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# The Potential for Cloud Computing to Lower Power Consumption and Reduce Carbon Emissions

CAPSTONE REPORT

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The Potential for Cloud Computing to Lower Power Consumption and Reduce Carbon  
Emissions in the Data Center When Compared to Traditional Data Centers

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**Abstract**

This annotated bibliography reviews literature published between 2008 and 2011 to identify the potential for cloud computing to lower power consumption and reduce carbon emissions.

Accounting for varied energy efficiency factors (location, virtualization, architectural design, and management systems), cloud providers implementing carbon/energy based scheduling policies can achieve energy savings in comparison to profit based scheduling policies, leading to higher profit and less carbon emissions (Garg, S., Yeo, C., Anandasivam, A. , & Buyya, R. (2011).

*Keywords:* cloud computing, energy-efficient data centers, carbon emissions, energy savings



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## Introduction

### Problem Area

Bauman (2010) states that by 2009 an estimated 79% of Americans were using the Internet in a wide variety of ways, including banking online, shopping online, socializing online, and going to school online. As more people use online services, information technology (IT) infrastructure and especially data centers will increase in both size and number to handle increasing demand (Hang, Kuo & Ahmad, 2010). An example of an IT infrastructure that is growing to meet the demands of its user base is Facebook, a social networking site with over 800 million users worldwide, half of whom log on daily (Facebook, 2011).

As of 2009, it was estimated that Facebook had as many as 60,000 servers (Miller, 2010) in order to meet the needs of their user base. Facebook is just one example of massive infrastructure growth; many IT organizations are tasked with managing expanding IT infrastructures (Ruth, 2011). While expansion and growth are often seen as positive signs of economic growth, negative factors can also arise such as increased energy consumption and carbon emissions output (Ruth, 2011, p 207). Both within the United States and globally, data center markets are expected to grow 50% by 2020 (Savitz, 2011). As a consequence, those data centers are also expected to increase power consumption. Mehta, Menaria, Dangi, and Rao (2011) note that “it is estimated that in 2006, the cost of electricity consumed by IT infrastructure in the US was around \$4.5 billion US, which came to about 1.5% of the total US energy consumption that year; these figures are expected to double by 2011” (p.10).

According to recent study by CompTIA (2011), IT organizations are adopting green IT initiatives with 37% of organizations surveyed adopting such measures in 2011; the expectation is that initiatives will rise to 54 percent in 2013 (CompTIA, 2011). Green IT, also known as

green computing, is the practice of maximizing the efficient use of computing resources to minimize environmental impact” (Harmon & Auseklis, 2009). A main tenant of green IT is to achieve energy reduction and thus lower carbon dioxide output or carbon footprint (Jenkin, McShane & Webster, 2011). Harmon and Auskelis (2009) state that due to the immediate impact on business value, it is likely that green computing will remain focused for some time on reducing costs while improving the performance of energy hungry data centers and desktop computers. They also note that “the rapid growth of Internet-based business computing, often metaphorically referred to as “cloud” computing, and the costs of energy to run the IT infrastructure are the key drivers of green computing (2009, p. 1707). Jenkin, McShane, and Webster (2011) indicate that organizations including IBM, Dell, Microsoft, and HP have joined Green Grid, an organization “dedicated to advancing energy efficiency in data centers and business computing ecosystems” (p. 271).

**What is cloud computing?** There are various ways to define cloud computing. Buyya, Beloglazov and Abawajy (2010) define cloud computing or the cloud as a type of parallel and distributed system consisting of a collection of interconnected and virtualized computers that are dynamically provisioned and presented as one or more unified computing resource(s) based on service-level agreements established through negotiation between the service provider and consumers. (p.601)

Garg, Yeo, and Buyya (2011) define cloud computing as “essentially datacenters hosting application services offered on a subscription basis” (p. 732).

For the purpose of this study, the definition of cloud computing provided by the National Institute of Standards and Technology (NIST) (2011) is used, which reads:

a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. (para. 1)

**Cloud computing as a way to lower power consumption.** “Among all industries, the information communication technology (ICT) industry is arguably responsible for a large portion of the world-wide growth in energy consumption” (Chu, Chen, & Cheng, 2011, p.1).

AbdelSalam, Maly, Mukkamala, Zubair, and Kaminsky (2009) state “due to the tremendous increase in energy costs in the past few years, it is expected that efficient power management will play an essential role in the success of large IT environments such as computing clouds (p.162, 2009). According to Harmon and Auseklis (2009) “data centers typically account for 25% of total corporate IT budgets and their costs are expected to continue to increase as the number of servers rise and the cost of electricity increases faster than revenues” (2009, p.1708). Mehta, Menaria, Dangi, and Rao (2011) state:

it is estimated that in 2006, the cost of electricity consumed by IT infrastructure in the US was around \$4.5 billion US, which came to about 1.5% of the total US energy consumption that year; these figures are expected to double by 2011 and by 2015, the costs of operations, of which the cost of electrical power is an important part, will cross the initial cost of IT infrastructure or hardware. (2011, p.1)

One of the major causes of energy inefficiency in data centers is the idle power wasted when servers run at low utilization. Even at a very low load, such as 10% CPU utilization, the power consumed is over 50% of the peak power (Srikantaiah, Kansal, & Zhao, 2008). Berl, Gelenbe, Di Girolamo, Giuliani, De Meer, Dang, and Pentikousis (2009) state that “the key

current technology for energy-efficient operation of servers in data centres is virtualization” (p.4). “Virtualization is a key feature of the Cloud, as it allows high performance, improved manageability, and fault tolerance” (Lefèvre & Orgerie, p. 353, 2010). Virtual servers use less power and have higher levels of efficiency than standalone servers. Energy efficiency can be achieved through reducing redundancy and consolidating hardware (Berl et al., 2009).

**Cloud computing as a way to reduce carbon emissions.** “Carbon emissions are proportional to energy usage” (Harmon & Auseklis, 2009, p.1707). As more energy is consumed, the output of carbon emissions will increase. The amount of carbon emissions released is dependent upon the type of power used (Harmon & Auseklis, 2009). Cloud computing allows IT to move VMs to data centers that are powered by lower carbon emission power plants such as wind, solar, or hydro electric (Moghaddam, Cheriet, & Kim Khoa, 2011). Moghaddam, Cheriet, and Kim Khoa (2011) state that using “VM migration as a server consolidation tool results in lower power consumption and a reduced carbon footprint which means that a carbon footprint reduction is an immediate result of power consumption reduction” (2011, p. 260).

### **Purpose**

A large amount of electricity is needed to power and cool servers hosted in traditional data centers resulting in high energy costs and huge carbon footprints (Buyya, Beloglazov, & Abawajy, 2010). Data center energy management has become an important factor for IT organizations not only from an economic perspective, but also for environmental conservation (Hang, Kuo, Ahmad, & Ming, 2010). The purpose of this annotated bibliography is to present literature that addresses the potential to use cloud computing to support data center operations with the goal to lower power consumption and reduce carbon emissions (Berl et al., 2009). Cloud

computing is “a new paradigm in which computing resources such as processing, memory, and storage are not physically present at the user’s location. Instead, a service provider owns and manages these resources, and users access them via the Internet” (Kumar & Yung-Hsiang, 2010, p733). Ruth (2009) states that “every time an organization shifts a workload of storage or processing to the cloud they are reducing their overall electricity usage” (p. 209). In virtual private clouds (VPCs), server consolidation can be used to reduce the power consumption and the carbon footprint (Moghaddam, Cheriet, & Kim Khoa, 2011). To avoid nomenclature confusion, Moghaddam, Cheriet, and Kim Khoa (2011) state that VPCs and local area network (LAN)-based clouds provide the same services. Local Area Networks are network infrastructure consisting of servers, storage, and networking gear within a single site or location. And while significant concerns regarding the reliability and security of cloud computing exist, (Ruth, 2009) early studies indicate that this technology paradigm shift may be a more environmental-friendly option for expanding IT infrastructure when compared to traditional data centers (Mehta, A., Menaria, M., Dangi, S., & Rao, S., 2011).

### **Audience**

Chief Information Officers (CIO), Directors of Technology, Data center managers, and IT infrastructure managers who are responsible for “green” IT may be interested to learn how to find energy efficiencies and reduce carbon emissions through the adoption of cloud computing (Berl et al., 2009). Buyya, Beloglazov, and Abawajy (2010) state that technology providers including Google, IBM, Yahoo, and Microsoft are “rapidly deploying data centers in various locations around the world to deliver Cloud computing services” (p.1). Burdick (2010) predicts that the adoption of cloud computing will accelerate and that within 10 years, 80 % of all computing and data storage worldwide will transpire in the cloud. Additionally, as noted by

Ruth (2011), IT organizations are moving to the cloud in order to reduce their overall electricity usage.

### **Research Question and Sub-questions**

**Main question.** How can moving the data center to the cloud lower energy consumption and reduce carbon emissions, when compared to traditional data centers? (Moghaddam, Cheriet & Kim Khoa, 2011)

#### **Sub-questions.**

- What is cloud computing and how is it related to virtualization? (Iyer & Henderson, 2010)
- Why are organizations moving data centers to the cloud? (Buyya, Beloglazov, & Abawajy, 2010)
- How does cloud computing reduce energy consumption in the data center; what are the associated risks? (Moghaddam, Cheriet, & Kim Khoa 2011)
- How does cloud computing reduce carbon emissions in the data center; what are the associated risks? (Moghaddam, Cheriet, & Kim Khoa, 2011).

#### **Significance**

The energy consumed by servers and data centers is significant as demonstrated by the fact that the “estimated level of electricity consumption is more than the electricity consumed by the nation’s color televisions and similar to the amount of electricity consumed by approximately 5.8 million average U.S. households (or about five percent of the total U.S. housing stock)” (EPA, 2007). IT organizations are the most costly power expense in a company (Dembo, 2008). IT management is under increasing pressure to consider environmental impacts, both in their



business strategies and operations (Henriques & Sadorsky, 1999; Ramus & Steger, 2000; Stead & Stead, 1995).

Data centers consume 1.5-2% of all global electricity, which is growing at a rate of 12% a year (Koomey, 2008). Increased energy consumption results in increased carbon dioxide (CO<sub>2</sub>) output also known as carbon dioxide emissions (Solomon, Plattner, Knutti, & Friedlingstein, 2008). “A 2008 study by the management-consulting firm McKinsey & Co. projected that the world’s data centers would surpass the airline industry in greenhouse gas emissions by 2020” (Gordon, 2011, p1). It is estimated that “IT manufacture and use is responsible for 2 percent of global carbon emissions – the same amount as the airline industry – and is heading for 3 percent by 2020, when it will be responsible for the same amount of carbon as the United Kingdom produced in 2008” (Cubitt, Hassan & Volkmer, 2011, p154). Increased carbon dioxide emissions can have a negative effect on the environment by potentially altering climate or inducing climate change (Solomon, Plattner, Knutti & Friedlingstein, 2008).

Data centers now produce more carbon emissions than both Argentina and the Netherlands (Kaplan, Forrest, & Kindler, 2009). Carbon emissions from data center operations are expected to grow at more than 11% per year to 340 metric megatons by 2020 (Harmon & Auseklis, 2009). As noted by Hang, Kuo, and Ahmad (2010), “as large data centers emerge for media-rich Internet services and applications, their energy efficiency has become a central issue of both economic importance and environmental urgency” (p. 1).

## **Delimitations**

**Topic scope.** This annotated bibliography is intended to provide insights concerning the potential to achieve energy efficiencies and reduce carbon emissions in the data center through cloud computing. While significant concerns regarding the reliability and security of cloud computing exist, (Ruth, 2009) early studies indicate that this technology paradigm shift may be a more environmental-friendly option for expanding IT infrastructure when compared to traditional data centers (Mehta, Menaria, Dangi, & Rao, 2011). According to Lee and Zomaya (2010), “energy consumption and resource utilization in clouds are highly coupled. Specifically, resources with a low utilization rate still consume an unacceptable amount of energy compared with their energy consumption when they are fully utilized or sufficiently loaded” (p. 2).

**Focus and exclusions.** This study does not focus on a specific virtualization vendor such as Microsoft Hyper V (Microsoft, 2011) or Vmware ESXi (Vmware, 2011). This study also does not take into consideration the type of energy source used by a data center or cloud vendor. For example, “if a data center is powered by a renewable energy source, its carbon footprint will be small, or even zero, compared to a data center powered by non-clean energy sources” (Moghaddam, Cheriet, & Kim Khoa, 2011). While other technologies for energy reduction and carbon emission reduction exist such as lower power CPUs, and power management software, this study focuses solely on cloud computing. While cost savings from cloud computing may increase profitability this study does not focus on how to reduce energy usage and carbon emissions from the perspective of improving profits.

**Time frame.** Due to the recent emergence and adoption of cloud computing as a business model, (Mehta, Menaria, Dangi, & Rao, 2011) the literature selection is limited to materials published between 2008 and 2011.

**Selection criteria.** Literature used in the study is obtained using online databases from the University of Oregon Libraries (Articles, Databases, Indexes) as well as Academic Search Primer, JSTOR, Project Muse, Web of Science, Google Scholar, IEEE Xplore Digital Library and search engines including Google and Bing. This study gives preference to scholarly or peer reviewed materials over that of editorials and non-peer reviewed publications. In addition, literature is also obtained from trade journals and professionally recognized IT organizations, when the information can be substantiated using Evaluation Criteria established for this study (see criteria from Bell and Smith, 2009).

### **Reading and Organization Plan Preview**

Each selected reference is reviewed to determine the relation to the main research question as well as sub-questions based upon evaluation criteria (Bell & Smith, 2009). References are then categorized by research question focus, and then the following procedures are used during the reading and analysis process.

**Reading plan.** Each reference is reviewed to determine its relevance to the main topic question of how moving the data center to the cloud lowers energy consumption and reduces carbon emissions, when compared to traditional data centers? (Moghaddam, Cheriet & Kim Khoa, 2011). A spreadsheet is used to record and track the search term, database used, article title, publication date, as well the abstract and APA citation. If the reference is an online resource, the web address is noted within the spreadsheet. The authority of the authors is evaluated for each reference based on institutional affiliation, past writings, citations in other articles, and relevance within his/her field or employment experience (Bell & Smith, 2009). References that are deemed to be relevant to the main topic question and sub questions are downloaded (Bell & Smith, 2009).

After the references are selected, each is read according to a coding plan to identify key terms and phrases related to the concepts embedded in the research questions. The approach is similar to conceptual analysis (Busch, De Maret, Flynn, Kellum, Le, Meyers, Saunders & White, 2005).

**Organization plan.** The results of the analytic coding plan are presented thematically in the Annotated Bibliography (University of North Carolina, n.d.). The four themes are related to the topics of the main research question and sub questions including:

1. Cloud computing and its relation to virtualization (Iyer & Henderson, 2010).
2. Reasons organizations are moving from traditional data center models to cloud computing (Buyya, Beloglazov, & Abawajy, 2010).
3. Cloud computing potential for reducing energy consumption in the data center (Moghaddam, Cheriet, & Kim Khoa 2011).
4. Cloud computing potential for reducing carbon emissions in the data center (Moghaddam, Cheriet, & Kim Khoa, 2011).

### Definitions

The definitions provide a guide for readers to familiarize themselves with unique terms related to cloud computing as they are used in this study. The definitions are intended to reduce ambiguity concerning cloud computing terminology.

**Cloud computing** – “a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction” (NIST, 2011).

**Cloud provider** – “A Cloud provider has multiple data centers distributed across the world” (Garg, Yeo, & Buyya 2011).

**CO<sub>2</sub>** – “Carbon dioxide emissions contributing to the greenhouse effect” (Beloglazov, & Buyya, 2010).

**CompTIA** – A non-profit trade association that focuses on advancing the global interests of IT professionals and companies (CompTIA, 2011).

**Data center** – Defined by IDC and EPA (as cited by Koomey, 2008) as any space whose main function is to house servers, including data closets and server rooms.

**Green Computing** – Also known as green IT is “the practice of maximizing the efficient use of computing resources to minimize environmental impact” (Harmon & Auseklis, p. 1707).

**Green Grid** – A global consortium promoting data center energy efficiency and minimizing their environmental impact (Buyya, Beloglazov, & Abawajy, 2010).

**Green Networking** – Green networking consists of networking technologies that play a significant role in reducing energy consumption. (Sigcomm, 2010).

**ICT** – Acronym for information and communication technology (Berl et al., 2010). Information and communication technology is often used as a synonym for information technology.

“This is the common term for the entire spectrum of technologies for information processing, including software, hardware, communications technologies and related services” (Gartner, 2012).

**IDC** – “Internet Data Center (IDC) is a common form to host cloud computing. An IDC usually deploys hundreds or thousands of blade servers, densely packed to maximize the space utilization. Running services in consolidated servers in IDCs provides customers an alternative to running their software or operating their computer services in-house” (Liu et al., 2009).

**Local Area Network (LAN)** – “A geographically limited communication network that connects users within a defined area. A LAN is generally contained within a building or small group of buildings and is managed and owned by a single enterprise” (Gartner, 2012).

**National Institute of Standards and Technology (NIST)** – “NIST is a non-regulatory federal agency within the U.S. Department of Commerce. NIST’s mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life” (NIST, 2011).

**Public Cloud** – “With a public cloud, the infrastructure is available to the general public or large industry groups and is owned by an organization selling cloud services” (Iyer & Henderson, 2010).

**Private Cloud** – “A private cloud infrastructure is operated solely for an organization. The cloud may be managed by the organization or a third party and may exist on- or off-premise”

(Iyer & Henderson, 2010).

**Server Consolidation** – Multiple virtual machines running on a single hardware unit (Berl et al., 2009).

**The Cloud** – The Cloud is a commonly used term also known as cloud computing or cloud.

The “*cloud* is a type of parallel and distributed system consisting of a collection of interconnected and virtualized computers that are dynamically provisioned and presented as one or more unified computing resources based on service-level agreements established through negotiation between the service provider and consumers” (as cited by Liu et al., 2009).

**Virtualization** – Virtualization is “a technique used to run multiple virtual machines on a single physical machine, sharing the resources of that single computer across multiple environments” (Chilamkurti, Zeadally, & Mentiplay, 2009).

**Virtual Machine (VM)** – An acronym for Virtual Machine. VMs “allow both the isolation of applications from the underlying hardware and other VMs” (Buyya, Beloglazov, & Abawajy, 2010).

**Virtual Private Cloud (VPC)** – A Virtual Private Cloud “A Virtual Private Cloud (VPC) is a cloud identity consisting of a network of data centers connected to one another in a WAN (Moghaddam, Cheriet, & Kim Khoa, 2011).

### **Research Parameters**

This study is designed as an annotated bibliography; information is derived through a review of selected literature. An annotated bibliography is an account of research on a particular topic that provides a summary of each resource as well as its relevance to the selected topic (Taylor, n.d.). The following systematic approach is used in designing the research method:

- **Keywords** – Keywords consist of words and terms used in conjunction with search engines to locate reference material.
- **Search Patterns** – Search patterns describes the search engines and databases used to locate reference material.
- **Documentation Approach** – Documentation Approach describes how reference materials are recorded and then coded during further analysis.
- **Reading Plan** - Reading Plan describes the process how each reference is read and coded in relation to main research question and subquestions.
- **Organization Plan** – Organization Plan describes the thematic (University of North Carolina, n.d.) organization of the references in relation to the main research question and subquestions.

### **Search Report**

**Keywords.** References for the study are collected using keywords and related search terms. Each keyword identifies part of the subject and provides a focus for the search (Hewitt, 1998). Terms are selected in relation to cloud computing, data centers, green IT, carbon emissions, and energy reduction.

**Search patterns.** Searches using the terms *cloud computing* or *carbon emissions* generate a significant amount of returns. A search using the terms cloud computing and carbon



emissions results in 64 returns using The University of Oregon's OneSearch. The ACM Digital Library returns more results using the same key words. The IEE Xplore Digital Library returns the lowest amount of results when compared to the other search tools; only 20. Google Scholar returns 7,580 results which is the largest number of results when compared to other search tools.

Table 1

*Keywords and number of search results*

Keywords and search results from Google Scholar, IEE Xplore Digital Library, and ACM Digital Library.

<i>Search Term</i>	<i>Search Tool</i>	<i>Results Returned</i>
Cloud computing and carbon emissions	OneSearch	64
	ACM Digital Library	174
	IEE Xplore Digital Library	20
	Google Scholar	7,580
Cloud computing and energy efficiencies	OneSearch	32
	ACM Digital Library	1,690
	IEE Xplore Digital Library	185
	Google Scholar	19,500
Green data centers and green IT initiatives	OneSearch	34
	ACM Digital Library	1,581
	IEE Xplore Digital Library	7
	Google Scholar	107,000

Google Scholar provides the largest number of results, yet not all results are available freely available or without a paid membership. ACM Digital Library and IEE Xplore Digital Library Preliminary allow proxy access via the University of Oregon Libraries. Not all full articles are retrieved via their sites, but abstracts and article information enable the author to determine if the article should be obtained via the University of Oregon Library system or other online resources. Refined search terms based on Boolean strings combining terms allow for more targeted results.

**Preliminary search terms.**

- Cloud computing
- Carbon emissions
- The Cloud
- Energy efficient cloud computing
- Carbon footprint
- Global warming
- Virtualization

**Refined search terms.**

- Cloud computing carbon emissions reductions
- Cloud computing energy reduction
- Carbon emission reductions
- Cloud computing energy efficiency
- Green data centers

- IT green initiatives
- Software as a Service (SaaS)
- Infrastructure as a Service (IaaS)
- Green computing
- Energy savings cloud computing
- Rising energy costs
- Carbon dioxide greenhouse effect
- Server Consolidation
- Data center expansion

**Databases used.** The primary search was done using the University of Oregon Libraries via OneSearch. Additional queries were applied against Google Scholar, IEE Xplore Digital Library, and ACM Digital Library. The search consists of focused queries with the above stated key words using the following databases and Google:

- University of Oregon Libraries (Articles, Databases, Indexes)
- Academic Search Primer
- JSTOR
- Project Muse
- Web of Science
- Google Scholar
- ACM Digital Library
- IEEE Xplore Digital Library
- Google

### **Documentation Approach**

Once articles and other sources show potential value and align with the delimitations of this study, content is downloaded in electronic form such as PDF, text, or HTML files for further review. A spreadsheet is kept listing the Boolean search term, the database used, article title, publication date, abstract, and APA citation. Priority is given to articles published in recognized journals (Creswell, 2009).

### **Evaluation Criteria**

Peer reviewed and professional trade publications are used searched to collect relevant references regarding cloud computing for the purpose of (a) lowering power consumption and (b) reducing carbon emissions. Both types of publications are necessary for this review in order to build a broad-based picture of the evolving state of cloud computing relative to these two aspects (Beloglazov & Buyya, 2010). References are evaluated based upon the following guidelines (Bell & Smith, 2009):

**Authority.** Authority is evaluated by the author's institutional affiliation, past writings, and reputation among his or her peers.

**Objectivity.** Objectivity is determined by examining the content for "emotion-around words and bias" (Bell & Smith, 2009). It should be the goal of the author(s) to inform, explain, or educate without emotional assumptions or conclusions.

**Quality.** Quality of a reference is based upon logical structure that is free of spelling or typographical errors. Main points should be clearly presented without repetition of author's arguments.

**Coverage.** Coverage should provide multiple points of view and include a diversity of sources.

**Currency.** Currency is determined by publication or copyright date. In the case of a journal, the publication date is obtained by the cover or title page. In the case of a website, the date the page was created or last revised is taken into account. As noted in the delimitations, preference is given to articles published between 2008 and 2011.

### **Reading and Organization Plan**

**Reading plan.** The reading plan is designed to analyze the selected references in regards to concepts embedded in the four main research questions including: (a) What is cloud computing and how is it related to virtualization? (Iyer & Henderson, 2010); (b) Why are organizations moving data centers to the cloud? (Buyya, Beloglazov, & Abawajy, 2010); (c) How does cloud computing reduce energy consumption in the data center; what are the associated risks? (Moghaddam, Cheriet, & Kim Khoa 2011); and (d) How does cloud computing reduce carbon emissions in the data center; what are the associated risks? (Moghaddam, Cheriet, & Kim Khoa, 2011). The analytic approach is similar to conceptual analysis as described by Busch et al. (2005). Each reference is read and coded using a predetermined set of terms and phrases related to each research question.

*Table 2* provides a sample of the coding keys used during content analysis.

Table 2

#### *Coding Key During Content Analysis*

<b>Concepts Derived from Research Questions</b>	<b>Key words or Phrases</b>
Cloud computing and its relation to virtualization	Cloud computing, virtualization, virtual machines, VMware, Hyper V, Virtual Private Clouds
Reasons organizations are moving from traditional data center models to cloud	Next generation data centers, cloud computing, the cloud, data center consolidation,

computing	Software as a Service (SaaS), Infrastructure as a Service (IaaS)
Cloud computing potential for reducing energy consumption in the data center	Data center energy consumption, green data centers, energy efficient data centers, IT green initiatives, rising energy costs
Cloud computing potential for reducing carbon emissions in the data center	Data center carbon footprint, data center carbon emissions, green data centers, IT green initiatives

**Organization plan.** Once an in-depth reading process has occurred, the references are organized and presented thematically in the Annotated Bibliography section of this paper (University of North Carolina, n.d). Each theme addresses one of the research questions; as a set the themes examine the potential for cloud computing to lower power consumption and reduce carbon emissions in the data center when compared to traditional data centers.

Theme one: Cloud computing and its relation to virtualization. The first theme addresses cloud computing and its inextricable relationship to virtualization (Chu, Chen, & Cheng 2011). The theme provides definitions for both cloud computing (NIST, 2011) and virtualization (Chilamkurti, Zeadally, & Mentiplay, 2009) as these are used in this study.

Theme two: Reasons organizations are moving from traditional data center models to cloud computing. The second theme provides insight as to why organizations are moving from traditional data center models to cloud computing (Cubitt, Hassan, & Volkmer, 2011). This theme addresses the paradigm shift and rapid adoption of cloud computing (Moghaddam, Cheriet, & Kim Khoa, 2011).

Theme three: The third theme addresses the potential for cloud computing to reduce energy consumption in the data center (Doyle, O'Mahony, & Shorten, 2011). This theme

describes the rise in energy cost within data centers and how cloud computing can create energy efficiencies (Kaplan, Forrest, & Kindler, 2009).

Theme four: The fourth theme addresses the potential for cloud computing to reduce carbon emissions in the data center (Beloglazov & Buyya, 2010). This theme describes how IT management is under increasing pressure to consider environmental impacts of IT projects (Henriques & Sadorsky, 1999; Ramus & Steger, 2000; Stead & Stead, 1995).

### **Annotated Bibliography**

The purpose of this annotated bibliography is to present literature that addresses the potential to use cloud computing to support data center operations with the goal to lower power consumption and reduce carbon emissions (Berl et al., 2009). The annotated bibliography as noted by Taylor (n.d) briefly identifies how the intended source will be used and why. This annotated bibliography consists of 30 references that are presented thematically (University of North Carolina, n.d); collectively the references examine the potential for cloud computing to lower power consumption and reduce carbon emissions in the data center when compared to traditional data centers. The annotated bibliography is segmented into four themes, each addressing key concepts embedded in one of the central research questions:

1. Cloud computing and its relation to virtualization.
2. Reasons organizations are moving from traditional data center models to cloud computing.
3. The potential for cloud computing to reduce energy consumption in the data center.
4. The potential for cloud computing to reduce carbon emissions in the data center.

#### **Theme 1: Cloud Computing and its Relation to Virtualization**

**Beloglazov, A., & Buyya, A.** (2010). *Energy efficient resource management in virtualized cloud data centers*. Cluster, Cloud and Grid Computing (CCGrid), 2010 10<sup>th</sup> IEEE/ACM International Conference on Cluster, Cloud, and Grid Computing, 826-831.

**Abstract.** Rapid growth of the demand for computational power by scientific, business and web-applications has led to the creation of large-scale data centers consuming



enormous amounts of electrical power. We propose an energy efficient resource management system for virtualized Cloud data centers that reduces operational costs and provides required Quality of Service (QoS). Energy savings are achieved by continuous consolidation of VMs according to current utilization of resources, virtual network topologies established between VMs and thermal state of computing nodes. We present first results of simulation-driven evaluation of heuristics for dynamic reallocation of VMs using live migration according to current requirements for CPU performance. The results show that the proposed technique brings substantial energy savings, while ensuring reliable QoS. This justifies further investigation and development of the proposed resource management system.

**Summary.** The article describes the increasing amount of power consumption within the data center. A correlation is made between energy savings and consolidation of virtual machines, with the statement that virtualization can reduce the amount of physical hardware necessary for an operation. The authors point out that virtualization is a key component to cloud computing.

**Credibility.** Anton Beloglazov has a BS in Computer Science and Computer Engineering and a MS in Computer Science and Computer Engineering from Novosibirsk State Technical University. Dr. Beloglazov has a PhD in Computer Science from the University of Melbourne where he is a faculty member in the Department of Engineering and Director of the Cloud Computing and Distributed Systems (CLOUDS) Laboratory at the University of Melbourne. Rajkumar Buyya holds a BE in Computer Science and Engineering from the University of Mysore. In addition, Buyya holds a ME in Computer Science and Engineering from Bangalore University and a PhD in Computer

Science and Engineering from Monash University. He is the 2008 recipient of IEEE Computer Society Distinguished Service Award. This article was presented at the 2010 IEEE/ACM International Conference on Cluster, Cloud and Grid Computing.

**Chilamkurti, N. , Zeadally, S. , & Mentiplay, F. (2009).** Green networking for major components of information communication technology systems. *Eurasip Journal on Wireless Communications and Networking*,.

**Abstract.** Green Networking can be the way to help reduce carbon emissions by the Information and Communications Technology (ICT) Industry. This paper presents some of the major components of Green Networking and discusses how the carbon footprint of these components can be reduced.

**Summary.** The article focuses on how Green Networking (i.e., selecting energy efficient networking technologies) can lead to carbon emission reductions. The article provides cited examples of the growing power consumption requirements of IT. The article outlines some steps that can be taken to reduce carbon footprint and ties virtualization to cloud computing. Concepts addressed align with those examine in Theme 1 and Theme 3.

**Credibility.** Chilamkurti earned his Bachelor and Master's degrees in Computer Science from the University of Cambridge and is now an Associate Professor in the Department of Computer Science and Computer Engineering at La Trobe University. Zeadally has a PhD and is in the Department of Computer Science and Information Technology at the University of the District of Columbia. Frank Mentiplay is a member of the Department of Computer Science and Computer Engineering at La Trobe University. Zeadally's work was supported by grants from Cisco Systems and the District of Columbia NASA Grant

Space Consortium. The article is peer reviewed and contains 20 cited references. It appears in the EURASIP Journal on Wireless Communications and Networking, published by Springer in its SpringerOpen portfolio of open access journals.

**Ye, K., Huang, D., Jiang, X., Chen, H., & Wu, S.** (2010). Virtual machine based energy-efficient data center architecture for cloud computing: A performance perspective. In *Proceedings of the 2010 IEEE/ACM Int'l Conference on Green Computing and Communications & Int'l Conference on Cyber, Physical and Social Computing (GREENCOM-CPSCOM '10)*. IEEE Computer Society, Washington, DC, USA, 171-178. DOI=10.1109/GreenCom-CPSCom.2010.108 <http://dx.doi.org/10.1109/GreenCom-CPSCom.2010.108>

**Abstract.** Consolidation of applications in cloud computing environments presents a significant opportunity for energy optimization. As a first step toward enabling energy efficient consolidation, we study the inter-relationships between energy consumption, resource utilization, and performance of consolidated workloads. The study reveals the energy performance trade-offs for consolidation and shows that optimal operating points exist. We model the consolidation problem as a modified bin packing problem and illustrate it with an example. Finally, we outline the challenges in finding effective solutions to the consolidation problem.

**Summary.** Virtualization and cloud computing are inseparable. Virtualization allows multiple operating systems to run on a single physical machine. The authors suggest there is a tradeoff between energy efficiency and performance when employing virtualization. The article supports the perspective that consolidation and migration

strategies used in virtualization initiatives can improve energy efficiency. The article provides support for both Theme 1 and Theme 3.

**Credibility.** Kejiang Ye is a PhD student at Zhejiang University where his research interests include cloud computing and virtualization. The article appears in the 2010 IEEE/ACM International Conference on Green Computing and Communications.

## **Theme 2: Reasons Organizations are moving from Traditional Data Center Models to Cloud Computing**

**Cubitt, S., Hassan, R., & Volkmer, I.** (2011). Does cloud computing have a silver lining? *Media, Culture & Society*, 33(1), 149-158.

**Abstract.** A commentary on cloud computing is presented. Cloud computing uses remote servers to store documents as well as software required for access. The authors explore the environmental impact of cloud computing. They consider the server business introduced by Google. They believe sustainability will be obtained once the larger population realizes that the Internet is not ethereal and data does have weight or a value in terms of energy consumption.

**Summary.** This article provides examples of the growth trends concerning the use of traditional servers within data centers and how the paradigm shift of cloud computing has begun. Google is used as an example of data and server growth, because the company can be viewed as one key example of the overall expansion of the Internet and the growth of data centers. The authors suggest that one of the reasons organizations are considering cloud computing is to effect energy reductions.

**Credibility.** Sean Cubitt is the Director of the Program in Media and Communication at the University of Melbourne. He holds a MA from Cambridge and a PhD from Liverpool Johns Moores. Cubitt has been published in several books including *EcoMedia*, *The Cinema Effect*, *Simulation and Social Theory*. His work appears in various publications which include reviews, essays, and book chapters. Dr. Robert Hassan is ARC Senior Research Fellow in the Media and Communication department at the University of Melbourne. He holds a BA and PhD from Swinburne University of Technology. Dr. Hassan has published several books including *Information Society and 24/7: Critical Essays on Time in the Network Society*. Dr. Ingrid Volkmer is an Associate Professor and Deputy Director in Media and Communications at the University of Melbourne. In addition, she is Vice Chair of the Philosophy of Communication Division of the International Communication Association in Washington, D.C. The article is published in *Media, Culture & Society* which is one of a group of online peer-reviewed international forums from Sage Publications. The language of the article is clear and concise. The article appears unbiased as it questions the long-term sustainability of network computing whether using traditional data center models or cloud computing. In addition, cited references are provided.

**Gordon, D.** (2011). Five essentials to greening the data center. *T.H.E. Journal*, 38 (4), 21-22.

**Abstract.** A 2008 study by the management-consulting firm McKinsey & Co. projected that the world's data centers would surpass the airline industry in greenhouse gas emissions by 2020. Certainly adding to those emissions are K-12 districts, whose data centers hold the equipment that serves as the backbone for an ever-growing number of

computing initiatives. Inevitably, the dramatic rise in K-12 technology use in recent years has given way to soaring energy usage and power bills in many districts. The good news is that many K-12 school districts are recognizing their data centers as fertile ground for energy and cost savings and are taking steps to improve their energy efficiency. Not all energy-saving plans are created equal; some greening measures clearly rise to the top of the list of best practices.

**Summary.** The author discusses five essential elements to any data center greening initiative: (1) measuring energy usage; (2) virtual servers; (3) incorporating the cloud; (4) climate control; and (5) collaboration. He notes, “these essential elements may help ensure one is not missing steps integral to achieving strategic energy and cost savings. Tools for tracking energy usage and top energy-saving consolidation measures are presented”. The article focuses on how more school districts are making changes to their data centers and technology strategies in order to reduce spending and conserve energy. While this study is not specific to the education sector, the key concepts of carbon emission reduction and energy efficiencies are highly relevant. The article provides examples of how schools and school districts have achieved measurable energy reductions and suggests that energy reductions are a result of cloud computing.

**Credibility.** The article is peer reviewed and appears in the *The Journal*; a website and newsletter that serve as a resource for academic technology leader in K-12 education. The article provides support of ideas with other studies including a 2008 McKinsey study regarding the carbon emission and cost reductions in the data center. The author is a freelance writer.

**Iyer, B., & Henderson, J. C.** (2010). Preparing for the future: Understanding the seven capabilities of cloud computing. *Mis Quarterly Executive*, 9, 2, 117-131.

**Abstract.** To date, conversations about cloud computing have been dominated by vendors who focus more on technology and less on business value. While it is still not fully agreed as to what components constitute cloud computing technology, some examples of its potential uses are emerging. We identify seven cloud capabilities that executives can use to formulate cloud-based strategies. Firms can change the mix of these capabilities to develop cloud strategies for unique competitive benefits. We predict that cloud strategies will lead to more intense ecosystem-based competition; it is therefore imperative that companies prepare for such a future now.

**Summary.** This article outlines some issues that organizations should consider before implementing cloud computing. The article provides not only a definition of cloud computing, but also defines the various platforms of cloud computing including Platform-as-a-Service, Infrastructure-as-a-Service, and Software-as-a-Service. While this study is not cloud platform specific, this article does address the various platforms and reasons organizations are adopting each one. Reasons for moving to cloud computing include (a) cost and (b) support for on-demand use. The authors state that “green” cloud computing options may be powered by renewable energy sources.

**Credibility.** The article appears the MIS Quarterly, a peer reviewed scholarly journal published by the Management Information Systems Research Center at the University of Minnesota. Iyer received his PhD from New York University. In addition he holds a BE from Anna University and a MS from Louisiana State University. He is currently Associate Professor of Information in the Technology Operation Information and

Management Division at Babson College. He has published papers in the Journal of Management Information Systems, California Management Review, Communications of the ACM, Communications of AIS, Decision Support Systems, Annals of Operations Research, and Journal of the Operational Research Society. John Henderson is a professor at Boston University where he serves as the director of the Institute for Global Work. In addition he is a researcher and consultant with published works appearing in MIS Quarterly, Sloan Management Review, and Management Science. He holds a PhD from the University of Texas in Operations Research. Dr. Henderson currently serves on ICEX Board of Directors and SDG Advisory Board.

**Koomey, J. (2008).** Worldwide electricity used in data centers. *Environmental Research Letters*, 3(3).

**Abstract.** The direct electricity used by data centers has become an important issue in recent years as demands for new Internet services (such as search, music downloads, video-on-demand, social networking, and telephony) have become more widespread. This study estimates historical electricity used by data centers worldwide and regionally on the basis of more detailed data than were available for previous assessments, including electricity used by servers, data center communications, and storage equipment. Aggregate electricity use for data centers doubled worldwide from 2000 to 2005. Three quarters of this growth was the result of growth in the number of the least expensive (volume) servers. Data center communications and storage equipment each contributed about 10% of the growth. Total electricity use grew at an average annual rate of 16.7% per year, with the Asia Pacific region (without Japan) being the only major world region with growth significantly exceeding that average.



**Summary.** The demand for electricity in data centers is inextricably tied to the expansion of Internet services. Internet growth and data center expansion show no signs of slowing. The article focuses on the worldwide consumption of electricity in data centers. Direct electricity used by information technology equipment in data centers represented about 0.5% of total world electricity consumption in 2005. When electricity for cooling and power distribution is included, that figure is about 1%. Worldwide data center power demand in 2005 was equivalent (in capacity terms) to about seventeen 1000MW power plants. As energy consumption within the data center increases, so do environmental concerns. While this article does not focus on cloud computing, it is nonetheless important to understand current power consumption trends and future power consumption trends in data centers as a point of comparison.

**Credibility.** Jonathan Koomey has an AB, from Harvard University, MS in Energy and Resources and a PhD in Energy and Resources from the University of California, Berkeley. He has over 25 years of interdisciplinary academic experience on energy and environmental issues, public policy, and environmental sciences. Dr. Koomey has authored and co-authored several books, conference papers, and magazine articles. He is a research affiliate for the Energy and Resources Group at the University of California, Berkeley and a consulting professor at Stanford University. As stated on the website, *Environmental Research Letters* covers all of environmental science, with the goal to provide a coherent and integrated approach including research articles, perspectives and editorials.

**Ruth, S.** (2011). Reducing ict-related carbon emissions: An exemplar for global energy policy? *IETE Technical Review*, 28(3), 207-211.

**Abstract.** While controversy swirls globally about carbon emissions and electricity use, the Information and Communications Technology (ICT) sector has achieved significant, positive results already, especially in the developed nations. Some central processing units have reduced power use by 90% or more, and data centers are achieving previously unimaginable results in decreasing the use of electrical power. Several of the leading approaches to this improvement, sometimes called “Green IT”, are discussed, including E-waste mitigation, data center economies like virtualization and PUE improvement, telework and telepresence, smart grid devices, power management technologies, cloud computing, and dematerialization. In addition, several ICT power rating systems and return-on-investment methodologies are examined.

**Summary.** The ITC sector serves as an example of high achievement in reducing electricity and the resulting carbon emissions. Worldwide focus and governmental regulations are driving green IT. Organizations that shift processing or storage loads to the cloud are reducing their overall electricity usage. As a brief example of a national agenda for ICT-specific focus on energy management, the case of Australia is described. Even though ICT represents only about 3–5% of the world’s electrical use, its aggressive, successful, and continuing pursuit of reduced electricity use and lower carbon footprint is a model for other sectors. Ruth reaffirms that as cloud computing and other major power saving opportunities become commonplace, new opportunities to save and reduce power will arise.

**Credibility.** Stephen Ruth is Professor of Public Policy at George Mason University, and Director of the International Center for Applied Studies in Information Technology. Ruth has consulted with The U.S. Department of State, National Archives and Records

Administration, Price Waterhouse Coopers, and Johns Hopkins School of Public Health. Professor Ruth has a BS from the U.S. Naval Academy and MS from the Navy Postgraduate. In addition he holds a PhD from the Wharton School at the University of Pennsylvania. He has authored and co-authored of four books and more than 100 published articles. The article appears in a peer-reviewed journal and contains 30 cited references.

**Savitz, E.** (2011, May 25). Data centers: The energy problem. *Forbes.com*, Retrieved from <http://www.forbes.com/sites/ciocentral/2011/05/25/data-centers-the-energy-problem/>

**Abstract.** The article discusses the rising energy use of data centers. It notes the service charges imposed on consumers for the convenience of transacting over the Internet and data centers. According to the article, the high rate of energy use by data centers may boost consumer surcharges for data use. Pike Research's report on cloud computing and energy efficiency showed that data centers consumed 201.8 terrawatt hours (TWh) in 2010, resulting to energy expenditures of 23.3 billion U.S. dollars.

**Summary.** This article focuses on the energy consumption within U.S. datacenters and forecasts future data center growth. The article articulates that high energy costs associated with operating data centers are no longer just an IT problem, but one that affects a global community as data center growth will impact the world's energy resources. CIOs and IT Managers must become more aware of their data center energy use and implement more efficient uses of power within their data centers.

**Credibility.** Eric Savitz is the San Francisco bureau chief at Forbes and has been writing about investing and technology for more than 25 years. This article is written for a

popular audience and articulates a perspective on the energy problem associated with world-wide data center growth.

**Solomon, S., Plattner, G., Knutti, R., & Friedlingstein, P.** (2008). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 106(6), 1704-1709.

**Abstract.** The severity of damaging human-induced climate change depends not only on the magnitude of the change but also on the potential for irreversibility. This paper shows that the climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop. Following cessation of emissions, removal of atmospheric carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years. Among illustrative irreversible impacts that should be expected if atmospheric carbon dioxide concentrations increase from current levels near 385 parts per million by volume (ppmv) to a peak of 450–600 ppmv over the coming century are irreversible dry-season rainfall reductions in several regions comparable to those of the “dust bowl” era and inexorable sea level rise. Thermal expansion of the warming ocean provides a conservative lower limit to irreversible global average sea level rise of at least 0.4–1.0 m if 21st century CO<sub>2</sub> concentrations exceed 600 ppmv and 0.6–1.9 m for peak CO<sub>2</sub> concentrations exceeding  $\approx$ 1,000 ppmv. Additional contributions from glaciers and ice sheet contributions to future sea level rise are uncertain but may equal or exceed several meters over the next millennium or longer.

**Summary.** The article points toward human activity as one reason behind climate change. While the article does not focus on technology or cloud computing, it provides

information that is necessary in order to define carbon emissions and the negative effects of climate change.

**Credibility.** The article is peer reviewed and appears in the Proceedings of the National Academy of Sciences of the United States of America. The Proceedings consists of highly cited research reports, commentaries, and featured articles. Susan Solomon has both a M.S. and PhD in Chemistry from the University of California, Berkeley and is a former scientist at the National Oceanic & Atmospheric Administration. Gian-Kasper Plattner is a member of the Institute of Biogeochemistry and Pollutant Dynamics. Reto Knutti is a member of the Institute for Atmospheric and Climate Science. Pierre Friedlingstein is a member of the Institut Pierre Simon Laplace/Laboratoire des Sciences du Climat et de l'Environnement. The article is scientific in nature, but clear and concise enough for a more general audience. Forty seven references are cited.

### **Theme 3: The Potential for Cloud Computing to Reduce Energy Consumption in the Data Center**

**Abdelsalam, H., Maly, K., Mukkamala, R., Zubair, M., & Kaminsky, D.** (2009). Towards energy efficient change management in a cloud computing environment. In *Proceedings of the 3rd International Conference on Autonomous Infrastructure, Management and Security: Scalability of Networks and Services* (AIMS '09), Ramin Sadre and Aiko Pras (Eds.). Springer-Verlag, Berlin, Heidelberg, 161-166. DOI=10.1007/978-3-642-02627-0\_13 [http://dx.doi.org/10.1007/978-3-642-02627-0\\_13](http://dx.doi.org/10.1007/978-3-642-02627-0_13)

**Abstract.** The continuously increasing cost of managing IT systems has led many companies to outsource their commercial services to external hosting centers. Cloud computing has emerged as one of the enabling technologies that allow such external hosting efficiently. Like any IT environment, a Cloud Computing environment requires high level of maintenance to be able to provide services to its customers. Replacing defective items (hardware/software), applying security patches, or upgrading firmware are just a few examples of the typical maintenance procedures needed in such environments. While taking resources down for maintenance, applying efficient change management techniques is a key factor to the success of the cloud. As energy has become a precious resource, research has been conducted towards devising protocols that minimize energy consumption in IT systems. In this paper, we propose a pro-active energy efficient technique for change management in cloud computing environments. We formulate the management problem into an optimization problem that aims at minimizing the total energy consumption of the cloud. Our proposed approach is pro-active in the sense that it takes prior SLA (Service Level Agreement) requests into account while determining time slots in which changes should take place.

**Summary.** The article describes how to minimize power consumption in cloud computing under a particular set of parameters and service level agreements. The efficiencies introduced in the article use a homogenous server environment, but similar efficiencies can be applied to heterogeneous environments under certain conditions. The article predicts that power management will play an essential role in determining success in cloud computing. The article formulates that minimizing the total energy consumption of the cloud is more of an optimization problem than a management problem.

**Credibility.** Hady AbdelSalam has a BS and MS degrees in Computer Science from Alexandria University. In addition, he has PhD in Computer Science from Old Dominion University. Dr. AbdelSalam has 10 publications in different IEEE and ACM conferences/workshops and 3 IEEE transactions manuscripts. Kurt Maly is former chair of the Computer Science Department at Old Dominion University. He has both a MS and PhD in Computer Science from New York University. Dr. Maly has served as associate editor, Journal for Microcomputer Application Technology. Ravi Mukkamala has a PhD from the University of Iowa and is a current professor at Old Dominion University. Dr. Mukkamala is member of the Association for Computing Machinery and the IEEE and the IEEE Computer Society. Mohammad Zubair is a professor of computer science in Old Dominion University. David Kaminsky is a member of Strategy and Technology division of IBM.

**Berl,A., Gelenbe, E., Di Girolamo, M., Giuliani, G., De Meer, H., Dang, M., & Pentikousis,**

**K.** (2009). Energy-efficient cloud computing. *The Computer Journal*, 53(7), 1045-1051.

**Abstract.** Energy efficiency is increasingly important for future information and communication technologies (ICT), because the increased usage of ICT, together with increasing energy costs and the need to reduce green house gas emissions call for energy-efficient technologies that decrease the overall energy consumption of computation, storage and communications. Cloud computing has recently received considerable attention, as a promising approach for delivering ICT services by improving the utilization of data centre resources.

**Summary.** In principle, cloud computing can be an inherently energy-efficient technology for ICT provided that its potential for significant energy savings that have so

far focused on hardware aspects, can be fully explored with respect to system operation and networking aspects. Thus this paper, in the context of cloud computing, reviews the usage of methods and technologies currently used for energy-efficient operation of computer hardware and network infrastructure. After surveying some of the current best practice and relevant literature in this area, this paper identifies some of the remaining key research challenges that arise when such energy-saving techniques are extended for use in cloud computing environments.

Communications, specifically ICT based communications, is one of the largest consumers of energy. Authors propose that cloud computing with virtualization may be used to identify main sources of energy consumption and determine the trade-off between performance and energy consumption.

**Credibility.** Dr. Andreas Berl is a Chair of the Computer Networks and Computer Communications at the Universität Passau. Erol Gelenbe is the Professor in the Dennis Gabor Chair in the Electrical and Electronic Engineering Department at Imperial College in London. He has a MSc and a PhD from the Polytechnic Institute of New York University and the Docteur-ès-Sciences degree from the University Pierre et Marie Curie. Marco di Girolamo and Giovanni Giuliani are members of the 3HP-European Innovation Centre, HP IIC (Italy Innovation Centre). Dr. Hermann de Meer is a professor at Universität Passau and is the head of the Computer Networks and Communications department. Dang Minh Quan is a member of the School of Information Technology at the International University in Germany. Kostas Pentikousis is a member of VTT Technical Research Center of Finland. The article appears in a peer-reviewed journal and contains 51 cited references.



**Chu, F., Chen, K., & Cheng, C.** (2011). Toward green cloud computing. *ICUIMC '11*

*Proceedings of the 5<sup>th</sup> International Conference on Ubiquitous Information Management and Communication*

**Abstract.** Cloud computing is emerging as a critical information communication technology with the potential to heavily impact our daily life in the future. We systematically analyze its energy consumption based on types of services and obtain the conditions to facilitate green cloud computing to save overall energy consumption in the related information communication systems. With a tremendously increasing number of mobile devices, green mobile communications would be the foundation of green cloud computing.

**Summary.** The article discusses the emergence and growing adoption of cloud computing. The authors analyzed and reported on the issue of energy consumption based on types of services such as email, BitTorrent, and FTP. The article includes discussion of the potential for cloud computing to reduce carbon emissions, as the concept is examined in this study.

**Credibility.** All authors listed on the article are members of the National Taiwan University. Kwang-Cheng Chen has a Bachelor of Science from the National Taiwan University. In addition Chen has a MS and PhD the University of Maryland. Dr. Chen has worked with SSE, COMSAT, IBM Thomas J. Watson Research Center, and National Tsing Hua University, in mobile communications. He is currently the Chairman of the Graduate Institute of Communication Engineering, and Director of Communication Research Center. Chen-Mou Cheng holds a BS from National Taiwan University, MS from the National Taiwan

University, and a PhD from Harvard University. Dr. Cheng is currently the Assistant Professor in the Department of Electrical Engineering at National Taiwan University.

The article is peer reviewed and written in a clear and concise manner, but is not intended for the general public. Some of the terms used within the article are more commonplace in the technology sector, but without definitions challenges for readers may exist. The article contains 10 cited references. The article was accepted at the 2011 International Conference on Ubiquitous Information Management and Communication.

**Hang, Y., Kuo, C., Ahmad, I., & Ming, H.** (2010). *Energy efficiency in data centers and cloud-based multimedia services: An overview and future directions*. Green Computing Conference, 2010 International, 15-18 Aug. 2010, 375-382.

**Abstract.** The expanding scale and density of data centers has made their power consumption an imperative issue. Data center energy management has become of unprecedented importance not only from an economic perspective but also for environment conservation. The recent surge in the popularity of cloud computing for providing rich multimedia services has further necessitated the need to consider energy consumption. Moreover, a recent phenomenon has been the astounding increase in multimedia data traffic over the Internet, which in turn is exerting a new burden on the energy resources. This paper provides a comprehensive overview of the techniques and approaches in the fields of energy efficiency for data centers and large-scale multimedia services. The paper also highlights important challenges in designing and maintaining green data centers and identifies some of the opportunities in offering green streaming service in cloud computing frameworks.

**Summary.** Much of the energy consumed within data centers is wasted on underutilized or idle resources. Considering the rising energy consumption of data centers, more efficient methods are needed to reduce energy consumption. The authors propose energy efficiency in the data center and cloud-based multimedia services including real-time scheduling, storage management, and power provisioning. The authors propose that energy optimization across the cloud is in the early stages.

**Credibility.** Hang Yuan is PhD Student and Research Assistant at the University of Southern California in the Ming Hsieh Department of Electrical Engineering. Ishfaq Ahmad has a BSc in Electrical Engineering from the University of Engineering and Technology. He has both a MS in Computer Engineering and a PhD in Computer Science from Syracuse University. He is currently a professor in the department of Computer Science and Engineering at the University of Texas at Arlington. C.-C. Kuo is currently a professor at the University of Southern California in the Ming Hsieh Department of Electrical Engineering. He holds a PhD from MIT and is a member of SIAM, ACM, and IEEE. Dr. Kuo is also Editor-in-Chief from the Journal of Visual Communication and Image Representation. The article contains 68 cited references.

**Kim, H., Shin, D., Yu, Y., Eom, H., & Yeom, H.** (2010). Towards energy proportional cloud for data processing frameworks. In *Proceedings of the First USENIX conference on Sustainable information technology* (SustainIT'10). USENIX Association, Berkeley, CA, USA, 4-4.

**Abstract.** Energy efficiency in cloud computing is becoming more and more important for IT operators of data centers. Several efforts to use low power machines in the data center level has been explored. Also, data processing frameworks such as MapReduce

and Hadoop are frequently used to process data intensive jobs. However, there has not been an extensive study on the impact of low power computers on such data processing frameworks. Actually, development of low power computers is demanding the architectural paradigm shift for cloud applications. In this paper, we evaluate Apache Hadoop on low power machines and study the feasibility of them in cloud systems. We also propose AnSwEr (Augmentation and Substitution), an energy saving method to reduce energy consumption by introducing low power machines. In An-Swer, augmentation and substitution complement each other to prevent data loss and to improve overall power consumption.

**Summary.** The article deals with the two major foci within the data center: cloud computing and energy efficiency. The authors suggest that some organizations have replaced traditional servers with low power consumption computers, but great opportunities exist for reducing power consumption within the data center. While the authors state that energy efficiency in cloud computing is becoming more important to data center operators, they are more concerned with low power consumption computers within a cloud model for energy efficiency.

**Credibility.** Hyeong Kim has a BS degree in Computer Science and Engineering from Seoul National University. He received his MS and is currently a PhD candidate in the School of Computer Science and Engineering from Seoul National University. Young Jin Yu has a BS and is currently a PhD candidate at Seoul National University.

Hyeonsang Eom is a professor in the School of Computer Science and Engineering at Seoul National University where his technical and research interests include distributed processing and computer/embedded systems, mobile application, and network

performance engineering. Heon Y. Yeom is a professor for the Distributed computing systems Lab in the School of computer Science and Engineering at Seoul Nation University. The article appeared in SustainIT'10 Proceedings of the First USENIX conference on Sustainable information technology. The article contains 31 cited references.

**Kim, K., Beloglazov, A., & Buyya, R.** (2009). Power-aware provisioning of cloud resources for real-time services. *MGC '09 Proceedings of the 7<sup>th</sup> International Workshop on Middleware for Grids, Clouds and e-Science.*

**Abstract.** Reducing energy consumption has been an essential technique for Cloud resources or datacenters (sic), not only for operational cost, but also for system reliability. As Cloud computing becomes emergent for Anything as a Service (XaaS) paradigm, modern real-time Cloud services are also available throughout Cloud computing. In this work, we investigate power-aware provisioning of virtual machines for real-time services. Our approach is (i) to model a real-time service as a real-time virtual machine request; and (ii) to provision virtual machines of datacenters using DVFS (Dynamic Voltage Frequency Scaling) schemes. We propose several schemes to reduce power consumption and show their performance throughout simulation results.

**Summary.** The article correlates the relationship between energy reduction and cloud computing with the data center. The article focuses on virtual machines that are aware of current power consumption as a way to have a direct impact on power reduction.

**Credibility.** Kyong Hoon Kim is member of the Department of Informatics at Gyeongsang National University. Dr. Beloglazov has a PhD in Computer Science from the University of Melbourne where he is a faculty member in the Department of

Engineering and Director of the Cloud Computing and Distributed Systems (CLOUDS) Laboratory at the University of Melbourne. Rajkumar Buyya holds a BE in Computer Science and Engineering from the University of Mysore. In addition, Buyya holds a ME in Computer Science and Engineering from Bangalore University and a PhD in Computer Science and Engineering from Monash University. He is the 2008 recipient of IEEE Computer Society Distinguished Service Award. The article contains 28 cited references and appears in Proceedings of the 7th International Workshop on Middleware for Grids, Clouds and e-Science.

**Mehta, A., Menaria, M., Dangi, S., & Rao, S.** (2011). Energy conservation in cloud infrastructures. *Systems Conference (SysCon), 2011 IEEE International*

**Abstract.** With the growth of cloud computing, large scale data centers have become common in the computing industry, and there has been a significant increase in energy consumption at these data centers. Data centers are often underutilized, suggesting that a significant amount of energy can be conserved by migrating virtual machines (VM) running on underutilized machines to other machines. This paper aims to design such a strategy for energy-efficient cloud data centers. It makes use of historical traffic data from data centers and uses a service request prediction model which enables the identification of the number of active servers required at a given moment, thus making possible the hibernation of underutilized servers. The simulation results indicate that this approach brings about a significant amount of energy conservation.

**Summary.** Cloud vendors face growing energy demands much like their traditional data center counterparts. Energy conservation or energy reduction efforts must also be considered in cloud computing. The authors have designed a service request prediction

model to determine the number active servers required at a given moment and hibernates underutilized servers. The authors propose a very specific scenario for energy reduction in cloud computing.

**Credibility.** Avinash Mehta, Mukesh Menaria, Sanket Dangi and Shrisha Rao are members of the International Institute of Information Technology in India. The article appears in the 5th Annual IEEE International Systems Conference and contains 17 cited references.

**Ricciardi, S., Careglio, D., Santos-Boada, G., Sole-Pareta, J., Fiore, U., & Palmieri, F.**

(2011). Saving energy in data center infrastructures. In *Proceedings of the 2011 First International Conference on Data Compression, Communications and Processing (CCP '11)*. IEEE Computer Society, Washington, DC, USA, 265-270.

DOI=10.1109/CCP.2011.9 <http://dx.doi.org/10.1109/CCP.2011.9>

**Abstract.** At present, data centers consume a considerable percentage of the worldwide produced electrical energy, equivalent to the electrical production of 26 nuclear power plants, and such energy demand is growing at fast pace due to the ever increasing data volumes to be processed, stored and accessed every day in the modern grid and cloud infrastructures. Such energy consumption growth scenario is clearly not sustainable and it is necessary to limit the data center power budget by controlling the absorbed energy while keeping the desired level of service. In this paper, we describe Energy Farm, a data center energy manager that exploits load fluctuations to save as much energy as possible while satisfying quality of service requirements. Energy Farm achieves energy savings by aggregating traffic during low load periods and temporary turning off a subset of computing resources. Energy Farm respects the logical and physical dependencies of the

interconnected devices in the data center and performs automatic shut down even in emergency cases such as temperature peaks and power leakages. Results show that high resource utilization efficiency is possible in data center infrastructures and that huge savings in terms of energy (MWh), emissions (tons of CO<sub>2</sub>) and costs (k) are achievable.

**Summary.** The growing energy demands of data centers are not sustainable. It is important to reduce the energy consumption while maintain service level agreements.

The authors suggest energy reduction in cloud computing by implementing a hibernation or sleep mode for idle virtual servers. Currently all servers are kept powered on regardless of utilization. The authors describe a data center energy manager and propose switching off most servers during off hours. Placing virtual servers in a sleep mode will directly reduce the amount of power being consumed in both traditional data centers and cloud computing models.

**Credibility.** Sergio Ricciardi is a research associate in the Advanced Broadband Communications Center at the Department of Computer Architecture of the Technical University of Catalonia and holds two Masters of Science in Computer Science.

Davide Careglio, Germán Santos-Boada, and Josep Solé-Pareta are members of the Department of d'Arquitectura de Computadors at the Universitat Politècnica de Catalunya in Barcelona Spain. Ugo Fiore is a member of the Centro Servizi Informativi Università di Napoli Federico II in Naples, Italy. Francesco Palmieri is a member of the Dipartimento di Ingegneria dell'Informazione Seconda Università di Napoli in Aversa, Italy. The article appears in the 2011 First International Conference on Data Compression, Communications and Processing and contains 17 cited references.



**Srikantaiah, S., Kansal, A., & Zhao, F.** (2008). Energy aware consolidation for cloud computing. *HotPower'08 Proceedings of the 2008 conference on Power aware computing and systems*, 10-10.

**Abstract.** Virtual machine technology is widely applied to modern data centers for cloud computing as a key technology to realize energy-efficient operation of servers. Server consolidation achieves energy efficiency by enabling multiple instantiations of operating systems (OSes) to run simultaneously on a single physical machine. Live migration of virtual machines can transfer the virtual machine workload from one physical machine to another without interrupting service. However, both technologies have their own performance overheads; there is a tradeoff between the performance and energy efficiency. In this paper, we study the energy efficiency from the performance perspective.

**Summary.** One major cause of energy inefficiency within the data center is due to underutilized servers. Virtualization allows for greater consolidation of environments. The article proposes energy aware server consolidation for energy optimization within a virtual machine based energy-efficient data center architecture for cloud computing and the potential performance overheads caused by server consolidation and live migration of virtual machine technology. Experimental results show that both technologies can effectively implement energy-saving goals with little performance overheads. Efficient consolidation and migration strategies can improve the energy efficiency.

**Credibility.** Shekhar Srikantaiah is a PhD candidate in the Department of Computer Science and Engineering at Pennsylvania State University. Srikantaiah holds a Master of Science in Computer Science from the Indian Institute of Science and a BE in Computer

Science from the National Institute of Technology Karnataka in India. In 2008, he interned at Microsoft Research. Aman Kansal and Feng Zhao are members of Microsoft Research. Microsoft Research is division of Microsoft dedicated to conducting basic and applied research in computer science and software engineering. The article includes nine cited references and appears in a 2008 USENIX conference on power aware computing and systems. USENIX is a technical association that started in 1975 and consists of a community of system administrators, scientists, engineers, and technicians.

**Yuan, H., Kuo, C., & Ahmad, I.** (2010). Energy efficiency in data centers and cloud-based multimedia services: An overview and future directions. In *Proceedings of the International Conference on Green Computing (GREENCOMP '10)*. IEEE Computer Society, Washington, DC, USA, 375-382.

**Abstract.** The expanding scale and density of data centers has made their power consumption an imperative issue. Data center energy management has become of unprecedented importance not only from an economic perspective but also for environment conservation. The recent surge in the popularity of cloud computing for providing rich multimedia services has further necessitated the need to consider energy consumption. Moreover, a recent phenomenon has been the astounding increase in multimedia data traffic over the Internet, which in turn is exerting a new burden on the energy resources.

**Summary.** This paper provides a comprehensive overview of the techniques and approaches in the fields of energy efficiency for data centers and large-scale multimedia services. The paper highlights important challenges in designing and maintaining green data centers and identifies some of the opportunities in offering green streaming service

in cloud computing frameworks. Media-rich Internet services and applications have expanded the scale and density of data centers. Economic and environmental issues have brought about the need for energy efficiency with the data center. While cloud computing has become a hot topic for energy management, the authors suggest that previous work on energy management in data centers lays the ground work for energy-efficient cloud computing.

**Credibility.** Ishfaq Ahmad has a BSc in Electrical Engineering from the University of Engineering and Technology. He has both a MS in Computer Engineering and a PhD in Computer Science from Syracuse University. He is currently a professor in the department of Computer Science and Engineering at the University of Texas at Arlington. C.-C. Kuo is currently a professor at the University of Southern California in the Ming Hsieh Department of Electrical Engineering. He holds a PhD from MIT and is a member of SIAM, ACM, and IEEE. Dr. Kuo is also Editor-in-Chief from the Journal of Visual Communication and Image Representation. Hang Yuan is PhD Student and Research Assistant at the University of Southern California in the Ming Hsieh Department of Electrical Engineering. The article contains 68 cited references. The article appears in the 2010 Green Computing Conference.

#### **Theme 4: The Potential for Cloud Computing to Reduce Carbon Emissions in the Data Center.**

**Buyya, R., Beloglazov, A., & Abawajy, J. (2010) *Energy-efficient management of data center resources for cloud computing: a vision, architectural elements, and open challenges*. In**

Proceedings of the 2010 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA 2010). Las Vegas, USA, July 2010.

**Abstract.** Cloud computing is offering utility-oriented IT services to users worldwide. Based on a pay-as-you-go model, it enables hosting of pervasive applications from consumer, scientific, and business domains. However, data centers hosting Cloud applications consume huge amounts of energy, contributing to high operational costs and carbon footprints to the environment. Therefore, we need Green Cloud computing solutions that can not only save energy for the environment but also reduce operational costs. We focus on the development of dynamic resource provisioning and allocation algorithms that consider the synergy between various data center infrastructures (i.e., the hardware, power units, cooling and software), and holistically work to boost data center energy efficiency and performance. We have validated our approach by conducting a set of rigorous performance evaluation study using the CloudSim toolkit. The results demonstrate that Cloud computing model has immense potential as it offers significant performance gains as regards to response time and cost saving under dynamic workload scenarios.

**Summary.** This paper presents vision, challenges, and architectural elements for energy-efficient management of cloud computing environments. In particular, this paper proposes (a) architectural principles for energy-efficient management of Clouds; (b) energy-efficient resource allocation policies and scheduling algorithms considering quality-of-service expectations, and devices power usage characteristics; and (c) a novel software technology for energy-efficient management of Clouds. The authors simulate a data center of 100 heterogeneous physical nodes along with 290 heterogeneous VMs.

Cloud computing is described as an elastic technology that offers both flexibility in terms of technology and service offerings. The work and simulations of the authors suggest that cloud computing plays a significant role in the reduction of energy consumption costs. Reduction of carbon emissions is derivative of energy reduction.

**Credibility.** Dr. Beloglazov has a PhD in Computer Science from the University of Melbourne where he is a faculty member in the Department of Engineering and Director of the Cloud Computing and Distributed Systems (CLOUDS) Laboratory at the University of Melbourne. Rajkumar Buyya holds a BE in Computer Science and Engineering from the University of Mysore. In addition, Buyya holds a ME in Computer Science and Engineering from Bangalore University and a PhD in Computer Science and Engineering from Monash University. He is the 2008 recipient of IEEE Computer Society Distinguished Service Award. Jemal Abawajy is an Associate Professor in the School of Information Technology at Deakin University. The article offers simulation parameters and graphical representation of the final simulation results. The article contains 34 cited references.

**Doyle, J., O'Mahony, D., & Shorten, R.** (2011). Server selection for carbon emission control. In *Proceedings of the 2nd ACM SIGCOMM workshop on Green networking (GreenNets '11)*. <http://doi.acm.org/10.1145/2018536.2018538>

**Abstract.** Cloud owners are allowing their users to specify the level of resources being used in the different geographical locations that make up the cloud. The carbon emissions caused by powering these resources can vary greatly between different geographical regions. The traffic for a given service can come from anywhere on the planet and the further the request has to travel the greater the negative effect on quality of service (QoS).

It is desirable to route traffic to the resources which causes the lowest carbon emissions but this can affect the QoS. A framework that characterizes this trade-off between carbon emissions and QoS is established in this paper.

**Summary.** The article describes an experiment used to simulate a real-world scenario to monitor and measure both average job time and carbon emissions. An algorithm that attempts to minimize the total cost of the trade-off described is presented. A traffic generator is used to generate load for a server to establish functions, which detail the carbon emissions and QoS of a service. These functions are used to simulate the performance of the algorithm in minimizing the total cost. Results imply that carbon emissions can be reduced with little effect on the QoS under static traffic conditions and favourable energy supply conditions. While the goal of the simulations was to show optimal cost points, carbon emissions could be reduced if a systems Quality of Service (QoS) was adjusted.

**Credibility.** Joseph Doyle is a postdoctoral student at the Trinity College. Donal O'Mahony is Professor of Computer Science at Trinity College where his interest include the cloud computing model and the environmental and energy impact of cloud computing. He is an author of two books including Local Area Networks & their Application and Electronic Payment Systems. He is a senior member of the IEEE. Robert Shorten is a professor at both the National University of Ireland, Maynooth and the Hamilton Institute in Ireland. During a search of the Hamilton Institute Thesis Archive, Professor Shorten is cited on 149 publications. This article comes from the Proceedings of the 2nd ACM SIGCOMM workshop on Green networking. This article is written in a clear and concise manner and contains 17 cited references.

**Harmon, R., & Auseklis, N.** (2009). Sustainable IT services: Assessing the impact of green computing practices. *Management of Engineering & Technology, 2009. PICMET 2009. Portland International Conference on*, 1707-1717.

**Abstract.** Green computing refers to the practice of using computing resources more efficiently while maintaining or increasing overall performance. Sustainable IT services require the integration of green computing practices such as power management, virtualization, improving cooling technology, recycling, electronic waste disposal, and optimization of the IT infrastructure to meet sustainability requirements. This paper provides a review of the literature on sustainable IT, key areas of focus, and identifies a core set of principles to guide sustainable IT service design.

**Summary.** Recent studies have shown that costs of power utilized by IT departments can approach 50% of the overall energy costs for an organization. While there is an expectation that green IT should lower costs and the firm's impact on the environment, there has been far less attention directed at understanding the strategic benefits of sustainable IT services in terms of the creation of customer value, business value and societal value. Energy costs within the data center can account for nearly 50 percent of a company's energy bill and half of their carbon footprint. Cloud computing as well as virtualization can support new and increased application loads while using less power and requiring less physical space. This reduction in power consumption leads to less environmental impact.

**Credibility.** Robert Harmon hold a BS and MBA in finance from California State University, Long Beach. He also holds a PhD in marketing, information systems, and psychology from Arizona State University. Dr Harmon is a professor of Marketing and

Technology Management at Portland State University and currently serves as Director of the Strategic Marketing Area in the School of Business and as a joint faculty member of the Division of Management in the School of Medicine, Oregon Health & Science University. Dr. Harmon has over 20 years of high-technology consulting experience in such fields as software services, e-commerce, and renewable energy. Nora Auseklis is a member of the Engineering Computing Department at Intel. The article contains 52 cited references and appeared in the 2009 Portland International Center of Management of Engineering and Technology (PICMET). PICMET is a non-profit organization that is focused on disseminating information on technology management via an international conference.

**Garg, S., Yeo, C., Anandasivam, A. , & Buyya, R.** (2011). Environment-conscious scheduling of HPC applications on distributed cloud-oriented data centers. *Journal of Parallel and Distributed Computing*, 71(6), 732-749

**Abstract.** The use of High Performance Computing (HPC) in commercial and consumer IT applications is becoming popular. HPC users need the ability to gain rapid and scalable access to high-end computing capabilities. Cloud computing promises to deliver such a computing infrastructure using data centers so that HPC users can access applications and data from a Cloud anywhere in the world on demand and pay based on what they use. However, the growing demand drastically increases the energy consumption of data centers, which has become a critical issue. High energy consumption not only translates to high energy cost which will reduce the profit margin of Cloud providers, but also high carbon emissions which are not environmentally sustainable. Hence, there is an urgent need for energy-efficient solutions that can address the high



increase in the energy consumption from the perspective of not only the Cloud provider, but also from the environment. To address this issue, we propose near-optimal scheduling policies that exploit heterogeneity across multiple data centers for a Cloud provider. We consider a number of energy efficiency factors (such as energy cost, carbon emission rate, workload, and CPU power efficiency).

**Summary.** High energy consumption produces high carbon emissions. The authors propose scheduling policies that are designed to reduce carbon emissions by considering CPU power, workload, energy costs, and carbon emission rates across multiple data centers for a cloud provider. Even though energy efficiency factors can change across different data centers depending on their location, architectural design, and management systems, the carbon/energy based scheduling policies are able to achieve on average up to 25% of energy savings in comparison to profit based scheduling policies leading to higher profit and less carbon emissions.

**Credibility.** Saurabh Kumar Garg currently works in the Computer Science Department as a research fellow at the University of Melbourne. Garg has a Bachelors and Masters degree in Mathematics and Computer science from Indian Institute of Technology. Chee Shin Yeo completed both PhD and Master of Software Systems Engineering in the Department of Computer Science and Software Engineering at The University of Melbourne. In addition, he holds a BSc in Computer and Information Sciences from the School of Computing at National University of Singapore. Arun Anandasivam is a research assistant and PhD student in the Institute of Information Systems and Management at Universität Karlsruhe in Germany. Rajkumar Buyya holds a BE in Computer Science and Engineering from the University of Mysore. In addition,

Buyya holds a ME in Computer Science and Engineering from Bangalore University and a PhD in Computer Science and Engineering from Monash University. He is the 2008 recipient of IEEE Computer Society Distinguished Service Award. The article appears in a peer-reviewed journal and contains 60 cited references.

**Garg, S., Yeo, C., & Buyya, R. (2011).** Green cloud framework for improving carbon efficiency of clouds. *Euro-Par'11 Proceedings of the 17<sup>th</sup> international conference on Parallel processing – Volume Part I*, 491-502.

**Abstract.** The energy efficiency of ICT has become a major issue with the growing demand of Cloud Computing. More and more companies are investing in building large datacenters to host Cloud services. These datacenters not only consume huge amount of energy but are also very complex in the infrastructure itself. Many studies have been proposed to make these datacenter energy efficient using technologies such as virtualization and consolidation. Still, these solutions are mostly cost driven and thus, do not directly address the critical impact on the environmental sustainability in terms of CO2 emissions. Hence, in this work, we propose a user-oriented Cloud architectural framework, i.e. Carbon Aware Green Cloud Architecture, which addresses this environmental problem from the overall usage of Cloud Computing resources. We also present a case study on IaaS providers. Finally, we present future research directions to enable the wholesome carbon efficiency of Cloud Computing.

**Summary.** The authors propose a carbon-aware architecture of cloud computing for reducing carbon footprint in cloud computing without affecting performance and availability. Their experiment analyzes the impact of different configuration with respect

to carbon emission rate and data center power efficiency. Results show that CO<sub>2</sub> emissions can be reduced and addressed using cloud computing.

**Credibility.** Saurabh Kumar Garg currently works in the Computer Science Department as a research fellow at the University of Melbourne. Chee Shin Yeo completed both PhD and Master of Software Systems Engineering in the Department of Computer Science and Software Engineering at The University of Melbourne. In addition, he holds a BSc in Computer and Information Sciences from the School of Computing at National University of Singapore. Garg has a Bachelors and Masters degree in Mathematics and Computer science from Indian Institute of Technology. Rajkumar Buyya holds a BE in Computer Science and Engineering from the University of Mysore. In addition, Buyya holds a ME in Computer Science and Engineering from Bangalore University and a PhD in Computer Science and Engineering from Monash University. He is the 2008 recipient of IEEE Computer Society Distinguished Service Award. The article contains 23 cited references.

**Lee, Y., & Zomaya, A.** (2010). Energy efficient utilization of resources in cloud computing systems. *The Journal of Supercomputing*, 1-13.

**Abstract.** The energy consumption of under-utilized resources, particularly in a cloud environment, accounts for a substantial amount of the actual energy use. Inherently, a resource allocation strategy that takes into account resource utilization would lead to a better energy efficiency; this, in clouds, extends further with virtualization technologies in that tasks can be easily consolidated. Task consolidation is an effective method to increase resource utilization and in turn reduces energy consumption. Recent studies identified that server energy consumption scales linearly with (processor) resource

utilization. This encouraging fact further highlights the significant contribution of task consolidation to the reduction in energy consumption. However, task consolidation can also lead to the freeing up of resources that can sit idling yet still drawing power. There have been some notable efforts to reduce idle power draw, typically by putting computer resources into some form of sleep/power-saving mode. In this paper, we present two energy-conscious task consolidation heuristics, which aim to maximize resource utilization and explicitly take into account both active and idle energy consumption. Our heuristics assign each task to the resource on which the energy consumption for executing the task is explicitly or implicitly minimized without the performance degradation of that task. Based on our experimental results, our heuristics demonstrate their promising energy-saving capability.

**Summary.** The authors describe the cloud, application, and energy model while providing a model designed to show how resource management can provide better system utilization and power consumption. The authors claim that the results of their study should not only provide evidence of a reduction in energy bills for cloud infrastructure, but also a reduction in the carbon footprint.

**Credibility.** Young Choon Lee is a Postdoctoral research fellow for the Centre for Distributed and High Performance Computing at the University of Sydney. Most recently he was the Program Vice-Chair at the International Conference on Cloud and Green Computing in 2011. In addition, he is a member of the IEEE/IEEE Computer Society. The article provides tables listing relative energy savings and graphical support of their experiment. Albert Y. Zomaya is currently the Chair Professor of High Performance Computing & Networking and Australian Research Council Professorial

Fellow in the School of Information Technologies at the University of Sydney. He is also the Director of the Centre for Distributed and High Performance Computing. He has authored or co-authored 16 books and multiple conference proceedings. The article provides models along with graphical representation and figures supporting the parameters and output of the experiment. The article is peer reviewed and contains 24 cited references.

**Lefèvre, L., & Orgerite, A.** (2010). Designing and evaluating an energy efficient cloud. *Journal of Supercomputing*, 51(3), 352-373

**Abstract.** Cloud infrastructures have recently become a center of attention. They can support dynamic operational infrastructures adapted to the requirements of distributed applications. As large-scale distributed systems reach enormous sizes in terms of equipment, the energy consumption issue becomes one of the main challenges for large-scale integration. Like any other large-scale distributed system, Clouds face an increasing demand in energy. In this paper, we explore the energy issue by analyzing how much energy virtualized environments cost. We provide an energy-efficient framework dedicated to Cloud architectures and we validate it through different experimentations on a modern multicore platform. We show on a realistic example that our infrastructure could save 25% of the Cloud nodes' electrical consumption.

**Summary.** Cloud computing and virtualization represent the next-generation data center. Cloud computing allows for provisioning on demand where software, storage, infrastructure, and computing are offered as a service. These scalable technologies allow for greater flexibility and consolidation of environments. The authors analyze the energy

consumed in virtualized environments and provide a real-world example that shows cloud computing can result in significant reductions in energy consumption.

**Credibility.** Laurent Lefèvre is a permanent researcher at INRIA (The French Institute for Research in Computer Science). His research interests include energy efficient computing and networking, grids and clouds, and cluster computing. Lefèvre is a former assistant professor in computer science in Lyon 1 University in France. Anne-Cécile Orgerie is currently a postdoctoral researcher at the Department of Electrical and Electronic Engineering of the University of Melbourne. She holds a PhD from the Laboratoire de l'Informatique du Parallélisme (LIP) in École Normale Supérieure de Lyon in France. The article supports findings with imperial and graphical evidence. Anne-Cécile Orgerie is a founding member of the Technical Subcommittee on Green Communications and Computing, IEEE Communications Society. The article appears in a peer-reviewed journal and contains 18 cited references.

**Liu, L., Wang, H., Liu, X., WenBo, H., QingBo, W., & Chen, Y.** (2009). Greencloud: A new architecture for green data center. *ICAC-INDST '09 Proceedings of the 6<sup>th</sup> international conference industry session on Autonomic computing and communications industry session, 29-38.*

**Abstract.** Power consumption of data centers has a huge impact on the environment. Researchers are seeking to find effective solutions to reduce power consumption in data centers while keeping the desired quality of service or service level objectives. Virtual Machine (VM) technology has been widely applied in data center environments due to its seminal features, including reliability, flexibility, and the ease of management. We present the GreenCloud architecture, which aims to reduce data center power

consumption, while guarantee the performance from users' perspective. GreenCloud architecture enables comprehensive online-monitoring, live virtual machine migration, and VM placement optimization. To verify the efficiency and effectiveness of the proposed architecture, we take an online real-time game, Tremulous, as a VM application. Evaluation results show that we can save up to 27% of the energy when applying GreenCloud architecture.

**Summary.** The authors use an online real-time game as a virtual machine to simulate a practical case for reducing data center power consumption while maintaining service level agreements. The authors use cloud computing to dynamically provision resources in a live migration where a virtual machine is migrated from one physical server to another while both are running. The simulation resulted in a 27% energy reduction while achieving required performance levels.

**Credibility.** Liang Liu, Hao Wang, Xing Jin, QingBo Wang, and Ying Chen are members of IBM China Research Laboratory. Wenbo He is an assistance professor in the School of Computer Science at University of New Mexico. He holds a Master of Electrical Engineering and PhD in Computer Science from the University of Illinois at Urbana-Champaign. Xue Liu is an associate professor in the School of Computer Science and the Department of Electrical and Computer Engineering at McGill University in Montreal, Canada. The article appears in the 6th international conference industry session on Autonomic computing and communications industry session and contains 41 cited references.

**Moghaddam, F., Cheriet, M., & Kim Khoa, N.** (2011). Low carbon virtual private clouds.

*2011 IEEE International Conference. Green Computing Conference, 2010 International, 4-9 July 2011, 259-266.*

**Abstract.** Data center energy efficiency and carbon footprint reduction have attracted a great deal of attention across the world for some years now, and recently more than ever. Live Virtual Machine (VM) migration is a prominent solution for achieving server consolidation in Local Area Network (LAN) environments. With the introduction of live Wide Area Network (WAN) VM migration, however, the challenge of energy efficiency extends from a single data center to a network of data centers. In this paper, intelligent live migration of VMs within a WAN is used as a reallocation tool to minimize the overall carbon footprint of the network. We provide a formulation to calculate carbon footprint and energy consumption for the whole network and its components, which will be helpful for customers of a provider of cleaner energy cloud services. Simulation results show that using the proposed Genetic Algorithm (GA)-based method for live VM migration can significantly reduce the carbon footprint of a cloud network compared to the consolidation of individual data center servers. In addition, the WAN data center consolidation results show that an optimum solution for carbon reduction is not necessarily optimal for energy consumption, and vice versa. Also, the simulation platform was tested under heavy and light VM loads, the results showing the levels of improvement in carbon reduction under different loads.

**Summary.** Data center energy consumption and carbon footprint reduction is gaining attention due to concerns about global warming. The authors measure the carbon footprint of a Virtual Private Cloud and work to minimize the carbon footprint of the



Virtual Private Cloud using a simulation employing virtual machines. The simulation provides evidence suggesting that cloud administrators were able to migrate virtual machines without impacting service level agreements. The simulation provides support for the premise that cloud computing can reduce carbon emissions.

**Credibility.** Fereydoun Farrahi Moghaddam holds a BSc degree in Electronics Engineering from Shahid Bahonar University of Kerman, in Iran. In addition, he holds a MS degree in Electronics Engineering from Khajeh Nasir Toosi University of Technology in Iran. Moghaddam is currently an instructor at Kerman University where his research interests include networking, artificial intelligence, and coding. Mohamed Cheriet holds a Bachelor's of Science in Computer Engineering from Bab Ezzouar University in Algiers and a Doctorate of University of Paris 6 (Paris 6, France). Professor Cheriet has published 70 international journal papers and 135 international conference papers. He has also served as chair of the IEEE's Montreal CIS Chapter and authored 6 books. Kim Khoa Nguyen holds a PhD in Electrical and Computer Engineering from Concordia University in Canada. He also holds an MS and a Bachelor's of Engineering in Computer Science. He is currently a Research Associate at Synchromedia Lab and has authored several publications in networking and telecommunication fields. The article appears in the 2011 IEEE 4th International Conference on Cloud Computing contains 18 cited references.

**Ruth, S.** (2009). Green it – more than a three percent solution? *Internet Computing, IEEE, 13*(4), 74-78.

**Abstract.** IT infrastructure is definitely going green. From significant new regulations for IT equipment disposal to stringent energy-efficiency specifications for PCs and

monitors to national standards for data center power savings, Green IT is an “in” topic. But many problems are unsolved. Information and communications technology (ICT) infrastructure accounts for roughly 3 percent of global electricity usage and the same percentage of greenhouse gasses (GHGs), but it seems to have a far greater role in the green debate than that. Many of the solutions being introduced for reducing the carbon footprint via more efficient energy use worldwide are heavily dependent on IT – for example, improvements in the power grid, “energy-smart” buildings and cities, and so on. Here, the author examines green issues and solutions in IT infrastructure and give a brief history behind green computing

**Summary.** Ruth states that “(ICT) infrastructure accounts for roughly three percent of global electricity usage and the same percentage of greenhouse gasses” (Ruth, 2009).

While regulations concerning IT equipment disposal and energy efficiency have been voluntary introduced by organizations, embracing green computing will continue to increase. ICT only accounts for less than 3% of total green house gas emissions, yet it has the potential to reduce 97.5 percent of emissions in other sectors. Ruth speculates that while concerns of security and reliability surround cloud computing, the potential to impact green IT could be significant.

**Credibility.** Stephen Ruth is Professor of Public Policy at George Mason University, and Director of the International Center for Applied Studies in Information Technology. Ruth has consulted with The U.S. Department of State, National Archives and Records Administration, Price Waterhouse Coopers, and Johns Hopkins School of Public Health. Professor Ruth has a BS from the U.S. Naval Academy and MS from the Navy Postgraduate In addition he holds a PhD from the Wharton School at the University of

Pennsylvania. He has authored and co-authored of four books and more than 100 published articles. The article appears in a peer-reviewed journal and contains 12 cited references.

## **Conclusions**

The information technology sector faces both growing demand for services and increasing energy costs (Doyle, O'Mahony, & Shorten, 2011). The National Institute of Standards and Technology (NIST) (2011) defines cloud computing as a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction (para. 1). Cloud computing, and in particular virtual private clouds (VPCs), has emerged as a method to reduce power consumption and the carbon footprint (Moghaddam, Cheriet, & Kim Khoa, 2011).

### **Cloud Computing and Virtualization**

Cloud computing is inextricably tied to virtualization (Chu, Chen, & Cheng 2011) (see Table 3). Chilamkurti, Zeadally, and Mentiplay state (2009):

Virtualization offers the following advantages: less power, less cooling, less facilities, and less network infrastructure. For example, assume a server room has 1000 servers, 84 network switches, consumes 400 K·W of electricity for ICT equipment, 500 K·W of electricity for cooling and requires 190 square meters of floor space. With virtualization we could typically reduce the number of physical servers. The power required for the ICT equipment would be reduced significantly and power required for cooling will be reduced, and the floor space required will only be about 23 square meters. We note that not only the power required for the servers has reduced but so have the cooling, network infrastructure, and floor space requirements. (2009, p.3)

Virtual Machines (VMs) that encapsulate virtualized services can be moved, copied, created and deleted depending on management decisions (Bert et al., 2009). Consolidating hardware and reducing redundancy can achieve energy efficiency (Bert et al., 2009). “Depending on their utilization, many VMs can run on a single hardware unit (server consolidation) and therefore, less hardware is needed overall, thus reducing energy wasted for cooling, while the deployed hardware utilization increases” (Bert et al., 2009). Beloglazov and Buyya (2010) state “cloud computing naturally leads to energy-efficiency by providing the following characteristics:

- Economy of scale due to elimination of redundancies;
- Improved utilization of the resources;
- Location independence – VMs can be moved to a place where energy is cheaper;
- Scaling up and down – resource usage can be adjusted to current requirements;
- Efficient resource management by the Cloud provider” (2010, p1).

Table 3

*Cloud Computing and Virtualization*

<b>Cloud Computing and its Relation to Virtualization</b>	
<b>Concepts</b>	<b>Citations</b>
<b>Cloud computing:</b> Shared pool of configurable resources that can be quickly provisioned	Beloglazov & Buyya (2010); Chilamkurti, Zeadally & Mentiplay (2009); Ye, Huang, Jiang, Chen, Wu (2010).
<b>Virtualization:</b> Technology that allows multiple virtual machines on a single physical machine	Beloglazov & Buyya (2010); Chilamkurti, Zeadally & Mentiplay (2009); Ye, Huang, Jiang, Chen, Wu (2010).
<b>Virtual machine:</b>	Beloglazov & Buyya (2010); Chilamkurti, Zeadally & Mentiplay (2009); Ye, Huang, Jiang, Chen, Wu

Isolation of operating systems and applications from physical hardware	(2010).
<b>VMWare:</b> Popular commercial tool for creating and managing server and infrastructure virtualization	Beloglazov& Buyya (2010); Chilamkurti, Zeadally & Mentiplay (2009); Ye, Huang, Jiang, Chen, Wu (2010).

**Shifting from the Traditional Data Center Model to Cloud Computing**

IT organizations are moving from traditional data center models to cloud computing for a variety of reasons (Cubitt, Hassan, & Volkmer, 2011) (see Table 4). Some organizations are adopting cloud computing as a means of cost reduction (Gordon, 2011). Data centers that take power consumption and carbon emissions output into consideration will gain popularity as electricity costs continue to increase (Solomon et. al, 2008). While the term *The Cloud* (Savitz, 2011) can encompass multiple technologies such as Software as a Service and Infrastructure as a Service (Koomey, 2008), next generations data centers will focus not only on availability of resources, but also the efficient use of energy resources (Ruth, 2011).

Table 4

*Why Organizations are Moving to the Cloud*

<b>Reasons Organizations are moving from Traditional Data Center Models to Cloud Computing</b>	
<b>Reasons:</b>	<b>Citations</b>
<b>Next generation data centers:</b> Data centers that take power consumption and carbon emissions into consideration	Gordon (2011); Iyer, & Henderson (2010); Ruth (2011)
<b>The Cloud:</b> Popular term for data centers offering on-demand services	Cubitt, Hassan, & Volkmer (2011); Ruth (2011); Savitz (2011); Solomon, Plattner, Knuttic, & Friedlingstein (2008)
<b>Software as a Service (SaaS):</b>	Koomey (2008); Ruth (2011)

On-demand provisioning of software in which applications are hosted	
<b>Infrastructure as a Service (IaaS):</b>  On-demand provisioning of network infrastructure in which network storage, servers, and networking components are hosted	Koomy (2008); Ruth (2011)

**Reducing Energy Consumption in the Data Center**

As energy consumption within the data center continues to rise (Kaplan, Forrest, & Kindler, 2009), some organizations are migrating from traditional data centers to cloud computing (Doyle, O'Mahony, & Shorten, 2011). As energy consumption increases and overall energy availability becomes more scarce, technologies that reduce energy consumption become necessary (Abdelsalam, Maly, Mukkamala, Zubair, & Kaminsky, 2009); Table 5 provides a number of ways in which the cloud can reduce energy consumption.

Table 5

*Cloud computing for reducing energy consumption*

<b>The Potential for Cloud Computing to Reduce Energy Consumption in the Data Center.</b>	
<b>Ways to reduce energy</b>	<b>Citations</b>
<b>Data center energy consumption:</b>  The current electricity consumption of traditional data centers and technologies that can be used to reduce power consumption	Abdelsalam, Maly, Mukkamala, Zubair, & Kaminsky (2009); Berl, Gelenbe, Di Girolamo, Giuliani, De Meer, Dang, & Pentikousis (2009); Chu, Chen, & Cheng (2011); Kim, Shin, Yu, Eom, & Yeom (2010); Kim, Beloglazov, & Buyya (2009)
<b>Green data centers:</b>	Beloglazov & Buyya (2010); Chilamkurti, Zeadally

Data centers that focus on environmentally aware power consumption	& Mentiplay (2009); Ye, Huang, Jiang, Chen, Wu (2010). Srikantaiah, Kansal, & Zhao (2008); Yuan, Kuo, & Ahmad (2010)
<b>Energy efficient data centers:</b> Data centers that attempt to reduce power consumption without negatively impacting	Beloglazov & Buyya (2010); Chilamkurti, Zeadally & Mentiplay (2009); Ye, Huang, Jiang, Chen, Wu (2010); Chu, Chen, & Cheng (2011); Mehta, Menaria, Dangi, & Rao (2011); Ricciardi, Careglio, Santos-Boada, Sole-Pareta, Fiore, & Palmieri (2011); Srikantaiah, Kansal, & Zhao (2008); Yuan, Kuo, & Ahmad (2010)
<b>IT green initiatives:</b> IT projects that take environmental concerns into account	Chu, Chen, & Cheng (2011) Kim, Beloglazov, & Buyya (2009) Ricciardi, Careglio, Santos-Boada, Sole-Pareta, Fiore, & Palmieri (2011); Yuan, Kuo, & Ahmad (2010)
<b>Rising energy costs:</b> Increasing cost of electricity within the data center	Abdelsalam, Maly, Mukkamala, Zubair, & Kaminsky (2009). Berl, Gelenbe, Di Girolamo, Giuliani, De Meer, Dang, & Pentikousis (2009); Chu, Chen, & Cheng (2011); Kim, Shin, Yu, Eom, & Yeom (2010); Kim, Beloglazov, & Buyya (2009) Ricciardi, Careglio, Santos-Boada, Sole-Pareta, Fiore, & Palmieri (2011)

### Reducing Carbon Emissions in the Data Center

Cloud computing can support data center operations with the goal to lower power consumption and reduce carbon emissions (Berl et al., 2009) (see Table 6). Green computing will continue to focus on reducing costs while improving performance within the data center (Harmon & Auskelis, 2009). Reducing power consumption results in an immediate reduction of carbon emission (Moghaddam, Cheriet & Khoa, 2011). IT management is under increasing pressure to consider environmental impacts of IT projects in general (Henriques & Sadorsky, 1999; Ramus & Steger, 2000; Stead & Stead, 1995). Moghaddam, Cheriet and Khoa (2011) state that “carbon footprint reduction is an immediate result of power consumption reduction” (p. 261).

Table 6



*Cloud computing for reducing carbon emissions*

<b>The Potential for Cloud Computing to Reduce Carbon Emissions in the Data Center.</b>	
<b>Ways to reduce carbon emissions</b>	<b>Citations</b>
<b>Data center carbon footprint:</b> Measure and reduce the carbon dioxide output from data centers	Buyya, Beloglazov, & Abawajy (2010); Doyle, O'Mahony, & Shorten (2011); Harmon & Auseklis (2009); Garg, Yeo, & Buyya (2011); Garg, Yeo, & Buyya (2011); Lee, & Zomaya (2010); Lefèvre & Orgerite (2010); Liu, Wang, ,Liu,WenBo, QingBo, & Chen (2009); Moghaddam, Cheriet, & Kim Khoa (2011); Ruth (2009)
<b>Green data centers:</b> Data centers that maximize computer resources to minimize environmental impact	Harmon & Auseklis (2009); Garg, Yeo, & Buyya (2011); Moghaddam, Cheriet, & Kim Khoa (2011); Ruth (2009)
<b>IT green initiatives:</b> IT projects that focus on minimizing environment impact	Harmon & Auseklis (2009); Garg, Yeo, Anandasivam, & Buyya (2011); Lee, & Zomaya (2010); Lefèvre & Orgerite (2010); Liu, Wang, ,Liu,WenBo, QingBo, & Chen (2009); Ruth (2009)

IT leaders are considering technologies that allow them to increase their IT infrastructure and at the same time reduce operational costs (Hang, Kuo & Ahmad, 2010). According to a survey of delegates by Platform Computing at the International Supercomputing Conference (2009), 28 % of IT executives surveyed were planning to deploy a private cloud in 2009 in order to scale their operations and reduce cost (Mainframe Computing, 2009). IT leaders reportedly have various reasons for migrating to cloud computing including the ability to “reduce complexity, minimize costs, and improve organizational agility” (Iyer & Henderson, 2010) as well as provide “scalability, cost, and reliability” (Lefèvre & Orgerie, 2010). As energy costs continue to rise (Abdelsalam et al., 2009), IT leaders may further embrace cloud computing in order to use the technology to efficiently manage resources (Beloglazov & Buyya, 2010). This study focuses on energy efficiencies and carbon footprint reduction; references support the

perspective that cloud computing has a significant potential to do both (Moghaddam, Cheriet & Kim Khoa, 2011).

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