# Green Performance Indicators for Energy Aware IT Systems: Survey and Assessment

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## Abstract

Green computing provides techniques to reduce the wastage of energy, making it very critical to the development of IT systems due to the increasing power and energy needed now-a-days to run data centers. Green metrics play a vital role in green computing since they are criteria for evaluating the green performance of the large scale IT systems. Green computing metrics need to be defined to measure power costs and energy consumption. Measuring the amount of energy consumed by IT systems is a direct way of quantizing the amount of energy wasted or used efficiently by data centers. Energy awareness in applications and data centers can be obtained and calculated through green metrics such as the *Green Performance Indicators* (GPIs). The GPIs are classified into four classes: IT Resource Usage GPIs that compute resource usage, the Application Lifecycle KPIs that define efforts required to develop or redesign applications and reconfigure IT-infrastructure, the Energy Impact GPIs that represent the environmental impact of data centers, and the Organizational GPIs that describe organizational factors. Dividing the GPIs into four classes is an approach accepted in the EU Project GAMES. Many metrics have been identified by many associations, but there still yet to exist a framework in which a set of metrics are defined and used by applications and data centers to measure energy efficiency. This paper is a survey that sums up all the known metrics defined by almost all associations, and explicitly states their different units, scopes, and most importantly compares between

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them to define similarities and replacements that may exist. Exact similarities may help eliminate metrics whose measurements can be accomplished by another metric. The gathered GPIs are defined into the four main classes mentioned above and frameworks built based on the similarities found in each class, are developed. We also define a framework for the relationship between green computing and GPIs to illustrate how GPIs are incorporated in the process. Since GPIs measure different factors related to energy consumption, they may have different units. We furthermore compare and critique different approaches to unify the various units of the different metrics, and implement one of the techniques on most of the metrics mentioned below with some improvements. We introduce the idea of correlations which can measure the amount of similarities found between the metrics to reduce the number of metrics to unify.

**Keywords:** Green Computing, Green Performance Indicators (GPI), Key Performance Service Indictors (KPI).

## 1 Introduction

The amount of energy needed to operate large scale systems such as the ever growing data centers is increasing. All data is sourced from or passes through a data center, making it the fundamental component in modern IT infrastructure. As the computing power of data centers grew so did the electricity usage causing an increase in heat dissipation, power consumption, and production. It is reported that power and cooling costs are the most dominant costs in data centers [4]. The disadvantage of the computing life cycle includes pollution in the form of carbon dioxide from power plants, and lead and mercury from manufacturing processes. For organizations with data centers to survive the boosting price of energy efficiency techniques must be implemented. Thus the study and idea of green computing is spreading in the branch of IT systems.

Green computing is a new approach which aims at designing computer systems that achieve better processing and performance with the least amount of power consumption [2]. There are many existing green computing techniques such as, reducing the overall power costs and developing energy aware and high performance computing systems traditionally, or virtualization technology, and waste recycling recently. To attain greener data centers, green computing metrics should be defined to measure their power usage and energy consumption. The metrics are criteria for evaluating the performance of data centers. Green performance metrics for data centers are a set of measurements that can qualitatively or quantitatively evaluate the environmental effects by operating a data center [4].

Green computing techniques can be implemented if needed, based on the values of the green performance metrics. Green Performance metrics play a key role in building new green applications and systems. Despite the importance of green metrics there has been quite little activity in collecting, summarizing, and agreeing on one set of performance metrics. There is no widely accepted metric set allowing for easy measuring and monitoring of energy consumed and wasted by applications and data centers, neither is there a clear method for applying these metrics. For the sake of simplicity, we will just use data centers instead of applications and data centers whenever we want to refer to both. Many associations defined different metrics, but they are not the same and if used improperly they may lead to contradictory conclusions. Thus a comprehensive and applicable framework to accurately measure energy efficiency and greenness of data centers is still scarce and not out there.

Recent works have been done such as in [2–6] presenting different frameworks for metrics associated with the different scopes of data centers but not all scopes. Tiwari [2], and Wang and Khan [4] for example, mainly mentioned metrics only associated with the energy/power. Kipp et al. [1], on the other hand, define green metrics into four classes that characterize the whole system view. The four class method defined in [1] is accepted and framed with the EU Project GAMES about green IT. But in [1], they only collect a small number of metrics that exist in each class, rather than mentioning almost all the metrics that are out there defined by many institutes. Other works have been presented to explain several green computing techniques like by Talebi and Way [10]. Fugini and Maestre [7] propose the idea of a *Green Certificate* which requires a unified unit for the several metrics to help compare the energy efficiency between different data centers and applications. Green computing has also been gaining a lot of attractions these days in works found in [8, 9, 12–14, 16–22]. This paper seeks to collect almost all the existing green metrics associated with all the scopes of a data center introduced and defined by many institutes such as the Green IT Promotion Council [30], the Uptime Institute [27], the Green Grid [26], the Nomura Research Institute [28], and the Emerson Corporation [29] and organizes each metric into one of four classes: IT resource usage, Application lifecycle, Energy impact, and Organizational. Each of these four classes comprises metrics that measure different parameters of different scopes in a computer system and data center. The four class method is based on the method proposed in [1]. The definition, unit, and scope of each metric are given along with comparisons with other metrics of the same class. This paper presents research, definition, and comparisons to find similarities, differences, and replacements among the various green performance metrics gathered. We then develop frameworks based on these comparisons. Another goal of this paper is to compare between different approaches to unify green metrics into one unit and to implement one of the techniques with some improvement. The difficulty of having many different metrics with many different units makes it a difficult task to define the "greenness" of an data center, and makes it difficult to compare between different applications built to perform the same functionality. Unifying the units for green performance indicators provides a standard for analyzing energy consumption in a comparative manner. Having a unified unit leads to implementing other ideas like green certificates as explained above. No such study exists that presents a survey of almost all the metrics associated with all the scopes of a data center defined by most associations, divides them into the four classes accepted in the EU Project GAMES, develops frameworks for the relationship between green computing and GPIs, and then compares between different approaches to unify the units of the different metrics along with critique and some improvements.

The rest of the paper is organized as follows. Section 2 explains the relationship between green computing and green performance metrics along with a framework. Section 3 defines GPIs in the IT Resource Usage class (first class). Section 4 defines key performance service indicators (KPIs) in the Application Lifecycle class (second class). Section 5 defines GPIs in the Energy Impact class (third class). Section 6 defines GPIs in the Organizational class (fourth class). Section 7 compares between different approaches to unify the units of different metrics with critique and includes our implementation on one of the techniques with some improvement. Section 8 concludes the paper and describes future work.

## 2 Green Computing and Green Performance Indicators

Green Computing is a discipline that studies, develops and promotes techniques for improving energy efficiency and reducing waste in the full life cycle of computing equipment from initial manufacture, through delivery, use, maintenance, recycling and disposal in an economically realistic way [10]. Through green computing, wastage of energy and power can be reduced by many techniques such as turning off the equipment when not in use. To achieve more energy efficiency and greener data centers, tools need to be defined to measure power costs and energy consumption. These tools are known as metrics [3]. Measuring the energy efficiency, power consumption, quality of the components deployed using various metrics can evaluate the environmental effects of a data center and its “greenness”. The green performance indicators (GPIs) are a set of metrics defined to serve the purpose of measurement. The metrics cannot just identify and specify how green a data center is, they can also evaluate the products to compare similar data centers, track the “green” performance to increase efficiency, and provide guidance to engineers and service providers to develop research on future green data center technologies. Green performance metrics can quantitatively and qualitatively evaluate the environmental effects of IT systems. GPIs measure the level of greenness of applications and large IT systems.

Having a measurement is the best way to identify and comprehend the energy usage of a data center to point out easily where energy is being consumed the most and where it is wasted. Measurements also help in comparing and assessing the energy usage of a data center with others. Green Performance metrics are aimed at providing information that allows designers to provide better design decisions that work toward green systems. The GPIs framed within the EU Project Games about green IT; consider service applications and systems from the hardware usage, service life cycle, environmental perspectives, and organizational perspectives. These four considerations form four classes in which GPIs can be categorized into: IT Resource Usage GPIs, Application Lifecycle KPIs, Energy Impact GPIs, and Organizational GPIs. It is assumed that the functional part of an application has been decided and that the green metrics depend on the application structure (namely data flow, control flow, type of employed volatile object or database requirements) and on the specific hardware and software infrastructure configurations. GPIs contribute to green computing by measuring the energy efficiency of data centers. Then various green computing techniques can be implemented or adopted to “greenify” a data center if needed, based on the measurements taken by the GPIs.

We represent the relationship between the different phases of the green computing process and how GPIs are incorporated in these phases to contribute to green computing by giving measurable values of energy efficiency of a data center in Figure 1. This diagram represents the green computing process in five different phases resulting in a green data center. The five phases begin with specifications, then design, implementation and usage, recycling and disposal, and finally analysis. Each phase is described next in detail. GPIs

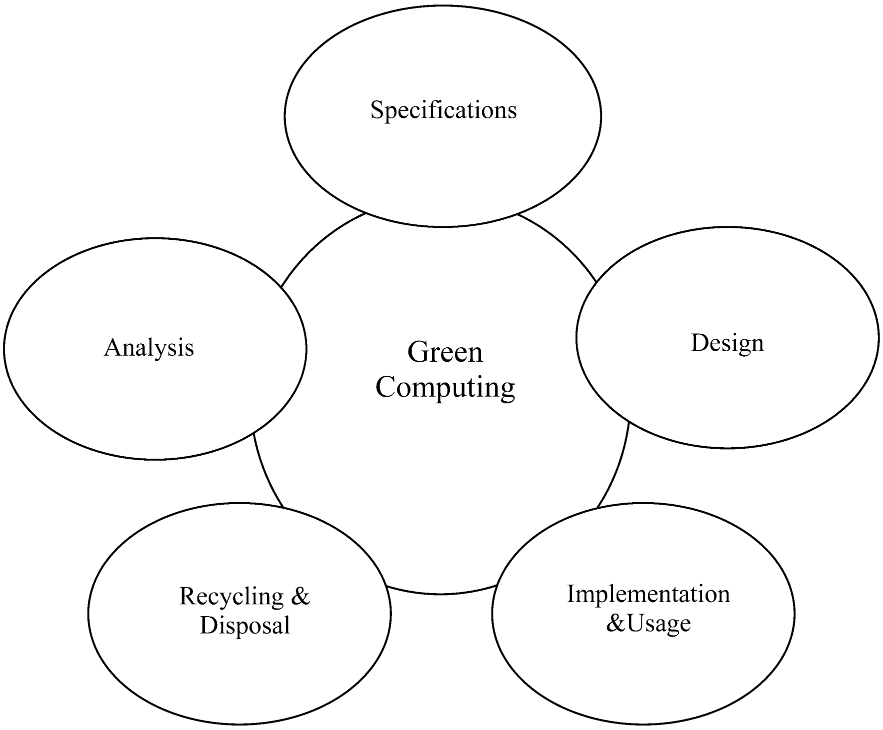


Figure 1 Green computing process.

are incorporated in all the phases of green computing to measure efficiency and performance, and to determine if greener solutions need to be adopted.

## 2.1 Specifications

The first phase involved in the green computing process is the specification stage. This phase identifies current green computing initiatives, best practices for implementing green data centers [24], and constraints. Green computing initiatives include buying greener office supplies and furniture, encouraging green-friendly transportation, increasing waste recycling programs, conserving water, buying wind or solar powered electricity, buying carbon offsets, installing air and water filtration equipment, and using green products in building renovations and new construction. Constraints are guidelines for managing data centers according to eco-related laws and regulations. Thus

GPIs play a role in the specification phase because they indicate the level of energy efficiency that is preferable.

## 2.2 Design

The second phase of the green computing process is design. This phase defines how to design an energy effect data centre. “Green” elements should be involved in the design process of a data center. Energy efficient data center design should address all of the energy use aspects included in a data center: from the IT equipment to the HVAC equipment to the actual location, configuration and construction of the building [23]. There are five primary areas to which energy efficient design practices can be implemented. These five areas are: IT system, Environment Conditions, Air Management, Cooling Systems, and Electrical System [23]. Green design decisions are effective at reducing environmental burdens and reducing costs as compared to the process of ignoring environmental effects during the design stage and ending up using clean up strategies. Some green design decisions include solvent substitution in which a toxic solvent is replaced with a benign alternative, or technology change such as more energy efficient semi-conductors. The Energy star program specifies maximum energy consumption standards for computers and other electronic devices [11]. GPIs definitely have an impact on decision making through classifying the efficiency of the elements used and the choices taken.

## 2.3 Implementation and Usage

The third phase of the green computing process is implementation and usage. This phase describes the implementation of green design decisions and usage of IT systems such computers, servers, and associated subsystems. These include such as monitors, printers, storage devices, and networking and communications systems. For instance, computer usage may generate a great deal of paper. User may minimize unnecessary waste by double-checking documents for accuracy before printing. Another useful way to practice green computing usage is by engaging power management features on the computer to allow screens and hard drives to become inactive after minutes of being idle. Operating Energy Star labeled equipment contributes to green computing implementation. A major part of this phase is applying metrics to measure efficiency of all the aspects in the data center.

### 2.4 Recycling and Disposal

The fourth phase of the green computing process is recycling and disposal. This phase covers the disposal or recycling of data center equipment at the end of its lifecycle in an environmentally responsible fashion. Like all other equipment, data center equipments are manufactured, sold, used, and often reused, and then ultimately disposed of [24]. A disposal may mean the equipment is discarded/destroyed or sold to be used again by another organization. Data centers managers replace the data center equipment either by regular refresh cycles, or wait till they have to, or utilize a continuous update process. The recycling policy should follow the 3R's policy (reduce, reuse, recycle) for proper recycling of the data center equipment. Reducing is associated with buying only what is needed which results in fewer good being produced and less throwing away of products. Reuse is associated with buying products that can be repeatedly used resulting in saving natural resources since the product is not thrown away. Recycling is associated with recycling materials leasing to reduction in energy needs for mining, refining, and other manufacturing processes.

### 2.5 Analysis

The fifth phase of the green computing process is analysis. This phase is related to measuring the performance of a data center regularly using metrics selected [24]. The steps associated to this phase begin with collecting data at regular intervals, then performing analysis energy metrics, comparing new values with old values, and finally look for greener solutions and continue the greening process.

Figure 2 shows our arrangement of the various green performance metrics (GPIs) categorized into four classes accepted by the EU Project Games. Each class contains two or more types of metrics. For example under the IT resource usage GPIs are metrics that either measure the utilization and efficiency of the equipment or metrics that measure the space efficiency of a data center based on the IT equipment deployed. In Sections 3 to 6, all the metrics related to the classes are discussed.

## 3 IT Resource Usage Metrics

The first class of Green Performance Indicators measures the energy consumption of an application/data center. The energy consumption varies on the type of application running. Some applications run the processor intens-

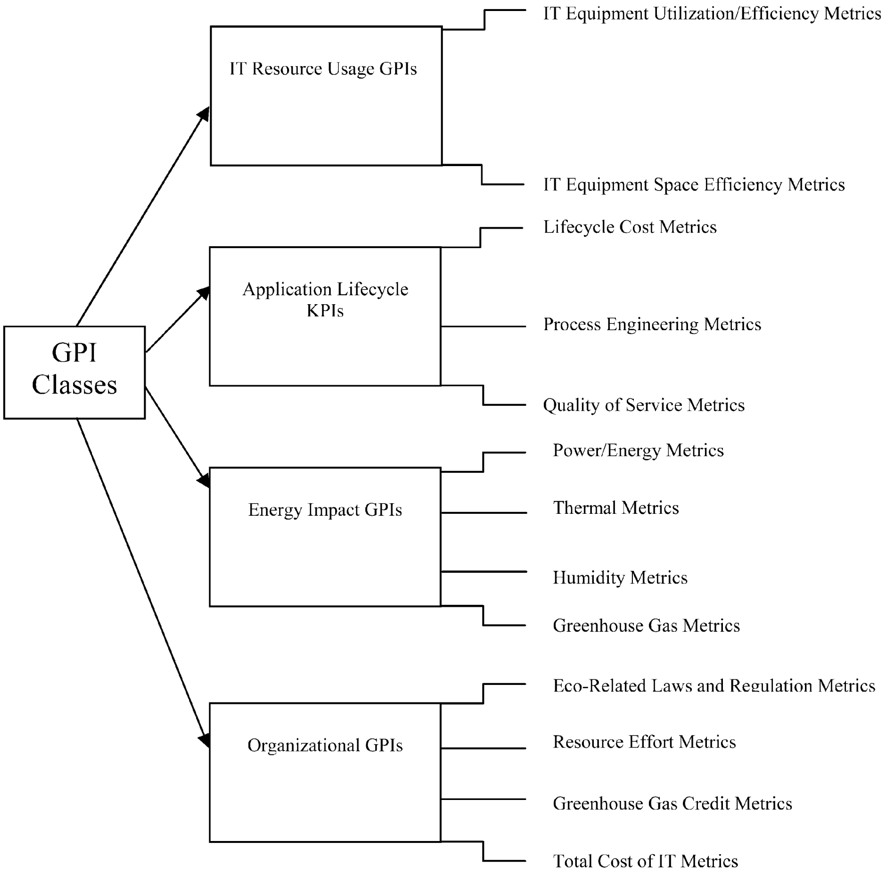


Figure 2 Green performance networks arrangement.

ively, others are data intensive, while others may even be a hybrid of both. Thus the energy consumption of an application is defined as a function of its resource utilization. These resources include CPUs, servers, storage devices, main memory, and I/O resources.

A suggested framework for the metrics found in the IT resource GPIs class is shown in Figure 3. Each metric is either an IT equipment/utilization metric or an IT equipment space efficiency metric. Metrics that have similarities between each other or may replace each other are grouped together in one rectangle. These similarities and replacements between the metrics, if any for IT resource GPIs are all found in Tables 1 and 2. Note the metrics in the IT equipment utilization/efficiency section are dimensionless (percentages). On

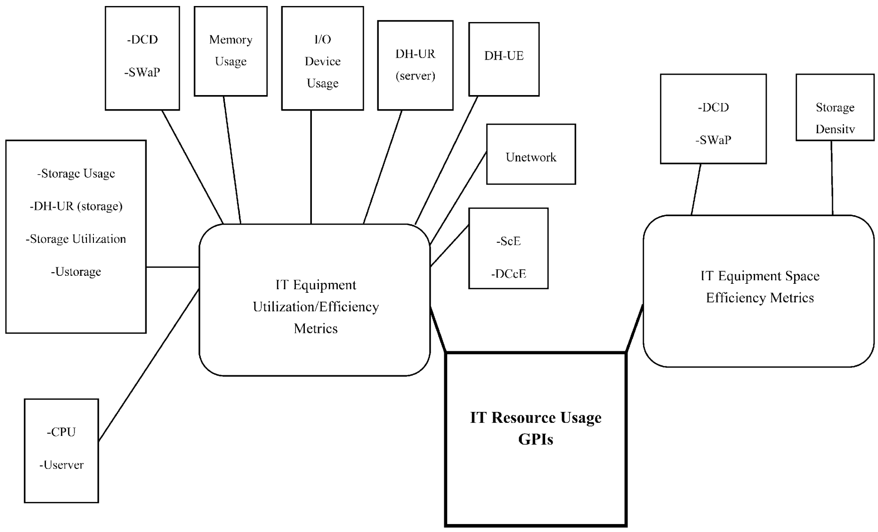


Figure 3 Framework for IT resource GPIs.

the other hand the dimensions of the IT equipment space efficiency section have dimensions. Most of the metrics in this category are defined in the rest of this section.

*CPU usage*: This metric refers to the amount of CPU utilization needed to process the instructions of an application. It is measured by evaluating the percentage of time that the allocated CPU spends on performing computing operations [1].

*Memory usage*: This metric refers to the amount of main memory (RAM) usage. It is measured by evaluating the percentage of RAM allocated for a specific application [1].

*I/O device usage*: I/O operations allow applications to communicate with system devices. This metrics refers to the occupation of an I/O device. It is measured by evaluating the percentage of occupation of a resultant I/O device for communication and the number of messages transferred by an application over a set of system components [1].

*Storage usage*: This metric refers to the amount of storage utilization for data read and write to a permanent storage such as local or remote hard disk drives [1]. It is measured by evaluating the entire storage utilization for an application.

These four resource usage GPIs can be used to measure energy consumption on different levels such as a single computer, on a class level, or for an entire IT service centre [1].

*Deployed Hardware Utilization Ratio (DH-UR)*: This metric is an indicator for the energy consumption of the main computing equipments from the IT Service Centre. This metric specified e-waste reduction approaches by removing or suspending IT equipment such as servers or storage within the data centre [3]. This metric is defined by the Uptime Institute.

- DH-UR (server) = Number of servers running live application/Total number of servers actually deployed.
- DH-UR (storage) = Number of terabyte of storage holding important frequently accessed data (within at least 90 days)/Total terabyte of storage actually deployed.

*Deployed Hardware Utilization Efficiency (DH-UE)*: This metric helps measure the potential improvement in energy savings by the utilization of servers and storage via virtualization [3]. Knowing the load of servers and the total number of servers helps in finding out how much energy is consumed during peak loads relative the number of servers being used actively. This metric is defined by the Uptime Institute.

DH-UE = Minimum number of servers necessary to handle peak compute load/Total number of servers deployed

*Storage Density (SD)*: This metric is defined by the Nomura Research Institute.

SD = Storage Utilization/Total Data Center Square Footage

*Storage Utilization (SU)*: This metric is defined by the Nomura Research Institute.

SU = Server Network and Backup Storage in Use/Total Storage Available

*Userver*: The Server utilization metric measures the rate of maximum ability of the processor in the highest frequency state [3]. This metric is defined by the Green Grid.

Userver = Activity of the server's processor/Maximum ability in the highest frequency state

*Ustorage*: The Storage utilization metric defines a ratio through which percentage of used storage regarding to overall storage capacity will be measured within the data center [3]. This metric is defined by the Green Grid.

Ustorage = Percent storage used/Total storage capacity of data center

*Unetwork*: The Network utilization metric depicts the percentage of used bandwidth over total bandwidth capacity within the data center [3]. This metric is defined by the Green Grid.

Unetwork = Percent network bandwidth used/Total bandwidth capacity of data center

*Server Compute Efficiency (ScE)*: This metric measures the efficiency of servers in data centers over anytime period by summing the number of samples where the server is found to be providing primary services (p) and dividing this by the total number of sample (n) taken over that time period and multiplying by 100 [2]. This metric helps managers improve total energy by determining the servers that are not providing primary services for specific periods. These servers can be switched off or even virtualized. This metric is defined by the Green Grid.

$$ScE = \left( \sum_{i=1}^{n} P_i / n \right) \times 100$$

*Data Center Density (DCD)*: This metric quantifies the data center space efficiency [1]. It is defined by the Green Grid Institute.

DCD = (Power of all Equipment)/(Data Center Space Area)

*Space, Watts, and Performance (SWaP)*: This metric gives users an effective cross comparison and total view of a server's overall efficiency [4]. It characterizes a data center's energy efficiency using three parameters.

SWaP = Performance/(Space $\times$ Power Consumption) where Performance is based on industry standard benchmarks, Space is the measurement of the height of the server in rack units, and Power is measured by determining the watts consumed by the system.

*Data Center Compute Efficiency (DCcE)*: This metric does not measure how much work is done, instead how much work is useful. It offers a track system that enables a data center operator to calculate efficiency of computing in servers and decide on the appropriate number of servers needed to do the job at hand [3]. This metric is defined by the Green Grid.

$$DCcE = \sum_{j=1}^{m} ScE / m$$

Table 1 IT equipment utilization/efficiency GPIs.

| Metric | Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|---|
| CPU usage | The amount of CPU utilization needed to process instructions | Percentage | Application/Data Center | The Userver is similar to this metric because it also measures CPU utilization. Either one of them can replace the other. |
| Memory Usage | The amount of main memory (RAM) usage | Percentage | Application/Data Center | |
| I/O Device Usage | The occupation of an I/O device | Percentage | Application/Data Center | |
| Storage Usage | The amount of storage utilization for data read and write | Percentage | Application/Data Center | This metric can be replaced by the DH-UR(storage) metric. |
| DH-UR (server) | Indicator for the energy consumption of servers | Percentage | Application | |
| DH-UR (storage) | Indicator for the energy consumption of storage | Percentage | Application | This metric can replace the Storage Usage, the Storage Utilization, and the Ustorage metrics. This metric not only measures the entire storage utilization, instead it also measures the number of terabyte storage in 90 days to suspend the storage that is not being used. |
| DH-UE | Measures the improvement in energy savings due to utilization of servers and storage via virtualization | Percentage | Data Center | |
| Storage Utilization | Utilization of Storage | Percentage | Application/Data Center | This metric can be replaced by the DH-UR(storage) metric. |
| Userver | Rate of maximum ability of the processor | Percentage | Application/Data Center | This metric is similar to the CPU usage metric because it also measures CPU utilization. Either one of them can replace the other. |
| Ustorage | Percentage of used storage regarding to overall storage capacity | Percentage | Application/Data Center | This metric can be replaced by the DH-UR(storage) metric. |
| Unetwork | Percentage of used bandwidth over total bandwidth capacity | Percentage | Application/Data Center | |
| ScE | Measures the efficiency of servers in data centers over anytime period | Percentage | Application/Data Center | Both this metric and the DCcE metric define the usefulness of the work being performed. |
| DCcE | Measures how much work is useful. | Percentage | Data Center | Both this metric and the ScE metric define the usefulness of the work being performed. This metric aggregates the ScE metric across all servers in a data center as well. |

In Tables 1 and 2 a list of all the metrics in class one are listed with their specified unit, scope in which they may be used, any similarities and differences that might exist between one metric and another. Finding similarities and differences helps compare between the different metrics. Exact similarities may help eliminate metrics whose measurements can be accomplished by another metric.

Table 2 Equipment space efficiency metrics.

| Metric | Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|---|
| DCD | Quantifies the data center space efficiency | KWatt/square footage | Data Center | This metric is similar to SWaP in that is quantifies the data center's space efficiency. |
| SWaP | This metric gives users an effective cross comparison and total view of a server's overall efficiency. | Operations/ (RU* Watts) | Data Center | This metric is similar to DCD in that is quantifies the data center's space efficiency, but this metric also allows for the comparison of IT server configurations. |
| Storage Density | Density of Storage | Percentage/ $(m/cm^3)$ | Data Center | |

## 4 Application Lifecycle KPIs

The metrics in this class are quite different from the ones found in classes one, three, and four. These metrics do not directly impact the energy consumption of data centers, instead they are used to determine the performance of applications. The metrics in this class characterize process quality and efforts for designing and maintaining the process. For this reason the metrics in this class are named Key Performance Service Indicators instead of Green Performance Indicators. The metrics in this class are categorized into three categories. The first category is the Lifecycle Cost indicators, the second is the Process Engineering category, and the last is the Quality of Service category. The metrics of the three categories are explained next.

In Figure 4, is our suggested framework for the metrics found in the Application Lifecycle class. Each metric is either a Lifecycle cost metric or a QoS metric or a process engineering metric. Metrics that have similarities between each other or may replace each other are found together in one rectangle. There are no relationships found between the metrics in this class.

### 4.1 Lifecycle Cost Indicators

Lifecycle cost indicators or metrics describe the total process lifecycle expenses. The scope of these metrics is the application being built. These metrics include:

1. Cost of conceptual modelling
2. Cost of analysis
3. Cost of design
4. Cost of development
5. Cost of deployment

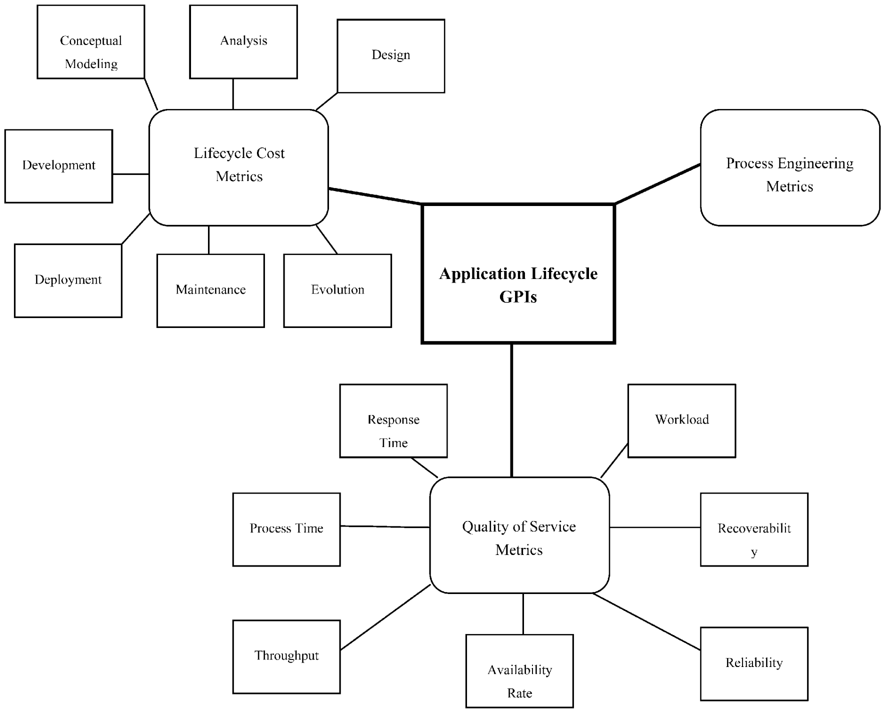


Figure 4 Framework for application lifecycle GPIs.

6. Cost of maintenance
7. Cost of evolution

The above metrics take into account potential parameters such as the developer's experience, the main service operation complexity, the level of abstraction, the reusability and integration rates, the required stability, and the closeness of the application to the business core. If we consider the cost of development metric, the parameters that are considered are the efforts placed by the developers during the application lifecycle. More precisely, if the application runs are observed throughout time it can be determined how an application should be redesigned to be more energy efficient. "The cost for redesign with respect to shorter executions, storage savings, and other application parameters create an index of energy saving" [1]. Thus the indicators in this category are given in energy measures.

### 4.2 Process Engineering

The indictors in this category illustrate the style of development used during design, coding, and deployment of an application. The scope of these metrics is the application being built. Parameters that affect the style of deployment include the level of maturity of the used development platform regarding the tools for coding, documentation and the engineering methods. Such parameters have an impact of energy consumption by enabling the developers to build applications faster with fewer errors, efficient coding, and built in elements that reveal energy leakages. Parameters that affect the style of code include indexes of data usage, service usage and branching probabilities. For example, the less number of times an application runs in dead branch flows, the more energy efficient it will be.

### 4.3 Quality of Service

The metrics in this class evaluate the quality measures of an application. The scope of these metrics is the application being built. These metrics have an indirect instead of a direct impact on the energy consumption of an application. An increased reliability or response time will result in a negative impact on energy consumption. This expected quality can be instead achieved by efficient resource utilization. These metrics include:

*Response Time*: This metric refers to the time it takes a service to handle a user's request. The response time given Tresponse of a given service S is calculated using the processing time Tprocess and the transmission time Ttrans [1]. The unit for this metric is time.

$$\mathrm{Tresponse} = \mathrm{Tprocress(S)} + \mathrm{Trans(S)}$$

*Process Time*: This metric is given by the average time taken to process a service S from the time of invocation Tinvocation to the time of completion Tcompletion including delays Tdelay [1]. The unit for this metric is time.

$$\mathrm{Tprocess(S)} = (\mathrm{Tcompletion(S)} - \mathrm{Tinvocation(S)}) + \sum \mathrm{Tdelay}$$

*Throughput*: This metric is the average number of service requests successfully served during a given period of time [1].

*Availability Rate*: The average rate of availability of a given service S is represented by the probability that a certain request is properly responded within a maximum expected time frame [1]. The unit for this metric is percentage.

Availability Rate=number of successful service requests/number of service requests

*Reliability*: This metric is given by the probability that a system remains operational over a certain period of time [1]. It can be represented by the exponential distribution that describes random failures.

$R = e^{[-(1*t)]}$ where $t$ is the expected execution time and l is the failure rate over the reference interval

*Recoverability*: Recoverability is given as the probability that a failed system is can be operational again within a certain period of time [1]. It can be measured from logs using process mining. The unit for this metric is percentage.

*Workload:* This metric includes the type and rate of requests, execution of the software packages, and in-house application programs sent to the system [1]. The unit for this metric is given by an index.

## 5 Energy Impact GPIs

The GPIs of the third class describe the impact if IT service centers and applications on the environment. Metrics in this class measure the amount of power supply needed by a data center, consumed materials, $CO_2$ emissions, and other energy related factors rereleased in the air. These metrics give a direct value of how "green" an application or data center is.

In Figure 5, is our suggested framework for the metrics found in the Energy Impact class. Each metric is either a power/energy metric or a thermal metric or humidity metric or a greenhouse gas metric. Metrics that have similarities between each other or may replace each other are found together in one rectangle. These similarities and replacements between the metrics, if any for Energy Impact GPIs are all found in Tables 3, 4, 5 and 6. In the power/energy section, a connection if found between the PUE metric and all the metrics in this rectangle. The same case is found between the ITEE metric and the rest of the metrics in that rectangle for the same section.

*IT Equipment Utilization (ITEU)*: Is a metric that defines the energy-saving level through implementing both virtual and operational techniques among IT equipments in a data centre [3]. It measures the average utilization of the entire IT equipment within a data center. This metric is defined by the Green IT Promotion Council.

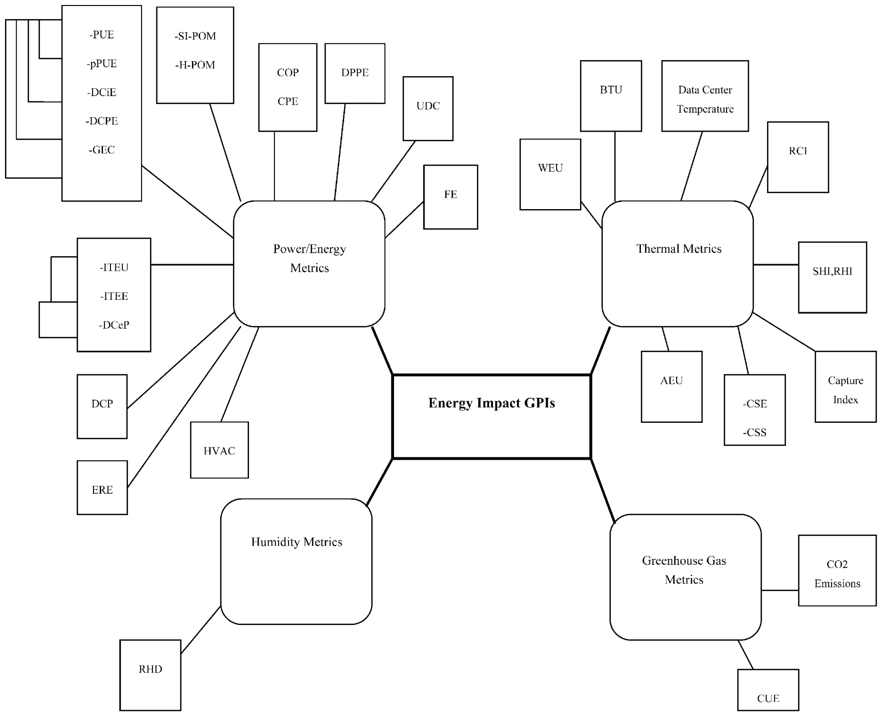


Figure 5 Framework for energy impact GPIs.

ITEU = Total measured power of IT equipment/Total rated power of IT equipment

*Data Centre Infrastructure Efficiency (DCiE)*: It is used to determine the energy efficiency of a data centre. This metric refers to how much energy the IT equipment consumes from the total energy consumption [1]. This metric is defined by the Nomura Research Institute.

DCiE = IT Equipment Power/Total Facility Power, where IT equipment power is defined as the load associated with computers, storage, and network equipment and Total Facility power is measured at or near the facility utility meter

*Power Usage Effectiveness (PUE)*: This is a metric that focuses on the data center infrastructure. Its value may range from 1.0 to infinity. A value 1.0 indicates 100% efficiency [2]. This metric is defined by the Green IT Promotion Council.

PUE = Total Facility Power/IT Equipment Power

*Partial Power Usage Effectiveness (pPUE)*: This is a conceptual metric where a PUE-like value for a subsystem is measured and reported [2]. This metric is defined by the Green Grid.

pPUE = Total Energy within a boundary/IT Equipment Energy within that boundary

*Site Infrastructure Power Overhead Multiplier (SI-POM)*: This metric defines how much power is consumed in overhead instead of critical IT equipments [3]. This metric is defined by the Uptime Institute.

SI-POM = Data center power consumption at the utility meter/Total hardware AC power consumption at the plug for all IT equipment

*IT Hardware Power Overhead Multiplier (H-POM)*: This metric defines how much power input to hardware is wasted in power supply for fans rather than useful computing components [3]. H-POM differs for a single device and for an entire data centre. This metric is defined by the Uptime Institute.

H-POM (single device) = AC hardware load at the plug/DC hardware Compute load
H-POM (data centre) = Total hardware load at the plug for the entire data centre/total hardware compute load for the entire data centre.

*Data Centre Energy Productivity (DCeP)*: This metric indicates the number of bytes which are processed per kWh of electric energy. This metric is capable of measuring site infrastructure and IT equipment while assessing data center efficiency [3]. This metric is defined by the Green Grid.

DCeP = Useful work produced in a data center/Total energy consumed in the data center to produce that work

*Data Centre Performance Efficiency (DCPE)*: This metric shows how effective a data centre is in terms of power consumption when work is given [3]. Because this metric is emerging over time, it is complicated to measure. This metric is defined by the Green Grid.

DCPE = Useful Work/Total Facility Power

*Coefficient of Performance of the Ensemble (COP)*: This metric measures the IT data centre greenness. "It reflects the energy efficiency of the data centre cooling system by taking into account the data centre performance per unit of used energy" [1].

COP Ensemble = Total Heat Dissipation/(Flow Work + Thermodynamic Work) of cooling system

*$CO_2$ Emission*: This metric is the amount of average carbon dioxide emissions from generating an average kWh of electricity [1].

*Compute Power Efficiency (CPE)*: This metric seeks to quantify the overall efficiency of a data center. It considers that not all electrical power delivered to the IT equipment is transformed by that equipment into useful work.

CPE = (IT Equipment Utilization × IT Equipment Power)/Total Facility Power
or CPE = IT Equipment Utilization/PUE

*Energy Reuse Effectiveness (ERE)*: It is a metric that measures the energy efficiency in data centers that re-use waste energy from their own data center [2]. This is a metric that focuses on recycling and reusing of components. This metric is defined by the Emerson Corporation.

ERE = (Cooling + Power + Lighting + IT-Reuse)/IT where IT is the energy used by all of the IT equipment (servers, network, storage) in the data center

*Carbon Usage Effectiveness (CUE)*: This metric measures sustainability of data centers [3]. It can help organizations recognize whether their current data centers are efficient before they decide to implement a new one. This metric is defined by the Greed Grid.

CUE = Total Carbon Dioxide Emissions from Total Data Center Energy/IT Equipment Energy

*Water Usage Effectiveness (WUE)*: This metric is defined by the Green Grid.

WUE = Annual Site Water Usage/IT Equipment Energy

*IT Equipment Energy Efficiency (ITEE)*: This metric improves energy saving through setting up new equipments with high processing capacity in term of power consumption [3]. This metric is defined by the Green IT Promotion Council.

ITEE = Total server capacity + total storage capacity + total NW equipment capacity/Rated power of IT equipment

*Green Energy Coefficient (GEC)*: This metric is meant to persuade operators to use renewable energy [3]. This metric replaces grid electricity with green energy. It is a ratio that originated from dividing the value of Green Energy used in a data center by the total power consumed in the data center. This metric is defined by the Green IT Promotion Council.

GEC = Green Energy/DC total power consumption

*Data Center Performance Per Energy (DPPE)*: This is an integrated metric created to improve energy savings in data centers [3]. It contains four metrics already explained above. This metric is defined by the Green IT Promotion Council.

DPPE = ITEU $\times$ ITEE $\times$ 1/PUE $\times$ 1/1-GEC

*Facility Efficiency (FE)*: This metric is defined by the Nomura Research Institute.

FE = Facility Energy Efficiency $\times$ Facility Utilization

*Data Center Utilization (UDC)*: This metric calculates the amount of power that IT equipment consume regarding to the data center's real capacity [3]. This metric is defined by the Green Grid.

UDC = IT Equipment Power/Actual Power Capacity of the Data Center

*Data Center Productivity (DCP)*: This metric is defined by the Nomura Research Institute.

DCP = Useful Computing Work/Total Facility Power

*Relative Humidity Difference (RHD)*: This metric aims at measuring the amount of humidity in the air. Humidity is the measurement of moisture content in the air. High humidity in data centers result in hardware failures and increase the cooling costs making humidity control an essential for physical media. Humidity is measured by looking at the relative humidity which is given as a percentage and measures the amount of water in the air at a given temperature compared to the maximum amount of water that air can hold [4].

RHD = Rhumidity – Shumidity where Rhumidity is the return air relative humidity and Shumidity is the supply air relative humidity

*Heating, Ventilation, and Air Conditioning (HVAC) Effectiveness*: The HVAC system of a data center includes the computer room air conditioning and ventilation, a central cooling plant, and minor load (lighting). The HVAC system effectiveness is the fraction of the IT equipment energy to the HVAC system energy [4].

HVAC Effectiveness = IT/(HVAC + (Fuel + Steam + Chilled Water) × 293) where IT is the annual IT Electrical Energy Use, and HVAC, Fuel, Stream, Chilled Water are all in terms of years

Another set of metrics that may be included in this section or class is thermal metrics. "It is reported that cooling costs can be up to 50% of the total energy cost in a data center" [3]. Thus thermal metrics are essential for operating a green data center.

*Data Center Temperature*: High temperature in a data center has a negative impact on the computing systems causing for reduction in reliability, quality of service, and longevity of components. It is recommended that IT equipment not be operating in a room temperature above 85°F (30°C). A small temperature differential between supply and return air temperature allows for an improvement in air management, the rise of supply air temperature, and thus reduction in energy usage [4].

*British Thermal Unit (BTU)*: "A BTU is the amount of energy required to raise the temperature of a pound of water 1°F" [4]. To calculate the amount of cooling power needed to cool a data center there a three issues to consider:

- Size of a data center (determines how many BTUs are required to cool down a data center) – BTU = 330 × Length × Width
- Equipment (BTUs required for equipment in a data center) – BTU = 3.5 × total wattage running the equipments
- Lighting (total BTUs required for lighting) – BTU = 4.25 × wattage of lighting

*Rack Cooling Index (RCI)*: This metric measures the effective coolness and maintaining of equipment racks with industry thermal guidelines and standards [4].

$RCI_{HI}$ = This metric measures the absence of over-temperatures or characterize the equipment health at the high end of the temperature range

$RCI_{LO}$ = This metric gives a measurement of the supply conditions when they are below the minimum recommended temperature. If the supply conditions of the equipment racks are below the recommended temperature then the humidity level may be harmful

*Supply Heat Index and Return Index (SHI, RHI)*: These two measurements assess the magnitude of recirculation and blend of hot and cold streams. Best results occur when RHI is high and SHI is low [4].

- SHI = This metric measures the extent to which warm return air mixes with cool supply air
- RHI = This metric measures the extent to which cool supply air mixes with warm return air.

*Capture Index (CI)*: This metric measure the cooling performance based on the airflow patterns related to the supply of cool air or the removal of hot air from the equipment rack. There are two CI metrics. The cold-aisle CI is the amount of air from local cooling resources ingested by the rack. The hot-aisle CI is the amount of air captures by local extract exhausted by the rack [4].

*Data Center Cooling System Efficiency (CSE)*: This metric describes the overall efficiency of the cooling system in terms of energy input per unit of cooling output [4].

CSE = Average cooling system power usage/Average cooling load

*Cooling System Sizing (CSS)*: This metric may indicate if a cooling system is scalable and has good potential. It is the ration of the installed cooling capacity to the peak cooling load [4].

CSS = Installed Chiller Capacity/Peak Chiller Load

*Air Economizer Utilization (AEU)*: The metric indicates the extent to which an air-side economizer system is used to provide free cooling. It is described as the percentage of hours in a year that the economizer system is in full operation [4].

AEU = Air economizer hours/24 $\times$ 365

In Tables 3, 4, 5, and 6 all the metrics in the third class are listed with a brief definition, their units, scope, and any similarities, differences, or replacements.

## 6 Organizational GPIs

Organizational GPIs are the fourth and last class of GPIs. The metrics in this class measure organizational factors. Organizational GPIs have a direct impact on high level decisions in data centers related to infrastructural costs and guidelines defined by eco-related laws and regulations for managing data centers. Infrastructural costs are costs for owning new energy saving software and hardware, or maintenance, etc.

Table 3 Power/energy metrics.

| Metric | Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|---|
| ITEU | Defines energy-savings due to implementing virtual and operational techniques. | Percentage | Data Center | This metric and the ITEE metric reduce energy consumption of IT equipments in data centers. |
| DCiE | Determines the energy efficiency of a data centre. | Percentage | Data Center | This metric and the PUE both identify the data center's energy consumption and are predecessor requirements for green measurements. |
| PUE | This metric focuses on the data center's infrastructure. | Percentage | Data Center | This metric and the GEC metric reduce energy consumption of facilities in data centers.<br>This metric and the DCiE both identify the data center's energy consumption and are predecessor requirements for green measurements |
| pPUE | PUE-like value for a subsystem. | Percentage | Data Center | This metric is exactly similar to the PUE metric except that is it limited to a subsystem. |
| SI-POM | Measures how much power is consumed in overhead in the site infrastructure. | Percentage | Data Center | This metric and the H-POM metric (single device/data center) measure the overhead power. This metric measures it in the site infrastructure as compared to the H-POM metric which measure the overhead in the IT equipment. |
| H-POM (single device) | Measure how much power input to hardware is wasted in power supply for non-computing components. | Percentage | Device | This metric and the H-POM metric for a data center, both measure the overhead power in IT equipment. |
| H-POM (data center) | Measure how much power input to hardware is wasted in power supply for non-computing components. | Percentage | Data Center | This metric and the H-POM metric for a single device, both measure the overhead power in IT equipment. |
| DCeP | Indicates the number of bytes which are processed per kWh of electric energy. | Tasks/kWhr | Data Center | This metric can be replaced by its equivalent metric ITEE. |
| DCPE | Measures how effective a data centre is using power to provide a given level of service. | Percentage | Data Center | This metric is an expansion of PUE. It is a refined version of PUE because is adopts all major power-consuming subsystems found in a data center. |
| COP | Measures the IT data centre greenness. | Dimensionless | Data Center | This metric and the CPE measure the overall efficiency or greenness on the data center. The COP metric measures the overall efficiency with respect to the cooling system and the CPE metric measures the overall efficiency with respect IT equipment. |
| CPE | Quantifies the overall efficiency of a data center. | Percentage | Data Center | This metric and the COP measure the overall efficiency or greenness on the data center. The COP metric measures the overall efficiency with respect to the cooling system and the CPE metric measures the overall efficiency with respect IT equipment. |
| ERE | This metric that focuses on recycling and reusing of components. | Percentage | Data Center | |
| ITEE | This metric improves energy saving through setting up new equipments with high processing. | DEC | Data Center | This metric can be replaced by its equivalent metric DCeP.<br>This metric and the ITEE metric reduce energy consumption of IT equipments in data centers. |
| GEC | It persuades operators to use renewable energy. | Percentage | Data Center | This metric and the PUE metric reduce energy consumption of facilities in Data Centers. |

Table 3 Continued.

| | | | | |
|---|---|---|---|---|
| DPPE | It is an integrated metric created to improve energy savings in data centers. | Operations/kWh | Data Center | |
| FE | Facility Efficiency | Joules | Data Center | |
| UDC | Calculates the amount of power that IT equipment consume regarding to the data center's real capacity | Percentage | Data Center | |
| DCP | Data Center Productivity | Joules/Watts=Time | Data Center | This metric and the DCcE metric both compute the amount of useful work. This metric measures useful work in all the data center |
| HVAC | Heating, Ventilation, and Air Conditioning | Percentage | Data Center | |

Table 4 Thermal metrics.

| Metric | Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|---|
| RCI-$RCI_{HI}$, $RCI_{LO}$ | Measures the effective coolness and maintaining of equipment racks | Percentage | Data Center | |
| SHI, RHI | Assess the magnitude of recirculation and blend of hot and cold streams. | Index | Data Center | |
| Capture Index-Cold-aisle CI, Hot-aisle CI | Measures the cooling performance based on the airflow patterns related to the supply of cool air or the removal of hot air from the equipment rack | Index | Data Center | |
| CSE | Describes the overall efficiency of the cooling system | kW/ton | Data Center | The metric along with the CSS metric measure the efficiency of the cooling system installed. |
| CSS | Indicate if a cooling system is scalable and has good potential | Percentage | Data Center | The metric along with the CSE metric measure the efficiency of the cooling system installed. |
| AEU | Iindicates the extent to which an air-side economizer system is used to provide free cooling | Percentage hours | Data Center | |
| WUE | Water Usage Effectiveness | Liters/kWh | Data Center | |
| Data Center Temperature | Measures the data center's temperature | Degrees | Data Center | |
| BTU | This metrics presents the amount of energy required to raise the temperature of a pound of water to 1°F | Dimensionless | Data Center | |

Table 5 Greenhouse gas metrics.

| Metric | Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|---|
| CO2 Emission | Measures the amount of average carbon dioxide emissions. | Percentage | Data Center | |
| CUE | This metric measures sustainability of data centers. | $Kg(CO_2)/kWh$ | Data Center | |

Table 6 Humidity metrics.

| Metric | Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|---|
| RHD | Measures the amount of humidity in the air. | Percentage | Data Center | |

In Figure 6, is our suggested framework for the metrics found in the Organizational class. Each metric is either eco-related laws and regulations metric or a resource effort metric or a greenhouse gas credit metric or a green solution metric or a cost of the IT center metric. Metrics that have similarities between each other or may replace each other are found together in one rectangle. These similarities and replacements between the metrics, if any for Organizational GPIs are all found in Table 7.

*Human Resources Indicator*: This metric assesses efforts spent by human resources involved in running and managing an application, service development [1].

*Compliance Indicator*: This metric evaluates the amount of efforts spent abiding with the government regulations and/or consortium policies [1]. Some consortium policies include EU Code of Conduct for Data Centers 2010.

*Infrastructural Costs Indicator*: This metric includes the costs related to the building, the facility, and IT equipments [1]. This metric also involves the costs related to replacement and maintenance of the IT equipments. Costs/efforts of humans who design, run, and manage the data center as a whole are also included.

*Carbon Credit*: This metric represents the offset credits that are bought and sold to offset carbon dioxide emissions [1]. This rules and conditions for this metric differ from country to country.

*Return of Green Investment (RoGI)*: This metric measures the time it takes for green solutions to pay off or recuperate [1].

*Consumables Index*: This metrics is associated with costs of printouts and materials produced by the service during executions [7].

*Total Cost of Ownership*: This is a metric that represents the cost it takes an owner to purchase or build, operate, and maintain a data center. The

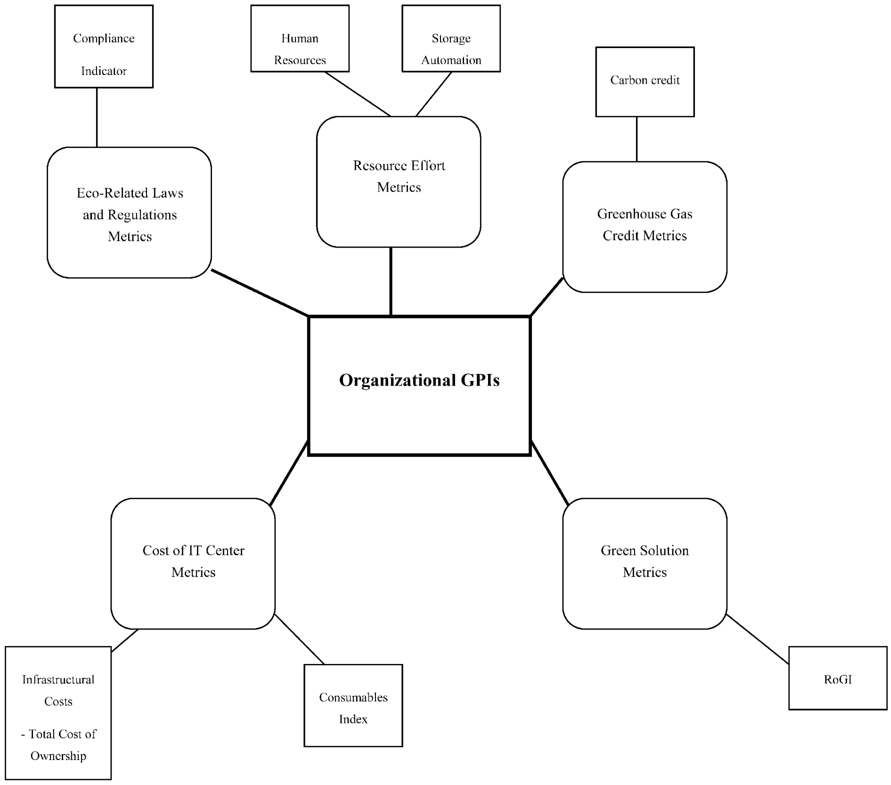


Figure 6 Framework for organizational GPIs.

total expenses are divided into two parts which the capital expenses and the operational expenses [4]:

- Capital Expenses: These are expenses related to the initial investments for purchasing and building a data center. The major subsystems of a data center such as the cooling and space are scale almost linearly with the amount of energy consumed. Thus the capital cost is represented in dollars per watt.
- Operational Expenses: These are the monthly expenses of running a data center. Factors that affect these expenses are climate changes, management costs, or even implementation techniques.

*Storage Automation*: Human Operators/Storage Density where Storage Density = Storage Utilization/Total Data Center Square Footage [3].

Table 7 Organizational GPIs.

| Definition | Unit | Scope | Similarities/Replacements |
|---|---|---|---|
| **Eco-related Laws and Regulations** | | | |
| Amount of efforts spent abiding with the government regulations and/or consortium policies | Index | Data Center | |
| **Resource Effort Metrics** | | | |
| Efforts spent by human resources | Costs | Application/Data Center | |
| Storage Automation | Percentage | Data Center | |
| **Greenhouse Gas Credit Metrics** | | | |
| Offset credits that are bought and sold to offset carbon dioxide emissions | Offset Credits | Data Center | |
| **Green Solution Metrics** | | | |
| The time it takes for green solutions to pay off or recuperate | Time | Data Center | |
| **Cost of IT Center Metrics** | | | |
| Costs related to the building, the facility, and IT equipments and costs/efforts of humans who design, run, and manage the data center | Cost | Data Center | This metric is similar to the Total Cost of Ownership metric because both refer to the costs of building, operating, and managing the data center. But this metric cannot replace the Total Cost of Ownership metric because, it also considers human efforts that run the data center. |
| Represents the cost it takes an owner to purchase or build, operate, and maintain a data center | Capital Costs and Operational Costs | Data Center | This metric is similar to the Infrastructural cost metric because both refer to the costs of building, operating, and managing the data center. |

In Table 7 all the metrics in the fourth class are listed with a brief definition, their units, scope, and any comparisons, or replacements.

## 7 Approaches to the Unification of Different Units of GPIs

In this section we define three different recent techniques found for unifying the different units of the green metrics to simplify the task of comparing data centers and application by having one value to represent the energy efficiency instead of many. Section 7.1 explains the different techniques with critique and Section 7.2 implements one of the techniques on most of the metrics mentioned above with some improvements.

### 7.1 Different Techniques to Unify the Different Units of GPIs

There are so many metrics with different units that measure different aspects in the whole IT system. This makes it very hard to distinguish between a data center and another based upon their energy efficiency or "greenness". Thus unifying the different units of the green metrics or having one value indicating the "greenness" of a data center will allow for evaluating energy consumption in a comparative manner. There are two main approaches that can be taken to unify the units of the different GPIs based on recent works found in [1, 15]. The first is aggregating the values for the GPIs via methods such as normalization, and the second is determining one metric or value that is enough to indicate the total "greenness" of a data center. Next we will describe and compare three techniques based upon the two approaches given above.

The first technique described in [1] uses an aggregating approach to unify the units. It based on the idea of entropy ($E_S$) and its associated threshold ($T_E$). The entropy is an indicator that measures the compliance of the level of greenness of a service center with specific energy-saving requirements [25]. This technique uses entropy to describe the "greenness" of a data center. The technique simply measures if for a given context situation meaning part of a system being considered, the evaluated entropy is below a predefined threshold ($T_E$), then all the GPIs/KPIs for this context are fulfilled, otherwise some GPIs/KPIs did not meet the expectations and "greener" techniques need to be adopted to bring down the entropy level. The way to calculate the entropy that they defined sets a predefined threshold or a related policy for each GPI/KPI and evaluates whether the threshold is satisfied or not. The entropy is given by this equation: $E_s = \sum f_n$ where the formula $f_n$ is defined as $f_n : pn\{0, 1\}$ and indicates whether the policy $p_n$ associated to a GPI/KPI condition is fulfilled or not.

The second technique described also in [1] uses an aggregating approach to unify the units as well. In this technique a new metric name Green Level describes the energy efficiency or "greenness" of a data center. The value of this metric can be evaluated as the sum of the weights of each metric multiplied by a function that produces a dimensionless value normalized between 0 and 1 for all the metrics. The Green Level is given by this equation:

$$\text{GREEN\_LEVEL} = \sum w_n * f_n(GPI_n)$$

where the weights $w_n$ are defined based on the preferences given by the involved stakeholders and the fn function is the evaluation function that allows to compare heterogeneous indexes to be compared [1].

The third technique described in [15] uses one metric that is enough to indicate the total "greenness" of a data center. The authors in [15] use a thermodynamic metric, *exergy* that measures the available energy in a system in joules to quantify the environmental impact from the operational phase of the system lifecycle. Exergy is formally defined as the maximum amount of useful work that can be derived relative to the surrounding reference state. For servers, the exergy consumption can be approximated by the total electricity consumption during operation. The authors state that when electricity is consumed by a server, it is converted to heat and loses most of the potential for useful work. To evaluate the server electricity consumption, for each component the maximum power rating is used to model how the power varies with workload and time periods of operation. In [15], the exergy consumption in infrastructures is also considered since cooling and power delivery infrastructure account for a large fraction of the total electricity consumption. The exergy consumption is modelled using the power usage effectiveness (PUE) metric. PUE is given by PUE = (operational power + infrastructure)/operational power.

The above techniques contain some vague areas that can certainly raise some questions and critiques. In the first scheme in which entropy is used to aggregate the different values of the different metrics, only a rough estimate is given to evaluate the total "greenness" of a data center. The measurement (entropy) is computed based on if a threshold value is fulfilled or not rather than the actual measurement value of each metric. The second technique aggregates all the values of the metrics after normalizing them to a range between {0–1} and multiplying by their weights. This technique gives a much more accurate measurement as compared to the first technique. The last technique which determines the total greenness of a data center based on exergy consumption only focuses one issue which is energy wastage/power consumption instead of taking into account the rest of the measurements computed by the other metrics. This value is not applicable in all cases; either a large data center or a small data center. Thus this technique does not reflect the overall picture because not all the metrics are considered. Overall, we believe the most appropriate technique is the second one.

### 7.2 Implementation of the Second Technique

The technique we will be implementing on one of the above metrics for all the classes is the second one based on normalizing the metric values to a range between {0–1}, multiplying by their weights, and then aggregating the results.

The above frameworks are structured based on the relationships between the metrics found in the same class. Similarities and replacements found between metrics in each class may also indicate correlations between the class. The idea of correlations between the metrics found in each class help us a lot in decreasing the total number of metrics to unify only since they measure the amount of similarities between them. It is not enough to define similarities between the metrics without a correlation measurement. Correlations may indicate direct proportionality between the metrics of one section or more than one section in a specific class as represented in the above frameworks. For example an increase in the PUE value indicates a greater amount of energy going to waste which as a result increases as well the Data Center Temperature metric. These two metrics as a result are correlated. The amount of correlation found between a metric and another with different units can be calculated as follow and found in [31]:

$$\text{Correlation} = \frac{\int_0^T F_i(t)G_j(t)dt}{\sqrt{\int_0^T {F_i}^2(t)dt \int_0^T {G_j}^2(t)dt}}$$

where $F$ is value of metric number $i$, $G$ is the value of metric number $j$, and $T$ is the time over which the metrics are measured. We assume here that the metric values change with time. If the data is given in discrete time, then the above integrations should be replaced by summations. We note that the correlation lies between 0 and 1. The smaller the correlation value, the more independent are the two metrics are. The correlations found between the metrics will decrease the number of metrics leading to a less number of units and thus ease the process of unification. We reduce the number of metrics in a class based on strong/high correlations between them. If a number of metrics with the same unit have correlations between them are strong then we may exclude some metrics, but if the correlations are weak then they should be all kept.

Now we will give an example of strong and weak correlations between four different metrics (these are hypothetical measurements):

$$F_i = \text{CPU Usage} = 0.9, 0.95, 0.8, 0.85, 0.90, 0.95$$

$$G_j = \text{Userver} = 0.7, 0.75, 0.6, 0.7, 0.75, 0.85$$

$$\text{Correlation} = (.9 * .7 + .95 * .75 + .8 * .6 + .85 * .7 + .9 * .75 + .95 * .85)/$$
$$\sqrt{(.7^2 + .75^2 + .6^2 + .7^2 + .75^2 + .85^2)(.9^2 + .95^2 + .8^2 + .85^2 + .9^2 + .95^2)}$$
$$= 0.99$$

0.99 indicates a strong correlation between the CPU Usage and Userver metrics.

$$F_i = \text{CPU Usage} = 0.15, 0.35, 0.45, 0.55, 0.65, 0.75$$

$$G_j = \text{Unetwork} = 0.9, 0.8, 0.7, 0.6, 0.4, 0.1$$

$$\text{Correlation} = (.15 * .9 + .35 * .8 + .45 * .7 + .55 * .6 + .65 * .4 + .75 * .1)/$$
$$\sqrt{(.15^2 + .35^2 + .45^2 + .55^2 + .65^2 + .75^2)(.9^2 + .8^2 + .7^2 + .6^2 + .4^2 + .1^2)}$$
$$= 0.67$$

0.67 indicates a weak correlation between the CPU Usage and the Userver metrics.

After finding the correlations which reduce the number of metrics we are working with, we can apply the second technique presented in [1] based on normalizing the metric values to a range between {0–1}, multiplying by their weights, and then aggregating the results. After obtaining the correlations between the metrics of the same class for the four classes, we will have a smaller applicable number of metrics which we can convert to a unified unit: cost instead of Green Level, the metric used in [1]. The equation that represents the "greenness" of a data center in terms of cost is given by:

$$\text{Cost} = \sum_{i=1}^{n} w_i f_i(M_i)$$

where $i$ is from 1 to $n$ (the total number of metrics).

This equation is inspired by the work found in [1] except that is measures the greenness of a data center is cost instead of its green level. There is no need in explaining each variable in the equation because it is exactly the equation presented in [1] and explained in the section above. $M_i$ is the actual

Table 8 Metrics where the expected cost is low and $F_i(M_i) = M_i$.

| Metrics | Range | $F_i(M_i)$= |
|---|---|---|
| CPU Usage, Memory Usage, I/O Device Usage, Storage Usage, DH-UR (server), DH-UR (storage), Storage Utilization, Ustorage, Unetwork, ITEU, SI-POM, H-POM, CO2, CUE, WUE, UDC, RHD, Data Center Temperature, SHI, AEU | 0-1 | $M_i$ |

Table 9 Metrics where the expected cost is low and $F_i(M_i) = 1 - 1/M_i$.

| Metrics | Range | $F_i(M_i)$= |
|---|---|---|
| PUE, pPUE, BTU, Human Resources, Infrastructural Costs, Carbon Credit, Consumables Index, Total Cost of Ownership | 1-∞ | $1-1/M_i$ |

value of each metric and the $f_i(M_i)$ function conditions each metric to a dimensionless value that lies between 0 and 1 and thus makes the different units transparent. The closer this value is to 0 the less is the cost and vice versa. Next, we define the value $f_i(M_i)$ for all the metrics above is given below:

If the value in terms of cost for the metric should be *high* to indicate a more "green" data center and:

- If the range of $M_i$ is between (0–1), with 1 being the most favourable value

  Then the value $f_i(M_i) = 1 - M_i$.
- If the range of $M_i$ is between (1–$\infty$), with $\infty$ being the most favourable value

  Then $(1/M_i)$ will give a range (1–0).

If the value in terms of cost for the metric should be *low* to indicate a more "green" data center then:

- If the range of $M_i$ is between (0–1), with 0 being the most favourable value

  Then the value $f_i(M_i) = M_i$.
- If the range of $M_i$ is between (1–$\infty$), with 1 being the most favourable value

  Then $(1/M_i)$ will give a range (1–0) and then a suitable definition is

  $f_i(M_i) = 1 - 1/M_i$ giving a range (0–1).

In Tables 8, 9, 10, and 11 the metrics are divided based on the range of their actual values $(M_i)$ and their associated normalized value. Note that metrics with a non-dimensionless metric should be divided by the maximum

Table 10 Metrics where the expected cost is high and $F_i(M_i) = 1 - M_i$.

| **Metrics** | **Range** | **$F_i(M_i)$=** |
|---|---|---|
| DH-UE, Userver, Server Compute Efficiency, DCD, SWaP, DCcE, DCiE, DCPE, COP, CPE, ERE, GEC, DPPE, FE, VAC, RCI, RHI, CI, CSE, CSS | 0-1 | 1- $M_i$ |

Table 11 Metrics where the expected cost is high and $F_i(M_i) = 1/M_i$.

| **Metrics** | **Range** | **$F_i(M_i)$=** |
|---|---|---|
| ITEE | 0-1 | $1/M_i$ |

possible their value to normalize them and allow them to fall between the range {0–1}.

We give now an example that compares between two different applications that perform the same function and are run in the same data center. The weights being used in this example are hypothetical.

| Metric | System A | System B |
|---|---|---|
| CPU Usage | 95% | 83% |
| Memory Usage | 93% | 60% |
| I/O Usage | 40% | 75% |

In this case, $M = 3$, weight$_1$ for CPU usage is 0.6, weight$_2$ for Memory usage is 0.6, weight$_3$ for I/O usage is 0.9.

$$\text{Cost}_A = \sum_1^3 (.95 * .6) + (.93 * .6) + (.4 * .9) = 1.49$$

$$\text{Cost}_B = \sum_1^3 (.83 * .6) + (.6 * .6) + (.75 * .9) = 1.53$$

As is shown, System A is better because its cost is less due to the difference in the weight values between the metrics.

## 8 Conclusion

Green Performance Indicators play a key role in building more energy efficient data centers. Although many metrics have been defined to measure all the factors that waste energy, there is no standard or popular framework till now that is to used define the “greenness” of a data center. We collected most of the GPIs defined by different associations and categorize them into four main classes accepted by the EU Project GAMES in which each metric is defined and compared with other metrics in the same class and frameworks are structured for each class. We also showed how GPIs contribute to every phase in the green computing process. Since GPIs measure different factors related to energy consumption, they may have different units. If unified into one single generic unit, it will be simpler to compare between the GPIs and indicate where energy is mostly wasted, and allow for the comparison between different IT systems or applications that do the same function. We compare and critique between three different techniques that define approaches for unification, and implement a technique on the metrics collected with improvements. In the future the complex correlations and dependences between GPIs in the same class can be clarified by applying experiences based on the collection of historical monitoring data for the corresponding GPIs.

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