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Review

Green Cloud Computing: A Literature Survey

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Abstract: Cloud computing is a dynamic field of information and communication technologies (ICTs), introducing new challenges for environmental protection. Cloud computing technologies have a variety of application domains, since they offer scalability, are reliable and trustworthy, and offer high performance at relatively low cost. The cloud computing revolution is redesigning modern networking, and offering promising environmental protection prospects as well as economic and technological advantages. These technologies have the potential to improve energy efficiency and to reduce carbon footprints and (e-)waste. These features can transform cloud computing into green cloud computing. In this survey, we review the main achievements of green cloud computing. First, an overview of cloud computing is given. Then, recent studies and developments are summarized, and environmental issues are specifically addressed. Finally, future research directions and open problems regarding green cloud computing are presented. This survey is intended to serve as up-to-date guidance for research with respect to green cloud computing.

Keywords: green cloud computing; green information and communication technologies; environmental protection; sustainability

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1. Introduction

Sustainability has been gaining importance among software and hardware developers and users in the last two decades, due to the rapid growth in energy consumption. The influence of information and communication technologies (ICTs) on the environment throughout the entire life cycle has been studied, in order to promote green and sustainable developments. These can contribute significantly to the improvement of the current condition of the environment by weakening the negative impacts that have intensified during the last decades. There is a great deal of pressure on producers to fall into line with environmental regulations and to develop products and services that minimize negative influences on the ecosystem. In relation to ICTs, the green characteristics of products and services are seen in sustainability-related concepts such as green ICTs, ecological informatics, environmental informatics, sustainable computing, and green computing. According to Hilty et al. [1], the decisions made with regard to the sustainable development of ICTs and the relation between these two fields must consider the positive and negative influences of ICTs on the environment both in the present and in the future. The attractiveness of the technologies has led, in many cases, to the neglect of environmental issues by both the producers and the users. Their degree of maturity, together with pressure from international environmental organizations, has determined a shift towards the use of ICTs in compliance with environmental regulations. It is also clear that there is an interest in monitoring and protecting the ecosystem. Nevertheless, there are some obstacles to developing and implementing certain sustainable strategies in ICTs, such as the associated costs, a lack of the time and interest required to deal with the strategies' challenges, lack of responsibility for environmental impacts, or lack of cooperation between departments within companies (ICT companies and others).

Cloud computing, as a subfield of ICTs, is the subject of studies on the environment. There are arguments and views for and against these technologies. Apart from the interest shown by the providers of cloud-type products and services, there is considerable pressure from governmental organizations to reduce negative effects on the environment.

The development of green cloud computing is closely related to the evolution of green data centers, because the data centers are the core of the cloud computing. According to Koomey [2], the energy consumed by data centers in 2010 represented 1.3% of the total consumption. A report published by GeSI [3], which is considered “one of the most comprehensive and well-recognized snapshots of the Internet’s energy demand at the global level”, estimates an increase in the share of total carbon dioxide (CO_2) emissions from ICTs from 1.3% of global emissions in 2002 to 2.3% in 2020. With cloud computing and energy consumption in mind, a group of researchers at Lawrence Berkeley National Laboratory and Northwestern University created a modeling tool called the Cloud Energy and Emissions Research Model (CLEER). Their model calculates the energy savings from transferring local network software and computing into the server farms. These server farms make up the cloud. The results estimate that the primary energy footprint of email, productivity software and Customer Relationship Management software might be reduced by as much as 87% if all business users in the US shifted to cloud computing [4]. Even if the model does not take into account all the variables, it can prove useful in leading to energetic efficiency in the data centers which belong to Internet companies. It could ensure an increase in energetic transparency and inform consumers to enable them to choose the best offer. The benefits of cloud computing are more significant for environment protection if data centers are built on the green computing principle.

The purpose of this paper is to survey the existing literature on green cloud computing and to identify the key issues that have been researched and applied. The most important contributions of cloud computing to environmental protection are identified in the following sections. This paper does not present new solutions for green cloud computing. Instead, it highlights the interest and efforts of researchers and society in a very important area: sustainable technological evolution. Academic literature is concerned with innovation and always presents the latest discoveries and achievements in the researched field. However, in the field of environmental protection, many actors in society, such as journalists, bloggers, Non-Governmental Organizations (NGOs), human rights defenders and ordinary people, play an important role. For this reason, we choose to present both academic literature and non-academic studies in the field of green cloud computing in this paper.

The rest of the survey is organized as follows. In Section 2 we present a brief overview of cloud computing. In Section 3, we provide a discussion on research methods. In Sections 4 and 5, we present recent developments in green cloud computing in the academic literature. In Section 6, we explore how this field is presented in non-academic studies in reports published, respectively, by ICT companies, NGOs, ICT consulting companies, and other sources. Finally, the future research directions and open problems regarding green cloud computing are given in Section 7, and conclusions are formed in Section 8.

2. Overview of Cloud Computing

Cloud computing has become an important paradigm because it offers dynamic, high-capacity computing capabilities, including access to complex applications and data archiving, without requiring additional computing resources [5]. It uses cloud data centers through virtualization technologies to offer a powerful and adaptable computer environment. The concept, widely promoted and developed, has gained the interest of many organizations, mainly due to the reduction in expenses which could be achieved by diminishing the investment in hardware and software. Cloud computing is “an old idea whose time has (finally) come” [6] (p. 2). Service-Oriented Architecture (SOA), Microservice Architecture, parallel computing, distributed computing and grid computing, virtualization, and containerization are the basic concepts of cloud computing [7]. Some of them are older, such as parallel computing, distributed computing, and virtualization; others are newer, such as SOA, Microservice Architecture, grid computing, or containerization. Cloud computing solutions are extremely dynamic. They are continuously being improved both from the hardware and software perspectives. According to Heininger [8], the following keywords characterize this new ICT provisioning model offered by cloud computing: ubiquitous, service-centric, scalable, consumption-based and self-service. The concept is defined mainly by its characteristics. The National Institute of Standards and Technology (NIST) has presented cloud computing as "a model for enabling ubiquitous, 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" [9] (p. 2). According to Buyya et al. [10] (p. 3) "a cloud is a type of parallel and distributed system consisting of a collection of inter-connected 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". Cloud computing integrates existing technologies and models to optimize the use of physical and logical resources. The resources are treated as services and are available to users according to their requirements. There are three main models: IaaS (Infrastructure as a Service), PaaS (Platform as a Service), and SaaS (Software as a Service). IaaS and PaaS provide services to independent software vendors and developers, while SaaS provides services to end users.

A typology of cloud computing should consider the degree of accessibility it offers so that it can be ranked as private, public, hybrid, and/or community (Figure 1).

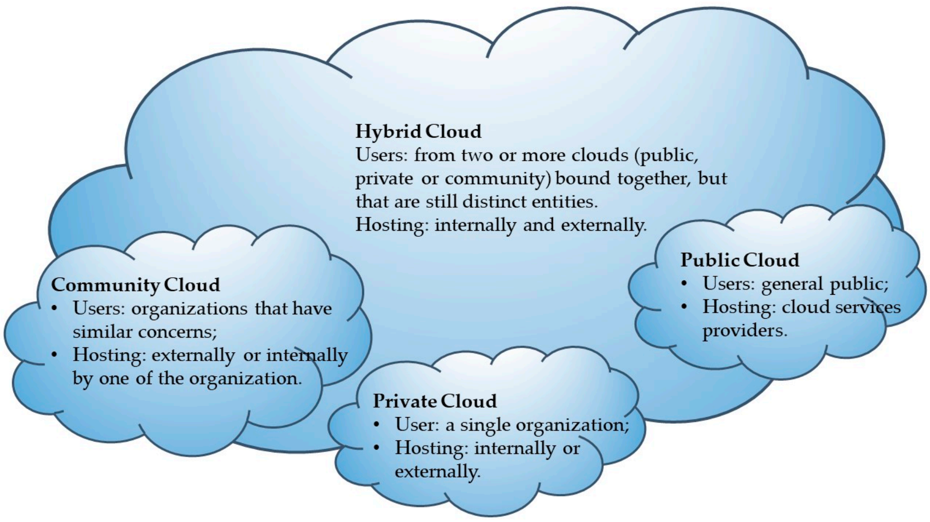

Figure 1. Types of cloud computing.

According to Kliazovich et al. [11] (p. 2) and with regard to the topic of this paper, "from the energy efficiency perspective, a cloud computing data center can be defined as a pool of computing and communication resources organized in the way to transform the received power into computing or data transfer work to satisfy user demands". This definition refers to the energy efficiency of the IaaS model. SaaS also provides benefits for environmental protection: through centralization of processing and service sharing, it consolidates data center operations in order to use less equipment. SaaS providers could offer green software services deployed on green datacenters with less replications or they could use algorithms that improve software energy efficiency without violating Service Level Agreements (SLAs). The cloud providers have more resources and more motivation than individual users have to invest in environmental protection. In the case of PaaS, the providers could offer facilities such as green schedule and green compilers. To help environmental protection through green cloud computing, both SaaS and PaaS providers have methods and tools to achieve software-level energy optimization.

The increase in the popularity of cloud technology was due to the benefits it brought to individual consumers and companies. These benefits include: flexibility, disaster recovery, reduced investment in ICT resources, optimized collaboration between members of an organization, and automatic software updates. Cloud computing is attractive to business owners, due to the possibility of dynamically increasing the resources accessed to match increases in the company's activities. For the environment, the advantages of cloud computing are: better strategies for energy efficiency, and reduced equipment requirements and lower CO_2 emissions, with, consequently, less e-waste [4,11,12].

In order to switch to cloud computing, enterprises might also face the challenges of a change of software/hardware architecture, obstacles to data transfer, and concerns about interoperability [13]. These technologies carry some risks, mainly related to security issues. In spite of this, cloud computing technologies are constantly growing as a result of the major benefits they offer to companies, i.e., access to high-performance computing resources and high-capacity storage together with lower costs. With regard to the influence on the environment, the sections below present in detail the main problems identified in both the academic and the non-academic studies.

3. Research Method

According to Webster and Watson [14], reviewing the literature is important for creating a reliable foundation for advancing knowledge. In order to obtain a sense of the current state of green cloud computing studies, we surveyed both the academic literature and non-academic studies. In the former case, we collected information from conference papers, journal papers, technical reports, and books from multiple scientific databases, including ISI Web of Science, Association for Computing Machinery (ACM) Digital Library, IEEE Computer Science, Scopus, and Science Direct. These databases allow access to leading computer science journals and high-quality peer-reviewed computer science conference publications [15]. The keywords used were "green cloud computing", "sustainable cloud computing" and "sustainable" in combination with "cloud computing". Using these searches, we identified 1922 results (Table 1).

Table 1. Numbers of papers in international databases.

Year	Database				
	Web of Science	ACM Digital Library	IEEE Computer Society	Scopus	Science Direct
2009	7	4	4	8	10
2010	3	4	12	17	19
2011	12	15	21	42	41
2012	22	12	37	70	73
2013	31	12	43	82	83
2014	61	12	51	84	142
2015	65	3	63	84	201
2016	48	16	48	94	266
Total	249	78	279	481	835

For the following steps, we used EndNote. The filtering criteria involved the exclusion of redundant articles, conference reviews, and announcements of conferences or other events. For the rest of the papers we read the title, keywords, and abstracts, and eliminated the papers unrelated to the topic of this research. These exclusion criteria reduced the results to 90 articles that were considered relevant and reasonable for our research. The year 2009 was selected as starting point, since the concept of green cloud computing has attracted the attention of researchers since that year.

For non-academic studies, we analyzed reports published directly by ICT organizations, by ICT consulting companies, NGOs, and other sources. We analyzed these studies and opinions because they strongly influence the attitude towards green cloud computing for a wide variety of users (companies, governmental organizations, and individuals). In some cases, they could better reflect the real impact of technological change, as they can control the market and, implicitly, the new trends. Academic and non-academic research complement each other. The study of both sources offers a complete picture of green cloud computing, which is very important technically and socially.

4. Green Cloud Computing Status and Trends

Interest in studying the influence of cloud computing on the environment is on the rise due to the attention received by green computing from the computing community. It was a reaction to the report published by Gartner [16], which estimated that the global ICT industry accounted for approximately 2% of global CO_2. In 2009, Liu et al. [11] presented GreenCloud a new architecture which aims to decrease data center power consumption. However, the interest in finding methods to decrease energy consumption in data centers is even older, and has intensified since 2009. These studies were very important for green cloud computing evolution. Green data centers—where energy efficiency is maximized and CO_2 emissions and e-waste are minimized, not only for ICT equipment, but for all environmental aspects (building, lightning, cooling, etc.)—are the basis for actual and future green cloud computing. Green computing is not limited to the energy consumption of computer devices. It includes the energy consumption of networks or cooling equipment, but also other environmental issues, such as CO_2 emissions, (e-)waste management, and consumption of natural resources. In this context, researchers' interests have been divided in the subfield of green computing. They began by analyzing the relationship between "sustainability" and "cloud computing". The evolution of this research was determined by the increase in interest in the environment and by the extended use of cloud computing. Figure 2 illustrates the growing interest in green cloud computing in the academic literature between 2009 and 2016, with the single exception of 2013.

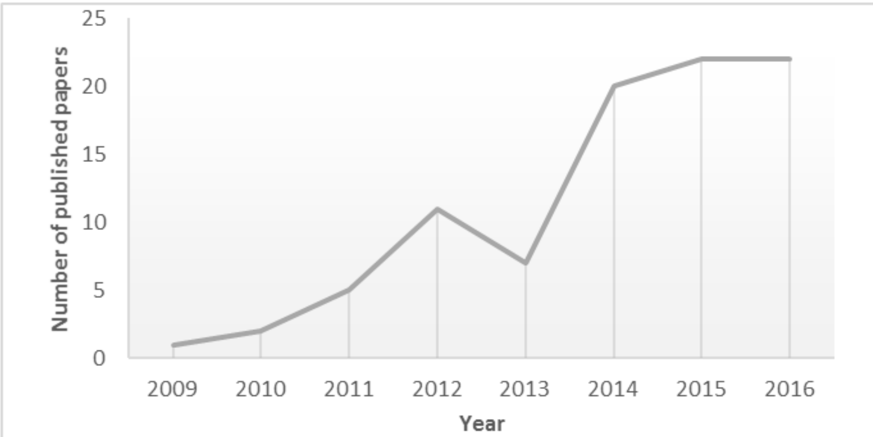

Figure 2. Distribution of surveys over years.

We identified five categories of green cloud computing studies: models and methods, architectures, frameworks, algorithms, and general issues. These studies analyze and propose solutions for the following environmental issues: improving energy efficiency, efficient management of data center resources (hardware and software), reducing operational costs, and reducing carbon emissions. Some authors present their proposals and solutions for two or more environmental issues and some studies could fall into two of the categories mentioned above, e.g., frameworks and algorithms, models and/or methods and architectures or models and/or methods and algorithms.

Table 2 presents the reviewed papers by category and according to the environmental issues addressed. For each paper, we identified the main category and one or more environmental issues for which solutions were proposed.

Efficient resource management will improve cloud computing performance by reducing energy consumption, e-waste, and costs. In green cloud computing, resource management means using heterogeneous and geographically distributed resources to meet clients' requests with the minimum negative effect on the environment. Fortunately, some factors which benefit cloud computing providers also bring benefits for the environment. For example, reducing energy consumption will cut providers' costs, but will also result in reduced CO_2 emissions.

Table 2. Classification of the papers reviewed.

Category	Surveys	Survey Focus			
		Energy Efficiency	Resource Management	Operational Costs	CO_2 Emissions
Algorithms	[17–25]	√	√		
	[26,27]	√			√
	[28–38]	√			
	[39,40]	√		√	
	[41]	√	√	√	
	[42]	√	√	√	
Architectures	[11,43–45]	√	√		
	[12,46–50]	√			
	[51]	√		√	
Frameworks	[52]				√
	[53,54]	√	√		
	[55,56]	√		√	√
	[57]	√		√	
	[58,59]	√			
General Issues	[60–65]	√			
	[66–68]	√			√
	[69]	√	√		
	[70]	√	√		√
	[71]	√		√	
	[72]				√
	[73]	√		√	√
Models & Methods	[74,75]	√	√		√
	[76–80]	√			√
	[81–87]	√	√	√	
	[88]		√		
	[89–98]	√			
	[99–101]				√
	[102]	√		√	√
	[103]	√		√	
	[104]	√			√

The most studied topic is optimization of energy consumption, followed by resource management (Figure 3).

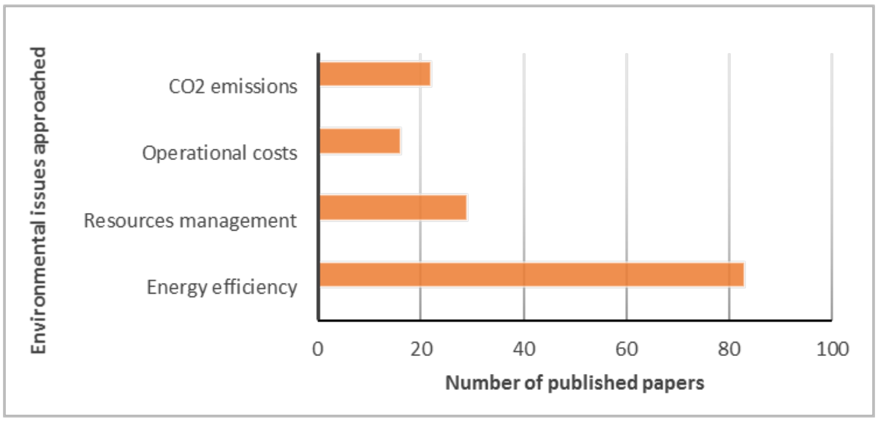

Figure 3. Distribution of surveys on environmental issues between 2009 and 2016.

Figure 4 presents the five categories of green cloud computing studies (models and methods, architectures, frameworks, algorithms, and general issues) identified in the literature review between 2009 and 2016.

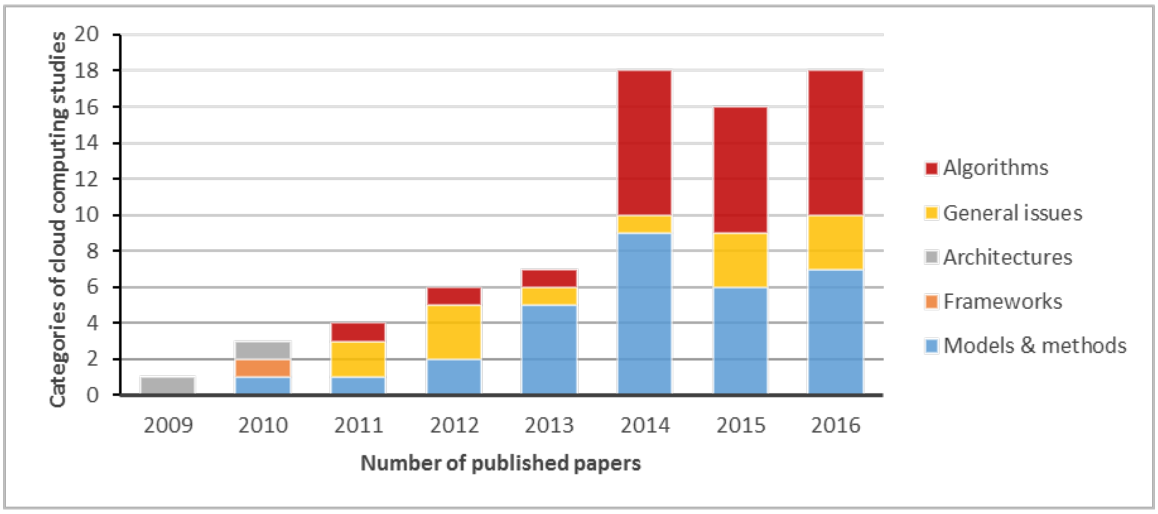

Figure 4. Distribution on categories of green cloud computing surveys.

In the papers on green cloud computing, the authors have proposed new methods and models to optimize resource management or to reduce energy consumption. Algorithms are presented in a substantial number of articles. Other aspects such as metrics, general studies of negative influences on the environment, and the involvement of providers in environmental protection are included in the general issues category.

5. Discussion of the Topics in the Review Articles

The benefits of green cloud computing are focused mainly on energy saving and carbon-footprint reduction. From the energy-efficiency perspective, there are two ways for cloud providers to achieve greener cloud computing: improving the energy efficiency of the cloud, and using clean energy. For cloud users, replacing high-powered computers with low-powered devices will improve energy efficiency. Methods for reducing energy consumption might be simple techniques such as ensuring energy management for servers in the cloud, such as turning them on and off or putting them to sleep [68,79], or more complex techniques such as auto-scaling infrastructure to create greener computing environments [81] or the use of virtualization techniques for better resource management [29,40,43,45,61,78]. Green cloud computing development is influenced by green data center development. In green data centers, the entire infrastructure is designed to achieve maximum energy efficiency with minimum environmental impact. This includes lightning, electrical, mechanical, building, and computer systems. These data centers use low-emission material for buildings, use alternative energy sources, and consume minimal power resources for operations and maintenance for all equipment. Green cloud computing would be much easier to implement if all data centers would have these characteristics.

In order to minimize servers' energy consumption, we identified two main levels of solutions in the academic literature: (1) the server level—minimizing the power consumption of a single server and (2) the data center level—optimizing the power consumption of a pool of servers [50]. For the first level, specific methods and techniques have been proposed for reducing energy consumption at the compiler layer, the operational layer, and the application layer [50,76,90,96,98,100]. These techniques include: powering off parts of the chips, slowing down CPU clock speeds, improving the performance per watt, developing the ability to run in higher-temperature environments, increasing the efficiency of workload management, and powering off parts of the components when they are idle [50,83,85,90]. For the second level, i.e., the case of power consumption in a server pool, the researchers' efforts focused on virtualization techniques. These improve resource utilization, and offer flexibility and reliability.

The optimization of data centers' architectures and energy-aware scheduling may contribute to important energy savings. According to Kliazovich et al. [11], energy-saving solutions attempt to use a minimum set of resources to accomplish the necessary tasks and, hence, to maximize the amount of resources that can be put into sleep mode. They identified three components that consume energy: (a) "computing energy", (b) "communicational energy", and (c) "the energy component related to the physical infrastructure of a data center".

Energy consumption can be improved using software techniques or hardware techniques. According to Jing et al. [90], cloud infrastructure is the most important component (servers, storage, network equipment, lighting, cooling devices, etc.). For hardware optimization, researchers mostly used dynamic voltage frequency scaling (DVFS) techniques [23,30] and power management (DPM) technologies [17,83]. Software technologies for green cloud computing include design methods to improve program efficiency and to use less storage space, and computing modes such as high-performance computing, and distributed and grid computing [49,64,86].

In 2009, a heuristic algorithm based on a virtual machine (VM) dynamic migration technology was proposed to optimize the placement strategy of VMs [12]. The energy consumption of these solutions was 27% less compared with that of the traditional cloud. In the following years, the amount of research in the field of algorithms for cloud resource optimization increased. Shu et al. [39] proposed an algorithm for clonal selection in the cloud, based on time, cost, and energy consumption. Xu et al. [56] realized a management cloud computing framework to minimize energy consumption. Azaiez et al. [20] proposed a genetic algorithm that scheduled customer applications dynamically and, therefore, reduced energy consumption and CO_2 emissions. Other models or frameworks were proposed by Liu et al. [12], Hulkury and Doomun [46], and Guazzone et al. [53]. Scheduling algorithms that efficiently increased resource utilization were proposed by Kolodziej et al. [21], Wu et al. [30], Xu et al. [22], Cao et al. [27], Kaur and Midha [23], Koutsandria et al. [34], Liu and Shu Zhang [24], and Zhang [25].

Thermal management is very important for optimal operation of data centers. It has a significant impact on the environment. In this case, energy savings can be achieved by altering the layout of hardware to optimize the flow of hot and cold air in the data center, by improvements in cold air delivery using an intelligent system controller, or by choosing the geographical locations for data centers such that the outside temperature is less than 13 °C for at least four months of the year [90]. In the GENETiC project, the authors proposed an integrated energy management system that optimized energy consumption by considering the workload of monitoring and control information technology, data center cooling, local power generation, and waste heat recovery [36].

However, sustainable energy has two key components: one is energy efficiency and the other is the use of renewable energy. According to Bateman and Wood [105], cloud computing has "green" credentials as long as it uses renewable sources of energy.

Another major benefit of green cloud computing is reducing carbon footprints [52,55,56,99–102]. The research papers on this aspect of green cloud computing have addressed both users and providers who are interested in using and delivering greener services. According to Garg et al. [52], CO_2 emissions measure the environmental sustainability of cloud computing. They are linked both directly and indirectly with energy consumption [27,72,75]. This issue has been addressed as an effect of improving energy efficiency, rather than as a stand-alone problem. Renewable energy usage will reduce CO_2 emissions. Garg et al. [52] proposed an architecture to reduce the carbon footprint across the entire cloud infrastructure in a unified manner, based on three parameters: CO_2 emission rate, the power efficiency of the data center (the fraction of total power dissipated that is used for information technology resources), and VM efficiency (the amount of power dissipated by a fully active VM running at maximum utilization level). In order to reduce carbon emissions, Wadhwa and Verma [68] proposed a technique for VM allocation and migration in two steps: first, the placement of the VM with a host having the minimum CO_2 emissions from the distribution of data centers and, second, optimization of VM allocation within each data center. Their technique is dedicated to a geographically distributed cloud. For the reduction of carbon emissions at the applications level, Cappiello et al. [100] designed an application controller that allows an improvement in the trade-off between Quality of Service (QoS) and carbon footprint reduction by adopting a strategy appropriate to the specific context. The benefits of cloud computing adoption for small and medium enterprises in terms of reducing energy consumption and carbon emissions were analyzed by Williams et al. [99]. The results indicated that the carbon footprint of the ICT sector could be reduced by 1.7% if 80% of enterprises use cloud computing. The results of studies by companies or others concerned with environmental protection are presented in the following section of this paper.

Reducing operational costs is another important advantage of moving to green cloud computing for both users and providers. For cloud service users, costs will decrease as a result of reduced expenditure on energy and on the necessary infrastructure. For cloud computing providers, using energy-saving techniques and optimal cooling systems can reduce maintenance and operational costs. There is overwhelming evidence that company servers are using only 10 to 30% of their available computing power, and desktop computers have an average capacity utilization of <5% [106,107]. In these circumstances, there are substantial underutilized investments in hardware and software. Less infrastructure is important for the environment since it results in less e-waste generated by the consumers of cloud services [17,42]. To achieve maximum cost-effectiveness, some authors have proposed different approaches to scheduling workloads across servers depending on their cost of operation [81,87,89,96,103].

In cloud computing, the providers are responsible for hardware and software resource management. Business owners and managers can therefore focus less on the technology required to run their business and more on their core business. Technical problems such as upgrading and maintaining servers and data centers are the responsibility of cloud computing providers [107]. E-waste minimization by encouraging equipment recycling and reuse is a basic requirement for green data centers. This is very important for green cloud computing, taking into account the negative opinions related to this issue. According to Robinson [108] (p. 1) "miniaturization and the development of more efficient cloud computing networks, where computing services are delivered over the Internet from remote locations, may offset the increase in e-waste production from global economic-growth and the development of pervasive new technologies". At the same time, moving to cloud computing might reduce the lifetime of the suppliers' equipment as a consequence of the increased amount of information and the speed of data processing. In many cases, a new technology leads to a total or partial replacement of the equipment. Thus, it results in an increase in the amount of e-waste. This is a serious problem for the environment. Factors such as increased cooling requirements, low server utilization rates, or increasing equipment power densities persuade companies to use cloud computing services. Efficient resource management involves maximizing the use of available resources. In green cloud computing, this can be achieved with smart task-assignment algorithms [17,18,22,23]. These algorithms decide where tasks should be placed upon their arrival, depending on the availability of VMs. They must allocate resources to improve resource utilization and to reduce task execution time. In order to achieve this, Liu et al. [24] proposed a green cloning scheduling optimization algorithm using a clonal immune algorithm. If the hardware and software used have different negative environmental influences, the tasks can be scheduled according to the ecological efficiencies of the physical and virtual machines.

Zhang et al. [25], analyzed sustainable resource allocation for green cloud radio access networks powered by renewable energy. He proposed an algorithm to maximize the aggregate user utility and the sustainability of the energy buffer. CyberGuarder is a security assurance architecture for NetApp operating systems designed to address several key security problems in green cloud computing [43]. Frameworks able to automatically and sustainably manage resources for cloud computing and simultaneously achieve a high level of QoS have been proposed by Guazzone [53] and Chaudhry [54].

Models and methods to optimize hardware and software resource allocation for greener clouds have been developed by Dougherty et al. [81], Hussein et al. [83], Luo et al. [84], Rocha and Cardozo [85], Carrega and Repetto [86], and Aswal [87]. They aim to increase energy efficiency and to cut down operational expenses by improving the use of resources.

The benefits of green cloud computing identified in literature are interdependent. The reduction of energy consumption entails lower costs and lower CO_2 emissions. In addition, a reduction in the amount of equipment leads to a cut in energy consumption (with the above-mentioned advantages) and in the quantity of e-waste. The reduction in infrastructure and improvement in energy efficiency can decrease CO_2 emissions in cloud computing [52,63,75,76,86,90]. Apart from the direct effects on the environment, there are also expected to be indirect effects, which can be clearly seen in education, transmission of information to increase environmental awareness, sustainable environmental governance, and better communications for environmental projects and networks.

Other general solutions for achieving green cloud computing identified in the reviewed articles are related to the fact that providers and customers should buy and use the most environmentally friendly ICTs (hardware and software). Cloud computing providers should measure and understand the existing power consumption of servers, their cooling requirements, the power consumption of various applications used by clients, and their influences on the environment. Software used at different levels should facilitate ecological efficiency, and the design solutions should be holistic and should consider all the factors (cooling, memory, network, CPU, etc.) in the scheduling and resource provisioning of software.

6. Green Cloud Computing in Non-Academic Studies

In non-academic studies, both the negative and positive effects of cloud computing on the ecosystem have been studied and highlighted in various moments by different authors and organizations. According to Mines [109], cloud computing infrastructure has two critical elements regarding its influence on the environment: energy efficiency and resource efficiency. According to the same author, cloud computing characteristics bring benefits to environmental protection even when they don't have this scope explicitly. Virtualization and automation software increase energy efficiency and decrease the physical footprint and e-waste. The same activities will be performed with less equipment and less energy consumption both for users and green data centers, due to enhanced resource efficiency. Pay-per-use and self-service encourages users to limit consumption to real needs. Shared resource access allows users (organizations or individuals) to use the same infrastructure and services. This characteristic will decrease the amount of equipment required. Demand for cloud computing services is expected to continue to increase. This will increase the energy consumption and equipment, without the adoption of appropriate measures to protect the environment by cloud computing providers that will make the cloud greener. Figure 5 presents these influences.

In this case, most of the studies concentrate on energy consumption in cloud computing. In a report from Accenture [110], it is claimed that, by energy optimization, CO_2 emissions in cloud computing might be reduced by at least 30%. Another study, undertaken in 2011 by an independent company on several multinational companies that had been using cloud computing for at least two years, estimates that the energy saving for US companies would be more than $12 billion per year. The annual carbon reduction is estimated, in the same study, at 85.7 million metric tons—equivalent of 50% of CO_2 emissions [111].

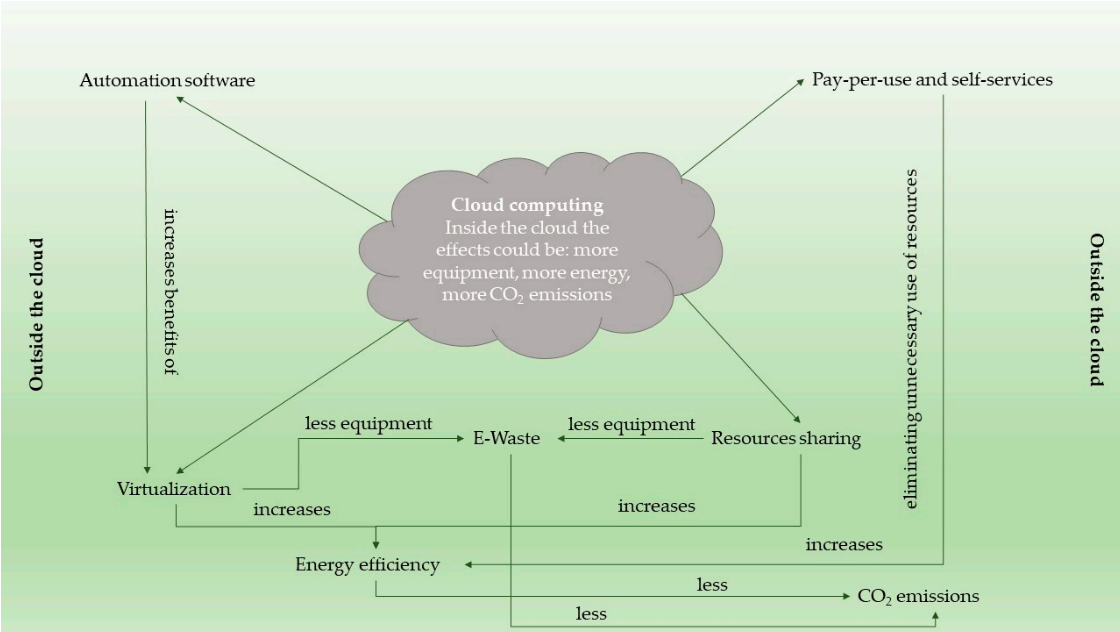

Figure 5. Cloud computing characteristics and their influences on the environment.

The cut in energy consumption and the required hardware is accompanied by reduced CO_2 emissions, as well as reduced (e-)waste. An important role is played by the major cloud companies—Apple, Facebook, Google, Amazon, Microsoft, IBM, Salesforce, etc.—which have committed to use only renewable energy in data centers, and are showing early signs of accomplishing this promise [112]. The amount of clean energy used by these companies has increased significantly in the last few years. Table 3 presents the data collected by Greenpeace in 2012 and 2016 about the energy sources used by some of the big cloud computing providers.

Table 3. Comparison of significant cloud data centers in 2012 and 2016 [113,114].

Cloud Datacenters	Coal		Nuclear		Clean	
	2012	**2016**	**2012**	**2016**	**2012**	**2016**
Amazon	34%	30%	30%	26%	14%	17%
Apple	55%	5%	28%	5%	15%	83%
Facebook	39%	15%	13%	9%	36%	67%
Google	29%	15%	15%	10%	39%	56%
HP	50%	27%	14%	5%	19%	50%
IBM	50%	27%	12%	15%	12%	29%
Microsoft	39%	31%	26%	10%	14%	32%
Oracle	49%	36%	17%	25%	7%	8%
Salesforce	34%	16%	31%	15%	4%	43%

According to Wheeland [115] "the simple business imperative of maximizing profit and minimizing costs is sure to drive cloud providers toward the most efficient computing practices possible, and the side benefits of energy efficient computing in a world of carbon limits and climate legislation makes green IT a necessity from a compliance standpoint as much as an operations standpoint". The power of the servers and their efficiencies are the most important factors for reducing energy consumption. The industry has identified new ways to use servers' total capacity thanks to their virtualization [116]. For this reason, hardware requirements have had a much slower growth than expected.

"Servers have gotten a lot more powerful and efficient, and the industry has figured out ways to utilize more of each server's total capacity, thanks primarily to server virtualization, which enables a single physical server to host many virtual ones." [116] Not all the opinions were favorable to the expansion of the cloud computing phenomenon. A study published by Greenpeace [117] estimated an increase in the intensities of CO_2 emissions and global warming due to the expansion of cloud computing. This could happen only if the organizations will insist on savings from reducing energy consumption rather than on improving the effects on the environment. At present, none of the data centers has proved to be fully green, but they are greener than ever before in their history.

As we have previously mentioned, cloud computing may lend support to environmental protection by reducing the amount of e-waste. By promoting eco-friendly aspects, cloud computing may lead to a reduction in equipment and, consequently, diminished associated negative effects, mainly resulting from the amount of e-waste, but also from CO_2 emissions. The use of cloud computing might contribute to the reduction of e-waste in at least two ways: the cloud computing clients will use less equipment and will reduce the speed of their replacement, and the cloud providers will use the equipment more efficiently due to resources shared between more clients. These changes are important, considering that the amount of e-waste has risen over the years, reaching 49 million tons in 2012 [118]. This represents more than 5% of all municipal solid waste. The contribution to reducing e-waste is still debatable, since the global ICT sector spent about $3.8 trillion in 2015 on devices, services, and data center systems. This is an increase of 2.4% from 2014 [119]. We do not have enough information regarding the actual amount of e-waste generated by cloud computing. It is accepted that a significant amount of e-waste has been transferred from the end user to the cloud providers, which are often located in another country. As can be seen from the non-academic publications, the same real or potential contributions of cloud computing to environmental protection are identified, analyzed, and debated. The merits and demerits are reasonably abundant in this case, and information regarding the real influences of cloud computing on the environment is limited.

7. Challenges and Future Research Directions

Research into environmental protection is a challenge, with winners and losers. All efforts are important and could lead to constructive results. The final winner is the entire society and the next generation. Green ICT is very important in this field, and it is seen as solution and problem for the environment. Green cloud computing is an important component of this field. A significant part of research was focused on cloud computing security [120] and on quality of services. This quality has to include both customer satisfaction [121] and meeting the requirement of environmental protection. The design of a green cloud has two types of challenges: technical and non-technical. Some of the technical aspects related to green cloud computing are software design, virtualization techniques, and thermal-aware management techniques.

Software design is important for green cloud computing. Applications can improve energy efficiency and resource management. The communication between software components has to be efficient. The typology has to be dynamic: resources should be automatically added or removed based on server loading. Some of the open problems are: the dynamic allocation of resources and energy, the reduction of execution costs and time of the tasks, and the reduction of energy consumption.

A VM allocation strategy could reduce energy consumption and expenses. The virtualization techniques could be improved by the migration of workload between machines, along with VM migration, between geographically distributed data centers. The workloads could be concentrated in green cloud data centers. Open problems in this case are: balancing the workload between energy efficient data centers, especially to those based on renewable energy; reducing the number of physical servers but increasing the processing power; increasing the VM size while maintaining or reducing energy consumption.

Thermal-aware management techniques are important for the heating problem in cloud data centers. To solve this problem, the workload schedule has to be performed based on thermal aspects, and the heat recirculation has to be improved. The building of data centers in areas with free cooling resources is a non-technical solution for this problem.

"Non-technical aspects" refers to standards, internal and international regulations regarding the environment, and the internal policies and strategies of the organization. There are two problems in this case: the international regulations are focused on security issues in the cloud, and the international regulations are different across countries. Some of them have adopted and applied strict environmental protection regulations. Others are very permissive in this field—they either do not have regulations, or do not apply them properly. Another non-technical issue is the cost of green cloud computing. These costs are transferred from the cloud providers to the cloud customers, and providers will increase the price of services. The use of renewable energy is a non-technical issue. The intermittency of this energy is a challenge for cloud computing providers and disrupts the conventional methods for planning operations in the cloud. To ensure that SLAs' requirements are respected, the use of a mix of energy sources that complement one another is necessary. Some cloud providers have already built data centers in geographical areas where renewable energy sources are available or may become available during the operational stage.

This paper is not without limitations: The first limitation is that we included only five databases. Others which are very important in the field (such as SpringerLink) were not analyzed in our study. Fortunately, some papers published by these are indexed in researched databases (such as Scopus, ISI Web of Science, ACM Digital Library) and were extracted, filtered, read, and cited in our article. A second limitation is that the paper is a theoretical piece. It does not offer new solutions, technical or non-technical, for green cloud computing. Third, the environmental issues of green cloud computing have been analyzed separately. A holistic management of green cloud computing problems is also necessary to meet specific sustainable development requirements. Future research should be oriented in this direction.

8. Conclusions

Cloud computing is a new model that integrates already-existing technologies in order to increase the efficiency of resource use. The results of using these technologies are varied. The suppliers of such services and the authors of studies undertaken by organizations interested in environmental protection have highlighted both favorable and unfavorable aspects of the effects of cloud computing on the ecosystem. Broadly speaking, cloud computing is likely to favor a harmonious relationship with the environment to the extent to which the ICT equipment producers and the companies supplying services in the field align themselves with environmental policies and agree to the proposals of non-governmental organizations regarding methods of diminishing the negative effects of hardware and software. This paper discusses the contribution of cloud computing to environmental protection according to the studies on this topic undertaken so far. The most important aspects are as follows:

- The main advertised benefits are those which refer to energy efficiency. In order to comply with regulations on environmental protection, the companies which offer cloud services should reduce to a minimum the consumption of energy from non-renewable sources and replace it with renewable energy consumption. The studies undertaken so far have highlighted that the index of clean energy usage is still quite high, outrunning the energy obtained from non-renewable sources.
- An increase in the consumption of energy from renewable sources will lead to lower CO_2 emissions, but considering that the first indicator is not yet accomplished as expected, carbon emission reductions are unlikely to meet the expectations of environmental organizations.
- Minimizing e-waste is another controversial aspect leading to high expectations. The use of cloud computing may influence the reduction in the amount of equipment required by organizations and the speed of replacement. Nevertheless, this is a long-term benefit and it is difficult to estimate if cloud computing will be a solution to this current, controversial, and global issue.

However, the cloud market is constantly growing and, if the current tendency continues, the effects on the system will be seen sometime in the future. Clearly, favorable effects on the ecosystem will be seen if cloud computing suppliers and consumers become fully involved in the issues, as is the case for any policy or strategy which highlights the importance of the environment.

The data collected in this study should help to familiarize readers with the current state of green cloud computing. As a result of the research undertaken, we mention the following aspects, which should be considered by cloud suppliers as well as users if cloud computing is to have a favorable relationship with the environment. (1) Providers of cloud computing services should justify the benefits to organizations in terms of a proper cost–benefit ratio. (2) Cloud technologies should be implemented according to green ICT principles, with the minimum possible negative influences on the environment. (3) Reducing energy consumption, CO_2 emissions, and e-waste should be a priority for the suppliers of cloud services, as well as for consumers when they choose their suppliers. (4) Environmental organizations should make sure that information is clearly available on the influence of cloud technologies on the environment. Specific objective analyses should be performed, aimed at providing data to organizations interested in adopting these technologies. (5) Cloud service suppliers should be aware of all the environmental recommendations in every country and adapt their activities accordingly.

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