cable subscriber (customer). Cable operators reference the number of subscribers in other metrics such as truck rolls, trouble calls, and technicians per subscriber to name a few.

In the context of energy metrics for critical facilities, supporting a subscriber is considered a fundamental work output of a critical facility. As typically operators track counts of subscribers connected to core and edge facilities for operational reasons, they make a reasonable proxy for work output to be used for metrics to compare facilities in relation to energy productivity.

7.1.1. Definition of Subscriber

In terms of power and subscribers, a subscriber ***shall*** be defined as any individual or business invoiced for service.

7.1.2. Counting Subscribers

The number of customers connected to a facility changes month to month based on a number of factors, including seasonal variations, sales pushes, expiration of incentives, etc. A customer is defined specifically as an invoiced entity (i.e. one invoice = one customer). For the purpose of using subscriber counts for energy metrics, customer count used ***shall*** be the average numbers of customers across the period being measured. Mathematically, this is defined as listed below:

$$\boldsymbol{S_{Ave} = \frac{S_{BP}+S_{EP}}{2}} \qquad \textbf{Equation 5}$$

Where
S_{Ave} = Average Number of Subscribers in the measurement period

S_{BP} = Subscribers at beginning of measurement period (default monthly)

S_{EP} = Subscribers at end of measurement period (default monthly)

8. Critical Facility Data Throughput

The equipment in the critical facility is deployed to service the cable subscriber (customer). The IT equipment in critical facilities supplies those customers with services, services which are composed of digital bits that transit the critical facility. As such, in the context of energy metrics, the sending and receiving of digital bits is considered a fundamental work output of a critical facility.

8.1. Definition of Consumed Bit

The concept of consumed bit has been introduced for cable access networks in the document SCTE 210 2015 [i3]. In that document, consumed bits in an access network were summed to determine total bits delivered over a period of time.

For the purpose of critical facility energy metrics, definition of consumed bits for data transported to and from customers ***shall*** be defined as follows

- In the downstream, all bits leaving the critical facility and transported to subscribers are considered consumed bits.
    - All data or telephony bits delivered to a user or device are defined as consumed.
    - All video on demand or switched video bits are defined as consumed.
    - Because of its size and scale, it is assumed that for a critical facility, all linear broadcast bits transported to customers in the access network from the critical facility are consumed.
    - Linear broadcast MPEG transport streams utilizing a full 6 MHz channel shall be defined to have a bit rate of 42.88 Mbps (approximately 38 Mbps payload + overhead), consistent with 256-QAM transport on the channel. *Should* other QAM types be used, operators *should* make adjustment to the bitrate accordingly. Consult [3] for examples on how this can be done.
    - With respect to linear broadcast analog channels emanating from the critical facility, any analog video channel being carried ***shall*** be defined to have an equivalent bitrate of 3 Mbps in the downstream direction from the facility to all subscribers. All bits from analog channels broadcast from a facility ***shall*** be considered consumed.
- In the upstream, all bits coming into the facility from subscribers are defined as consumed.
- Data overhead bits such as bits used in packet headers are considered to be consumed bits, because they are part of the information that is delivered to the user or device.
- Forward error correction (FEC) bits or other bits added to the data stream which are used to enable transmission across the access network ***shall not*** be considered to be consumed since the information is not delivered to the user or device.
- In addition to bits that transit the facility to and from customers, all bits which ingress and egress the facility via backbone network are also counted as consumed bits.

8.2. Determining Consumed Bits/Bytes

8.2.1. Consumed Bitrate

Measurement of consumed bits typically does not occur in the field at the bit or byte level directly. Instead, measurement devices typically measure the transport of bits as a consumed bitrate. For the purposes of determining consumed bits for a critical facility, the consumed bitrate ***shall*** be defined as the rate of consumed bits per second, C_{BR}.

8.2.2. Consumed Bytes

As opposed a bit rate, which measures a rate of transport of bits in and out of a critical facility, certain metrics require measurement of an absolute number of bytes transported over a period of time. For this, the concept of Consumed Bytes (CB) is introduced. To calculate consumed bytes, C_{BR} must be multiplied by the amount of time ΔT in seconds, and divided by 8 (as there are assumed to be eight bits per byte). Mathematically, this is shown in Equation 6.

$$\boldsymbol{C_{BYTE} = C_{BR} * \frac{\Delta t_c}{8}} \qquad \textbf{Equation 6}$$

Where

C_{BYTE}= Consumed Bytes

C_{BR} = Consumed Bitrate in bits/second

Δt_c = Time in seconds

As C_{BYTE} is a function of C_{BR}, there is no separate measurement of C_{BYTE}. Measurement of C_{BR} is performed as indicated in Section 8.2.3. C_{BYTE} is calculated per Equation 6 from that measurement.

8.2.3. Measurement of Consumed Bit Rate in a Critical Facility

To measure the total number of bits consumed in a critical facility, operators must sum up all the different consumed bitrates of traffic which go to and from subscribers, as well as the consumed bitrates of traffic which enter and leave the facility as part on the backbone network. Two types of sources exist in the facility, variable and fixed bitrate sources. Variable bitrate sources vary in time based on subscriber demand. Typical points in the network where measurement of consumed bitrates for variable sources can be taken include:

- CMTSs
- Edge and Core Routers
- Switches

As the consumed bitrate for each of these sources by definition varies over time, for variable source of traffic in the facility, the average value of C_{BR} over a period of time ***shall*** be used as the consumed bitrate C_{BR} in metric calculations. The amount of time C_{BR} is averaged over for the bitrate streams *should* be consistent with the timeframe associated with metric frequency and/or frequency of other data in the metric (e.g., if metric is bytes/watt, and the energy information is calculated across a month, then the consumed bitrate for variable sources *should* be averaged across the month). Additionally, if within any of the source bitrate streams duplicate bits are transported over redundant links for reliability purposes, they *should* also be counted as consumed bits for the purposes of this calculation.

Fixed consumed bitrate sources, such as those that emanate from broadcast services, *should* use the assumed consumed bitrate as detailed in Section 8.1. for C_{BR} for those source streams.
To determine C_{BR} for a critical facility, operators ***shall*** sum all individual C_{BR} measurements for the facility. Mathematically, this is summarized in equation below:

$$\boldsymbol{Total\ Facility\ C_{BR} = \sum_1^n C_{BR(n)}} \qquad \textbf{Equation 7}$$

Where

$C_{BR(n)}$= Consumed Bit Rate for the nth stream in the facility

n = number of consumed bitrate streams in the facility

8.3. Measurement Example: Calculating C_{BR} and C_{BYTE} for a Critical Facility

Assumptions:

Monthly Average Measured Bit Rate into Facility: 3.1 Gbps
Monthly Average Measured Bitrate out of Facility: 39.6 Gbps
Digital Broadcast TS: 73
Analog Channels: 0

$From\ Equation\ 7, C_{BR}$ for the Facility would be:

$$\boldsymbol{Total\ Facility\ C_{BR} = \sum_{1}^{n} C_{BR(n)}}$$

$$Total\ Facility\ C_{BR} = 3.1\ Gbps + 39.3\ Gbps + ((73 * 42.88) Mbps * \frac{1\ Gbps}{1000\ Mbps})$$

$$Total\ Facility\ C_{BR} = 3.1\ Gbps + 39.3\ Gbps + 3.1\ Gbps$$

$$\boldsymbol{Total\ Facility\ C_{BR} = 45.5\ Gbps\ (\text{averaged across the month})}$$

Knowing C_{BR}, C_{BYTE} can then be calculated across the month from Equation 6

$$\boldsymbol{C_{BYTE} = C_{BR} * \frac{\Delta t_c}{8}}$$

$$C_{BYTE} = 45.5\ Gbps * \frac{1\ Byte}{8\ Bits} * \frac{60 * 60 * 24 * 30\ sec}{Month}$$

$$C_{BYTE} = 45.5\ Gbps * \frac{1\ Byte}{8\ Bits} * \frac{60 * 60 * 24 * 30\ sec}{Month}$$

$$C_{BYTE} = 14{,}742{,}000\ GB\ transported\ in\ the\ month$$

OR

$$C_{BYTE} = 14{,}742\ TB\ transported\ in\ the\ month$$

OR

$$\boldsymbol{C_{BYTE} = 14.7\ PB\ transported\ in\ the\ month}$$

9. Critical Facility Productivity Metric (DCeP)

The development of productivity metrics for facilities has been taken up by other forums. TGG [i6] has developed a framework approach to productivity called Data center energy productivity (DCeP). DCeP is an equation that quantifies useful work that a data center produces based on the amount of energy it consumes. “Useful work” is a sum of tasks that are completed in a specified period of time. DCeP allows each user to define useful work and the weighting for various forms of useful work (if measuring more than one type) that apply to that user’s business. For example, a retail business *may* use the number of sales as its measure for useful work, an online search company *may* use the number of searches completed, and so on. The definitions can get as granular as necessary for the entity using the equation: web pages served, database transactions executed, emails served, etc.

Mathematically, DCeP can be expressed as:

$$\boldsymbol{DCeP = \frac{Useful\ Work\ Produced}{Total\ Data\ Center\ Source\ Energy\ Consumed\ Producing\ the\ Work}}$$

In keeping with TGG approach outlined previously of leaving it to the users to define what “useful work”, this document in Sections 7. and 8. has defined two types of useful work performed by the energy in a critical facility:

- Subscribers (measurements/calculation detailed in Section 7.)
- Consumed Bitrate or Consumed Bytes (measurement/calculation detailed in Section 8.)

9.1. Per Subscriber Critical Facility Productivity Metrics

As noted in Section 7., subscribers connected to a facility provide a reasonable proxy for work performed by a critical facility, making subscribers connected a useful “unit of work” to use in DCeP metrics. Additionally, subscribers connected to a facility are also something most all operators track, so data availability for this particular “unit of work” is considered to be a plus across the MSO base.

9.1.1. Per Subscriber Critical Facility Productivity Metrics using Total Facility Power

For the purpose of individual operator site performance comparisons and evaluation, an operator can calculate a power to subscriber metric by the following formula:

$$\boldsymbol{DCeP\ Subscriber\ Metric = \frac{Total\ Number\ of\ Critical\ \text{Facility}\ Subscribers}{Total\ Critical\ Facility\ Power}}$$

In mathematical terms, this is:

$$\boldsymbol{SPkW_{FAC} = \frac{S_{Ave}}{P_{TF}}} \qquad \textbf{Equation 8}$$

Where

$SPkW_{FAC} = Subs\ per\ Total\ Facility\ kW$

S_{Ave} = Average Subs in a Month (as defined in Section 7.)

P_{TFkW} = Total Facility Power in kW per hour as per Equation 3 in Section 6.2.4.

Sample calculation of $SPkW_{FAC}$ is shown below

Assumptions:

Beginning month Subscribers: 80,094
End month Subscribers: 81,094
Critical Energy Usage: 114,398 kWh (from utility bill)
Billing Days in the Month: 33 (from utility bill)

As noted previously in Equation 8

$$SPkW_{FAC} = \frac{S_{Ave}}{P_{TFkW}}$$

From Equation 4

$$S_{Ave} = \frac{S_{BP} + S_{EP}}{2} = \frac{81{,}094 + 80{,}094}{2} = 80{,}594$$

From Equation 3

$$P_{TFkW} = \frac{P_{TF}}{\Delta t} = \frac{114{,}398}{33*24} = 145.2\ kWh/hour$$ or alternatively 145.2 k

Therefore:

$$\boldsymbol{SPkW_{FAC} = \frac{S_{Ave}}{P_{TFkW}} = \frac{80{,}594}{145.2} = 555\ Subs\ per\ Total\ Facility\ k}\text{W}$$

9.2. Critical Facility Productivity Metric (DCeP) using Data Throughput

As noted in Section 8., data throughput coming into and leaving a facility is fundamental indicator of work performed by the facility. In fact, as all services provided from the facility are digital in nature, with amount of work performed by the facility directly related to the bits transiting to and from customers and the facility, a DCeP based metric utilizing data throughput of the facility to/from customers would be considered a high quality indicator as to the productivity of the energy used in a facility.

9.2.1. Per Subscriber Critical Facility Productivity Metrics using Total Facility Power

For the purpose of individual operator site performance comparisons and evaluation, an operator can calculate a power to data throughput metric by the following formula:

$$\boldsymbol{DCeP\ Throughput\ Metric = \frac{Total\ Critical\ Facility\ Data\ Thruput}{Total\ Critical\ Facility\ Power}}$$

It *should* be noted that this metric is the inverse of the DCeP metric as defined in [i6], with energy in the numerator, and work product in the form of throughput in the denominator. This flip of numerator and denominator has quantitative impact on the metric itself, but allows the metric to be consistent in units with the Energy per consumed byte metric as defined in [i2].
In mathematical terms, this is

$$\boldsymbol{EPCB_{FAC} = \frac{P_{TF}}{C_{BYTE}}} \qquad \textbf{Equation 9}$$

Where
$EPCB_{FAC} = Energy\ per\ Consumed\ Byte$

C_{BYTE} = Consumed Bytes in TB (as defined in Section 8.)

P_{TF} = Total Facility Energy in kWh in time period

It *should* be noted that for this metric, the timeframe Δt_pused to calculate P_{TF} as per Equation 3 in Section 6.2.4. MUST equal the timeframe Δt_c used to calculate C_{BYTE} as per Equation 6 in Section 8.2.2.

A sample calculation of $EPCB_{FAC}$ using the assumptions from previous sections is shown below

Assumptions:

Total Facility $C_{BR} = 45.5\ Gbps$ (as per example in Section 8.3.)
Critical Energy Usage: 114,398 kWh (from utility bill)
Billing Days in the Month: 33 (from utility bill)

To calculate $EPCB_{FAC}$, one must calculate its two component parts, C_{BYTE} and P_{TF}. Starting with C_{BYTE}, using Equation 6 to convert to C_{BR} to Bytes,

$$C_{BYTE} = C_{BR} * \frac{\Delta t_c}{8}$$

For the metric, Δt_c must equal Δt_p. As per assumptions, Δt_p = 33 days, Δt_c must also equal 33 days, converted to seconds. As such, calculation becomes

$$C_{BYTE} = 45.5\ Gbps * \frac{1\ Byte}{8\ Bits} * \frac{60\ sec}{minute} * \frac{60\ min}{hour} * \frac{24\ hrs}{Day} * 33\ Days$$

$$C_{BYTE} = 16{,}216{,}200\ GB\ transported\ in\ the\ billing\ period$$

OR

$$C_{BYTE} = 16{,}216\ TB\ transported\ in\ the\ billing\ period$$

From the assumptions

$$P_{TF} = kWh\ in\ the\ period\ \Delta t_c = 114{,}398\ kWh$$

Therefore:

$$\boldsymbol{ECBS_{FAC} = \frac{P_{TF}}{C_{BYTE}} = \frac{114,398}{16,216} = 7.1\ kWh/TB}$$

10. IT Equipment Power

10.1. Definition of IT Equipment Power P_{IT}

Of the elements that make up P_{TF}, IT Equipment Power is an especially important component. P_{IT} is the power needed for the equipment providing service to customers. 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 [keyboard-video-mouse] switches, monitors, and workstations/laptops used to monitor or otherwise control the data center).

More specific to the cable industry, the term "network equipment" would include power for equipment that delivers voice, video, and data services (e.g., CMTS, QAM modulators, routers, data switches, soft-switches, etc.). SCTE 210 2015 [i3] provides a comprehensive list of equipment located in cable critical facilities that would be considered IT Equipment. As noted in previous section, all other power consumed is either needed to provide for the environment the equipment is in and/or deal with the inefficiencies encountered in delivering and backing-up power from the grid to the equipment.

Table 4.2 in TGG and ASHRAE's joint reference document PUE^{TM}: A Comprehensive Examination of the Metric [i5] provides more detail on the split of equipment in a typical datacenter between IT Equipment and non-IT Equipment. Refer to Table 1 for a summary.

Table 1 - IT Equipment vs. Facility Equipment

IT Equipment	
Compute Devices	Servers
Network Devices	Switches, Routers
IT Support Systems	Printers, PCs/Workstations, Remote Management (KVM, console, etc.)
Miscellaneous Devices	Security encryption, storage, encryption, appliances, etc.
Storage	Storage devices (switches, storage array), Backup Devices (media, libraries, virtual media libraries
Telecommunication	All Telecommunication Devices (this area includes all typical CATV equipment found in core and edge facilities)

Facility Equipment	
Power	Automatic transfer switches (ATS), Switchgear, UPS, DC batteries/rectifiers (non-UPS-telecommunications nodes), Generator, Transformer (stepdown), Static transfer switches (STS), Power distribution unit (PDU), Rack distribution unit (RDU), Breaker panels, Distribution wiring, Lighting
Heating Ventilation and Air Conditioning (HVAC)	Cooling tower, Condensers and condenser water pumps, Chillers, Chilled-water pumps, Water treatment, Well pumps, Computer room air conditioners (CRACs), Computer room air handlers (CRAHs), Dry cooler, Air compressors, Supply fans, Return fans, Air economizer, Water-side economizer, Humidifier, Heaters, In-row, in-rack, and in-chassis cooling solutions, Condensate, pumps
Physical Security	Fire suppression, Water detection, Physical security services/devices
Building Management System and Controls	Server/devices used to control/manage the data center, Probes/sensors, Plant controls

10.2. Determining P_{IT} for a Critical Facility

10.2.1. For all critical facility locations, total IT equipment power (P_{IT}) shall be measured.

10.2.2. In the event a facility is fed by multiple sources, P_{IT} is the sum of the measurement from all the sources feeding the critical facility. Mathematically, this is represented by the following equation:

$$P_{IT} = \sum_{1}^{n} P_{IT(n)}$$ **Equation 10**

Where
n = Total Number of Power Sources

$P_{IT(n)}$ = Power Measured at n^{th} source

10.2.3. Measuring P_{IT} in a critical facility can be complex and time-consuming. Unlike P_{TF}, there is no third-party grid/source billing data and/or utility meters that can be use to determine P_{IT}. P_{IT} must be measured in the facility by operators.

10.2.4. To allow operators the most flexibility in insuring that a useful measured value of P_{IT} can be attained, measurement of P_{IT} shall be defined in three (3) levels

Level 1: Read from the UPS/DC rectifier front panel through a meter on the UPS/DC rectifier output, or in cases of multiple UPS modules, through a single meter on the common UPS bus.

Level 2: 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

Level 3: Typically read and/or measured at the 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 (as defined in Table 1) must be excluded from these measurements.

Operators ***shall*** use one and/or some combination of the above three levels to measure total P_{IT}. Measurement can be in either kW or kWh depending on meter used – conversion from one to the other can be performed as needed. It *should* be noted that these three levels are as defined by TGG and ASHRAE TC 9.9 [i5]

10.2.5. As with P_{TF}, frequency of measurement of P_{IT} is largely a function of whether it is done manually, or with automated power monitoring equipment. In addition to defining levels with respect to where P_{IT} is measured.

TGG/ASHRAE TC 9.9 in [i5] defines frequency of measurement in three levels, to provide maximum flexibility to operators to produce useful measurements for use in energy efficiency metrics. Consistent with this, frequency of measuring P_{IT} ***shall be*** defined in the following three levels:

Level 1: Monthly – typical frequency if measurements made manually. Measurement *should* be taken on the same day each month, and at the same time of the day, for consistency sake. Measuring in this manner allows for the most basic of measurements to be used for P_{IT} in calculation of metrics

Level 2: Daily – can be done manually, but typically more practical using automated monitoring equipment. Measurement *should* be taken at the same time each day for consistency sake. Measuring in this manner provides a better average across the month to use for P_{IT} in calculation of metrics

Level 3: Minimum every 15 minutes - requires automated monitoring equipment. Measuring in this manner provides the continuous data which is the best base to work from when calculating metrics with P_{IT}.

Operators ***shall*** select a frequency of measurement for each critical facility based on their capability to measure at that facility.

It *should* be noted that these three levels used for how to measure as well as frequency of measurement for determining $\boldsymbol{P_{IT}}$ are as defined by TGG and ASHRAE TC 9.9 in [i5]. For the purpose of clarity, Table 1 (excerpted from Table 4.3 of [i5]) summarizes the level structure for measurement of P_{IT}.

Table 2 - Three Levels of Facility and IT Equipment Power

Three Level Approach to Determining Total Facility and IT Equipment Power			
Measurement	**Level 1 (L1)**	**Level 2 (L2) In**	**Level 3 (L3)**
IT Equipment Energy	UPS/DC Rectifier Outputs	PDU Outputs	IT equipment outputs
Total Facility Energy	Utility inputs	Utility inputs	Utility inputs
Measurement Intervals	Monthly	Daily	15 minutes

Additionally, TGG/ASHRAE TC 9.9 in [i5] provides a graphical view of the measurement point as Figure 4.4 in that document. For clarity, the figure is extracted in its entirety from [i5], and shown in Figure 1.

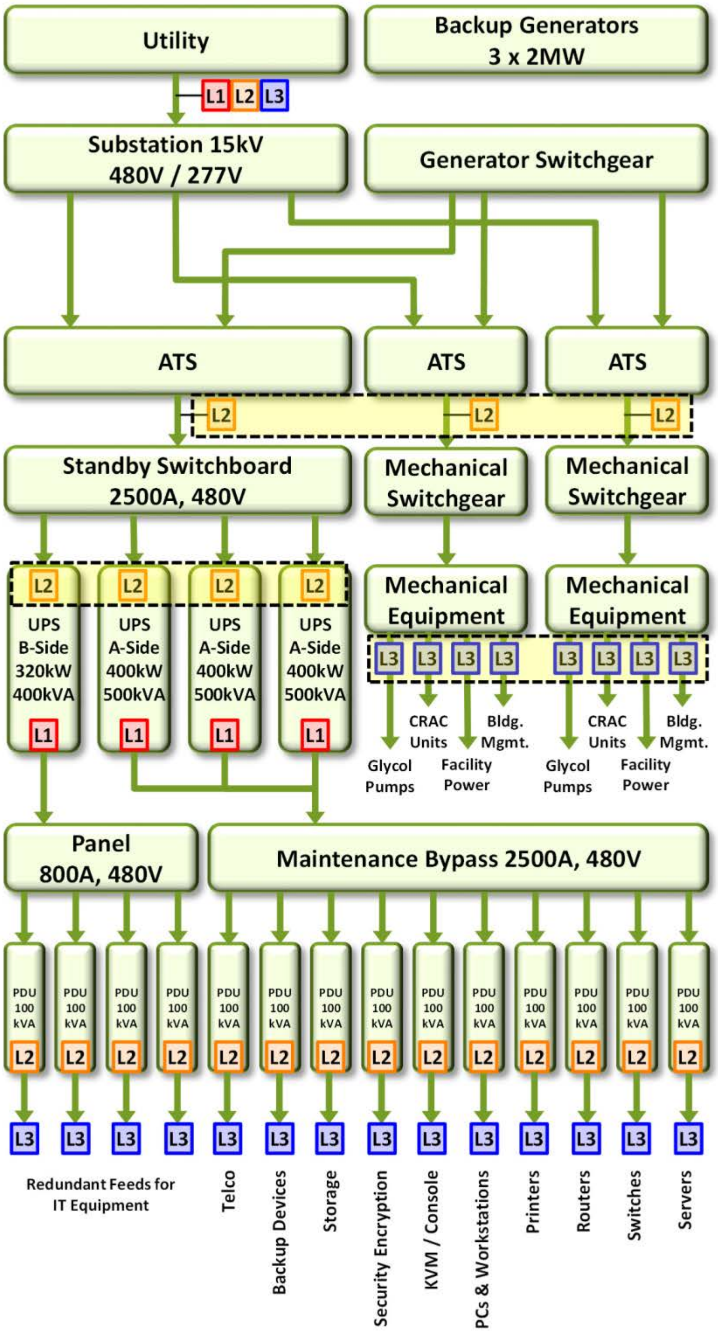

Figure 1 - Example Measurement Points for P_{TF} & P_{IT}

11. Critical Facility Efficiency Metric - PUE

Metrics can help operators better understand and improve the energy efficiency of their existing critical facilities. 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 critical facility. SCTE 184 [i1] specifically mentions PUE as a metric operators track for critical facilities. Operators can use PUE results to address and reduce the energy usage related to the supporting infrastructure within their critical facilities.

Mathematically, PUE can be used to illustrate a data center's energy allocation. A PUE of 3.0 indicates that the critical facility's total-energy usage is three times greater than the energy usage for the IT equipment alone. Or alternatively, that 1/3rd of the facility energy is used for the IT equipment, and 2/3rd of the energy is used for items in the facility other than that IT equipment providing service. PUE is a number that is always greater than 1, and the closer to 1, the more energy efficient the critical facility. PUE as a metric has been measured and reported by a number of different data center and critical facility owners across the world over the years. In general, best in class data centers perform with PUE <1.5 and approaching 1.15-1.2. Typical data center/critical facility PUE performance is in the 1.8-1.9 range [i5].

PUE as a metric is best applied when looking at trends in an individual facility over time and measuring the effects of different design and operational decisions within a specific facility. Assuming consistency in the measurement of PUE with-in their own company, operators can use PUE measurements from the facilities with-in their own footprint to compare facilities for the purpose of targeting investment in energy efficiency properly. PUE *should not* be used to compare facilities across operator, or to compare to facilities of companies in other industries, as such comparisons are meaningless and potentially misleading and harmful.

11.1. Definition of PUE

PUE is defined as the ratio of total critical facility energy to IT equipment energy.

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

11.2. Determining PUE

Total critical facility energy has already been defined as P_{TF} in Section 6.1. IT equipment energy was defined as P_{IT} in Section 10. Mathematically, PUE is:

$$\boldsymbol{PUE = \frac{P_{TF}}{P_{IT}}} \qquad \textbf{Equation 11}$$

Measurement and calculation of P_{TF} and P_{IT} are detailed in Sections 6. and 10. of this standard. PUE is a dimensionless metric – as such, when calculating PUE the two components used must be of the same dimensions (i.e. either both in kW, or both in kWh). If both are in kWh, then Δt_P is used for each measurement and must be the same.

11.3. Frequency of Measurement

Frequency of measurement of PUE ultimately is governed by what is possible with respect to frequency of measurement of P_{TF} and P_{IT}. As such, operators *should* measure PUE consistent with the frequency of measuring P_{TF} and P_{IT}. Consistent with measurement of frequency P_{TF} and P_{IT} as defined in Section 6., frequency of measurement for PUE ***shall*** be defined in three levels.

Level 1: Monthly – typical frequency if P_{IT} measurements made manually as per Section 6. This is the most basic PUE measurement, providing a snapshot of PUE at the time in the month P_{IT} is measured

Level 2: Daily – can be done manually, but typically more practical using automated monitoring equipment. This is a better way to track PUE, as it will be provide tracking of weather/environment changes across the month.

Level 3: Minimum every 15 minutes - requires automated monitoring equipment. This is best way to view PUE, as it provides full view of variations across the whole of each day due to weather/environment.

As continuous measurement of PUE needed for Level 3 Advanced PUE measurement requires automated power monitoring capability, it *may* not be practical for operators in all facilities initially. As such, PUE measured with a manual monthly "snapshot" measurement of P_{IT} PUE ***shall*** be deemed acceptable in determining PUE. An example of such a PUE calculation is detailed in the sample calculations following.

PUE as a metric is greatly advantaged if it is measured on a continuous basis. This is because P_{TF}in particular is impacted by the outdoor environment surrounding the facility, and as such can fluctuate in a statistically meaningful way through-out a day and through-out a year. Continuously measuring P_{TF} is the only way to insure full capture of these variations in the PUE measurement. As such, it is RECOMMENDED that operators move as quickly as practical to continuous measurement of PUE. This is because PUE as a metric is enhanced and more useful to an operator the more frequently it is measured.

11.4. Sample PUE Calculation

Assumptions:

Critical Energy Usage: 50373 kWh (from utility bill)
Billing Days in the Month: 33 (from utility bill)
DC Power: 21.0 kW (as read manually from rectifiers)
UPS Power: 13.4 kW (as read manually from UPS)

From Equation 10, P_{IT} is the sum of all DC and UPS measurements in the critical facility. As such

$$P_{IT} = \sum_{1}^{n} P_{IT(n)}$$

$$P_{IT} = DC + UPS$$

$$P_{IT} = 21.0 + 13.4$$

$$P_{IT} = 34.4\ kW$$

Total energy consumed in kWh during the month is available from the utility bill. As such, to ensure PUE stays dimensionless per Section 11.2., P_{TF} must be converted to kW. This is best done by converting the kWh information for the month to an average kW measurement for the month, P_{TFAVE}, as per Equation 3 in Section 6.2.4.

$$P_{TFAVE} = \frac{P_{TF}}{t_p} = \frac{50373}{33 * 24} = 63.6\ kW$$

Level 1 PUE for the month, then, would be

$$PUE = \frac{P_{TF}}{P_{IT}} = \frac{63.6}{34.4} = 1.85$$

11.5. Use of PUE

Much has been written about the use of the PUE metric in helping operators to improve critical facility energy efficiency. TGG, in particular, has written extensively on use of PUE for such purposes as noted in [i3] and [i4]. As with any metric, PUE is only useful if it is properly used. The PUE metric is associated with the critical facility infrastructure. PUE is not a data center productivity (DCeP) metric, nor is it a stand-alone, 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 infrastructure architectures, the deployment of equipment within those architectures, and the day-to-day operation of that equipment.

Proper use of PUE to improve energy efficiency in a critical facility is accomplished through a process of measurement of the metric performed for each facility. This includes

- Taking initial snapshot PUE measurement of all critical facilities in an operator's geographic footprint. Whilst not constituting a full baseline PUE profile, an initial snapshot PUE can identify obvious outliers with respect to energy efficiency, for immediate attention.
- Creating an initial baseline profile of a facility with respect to PUE. For a critical facility, it is RECOMMENDED that a critical facility baseline be created using a full years' worth of PUE measurements, so that facility variations due to weather/environment can be included in the baseline. Such data can aid operators in targeting energy efficiency improvement appropriately to critical facilities
- Continuing measurement of PUE as energy efficiency improvements are implemented, so that the impact of those improvements can be judged against the baseline.
- Continuing measurement of PUE also allows operators to quickly see anomalies in energy efficiency that might occur, and to deal with them quickly.

12. DCeP Measurements Using IT Equipment Power

An alternative approach to the subscriber productivity metric is to use IT equipment power in the denominator of the equation instead of total facility power. Using IT equipment power (P_{IT}) for the DCeP equations instead of total facility energy (P_{TF}) better focuses the metric on the productivity of the energy specifically used to produce real work, eliminating the part of the energy not directly related to producing work.

If an operator is determining and calculating PUE for critical facilities (and hence determining P_{IT}), then DCeP metrics using P_{IT}, *may* be a better partner metric to track with PUE, as it focuses each metric specifically to provide information squarely on the energy component it is meant to characterize. In the case of PUE, focus in on minimizing total facility power thru more efficient creation of the environment the IT equipment resides, regardless of how much IT equipment that might be. For the DCeP metric, it is about insuring that as much work output (in the form of subs and/or data throughput) is created with the IT equipment energy, regardless of the how efficient the environment in the facility is.

If an operator is not tracking PUE for a facility (and hence not determining P_{IT}), then it would be better to use $SPkW_{TF}$ for subscriber based DCeP metric as detailed in Section 9.

12.1. Per Subscriber Critical Facility Productivity Metrics using IT Equipment Power

Determining the DCeP metrics using P_{IT} is done by simply taking the DCeP techniques introduced in Section 9., and replacing P_{IT} with P_{IT} in all the equations. With respect to the subscriber based DCeP metric, mathematically it looks like:

$$\boldsymbol{SPkW_{IT} = \frac{S_{Ave}}{P_{IT}}}$$ **Equation 12**

Where

$SPkW_{IT} = Subs\ per\ IT\ Equipment\ kW$

S_{Ave} = Average Subs in a Month (as defined in Section 7.)

P_{IT} = IT Equipmentt Power in kW, (as defined in Section 6.)

Sample calculation using the assumptions from previous sections

Assumptions:

Beginning month Subscribers: 80,094
End month Subscribers: 81,094
DC Power: 21.0 kW (as read manually from rectifiers)
UPS Power: 13.4 kW (as read manually from UPS)

P_{IT} is the sum of all DC and UPS measurements in the critical facility. As such

$$P_{IT} = DC + UPS$$

$$P_{IT} = 21.0 + 13.4$$

$$P_{IT} = 34.4\ kW$$

As noted above in Equation 12

$$SPkW_{IT} = \frac{S_{Ave}}{P_{IT}}$$

From Equation 5

$$S_{Ave} = \frac{S_{BP} + S_{EP}}{2} = \frac{81{,}094 + 80{,}094}{2} = 80{,}594$$

From Equation 10

$$P_{IT} = DC + UPS$$

$$P_{IT} = 21.0 + 13.4$$

$$P_{IT} = 34.4\ kW$$

Therefore

$$SPkW_{IT} = \frac{S_{Ave}}{P_{TF}} = \frac{80{,}594}{34.4} = 2342\ Subs\ per\ IT\ Equipment\ kW$$

It *should* be noted that mathematically, PUE, $SPkW_{IT}$, and $SPkW_{TF}$ are related in the following way

$$\boldsymbol{SPkW_{IT} = SPkW_{TF} * PUE}$$ **Equation 13**

12.2. Data Throughput Critical Facility Productivity Metrics using IT Equipment Power

As with the subscriber based metric, an alternative approach to the subscriber productivity metric is to use IT equipment power in the denominator of the equation instead of total facility power. In mathematical terms, this is:

$$\boldsymbol{EPCB_{IT} = \frac{P_{IT}}{C_{BYTE}}}$$ **Equation 14**

Where

$EPCB_{IT} = IT\ Equipment\ Energy\ per\ Consumed\ Byte$

C_{BYTE} = Consumed Bytes (as defined in Section 8.)

P_{IT} = Total Facility Power in kW, averaged across 1 month (as defined in Section 10.)

Sample calculation using the assumptions from previous sections:

Assumptions:

Total Facility $C_{BR} = 45.5\ Gbps$ (as per example in Section 8.3.)
P_{TF} = 63.6 kW as per example above
Critical Energy Usage: 50373 kWh (from utility bill)
Billing Days in the Month: 33 (from utility bill)

Using Equation 14

$$EPCB_{IT} = \frac{C_{BYTE}}{P_{IT}}$$

$$EPCB_{IT} = Consumed\ Bytes\ per\ Total\ Facility\ kW$$

C_{BYTE} = Consumed Bytes (as defined in Section 8.)

P_{IT} = IT Equipment Power in kW

As the IT Equipment power is measured in kW, it needs to be converted to a kWh measurement consistent with the time used to measure the number of Bytes. To keep the calculation simple, $t_p = t_c$ = one hour so that the kW measurement will equal the kWh measurement.

From equation above

$$P_{IT} = 34.4 \text{ kW} = 34.4 \text{ kWh (for 1 hour)}$$

Calculating $C_{BYTE}\ from\ C_{BR}$, use equation 6

$$C_{BYTE} = C_{BR} * \frac{t_c}{8}$$

$$C_{BYTE} = 45.5\ Gbps * \frac{1\ Byte}{8\ Bits} * \frac{60 * 60\ sec}{hour}$$

$$C_{BYTE} = 20{,}475\ GB\ transported\ in\ 1\ hour$$

$$C_{BYTE} = 20.5\ TB\ transported\ in\ 1\ hour$$

Therefore:

$$EPCB_{IT} = \frac{C_{BYTE}}{P_{TF}} = \frac{34.4\ kWh}{20.5\ TB} = 1.7\ TB/kWh$$

As with the subscriber DCeP metrics, it *should* be noted that mathematically, PUE, DkW_{IT}, and DkW_{TF} are related in the following way

$$EPCB_{IT} = EPCB_{TF} * PUE$$

13. Using PUE and DCeP together to characterize facilities

In its whitepaper “Harmonizing Global Metrics for Data Center Energy Efficiency” [i6], TGG specifically identifies PUE and DCeP as important metrics for characterizing critical facility performance with respect to energy efficiency, and recommends characterization of data centers using these two metrics.

As noted previously, the two metrics provide different but complementary information with respect to the performance of the facility. PUE as a metric specifically focuses on the efficiency of the facility itself. It is a measure how energy efficient the facility is with respect to maintaining the environment the IT equipment uses to produce capabilities and service needs of the business. DCeP, on the other hand, focuses on how efficiently the energy is used to produce the capabilities and service needs of the business. Improvements in PUE generally manifest themselves in making HVAC and other support systems in the facility more energy efficient. Improvements in DCeP come from making the energy used better at producing real work output from the facility per unit energy.

One can characterize facilities by plotting these two metrics for facilities a quadrant grid as shown in Figure 2 below, using operator target PUE and DCeP to set the center points on the graph for splitting into quadrants.

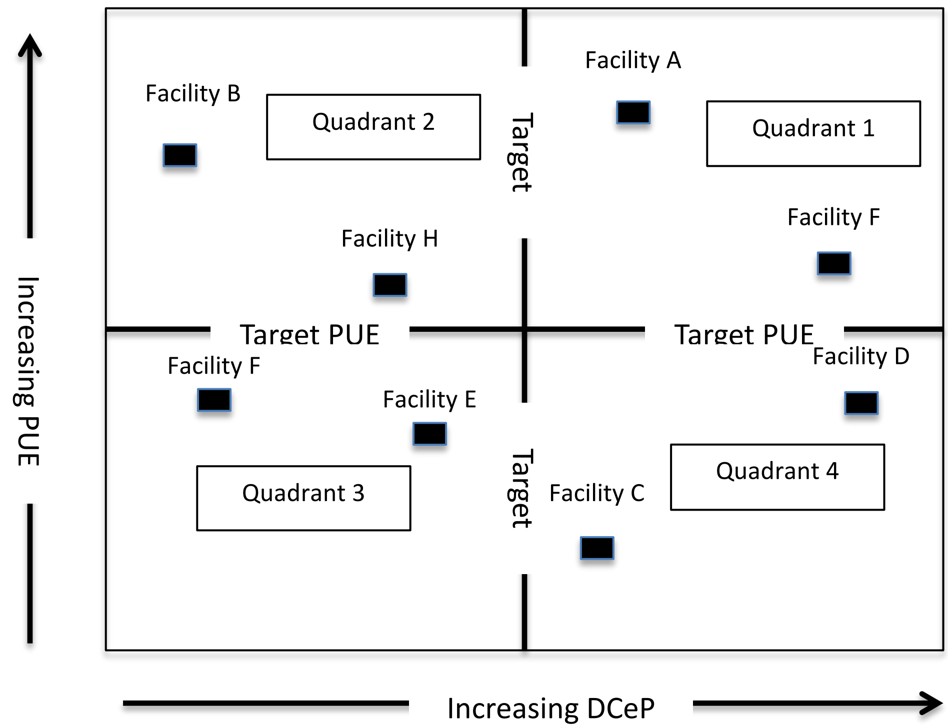

Figure 2 - PUE vs DCeP Quadrant Grid

Placement of the facilities in this grid based on their performance in these two metrics allows an operator to quickly characterize facilities with respect to energy efficiency and energy productivity. Facilities landing in the lower right-hand quadrant (quadrant 4) are better than target in both metrics – these facilities are the operators best in class with respect to energy performance. These are facilities from which best practices for facility operation *should* be taken. And if consolidation in the area around these facilities is to be done, from an energy perspective, these are the facilities that *should* be consolidated into, not consolidated away.

Facilities landing in quadrant 1 are making productive use of the energy, but are not efficient as facilities themselves. Depending on how poor the PUE is, operators would want to look at facilities in this quadrant for potential energy efficiency/HVAC/cooling improvements first over other facilities, as doing that could potentially move them in the direction of quadrant 4 and best practice. Facilities in quadrant 3 are performing efficiently as facilities, but are not productive. As they are efficient, facilities in this quadrant *may* be candidates for being consolidated into, as in theory they have available capacity for adding work units to better use the energy that is there. But the low PUE means that any power added to support the new work units would be added efficiently.

Facilities in quadrant 2 represent an operator's worst performers. Not only are they energy inefficient in their ability to create the proper environment for the IT equipment, the energy they are using is not productive. From purely an energy efficiency and productivity perspective, facilities in this quadrant *should* be looked at first for potential consolidation and/or elimination. Failing that, these are the facilities where presumably the most opportunity exists for improvement work. Characterizing facilities in this manner gives operators the ability to quickly and easily categorize and track facilities with respect to energy performance, as well as to integrate energy performance into the equations used to determine facility consolidation as well as facility improvement projects.