Challenges for Energy Efficiency in Local and Regional Data Centers

G. Koutitas[1] and P. Demestichas[2]

[1]*School of Science and Technology, International Hellenic University, Thessaloniki, Greece; e-mail: g.koutitas@ihu.edu.gr*
[2]*Department of Digital Systems, University of Piraeus, Piraeus, Greece; e-mail: pdemest@unipi.gr*

Abstract

This paper investigates challenges for achieving energy efficiency in local and regional datacenters. The challenges are divided into operational and planning categories that must be considered for the green transformation of the datacenter. The study shows that the standardization of the used metrics and guidelines are necessary for the reduction of the carbon emissions related to data centers. The paper presents a review of the available metrics and most modern techniques for energy efficiency. Numerous examples and reviews are discussed that introduce the reader to the most modern green technologies. Finally, the correlation of the energy efficient techniques to the overall carbon emissions is highlighted. It is shown that a green data center not only presents minimum operational expenditures but also produces low carbon emissions that are important to achieve sustainability in modern societies.

Keywords: data center design, energy efficiency of data center, energy efficient metrics, data center carbon footprint computation.

1 Introduction

Energy efficiency and low carbon strategies have attracted a lot of concern. The goal for 20% energy efficiency and carbon reduction by 2020 drove the Information Communication Technologies (ICT) sector to strategies that

Journal of Green Engineering, 1–32.
© 2010 *River Publishers. All rights reserved.*

incorporate modern designs for a low carbon and sustainable growth [1, 2]. The ICT sector is part of the 2020 goal and participates in three different ways. In the direct way, ICT are called to reduce their own energy demands (green networks, green IT), in the indirect way ICT are used for carbon displacements and in the systematic way ICT collaborate with other sectors of the economy to provide energy efficiency (smartgrids, smart buildings, intelligent transportations systems, etc.). ICT and in particular data centers have a strong impact to the global CO_2 emissions. Moreover, an important part of the OPEX is due to the electricity demands. This paper presents the sources and challenges that have to be addressed to reduce carbon emissions and electricity expenses of the sector.

The data center is the most active element of an ICT infrastructure that provides computations and storage resources and supports respective applications. The data center infrastructure is central to the ICT architecture, from which all content is sourced or passes through. Worldwide, data centres consume around 40,000,000,000 kW/hr of electricity per year and a big portion of this consumption is wasted due to inefficiencies and non-optimized designs. According to the Gartner Report [3], a typical data center consumes the same amount of energy as 25000 households per year, and the electricity consumption by data centers is about 0.5% of the world production. In terms of carbon emissions this power consumption pattern is identical to the airline industry and comparable to emissions generated by Argentina, Malaysia or the Netherlands.

Energy efficiency in ICT is defined as the ratio of data processed over the required energy (Gbps/Watt) and is different than power conservation where the target is to reduce energy demands without considering the data volume. Taking into consideration this ratio, green IT technologies have important benefits in terms of

- reduce electricity costs and OPEX;
- improve corporate image;
- provide sustainability;
- extend useful life of hardware;
- reduce IT maintenance activities;
- reduce carbon emissions and prevent climate change;
- provide foundations for the penetration of renewable energy sources in IT systems.

The demand for high speed data transfer and storage capacity together with the increasingly growth of broadband subscribers and services will drive the

green technologies to be of vital importance for the telecommunication industry, in the near future. Already, recent research and technological papers show that energy efficiency is an important issue for the future networks. In [2] a review of energy efficient technologies for wireless and wired networks is presented. In [4] the design of energy efficient WDM ring networks is highlighted. It is shown that energy efficiency can be achieved by increasing the CAPEX of the network, by reducing the complexity and by utilizing management schemes. The case of thin client solutions is investigated in [5] and it is shown that employing power states in the operation of a data center can yield energy efficiency. Efforts have been cited related to agreeing and enabling standard efficiency metric, real time measurement systems, modelling energy efficiency, suggesting optimal designs, incorporating renewable energy sources in the data center and developing sophisticated algorithms for designing and managing the data centers. These approaches have been published by various companies, experts in the field and organizations [6–17].

Although the IT industry has begun "greening" major corporate data centers, most of the cyber infrastructure on a university campus or SMEs involves a complex network of ad hoc and suboptimal energy environments, with clusters placed in small departmental facilities. This paper investigates challenges for achieving energy efficiency in local and regional data centers and reviews the most recent achievements in this direction. The paper is organized as follows. In Section 2 the data center infrastructure and the power consumption associated to each part are examined. Section 3 presents a review of the derived energy efficiency metrics found in the literature and the effect of energy efficiency to carbon emissions is examined. In Section 4 we investigate energy efficient techniques.

2 Data Center Infrastructure and Power Consumption

2.1 Data Center Infrastructure

Data centers incorporate critical and non-critical equipments. Critical equipments are related to devices that are responsible for data delivery and are usually named as IT equipments. Non-critical equipments are devices responsible for cooling and power delivery and are named as Non Critical Physical Infrastructure (NCPI). Figure 1 presents a typical data center block diagram [18, 19].

The overall design of a data center can be classified in four categories Tier I–IV each one presenting advantages and disadvantages related to power

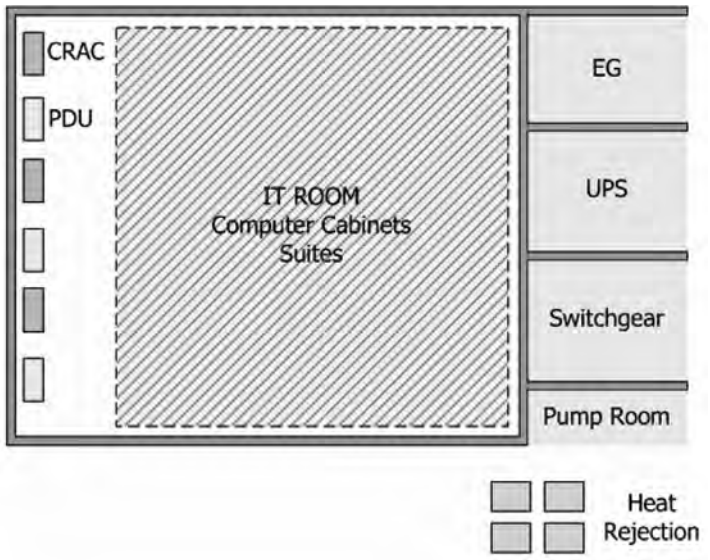


Figure 1 Typical data center infrastructure [18, 19].

consumption and availability [18, 19]. In most cases availability and safety issues yield to redundant $N+1$, $N+2$ or $2N$ data center designs and this has a serious effect on power consumption. According to Figure 1, a data center has the following main units:

- Heat Rejection – is usually placed outside the main infrastructure and incorporates chillers, drycoolers and present an $N+1$ design.
- Pump Room – they are used to pump chilled water between drycoolers and CRACs and present an $N+1$ design (one pump in standby).
- Switchgear – it provides direct distribution to mechanical equipment and electrical equipment via the UPS.
- UPS – Uninterruptible Power Supply modules provide power supply and are usually designed with multiple redundant configurations for safety. Usually 1000 kVA to 800 kW per module.
- EG – Emergency Generators supply with the necessary power the data center in case of a breakdown. Usually diesel generators.
- PDU – Power Distribution Units for power delivery to the IT. Usually 200 kW per unit and dual PDUs ($2N$) for redundancy and safety.

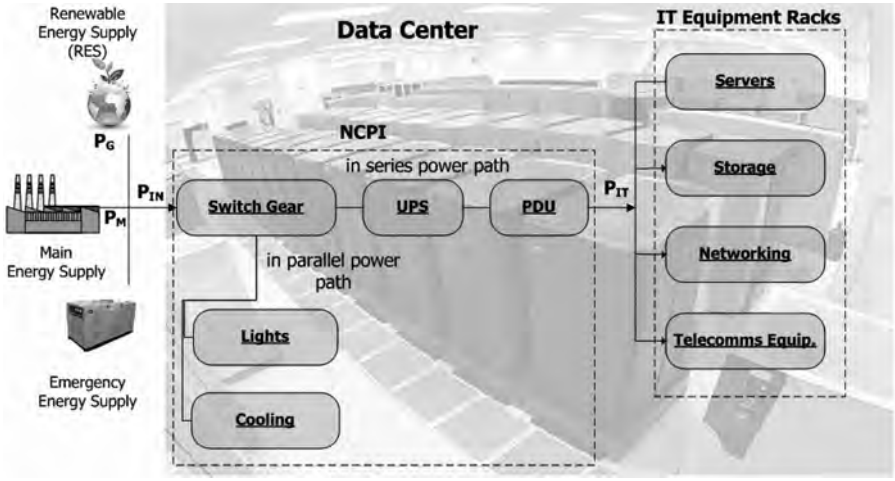


Figure 2 Power delivery in a typical data center [21].

- CRAC – Computer Room Air Conditioners provide cooling and air flow in the IT equipments. Usually air discharge is in upflow or downflow configuration.
- IT Room – incorporates computers and servers placed in blades, cabinets or suites in a grid formation. Provide data manipulation and transfer.

2.2 Power Consumption in Data Centers

The overall power consumption of a data center is related to the associated power consumed by each unit. Efficiency at individual parts is an important step for "greening" the data center but optimization is achieved when the efficiency aims to the overall data center design [20]. The power delivery in a typical data center is presented in Figure 2 [21]. The power is divided in an in-series path and a in-parallel path. The power enters the data center from the main utility (electric grid, generator), P_M or the Renewable Energy Supply (RES) utility, P_G, and feeds the switchgear in series. Within the switchgear, transformers scale down the voltage to 400–600 V [12]. This voltage flows in the UPS that is also fed by the EG in case of a utility failure. The UPS incorporates batteries for emergency power supply and process the voltage with a double AC-DC-AC conversion to protect from utility failures and smooth transition to the EG system. Of course, the AC-DC-AC conversion is a process that wastes power and reduces the overall efficiency. The out-

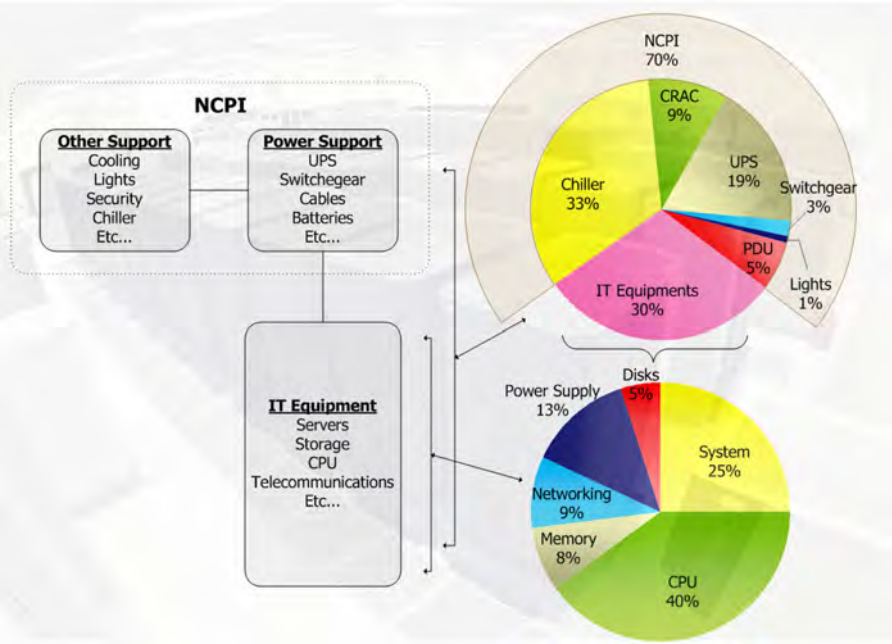


Figure 3 Power consumption by various parts of a data center (system refers to motherboards, fans, etc.) [19].

put of the UPS feeds the PDUs that are placed within the main data center room. The PDUs break the high voltage from the UPS into many 110–220 V circuits to supply the electronic equipments. Finally, power is consumed for the IT processes namely as storage, networking, CPU and in general data manipulation.

The parallel path feeds the cooling system that is important for the heat protection of a data center. The cooling system is also connected to the EG since without cooling a typical data center can operate for a few minutes before getting overheated. The cooling system incorporates fans and liquid chillers. The power distribution of these processes in an inefficient data center is presented in Figure 3 [19, 27]. It can be observed that almost 70% of the power is consumed for non-critical operations like cooling and power delivery and conversion and 30% is used by the IT equipments. Of course, a portion of this percentage is also wasted for networking, CPU, fans, storage and memory processing [19]. In other words, the useful work of the data

center is associated to a percentage of power, smaller than the 30% delivered to the IT equipments.

The power consumption pattern presented in Figure 3 is not constant with time but varies according to different parameters. The main are the workload of the data center and the outside environment. Modelling the energy efficiency and the losses of the data center's equipments is a complex tasks and crucial simplificative assumptions yielded great errors. First of all, the assumption that the losses associated to the power and cooling equipments are constant with time is wrong. It has been observed that the energy efficiency of these equipments is a function of the IT load and presents a nonlinear behaviour. In addition, these equipments are usually operating at lower than the maximum capacity loads and this increases the losses of the system. Finally, the heat generated by the NCPI equipments is not insignificant. In general, the losses of NCPI equipments are highly correlated to the workload of the data center in a complex nonlinear relationship [21].

According to the input workload the losses of NCPI equipments can be categorized as follows:

- No load losses – Losses that are fixed even if the data center has no workload. The loss percentage increases with decrease of load.
- Proportional losses – Losses that depend linearly on workload. The loss percentage is constant with load.
- Square law losses – Losses that depend on the square of the workload. These losses appear at high workloads (over 90%). The loss percentage decreases with a decrease of load.

The IT equipment also present non-constant losses and variable energy efficiency that depends on the input workload. Based on these observations it is concluded that energy efficiency of a data center is a complicate factor parameter, non-constant with time. For this reason, techniques for measuring and predicting the data center's energy efficiency is of great importance.

2.3 Sources of Losses at Data centers

The operation of data centers suffers great inefficiencies and a great amount of power is wasted for the operation of non-critical equipments and for the produced heat by the electronic equipments. The main disadvantage of real data centers is that a great amount of energy is wasted for cooling or it is transformed to heat because of the inefficient operation of electronic equip-

ments that can be NCPI or IT type. The main causes of power are summarized as

- Power units (UPS, Transformers, etc.) operate below their full load capacities.
- UPS are oversized to the actual load requirements in order to avoid operating near their capacity limit.
- Air conditioning equipment consumes extra power in order to deliver cool air flow at long distances.
- Inefficient UPS equipments.
- Blockages between air conditioners and equipments that yield to inefficient operation.
- No virtualization and consolidation.
- Inefficient servers.
- No closed coupling cooling.
- No efficient lighting.
- No energy management and monitoring.
- Underutilization due to $N + 1$ or $2N$ redundant designs.
- Oversizing of data center.
- Under-floor blockages that contribute to inefficiency by forcing cooling devices to work harder to accommodate existing load heat removal requirements.

The procedure to transform a data center into an energy efficient one (green data center) is complex and it can only be achieved by targeting both *individual part optimization* that can be considered as operational costs and *overall system performance* that can be considered as planning actions. According to Figures 2 and 3, the optimized operation of the data center requires the input power to be minimized without affecting the operation of the IT equipments.

3 Energy Efficiency Metrics

3.1 Review of Metrics

The energy efficiency of a data center is a complicate non-constant parameter that depends on the input workload and environmental conditions and its estimation has attracted a lot of research. In order to investigate and propose directions to optimize energy consumption in a data center it is important to quantize its performance. This can be achieved by using a standard metric to measure the inefficiencies. In past years the efficiency was incorrectly calcu-

lated by just adding the efficiencies of the individual parts as published by the manufacturers. This yielded great inaccuracies and overestimations and the need for a standard metric and accurate model was obvious. As an example, the efficiency of a UPS system is measured as the kW_{out} over the kW_{in} at full load. According to the workload that enters the UPS, the efficiency can vary from 0% at no load to 95% at full load in a nonlinear way [21]. Taking into consideration that common data centers operate at 30–40% of their maximum capacity workloads, the efficiency of the UPS cannot be considered constant and equal to the imposed by the manufacturer value.

In general energy efficiency in the telecommunication industry is related to

$$\text{Energy Efficiency} \sim \frac{\text{Joule}}{\text{bit}} \sim \frac{\text{Watt}}{\text{Gbps}} \sim \frac{\text{Watt}}{\text{bitrate/Hz}} \quad \text{(spectral efficiency)} \tag{1}$$

The optimal description of this value depends on the system's characteristics and the type of equipment. As an example, for modulation and coding techniques in wireless communications the spectral efficiency is a common measure. For electronic components the ratio of joule per bit best describes performance. In telecommunication networks and data centers the ratio of Watts consumed over the Gbps of data processed is preferred. In [22] an absolute energy efficiency metric is introduced, called $dB\varepsilon$. The metric is computed according to the following equation:

$$dB\varepsilon = 10 \log_{10} \left[\frac{\text{Power/bitrate}}{kT \ln 2} \right] \tag{2}$$

where k is the Boltzman's constant and T is the absolute temperature (300 K). The value $kT \ln 2$ represents the minimum energy dissipated per bit of information. Characteristic values of common systems are presented in Table 1 [22]. The smaller the $dB\varepsilon$ value is, the greater the achieved efficiency.

Data centers' energy efficiency can be broadly defined, according to (1) as the amount of useful computation divided by the total energy used during the process. The development of a standard metric has attracted a lot of research and initiatives have commenced by the green grid association [23]. The green grid has established metrics according to the infrastructure efficiency and the data center performance efficiency.

Data centers encounter power waste in the non-critical equipments and in the critical equipments. The metrics that best define the non-critical equipments' efficiency are the Power Usage Effectiveness (PUE) and the Data Center Efficiency (DCiE).

Table 1 Energy efficiency measured for typical systems.

System	Power	Effective bitrate	Energy/bit [J/b]	$dB\varepsilon$
BT network	1 GWatt	22 Tb/s	45×10^{-6}	162
Dell laptop	80 Watt	1.87 GHz (clock)	42.8×10^{-9}	131.7
Ultra-low power DSL/fiber	165 mWatt	10Mb/s	16.5×10^{-9}	127.6
Tb/s router	10 kWatt	1Tb/s	10×10^{-9}	125.4
Efficient CPU	2.8 Watt	1 Gflops	2.8×10^{-9}	119.9
Efficient 10 Gb/s system	10 Watt	10Gb/s	1×10^{-6}	115.4
Human brain	20 Watt	40 Tb/s	0.5×10^{-12}	82.3
1 photon/bit	1.28n Watt	10 Gb/s	0.128×10^{-18}	16.5

PUE is defined as the ratio of the total facility input power over the power delivered to IT. DCiE is the inverse of PUE. According to the notation in Figure 2 this is written in mathematical form as

$$\begin{aligned} \text{PUE} &= \frac{P_{\text{IN}}}{P_{\text{IT}}} = \text{CLF} + \text{PLF} + 1, \quad 1 < \text{PUE} < \infty \\ \text{DCiE} &= \frac{1}{\text{PUE}} = \frac{P_{\text{IT}}}{P_{\text{IN}}}, \quad 0 < \text{DCiE} < 1 \end{aligned} \tag{3}$$

where CLF represents the cooling load factor normalized to IT load (losses associated to chillers, pumps, air conditioners) and PLF represents the power load factor normalized to IT load (losses associated to switchgear, UPS, PDU). These metrics characterize the performance or the power wasted in the non-critical components of the data center. These are the cooling infrastructure and the power infrastructure. Figure 4 presents measured values of PUE over 24 different data centers.

It can be observed that the mean value of the measured PUE is 1.83 or 0.53 (53%) DCiE. This means that almost 53% of the power that enters the data center is wasted for cooling and power delivery in the non-critical components. The remaining 47% is used for data processing. The infrastructure efficiency metrics are variable in time and mainly depend on outdoor environmental conditions and traffic demands. For example in low temperature periods, losses due to cooling are minimized. In addition, in low traffic periods losses are increased since the data center is oversized.

In Figure 5 the NCPI efficiency metrics for two different data centers is presented. It can be observed that data center *A* is more energy efficient than data center *B* but at low input IT workload it is underutilized resulting to less energy efficiency.

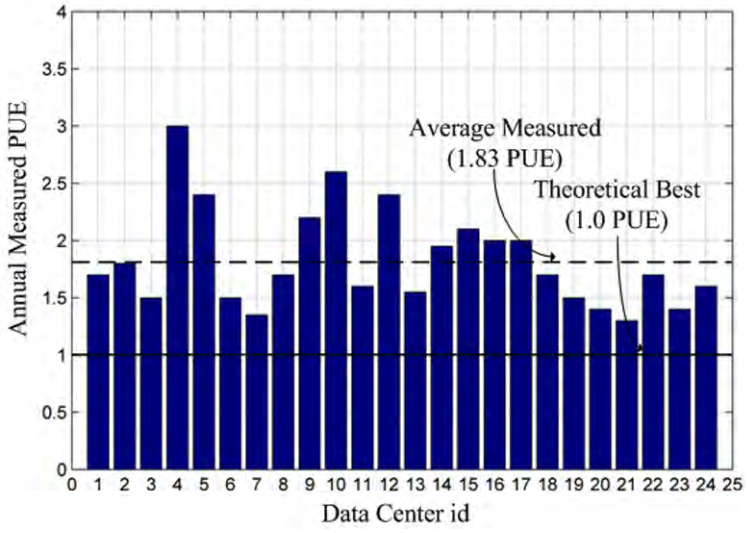


Figure 4 PUE measurements over 24 data centers [19].

The energy efficiency measure of the overall data center's performance is computed according to the DCeP (Data Center Performance) metric presented by the green grid [24]. This metric is preferred for long term measurements of the performance of the data center and in a mathematical form it is computed according to (4)

$$\text{DCeP} = \frac{\text{Useful Work}}{P_{\text{IN}}} = \frac{\sum_{i=1}^{m}[V_i \cdot U_i(t,T) \cdot T_i]}{E_{\text{DC}}} \tag{4}$$

The term "useful work" describes the number of tasks executed by the data center and P_{IN} or E_{DC} represents the consumed power or energy respectively for the completion of the tasks. In the above formulation m is the number of tasks initiated during the assessment window, V_i is a normalization factor that allows the tasks to be summed, U_i is a time based utility function for each task, t is the elapsed time from initiation to completion of the task, T is the absolute time of completion of the task, $T_i = 1$ when the task is completed during the assessment window, or 0 otherwise.

The assessment window must be defined in such a way to allow the capture of data center's variation over time. The DCeP factor gives an estimate of the performance of the data center and is not as accurate as DCiE or PUE due to its relativity. Proxies for computing the useful work according to the

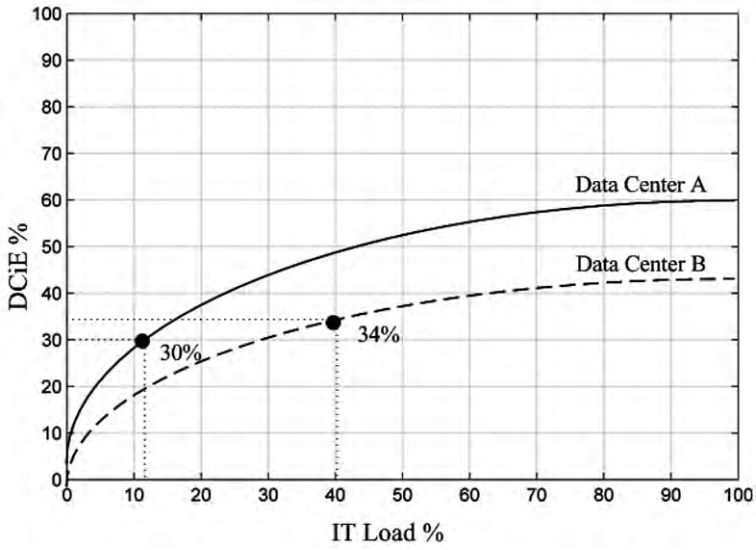


Figure 5 DCiE efficiency metrics for two data centers as a function of IT load.

scenario of interest are presented in [24]. These proxies incorporate computations regarding bits per kilowatt-hour, weighted CPU utilization, useful work self assessment and other cases.

In [9] a power to Performance Effectiveness (PPE) metric is introduced to help identify, at the device level, where efficiencies could be gained. It gives the IT managers a view of performance levels within the data center. It is computed according to the following equation:

$$\text{PPE} = \frac{\text{Actual Power Performance}}{\text{Optimal Power Performance}} \tag{5}$$

where the optimal power performance is computed as the ratio of the product of optimal server, optimal serever performance utilization, average Watts per server over 1000. The factor optimal server is equal to rack density multiplied by the optimal percentage. The metric PPE is used at the device level and compares its actual performance with the theoretical efficiency indicated by the manufacturers.

A more generic approach to define the efficiency metric of a data center is presented in [19]. The proposed efficiency metric combines the PUE (or

DCiE) and DCeP. The formulation is

$$\text{Efficiency} = \frac{\text{Computation}}{\text{Total Energy}(P_{\text{IN}})} = \left(\frac{1}{\text{PUE}}\right) \times \left(\frac{1}{\text{SPUE}}\right) \times \left(\frac{\text{Computation}}{P_{\text{IT}}}\right) \tag{6}$$

where the factor SPUE represents the server energy conversion and captures inefficiencies caused by non-critical equipments of the IT equipments. These can be the server's power supply, voltage regulator modules and cooling fans. SPUE is defined as the ratio of the total server input power over the useful server power, i.e the power consumed by motherboards, CPU, DRAM, I/O cards, etc. The combination of PUE and SPUE measures the total losses associated to non critical components that exist in the data center's NCPI and IT equipments.

In [25] the metric DPPE (Data Center Performance per Energy) is presented that correlates the performance of the data center with carbon emissions. The metric follows the general rules presented in (4) and (6) and introduces one more factor for the green energy supply. In a mathematical form it is

$$\text{DPPE} = \frac{\text{Data Center Work}}{\text{Carbon Energy}} = \text{ITEU} \times \text{ITEE} \times \frac{1}{\text{PUE}} \times \frac{1}{1 - \text{GEC}} \tag{7}$$

where

$$\text{ITEU} = \frac{\text{Total Measured Energy of IT [KWh]}}{\text{Total Specification Energy IT (by manufacturer) [KWh]}}$$

$$\text{ITEE} = \frac{a \cdot \sum \text{server capacity} + b \cdot \sum \text{storage capacity} + c \cdot \sum NW \text{ capacity}}{\text{Total Specification Energy IT (by manufacturer) [KWh]}}$$

$$\text{GEC} = \frac{\text{Green Energy}}{\text{DC Total Power Consumption}}$$

In the above formulation *ITEU* represents the IT equipment utilization, *ITEE* represents the IT equipment energy efficiency, *PUE* represents the efficiency of the physical infrastructure and *GEC* represents the penetration of renewable (green) energy into the system. *ITEU* is the average utilization factor of all IT equipment included in the data center and can be considered as the degree of energy saving by virtual techniques and operational techniques that utilize the available IT equipment capacity without waste. *ITEE* is based on *DCeP* presented in (4) and it aims to promote energy saving by encouraging the installation of equipment with high processing capacity per unit electric power. Parameters a, b, c are weighted coefficients. *PUE* is defined in (3) and

is the efficiency of the physical infrastructure of the data center. Finally, *GEC* is the available "green" energy that the data center is supplied additionally to the grid electricity. It is also presented in Figure 2 as P_G. The higher the value of DPPE the less the carbon emissions it produces and more energy efficient it is.

3.2 Carbon Emission and Cost Effects

The carbon emissions caused by the operation of data centers are related to the consumed power. The grid electricity is responsible for CO_2 emissions depending on the used material for energy conversion. In order to provide a measure of carbon emissions, the energy is converted to *gr* of CO_2. This is subject to each country energy sources. The relationship is $Q = 1$ KWh $\sim X$grCO$_2$. For anthracite electricity production $X = 870$, for gas electricity production $X = 370$ and for petroleum it is $X = 950$ [26]. The used metric is TonsCO$_2$/year. Therefore, the carbon footprint of a data enter is computed according to [27]

$$K^{CO_2} = 8.74 \cdot 10^{-6} \cdot P \cdot X \text{ [TonsCO}_2\text{/year]} \tag{8}$$

where P is shown in Figure 2 and represents the power in Watts consumed by the data center and is related to the grid electricity. In case the data center is also supplied by green energy then the corresponding Watts in equation (8) would be equal to $P = P_M = P_{\text{IN}} - P_G$ (according to Figure 2). The effect of the data center efficiency DCiE and the type of power supply to the produced carbon emissions is more obvious with the following example. Lets consider a data center that requires for the operation of the IT equipment, $P_{\text{IT}} = 300$ KWatts. The data center is supplied with grid electricity produced by anthracite ($X = 870$ grCO$_2$/KWh) and has also a G% renewable energy supply ($P_{\text{IN}} = GP_G + (1 - G)P_M$). The comparison of the additional carbon emissions produced by a data center with a non perfect infrastructure efficiency ($0 <$ DCiE < 1) in relation to a 100% efficient data center (DCiE $= 1$) and relative to a data center that is supplied by G% of green energy is computed according to

$$C^{\text{CO}_2} = 8.74 \cdot 10^{-6} \cdot P_{\text{IT}} \cdot \frac{1}{\text{DCiE}} \cdot (1 - G) \text{ [TonsCO}_2\text{/year]} \tag{9}$$

where P_{IT} is expressed in Watts. The effect of DCiE and green energy to the annual produced carbon emissions compared to a 100% efficient data center is shown in Figure 6a).

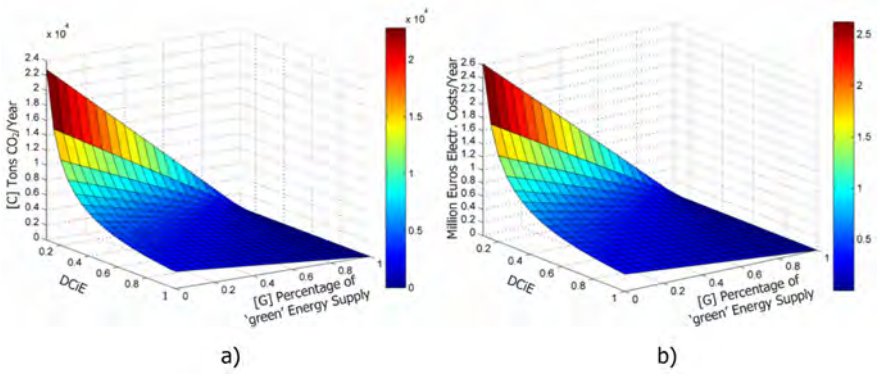


Figure 6 (a) Carbon emissions in CO_2/year (assuming anthracite electricity production $\sim$870grCO_2/KWh) as a function of DCiE and "green" energy relative to a 100% efficient data center; (b) operational costs due to electricity (assuming 0.1 €/KWh) as a function of DCiE and "green" energy relative to a 100% efficient data center.

The annual electricity costs (OPEX) a data center requires is computed according to

$$M^{\text{Euros}} = 8.74 \cdot P \cdot Y \text{ [Euros/year]} \tag{10}$$

where Y represents the relationship between cost of energy. For the purpose of our investigation it was assumed as 1 KW$\sim$0.1€. Similar to (9) the comparison of a data center with non-perfect infrastructure efficiency that is supplied by G% of renewable energy (no cost energy) is given by

$$E^{\text{Euros}} = 8.74 \cdot P_{\text{IT}} \cdot \frac{1}{\text{DCiE}} \cdot (1 - G) \text{ [Euros/year]} \tag{11}$$

where P_{IT} is expressed in Watts. The effect of DCiE and green energy to the annual electricity expenses compared to a 100% efficient data center is shown in Figure 6b). It can be observed that the DCiE is a very important factor that must be first consider for the efficient operation of data centers. Assuming a 0% supply of renewable energy, a data center with DCiE $= 0.3$ produces 7600 TonsCO_2/year and requires 874,000 €/year electricity expenses whereas a data center with DCiE $= 0.7$ produces 3260 TonsCO_2/year and requires 370,000 €/year electricity expenses.



Figure 7 Directions for green data center transformation.

4 Challenges for Energy Efficiency

In general, efficiency can be achieved through the optimization of the operation and the optimal planning. Moreover, standards can be engineered in order to drive energy efficiency. This process incorporates the domains presented in Figure 7.

4.1 Optimization of Operational Costs

The operational costs are associated to the optimization of individual equipments like the IT equipments and NCPI [14, 20].

4.1.1 IT Equipment

Efficiency of IT equipments is an important step for the green operation of a data center. The DCeP metric of (4) and the factors ITEE and ITEU of equation (7) show that energy efficiency is correlated to the efficient use of the

IT equipment. Achieving efficiency at the IT level can be considered as the most important strategy for a green data center since for every Watt saved in computation, two additional Watts are saved – one Watt in power conversion and one Watt for cooling [7]. In general the following actions are necessary to achieve this goal.

Retiring – some data centers have application servers which are operating but have no users. These servers add noload losses to the system and need to be removed. The usable lifetime for servers within the data center varies greatly, ranging from as little as two years for some x86 servers to seven years or more for large, scalable SMP server systems. IDC surveys [28] indicate that almost 40% of deployed servers have been operating in place for four years or longer. That represents over 12 million single core-based servers still in use. The servers that exist in most data centers today have been designed for performance and cost optimization and not for energy efficiency. Many servers in data centers have power supplies that are only 70% efficient.

This means that 30% of the power going to the server is simply lost as heat. Having inefficient power supplies means that excess money is being spent on power with additional cooling needed as well. Another problem with current servers is that they are used at only 15–25% of their capacity. A big problem with this, from a power and cooling perspective, is that the amount of power required to run traditional servers does not vary linearly with the utilization of the server. That is, ten servers running each at 10% utilization will consume much more power than one or two servers that each run at 80–90% utilization [29].

Migrating to more energy efficient platforms – use of blade servers that produce less heat in a smaller area around it. Non-blade systems require bulky, hot and space-inefficient components, and may duplicate these across many computers that may or may not perform at capacity. By locating these services in one place and sharing them between the blade computers, the overall utilization becomes more efficient. The efficiency of blade centers is obvious if one considers power, cooling, networking and storage capabilities [7, 29, 30]. An example is presented in [7] where 53 blade servers consuming 21 KWatts provided 3.6 Tflops of operation when in 2002 required Intel Architecture based HPC cluster of 512 servers arraigned in 25 racks consuming 128 KWatts. This means that compared to 2002 technology today 17% of the energy is necessary for the same performance.

- Power of Blade Servers – Computers operate over a range of DC voltages, but utilities deliver power as AC, and at higher voltages than

required within computers. Converting this current requires one or more power supply units (or PSUs). To ensure that the failure of one power source does not affect the operation of the computer, even entry-level servers have redundant power supplies, again adding to the bulk and heat output of the design. The blade enclosure's power supply provides a single power source for all blades within the enclosure. This single power source may come as a power supply in the enclosure or as a dedicated separate PSU supplying DC to multiple enclosures.

- Cooling of Blade Servers – During operation, electrical and mechanical components produce heat, which a system must displace to ensure the proper functionality of its components. Most blade enclosures, like most computing systems, remove heat by using fans. The blade's shared power and cooling means that it does not generate as much heat as traditional servers. Newer blade-enclosure designs feature high-speed, adjustable fans and control logic that tune the cooling to the system's requirements, or even liquid cooling systems.
- Networking of Blade Servers – The blade enclosure provides one or more network buses to which the blade will connect, and either presents these ports individually in a single location (versus one in each computer chassis), or aggregates them into fewer ports, reducing the cost of connecting the individual devices. This also means that the probability of wiring blockage to air flow of cooling systems in the data center is minimized.

More Efficient Server – For energy efficiency, vendors should focus on making the processors consume less energy and on using the energy as efficiently as possible. This is best done when there is close coordination in system design between the processor and server manufacturers [29]. In [31] practical strategies of power efficient computing technologies are presented based on microelectronic, underlying logic device, associated cache memory, off-chip interconnect, and power delivery system. In addition, replacement of old single core processors with dual or quad core machines is important. This combination can improve performance per Watt and efficiency per square meter.

Energy Proportional Computing – Many servers operate at a fraction of their maximum processing capacity [32]. Efficiency can be achieved when the server scales down its power use when the workload is below its maximum capacity. When search traffic is high, all servers are being heavily used, but during periods of low traffic, a server might still see hundreds of queries

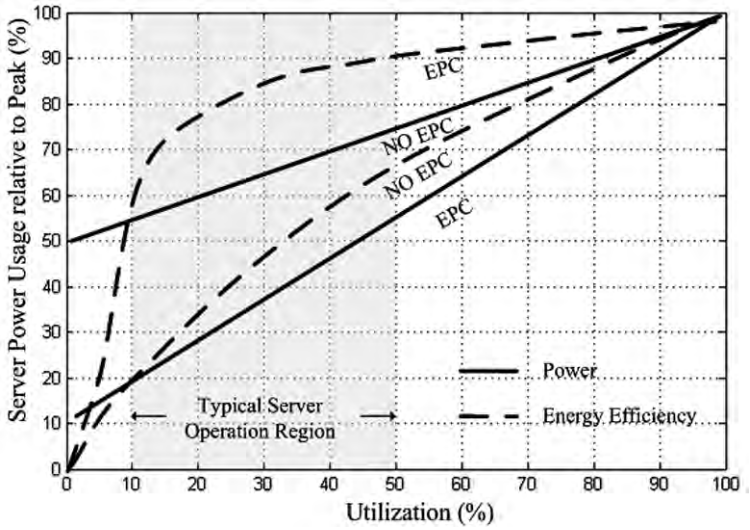


Figure 8 Comparison of power usage and energy efficiency for Energy Proportional Computing (EPC) and common server (NO EPC) [32].

per second, meaning that any idleness periods are likely to be no longer than a few milliseconds. In addition, it is well known that rapid transition between idle and full mode consumes high energy. In [33] a research over 5000 Google servers shows that the activity profile for most of the time is limited to 20–30% of the servers' maximum capacity. Server's power consumption responds differently at varying input workloads. In Figure 8 the normalized power usage and energy efficiency of a common server is presented as a function of the utilization (% of maximum capacity). It can be observed that for typical server operation (10–50%) the energy efficiency is very low meaning that the server is oversized for the given input workload. This means that even for a no workload scenario, the power consumption of the server is high. In case of energy proportional computing (EPC) the energy varies proportionally to the input work. Energy-proportional machines must exhibit a wide dynamic power range – a property that might be rare today in computing equipment but is not unprecedented in other domains. To achieve energy proportional computing two key features are necessary such as *wide dynamic power range* and *active low power modes*.

Current processors have a wide dynamic power range of even more than 70% of peak power. On the other hand the dynamic power range of other equipment is much narrower such as DRAM 50%, disk drives 25% and

network switches 15%. A processor running at a lower voltage-frequency mode can still execute instructions without requiring a performance impacting mode transition. There are no other components in the system with active low-power modes. Networking equipment rarely offers any low-power modes, and the only low-power modes currently available in mainstream DRAM and disks are fully inactive [33]. The same observations are presented in [34]. A technique to improve power efficiency is with dynamic Clock Frequency and Voltage Scaling (CFVS). CFVS provides performance-on-demand by dynamically adjusting CPU performance (via clock rate and voltage) to match the workload. Another advantage obtained by energy proportional machines is the ability to develop power management software that can identify underutilized equipments and set to idle or sleep modes. Finally, benchmarks such as SPECpower_ssj2008 provide a standard application base that is representative of a broad class of server workloads, and it can help isolate efficiency differences in the hardware platform.

4.1.2 NCPI Equipments

Efficiency of NCPI equipments is another step for the green operation of data center. This is highlighted by the DCiE or PUE metric of (3) and the effect of an efficient NCPI data center is presented in Figure 6. In general the following actions are necessary to achieve this goal.

Replacing chiller or UPS systems that have been in service for 15 years or more can result in substantial savings. New chiller systems can improve efficiency by up to 50% [20].

Free cooling is a complex technique and requires workload management according to the environmental conditions. Recently, the green grid association presented a European air-side free cooling map [35].

Air conditioners – use of airconditions that can operate at economizer mode. This can have a great effect especially for low outdoor temperatures. In addition, if air-conditioners work with low output temps there is a further increase of humidifier operation resulting to increased power demands.

Power delivery – energy efficient power delivery can be achieved using efficient voltage regulators and power supply units. In [7] a study of three different power delivery architectures is presented namely as: conventional alternating current (AC), rack-level direct current (DC), and facility-level DC distribution. Results showed that the greatest efficiency is achieved through facility-level 380V DC distribution. Intel calculated that an efficiency of approximately 75% may be achieved with facility-level 380V DC distribution using best-in-class components. Finally, in [10] a comparison of the energy

efficiency, capital expense and operating expense of power distribution at 400 and 600 V as alternatives to traditional 480 V is presented. The study confirmed that by modifying the voltage at which power is distributed in the data center, data center managers can dramatically reduce energy consumption and the cost of power equipment. The study recommended 400 V power distribution, stepped down to 230 V to support IT systems to yield end to end power delivery efficiency. Switch consolidation is also an effective strategy [34].

4.2 Planning Actions

The individual equipment optimization is a crucial step for the data center to operate in a green manner but it is inadequate to transform the overall system operation. Planning actions for the efficiency of the overall system are required and can be achieved by introducing new technologies and management techniques.

4.2.1 Reducing Cooling Needs

A data center usually occupies a large space and the optimum equipment installation can yield to great savings. The following steps are considered as important for energy efficiency:

- Organizing IT equipment into a hot aisle and cold aisle configuration [19, 20].
- Minimize blockage by wiring and secondary equipments that influence air flow and cooling and heat removal.
- Use raised floor environments.
- Positioning the equipment so that one can control the airflow between the hot and cold aisles and prevent hot air from recirculating back to the IT equipment cooling intakes.
- Leveraging low-cost supplemental cooling options.
- Use equipments with higher thermal tolerance and so reduce the need of cooling.
- Investigate heat and cooling transfer within the data center space by using advanced software of fluid mechanics and perform air flow management [36].

4.2.2 Exploitation of Virtualization

Virtualization and consolidation is a necessary step to overcome underutilization of the IT equipments of the data center. In [7] a study over 1000

servers showed that the servers operate at 10–25% usage relative to their maximum capacity. The need for consolidation is obvious. Consolidation is used for centralizing IT systems and when used at software level, consolidation means centralization of the solution, integration of data, redesign of business processes and when used at hardware level consolidation means centralization of multiple servers to one more powerful and more energy efficient. Virtualization can also be defined at a software level or hardware level or even a combination of the above. Virtualization can be oriented for servers, and can also be very effective for networking and storage. Virtualization enables multiple low-utilization OS images to occupy a single physical server. Virtualization allows applications to be consolidated on a smaller number of servers, through elimination of many low utilization servers dedicated to single applications or operating system versions [37]. The main advantage of server virtualization is that the total number of servers is reduced, lower infrastructure for cooling and power delivery is required, the energy costs are reduced, the virtual machines operate at their maximum capacity, where the energy efficiency is met, and it can provide business continuity and disaster recovery. A study presented in [38] showed that server virtualization in Bosnia-Herzegovina over 500 servers in 60 data centers can provide electricity costs saving of $500,000 over a three years period.

4.2.3 Remote Monitoring for Optimal Planning

The aim of remote monitoring is to provide the industry with a set of design guides to be used by operators and designers to plan and operate energy efficient data centers. Remote monitoring is an enabler for optimal planning since it provides the necessary information for planning actions. The design includes all IT and NCPI equipment. The outcome is an intelligent monitoring system that can provide real time information about power condition of the equipments involved in a data center by means of sensor networks implementation or SCADA systems.

The energy efficiency design incorporates the following directions [39]:

- *Fully Scalable*. All systems/subsystems scale energy consumption and performance to use the minimal energy required to accomplish workload.
- *Fully Instrumented*. All systems/subsystems within the data center are instrumented and provide real time operating power and performance data through standardized management interfaces.

- *Fully Announced*. All systems/subsystems are discoverable and report minimum and maximum energy used, performance level capabilities, and location.
- *Enhanced Management Infrastructure*. Compute, network, storage, power, cooling, and facilities utilize standardized management/interoperability interfaces and language.
- *Policy Driven*. Operations are automated at all levels via policies set through management infrastructure.
- *Standardized Metrics/Measurements*. Energy efficiency is monitored at all levels within the data center from individual subsystems to complete data center and is reported using standardized metrics during operation.

In order to accomplish this target a set of logical divisions can be extracted and a set of tasks are assigned as shown in Figure 9. An important goal of remote monitoring is that crucial information of the real data center will be gathered that will improve the development of efficiency predictions models and will guide to optimal planning actions. Furthermore, better management of the system is possible. As far as the power management is concerned with an adequate remote monitoring technology, workloads and efficiencies of different systems could be measured and ideally, power usage in a data center could be balanced to the workload. This feature is important for workload management actions, which are further investigated in a paragraph below. One way to achieve this balance is to idle unneeded equipment or transfer workloads in such a way to obtain high usage capacity of data centers.

A strategy towards real time remote monitoring and management of a data center is also supported in [40]. A data center management software is presented that supports energy efficiency, stadardization and benchmarking at different layers of the system.

4.2.4 Rightsizing

Data centers suffer low utilization fractions relative to their maximum capacity. In [41] a study shows that 70% of today's data centers operate at less than 45% of their maximum capacity limits. This has a serious effect on energy efficiency as presented in Figure 10.

There are numerous reasons why oversizing occurs, for example:

- The cost for not providing sufficient space for a data center is enormous and must be eliminated. This means that in case of undersizing, the total cost is dangerous.

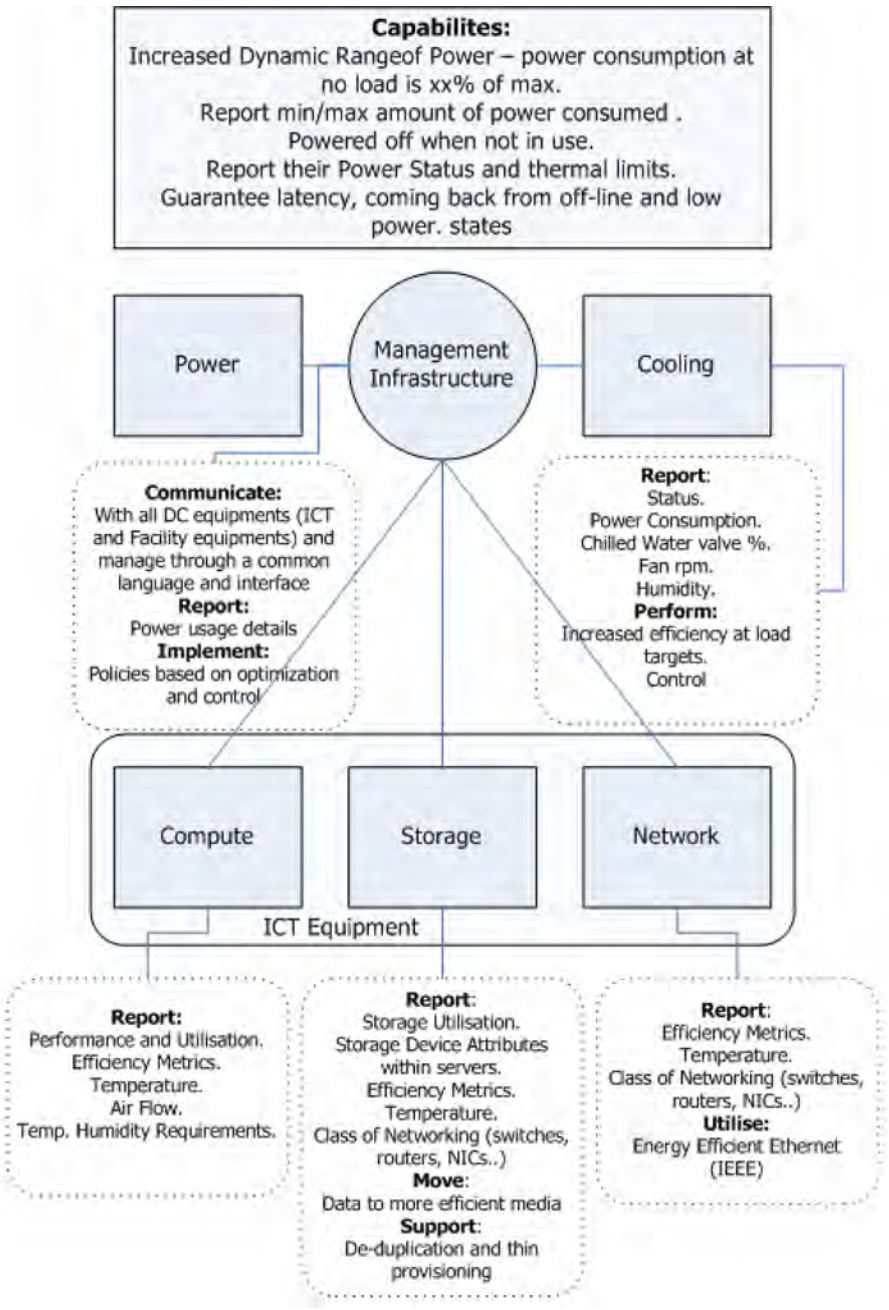


Figure 9 Logical division and tasks for green data centers and remote monitoring [39].

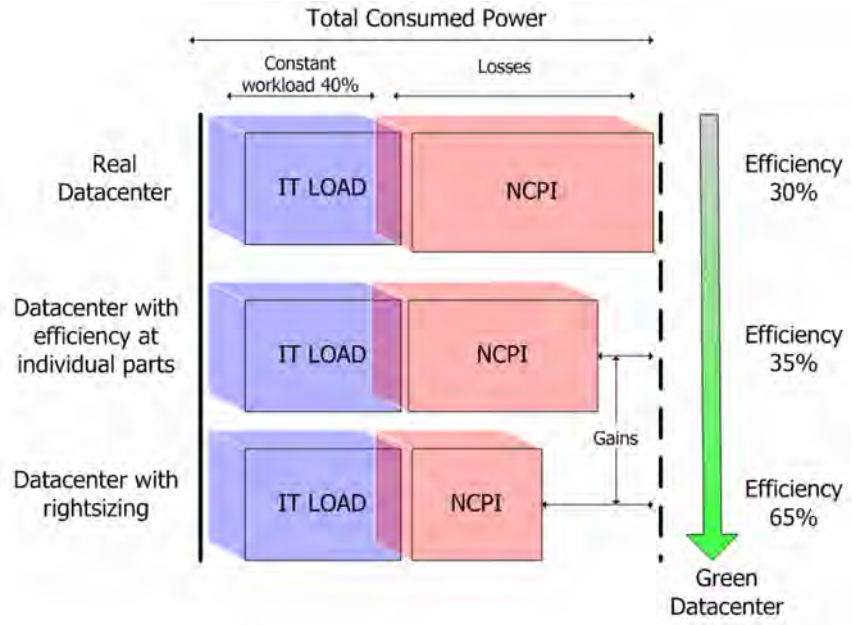


Figure 10 Effect of individual equipment efficiency and rightsizing [41].

- It is a tremendous cost to increase the capacity during data center lifecycle.
- There are numerous risks associated with an increase of the capacity during lifecycle.
- It is difficult to predict the final room size so one wants always to be above the threshold for safety reasons.

The result of oversizing is that the data center operates well below its maximum capacity (usually at 30–50%). At this input workload all the equipments are not efficiently operate. Rightsizing mainly affects NCPI power consumption. In this approach the power and cooling equipments should be balanced to the IT load of the data center.

There are fixed losses imposed by NCPI independently of IT load. These losses can exceed IT load in low load systems and they are becoming a large percentage when the IT load increases. Typical data centers draw approximately two to three times the amount of power required for the IT equipment because conventional data center designs are oversized for maximum capacity and older infrastructure components can be very inefficient.

Rightsizing a data center is a complex task since great losses and costs are associated to an improper sizing of the equipments. For that reason accurate models and great management skills need to be performed in order to achieve an optimum design. The steps that need to be followed are [41]:

- Investigation of data centers workload and sizing that already exist.
- Investigation about the estimated workload and future applications of the data center.
- Avoid underutilization of data center assuming that this will increase the reliability.
- Development of sophisticated prediction workload models.

An approach of adaptable infrastructure and dimensioning can provide rightsizing of the system and this is presented in [41]. The effect of rightsizing to the data center's energy efficiency can be observed in Figure 10.

4.2.5 Network Load Management/Network Topology

Various architectures of data center topologies and different routing algorithms than the already existing ones, can increase the system's performance. A fat tree data center architecture is presented in [42]. Instead of a hierarchical enterprise expensive switched (10GigE) to be used, commodity switched (GigE) are utilized in a fat tree configuration. Despite the fact that more intelligent and complex routing is required (two-level routing algorithm) the cost of the new deployment and the overall power consumption is reduced. The physical meaning of this observation is that for typical data centers where the workload is small and so oversizing is occurred, by incorporating in the data center small commodity instead of powerful enterprise equipments, the workload is distributed in such a way that most of the used elements are operating near their maximum capacity. This has a positive effect at the efficiency of the system. The study proved more than 50% reduction of power consumption and heat generation.

Another approach for electricity cost savings is the routing algorithm presented in [43]. The authors suggested an algorithm that moves workload to data centers placed at areas where the electricity cost is low using a real time electricity price information system coupled to the routing algorithm. The concept is to move workload at data centers placed in areas where the electricity cost is low and reduce the usage of the other. This means that the increased power consumption of the fully loaded data centers will result to low expenses.

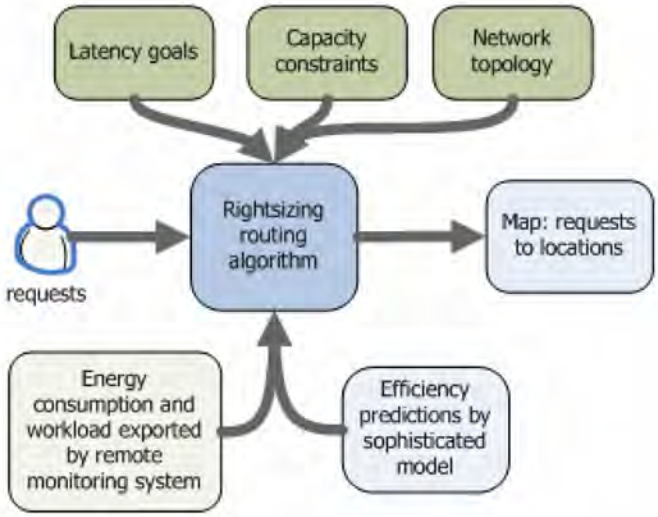


Figure 11 Rightsizing routing algorithm for energy efficiency.

Despite the fact that the presented technique is associated to cost savings it can also be used in future systems for workload management according to renewable energy availability or environmental conditions to provide free cooling.

Network load management techniques are implemented to provide workload balance to specific data centers in a network. The main aim is to reduce the workload of data centers that are underutilized and deliver the workload to other data centers to operate them near their maximum capacity. The concept is presented in Figure 11. The model utilizes the available data derived from the remote monitoring system and the required data for energy efficiency metric computation and performs workload management in the network devices to provide maximum energy efficiency. In addition, a real time feedback system that informs about environmental conditions and availability/production of renewable energy is coupled to the algorithm.

4.2.6 Avoid Data Duplication

Data duplication produces increase power consumption in storage devices. The fact that most of the data is duplicated, for safety reasons, reduces the energy efficiency of the system. Storage virtualization is one approach to overcome this phenomenon [37].

Table 2 Energy efficiency ranking for 25 typical data centers.

The Green Grid Benchmark	PUE	Number of Data Centers
Platinum	<1.25	0%
Gold	1.25–1.43	0%
Silver	1.43–1.67	0%
Bronze	1.67–2.0	27%
Recognized	2.0–2.5	40%
Non-Recognized	>2.5	33%

4.2.7 Alternative Energy Supply

The DCiE investigated in Section 3.1 proved that in order to increase the efficiency of a data center one approach is to reduce the needs of input power from the utility. This can be achieved by applying alternative energy supply in the data center. Of course the technology of renewable energy sources and the produced power is a small fraction of the actual required power to operate a data center. But it can be profitable for small traffic demands where the requirements are reduced. The effect of the penetration of alternative energy source is also more obvious in the DPPE metric shown in equation (7) and in Figure 6.

4.3 Standardization

Standardization of energy efficiency procedures and techniques is considered as a necessary step for achieving green operation of data centers [16]. The development and the design of data centers based on a common standard platform could provide great goals for energy efficient data centers. A benchmark, presented by the green grid association, categorizes data centers according to the measured DCiE factor. This can be considered as the first approach to this target and in the near future benchmarks that incorporate the DCeP or DPPE metrics are expected. Data center benchmarks are presented in Table 2 [16]. It can be observed that silver and gold benchmarks are not yet achieved.

5 Conclusions

This paper presented today's challenges for achieving energy efficiency in local and regional data center systems. The power consumption of different layers of the data center was investigated and it was shown that there are great portions of power wasted both in non critical infrastructure and IT equip-

ments. A review of the available metrics for energy efficiency was discussed and the effect of energy efficiency to carbon emissions and operational costs was computed. It was shown that there are great expectations for cost and carbon savings when the data center operates in a green manner. Strategies for developing and transforming a green data center were also presented based on operational and planning actions. It was shown that energy efficiency should target overall system optimization of both non critical and IT equipments with main focus placed on cooling, power delivery systems, virtualization and workload management.

References

[1] International Telecommunication Union (ITU), Report on Climate Change, October 2008.
[2] G. Koutitasa and P. Demestichas, A review of energy efficiency in telecommunication networks, in *Proc. in Telecomm. Forum (TELFOR)*, Serbia, November, pp. 1–4, 2009.
[3] Gartner Report, *Financial Times*, 2007.
[4] I. Cerutti, L. Valcarenghi, and P. Castoldi, Designing power-efficient WDM ring networks, in *Proc. ICST Int. Conf. on Networks for Grid Applic.*, Athens, 2009.
[5] W. Vereecken, et al., Energy efficiency in thin client solutions, in *ICST Int. Conf. on Networks for Grid Applic.*, Athens, 2009.
[6] J. Haas, T. Pierce, and E. Schutter, Data center design guide, White Paper, The Greengrid, 2009.
[7] Intel, Turning challenges into opportunities in the data center, White Paper, Energy Efficiency in the Data Center, 2007.
[8] P. Scheihing, DOE data center energy efficiency program, U.S. Department of Energy, April 2009.
[9] C. Francalanci, P. Gremonesi, N. Parolini, D. Bianchi, and M. Gunieti, Energ-IT: Models and actions for reducing IT energy consumption, Focus Group on Green IT and Green e-Competences, Preliminary Project Results, Milan, 2009.
[10] EATON, Is an energy wasting data center draining you bottom line? New technology options and power distribution strategies can automatically reduce the cost and carbon footprint of a data center, White Paper, 2009.
[11] R. Bolla, R. Bruschi, and A. Ranieri, Energy aware equipment for next-generation networks, in *Proc. Int. Conf. on Future Internet*, Korea, November, pp. 8–11, 2009.
[12] Report to Congress, Server and data center energy efficiency, U.S Envrionmental Protection Agency, Energy Star Program, August 2007.
[13] L. MacVittie, A green architectural strategy that puts IT in the black, F5 White Paper, 2010.
[14] IBM, The green data center, White Paper, May 2007.
[15] TheGreenGrid, Guidelines for energy-efficient data centers, White Paper, February 2007.
[16] Hewlett Packard, A blueprint for reducing energy costs in your data center, White Paper, June 2009.

[17] www.cost804.org
[18] Cisco, Cisco data center infrastructure 2.5 design guide, Technical Report, December 2006.
[19] L.A. Barroso and U. Holzle, *The Data Center as a Computer: An Introduction to the Design of Warehouse-Scale Machines*, Morgan and Claypool, 2009.
[20] N. Rasmussen, Implementing energy efficient data centers, White Paper, APC, 2006.
[21] N. Rasmussen, Electrical efficiency modelling for data centers, White Paper, APC, 2007.
[22] M. Parker and S. Walker, An absolute network energy efficiency metric, in *Proc. ICST Int. Conf. on Networks for Grid Applic.*, Athens, 2009.
[23] TheGreenGrid, Green grid metrics: Describing data center power efficiency, White Paper, February 2007.
[24] TheGreenGrid, Proxy proposals for measuring data center productivity, White Paper, 2008.
[25] GIPC, Concept of new metric for data center energy efficiency: Introduction to data center performance per energy DPPE, Green IT Promotion Council, February 2010.
[26] International Energy Agency (IEA), CO_2 emissions from fuel combustion: Highlights, Report, 2009.
[27] N. Rasmussen, Allocating data center energy costs and carbon to IT users, APC White Paper, 2009.
[28] M. Eastwood, J. Pucciarelli, J. Bozman, and R. Perry, The business value of consolidating on energy-efficient servers: Customer findings, IDC White Paper, May 2009.
[29] J. Murphy, *Increasing Energy Efficiency with x86 Servers*, Robert Francis Group, 2009.
[30] N. Rasmussen, Strategies for deploying blade servers in existing data centers, APC White Paper, 2005.
[31] L. Chang et al., Practical strategies for power-efficient computing technologies, *Proceedings of IEEE*, vol. 98, no. 2, February 2010.
[32] J. Koomey et al., Server energy measurement protocol, Energy Star, Report, 2006.
[33] L.A. Barroso and U. Hozle, The case of energy proportional computing, *IEEE Computer*, vol. 40, pp. 33–37, 2007.
[34] Force 10, Managing data center power and cooling, White Paper, 2007.
[35] www.thegreengrid.org.
[36] http://www.futurefacilities.com/software/6SigmaRoom.htm.
[37] S. Bigelow, D. Davis, and R. Vanover, Choosing to wait on virtualization, how can the open virtualization format help you, critical decisions for virtualization storage, *Virtual Datacenter*, vol. 20, March 2010.
[38] E. Cigic and N. Nosovic, Server virtualization for energy efficient data centers in Bosnia and Herzegovina, Int. Telecommunication Forum TELFOR, Serbia, November 2009.
[39] J. Haas, et al., Data center design guide. Program overview, Report by The Green Grid, 2009.
[40] IBM, Taking an integrated approach to energy efficiency with IBM Tivoli software, White Paper, August 2008.
[41] APC, Avoiding costs from oversizing data center and network room infrastructure, White Paper, 2003.

[42] M. Al-Fares, A. Loukissas, and A. Vahdat, A scalable, commodity data center network architecture, in *ACM SIGCOMM*, pp. 63–74, August 2008.
[43] A. Qureshi, et al., Cutting the electric bill for internet scale systems, in *APC SIGCOMM*, 2009.

Biographies

G. Koutitas was born in Thessaloniki, Greece. He received his B.Sc. degree in Physics from the Aristotle University of Thessaloniki, Greece, in 2002 and his M.Sc. degree, with distinction, in Mobile and Satellite Communications from the University of Surrey, UK, in 2003. He succeeded his Ph.D in radio channel modeling from the Centre for Communications Systems Research (CCSR) of the University of Surrey in 2007. His main research interests are in the area of radio wave propagation modeling, wireless communications (modeling and optimization) and in the area of ICT for sustainable growth and energy efficiency. He is involved in research activities concerning energy efficient network deployments and design, Green communications and sensor networks.

P. Demestichas was born in Athens, Greece, in 1967. Since December 2007 he is Associate Professor at the University of Piraeus, in the Department of Digital Systems, which he joined in September 2002 as Assistant Professor. From January 2001 until August 2002 he was adjunct lecturer at NTUA, in the Department of Applied Mathematics and Physics, of the National Technical University of Athens (NTUA). From January 1997 until August 2002 he was senior research engineer in the Telecommunications Laboratory of NTUA. Until December 1996 he had acquired a Diploma and Ph.D. degree in Electrical and Computer Engineering from NTUA, and had conducted his military service in the Greek Navy. He has been actively involved in a number of national and international research and development programs. His research interests include the design and performance evaluation of high-speed, wireless and wired, broadband networks, software engineering, network management, algorithms and complexity theory, and queuing theory. Most of his current activities focus on the Information Communications Technologies (ICT), 7th Framework Programme (FP7), “OneFIT” (Opportunistic Networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet), in which he is the project manager. Moreover, he will be involved in the ICT/FP7 projects “UniverSelf” (Autonomics for the Future Internet), “Acropolis” (Advanced coexistence technologies for ra-

dio optimization in licenced and unlicensed spectrum), and the COST action IC0902. He has been the technical manager of the "End-to-End Efficiency" (E3) project, which focused on the introduction of cognitive systems in the wireless world. He is the chairman of Working Group 6 (WG6), titled "Cognitive Networks and Systems for a Wireless Future Internet", of the Wireless World Research Forum (WWRF). He has further experience in project management from the FP5/IST MONASIDRE project, which worked on the development of composite wireless networks. He has actively participated in FP6/IST (E2R I/II, ACE), Eureka/Celtic, as well as FP5, ACTS, RACE I and II, EURET and BRITE/EURAM. He has around 200 publications in international journals and refereed conferences. He is a member of the IEEE, ACM and of the Technical Chamber of Greece.