Renewable and Sustainable Energy Reviews 69 (2017) 514–526

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Can cloud computing be labeled as "green"? Insights under an environmental accounting perspective

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ARTICLE INFO

Keywords:
Data center
Emergy
Cloud Computing
Green ICT

ABSTRACT

The importance of information and communication technology (ICT) sector on the global energy consumption and CO_2 emissions tend to grow. ICTs have a fundamental role in collaborating for a sustainable development by providing services in an efficient way, however, its own structure should also follow sustainable principles, for instance, by consuming lower energy amount. The quest for sustainability of ICTs has been focused on data centers (DC) optimization through techniques of sharing infra-structures, which would result in energy efficiency increase, carbon footprint reduction, and reduction of e-waste material disposal. In this scenario, the cloud computing technique rises as the most promising one, often receiving the "green" label. However, this label is usually based on electricity consumption reduction and disregards several other important "green" label-related aspects. This work uses emergy accounting (spelled with an "m") and direct energy consumption in calculating indicators of eco-energy efficiency for DC operating under traditional and cloud computing techniques. A traditional decentralized DC and a centralized cloud computing DC are herein considered for illustrating figures and for discussion. Results show that centralized DC is able to provide a virtual machine (VM) by demanding 51% less electricity than decentralized DC, and it consumes 87% less electricity to store a byte. Under an emergy accounting perspective, the centralized DC demands 45% less global resources than the decentralized DC to provide a VM while demanding 85% less global resources to store a byte. Although the assessed indicators point out better eco-energy efficiency performance for the DC using cloud computing techniques, labeling it as "green" could be considered as premature due to a lack of threshold which allows for categorizing a system as "green". Nevertheless, the centralized DC evaluated should be promoted due to its better performance as for the considered indicators.

1. Introduction

Recent energetic crises have resulted in higher awareness of the negative effects of energy waste and their relation with climatic changes, highlighting the importance of sustainability to society, industry, and the academic community [1]. The concepts behind sustainability can be applied to different production systems and scales, from a world strategic energy planning until a life-style for an individual person in a society. Specifically for companies that work on information and communication technology (ICT) issues, efforts aiming to improve their sustainability have been focused on the optimization of data centers (DC) in order to maximize computational resources usage [2]. Such efforts are relevant as DC's are infrastructures that demand high cost for maintenance and high energy consumption ([3–5]). This is especially important as about 30% of the existing servers in a DC are usually named "dead", i.e. they are kept switched on full time, consuming energy under a user-ratio ranging from 5% to 10% of their capacity [6]. This results in energy and material wastage and goes in the countercurrent of sustainability objectives.

Various concepts and technologies have emerged in the search for better efficiency in the use of energy and materials in DC, which is where cloud computing (CC) somehow stands out. According to Madhubala [7], CC is the result from the convergence and evolution of various concepts of virtualization, distributed applications projects, computer grid, and ICT management. Cloud computing attempts to maximize computational resources by sharing an infrastructure among several users. Estimates from Cisco Global Cloud Index [8] point out that 78% of the 2018 workload - including processing and storage – will be concentrated in cloud-operating DC's, including important worldwide energy sectors as oil &$2 gas ([9,10]). Among several

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http://dx.doi.org/10.1016/j.rser.2016.11.153
Received 9 October 2015; Received in revised form 25 August 2016; Accepted 12 November 2016
1364-0321/

potential alternatives focusing on a societal sustainable development, the increase usage of CC as a service provider has receiving special attention due to its advantages in supporting the management of critical areas as energy; an example is provided by Fang et al. [11] that emphasizes the importance of CC to smart grid in improving the preparedness disaster level and its resilience. Simultaneously, regarding its own structure, several advantages in using CC rather a traditional DC is emerged. For instance, Steenhof et al. [12] argue that resorting to CC brings about energetic-environmental benefits, including (i) reduction of wasted computing resources through better matching of server capacity with actual demand, (ii) flattening relative peak loads by serving large numbers of organizations and users in shared infrastructures, (iii) operating servers at optimal utilization rates. These benefits have been discussed by Markovic et al. [13] who point out that CC is more efficient in terms of electricity consumption per service offered than traditional computing. Buyya et al. [3] also state that clouds are projected to be efficient energetic-wise while contributing to the reduction in carbon-print, a result corroborated by Williams et al. [14] who foresee a 4.5 million-ton CO_2 reduction by the time CC reaches at least 80% of the market share in selected global countries. Beloglazov et al. [15] also emphasize that, besides having been projected to reduce operational costs, CC could also reduce impacts on the environment.

Advancements on CC technological and environmental performance have been done during last years, in which according to Fulgare and Bhargav [16], improvements in data centers will happen by focusing mainly on realtime measurement and control, model validation and heuristic based optimization, thermal energy storage and smart-grid capabilities. Shuja et al. [17] summarized studies that assessed the sustainable and green cloud data center paradigm, in which renewable energy usage and waste heat utilization techniques are the mostly used practices. According with these authors, using multiple sustainability techniques leads to a successful green cloud data center model, by reducing energy consumption and carbon footprint. Rong et al. [18] discuss about the possibilities in greening data centers by choosing reasonable site selection (this would reduce up to 15% of total energy consumption), choosing low-power servers and auxiliary energy-saving devices (that would lead to a reduction up to 30% of currently energy usage), and optimizing resources scheduling algorithm and management strategies (that would reduce up to 15% in the energy used). Ebrahimi et al. [19] indicates that absorption cooling and organic Rankine cycle are the most promising technologies for data center waste heat reuse. Zhang et al. [20] state that among the three categories of free cooling systems, the heat pipe system has good energy efficiency and cooling capacity.

Considering that reduction in direct energy consumption and its consequent reduction in CO_2 emissions are aligned with the aims of sustainability and the "green" label [2,5], all these presented CC benefits have been used to support the statement that CC is a technology that contributes to the concepts of green ICT [21]. However, according to Sharma et al. [22], by adopting mechanisms to provide reliability in CC services (i.e. an increase in its size and complexity) usually results in higher energy consumption and carbon footprint, indicating the existence of a trade-off and the need for further efforts in studying this threshold limit. . According to the Murugesan's et al. [23] definition of green computing as "the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems (i.e. monitors, printers, storage devices, and networking and communicating systems) efficiently and effectively, with minimal or no impact on the environment", considering only the direct electricity consumption and its indirect CO_2 emission to label CC as "green" could result in a reductionist approach, since it only considers the operational phase of DC, disregarding the materials and equipment manufacture and disposal phases. This is also recognized by Cramer [24] who discusses the hidden costs of the so-called green ICTs, in which the fallacy of disregarding much of the life-cycle of apparently "green" ICT devices are evaluated. Consumption of any product demands raw materials and energy from the Earth and the inoperable products must be disposed of when reaching their lifespan limit. In this sense, this kind of rebound effect[1] raises doubt about how green a data center might turn out to be by using cloud-computing techniques, i.e. a reduction on direct energy consumption can be obtained, but when viewed under a larger perspective, an energy increase can be observed In this sense, Schnitzer and Ulgiati [25] argue about the need for additional and complementary performance indicators in measuring sustainability of production systems, in which different scales and dimensions are considered by different scientific metrics.

In an attempt to provide scientific-based indicators closely related to the "green" concept, new CC assessment approaches should be used. Among others, (e.g. life cycle assessment, embodied energy analysis, material flow accounting, and so on), the emergy (spelled with an "m") environmental accounting emerges as an alternative. Emergy is the available energy of one kind, previously used up directly and indirectly to produce a service or a good [27]. It is a biophysical evaluation tool focused on a donor's-side view, which considers a holistic and global scale perspective. Supported by the laws of thermodynamics and general systems theory, this methodology aims to quantify all energy and materials flows (from both economy and nature) used in the production of a service or a good, and making it available. The advantage in using emergy accounting rather than directly used energy analysis and/or indirect $CO_{2\text{-eq.}}$ emissions, as it is usually considered to classify CC as "green", is in that emergy recognize the "quality" of energy. In this sense, the evaluation scale is broader and closely related to green computing definition as provided by Murugesan et al. [23].

The aim of this work is to use emergy accounting and direct energy consumption to calculate indicators of eco-efficiency and energy efficiency for DCs to support a critical discussion on the "green" label as usually provided to cloud computing. To illustrate figures and discussion, two equivalent ICT structures are considered as case study: a traditional decentralized DC is compared against a centralized cloud computing DC. Complementarily, insights about using emergy accounting to obtain indicators of sustainability for ICT systems is provided, which could be considered as an important step for emergy practitioners towards future discussions on concepts and calculations when studying this particular system.

2. Method

2.1. Case study description and raw data source

This work considers an important university in Brazil as a case study. In the year 2013, it had 92 thousand enrolled students in its various graduation and post-graduation courses. To support teaching, research and extension activities, the aforementioned university had a data processing complex with close to eighty-six thousand devices, 1,425 from which were web-servers located in 144 small DCs; these numbers emphasizes the importance of this university as a case study object. Every DC was directly linked to one university department, with an individual dedicated staff in charge of management and maintenance. Besides the web-servers, for every DC was provided all other necessary equipment, such as routers and no-breaks, among others, to guarantee the perfect system functioning. This one decentralized ICT infrastructure is referred to, in this paper, as the "Legacy".

Seeking to reduce energy consumption and the broadening of the ICT services to final users, in 2012, the university began implementing a cloud-computing project. This structure is herein referred to as

[1] Improving the efficiency in producing a good will result in a decrease of its effective price and should therefore encourage a consumption increase for that good. In the end, the overall result will indicate that energy and materials savings through initial efficiency reached was offset (or even exceeded) by the higher number of consumed goods [26].

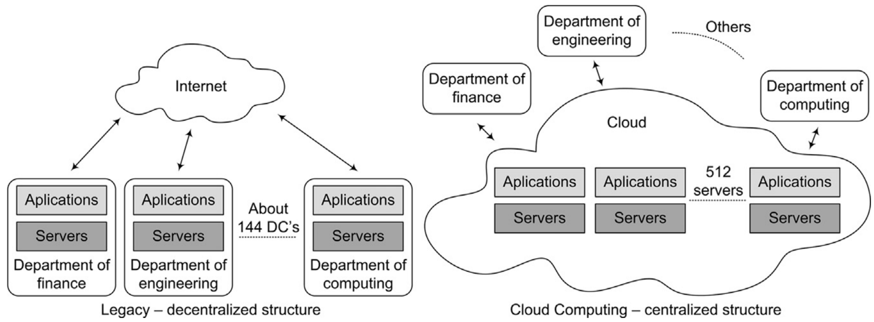

Fig. 1. Illustrative comparison between the legacy and the cloud.

Table 1
Legacy and Cloud main features.

Item	Legacy	Cloud
Number of DC	144	2 (n+1)[a]
Number of physical servers	1425	512
CPU's	6062	1024
Number of colors	12,124	9984
Number of virtual machines[b]	5700	7200
Total memory (in TB)	26	246
Storage (in TB)	2188	10,435

[a] Recursion, indicating that one DC is a backup of the other.
[b] Calculation details on Appendix A.

"Cloud". With an estimated initial budget of fifty million dollars, the goal envisaged by implementing the Cloud was to eliminate all 144 existing small DC's in the Legacy. The whole infrastructure was now to be connected to a single especially structured sector. A comparative schematic between the legacy and the cloud is on Fig. 1. The main features of each infrastructure can be visualized on Table 1.

Raw data for the assessment of both systems were collected *in loco* by means of visits to the site and personal meetings with the management staff. For the Cloud, reports containing part numbers of every piece of equipment were considered and compiled (Appendix B). For the Legacy, due to a secrecy agreement among the university departments, macro-data were obtained from unpublished reports, furnished by the university ICT management staff. Data on energy consumption by the ICT equipment were obtained from technical catalogs, based on manufacturer specifications.

2.2. Environmental accounting using emergy

Emergy approach is able to identify and quantify all energy and materials flows (both those from economy and those considered as freely provided by nature) used by a production system in the making of a good or a service [27]. Emergy can be considered as the energy memory of successive transformation processes from one energy type into another one, in which the starting point is the three main energy sources that drive the geo-biosphere (usually named as Earth emergy budget or emergy baseline): solar insolation, tidal energy, and deep Earth heat. The energy memory concept considered in emergy method is the same as the one considered in the embodied energy analysis [28] – one of the most widely recognized energy assessment approaches – in which the difference is related with the evaluation scale, i.e. the system boundaries or window of attention. In embodied energy analysis, the resource is counted backwards until it reaches its fossil fuel status point (crude oil), whereas emergy method reaches farther still, extending back to the existing natural resources in the geo-biosphere required to make fossil fuel available [29].

The "quality" of energy is acknowledged and could be considered as the main characteristic of emergy accounting as it advocates the existence of an energy hierarchy in the universe, meaning that, while on one hand a huge number of individuals have low influence over the Universe, on the other hand, a few individuals have a higher influence. Every system forms a hierarchical series of energy transformations along which the scale of space and time increases. A large number of small-scale processes contribute to the formation of a small number of large-scale processes, thus, energy is converted from low to high process orders. At every transformation step, available energy is wasted (2nd law of thermo-dynamics) whereas the energy "quality" increases. For example, Brown and Ulgiati [30] argue that a large number of solar energy joules are required for obtaining one Joule of organic matter, a large number of Joules of organic matter are required to obtain one Joule of fossil fuel, several Joules of fossil fuel are required to obtain one Joule of electricity, and so forth. Further definitions, rules and uses of emergy accounting are accessible, mainly in Odum [27].

The emergy method has been used in several different case studies, from the assessment of natural [31], agricultural [32–34], and industrial systems [35] to buildings and cities [36–38], and information [39]. However, emergy studies on ICT are hardly ever found in scientific literature.

Emergy accounting traditionally considers three categories of input flows to a system: (Fig. 2): (i) "R", renewable from the local environment, defined as the resources used at lower rates than their natural replacement cycle; (ii) "N", non-renewable from the local environment, those consumed at a faster rate than their natural replacement time; and (iii) "F", from the economy, which means every resource coming from a larger-scale economy; "F" resources are generally divided into materials and services. Independently of category or unit classification (i.e. energy, mass or currency units), every resource entering the system boundaries is accounted for in a common unit: solar emjoules (seJ). For this to be accomplished, conversion/intensity factors must be applied, which, according to Ulgiati and Brown [40] are generically referred to as Unit Emergy Value (UEV) and express the energy "quality" concept as presented by Odum [41]. All UEVs used in this work are based on a global emergy budget of 15.83 E24 seJ/yr [42] and do not include Labor and Services.

In performing emergy accounting, three main steps are to be respected: (1) Knowing, in detail, the functioning of the system under study and modeling it by using the energy symbols as proposed by Odum [27], presented in Fig. 2. The system boundaries, external energy sources, internal storages, input and output flows, as well as all internal relationships among elements and energy flows must be diagramed accordingly. (2) Classifying as R, N, or F and quantifying all energy flows previously identified and diagramed in the energy model crossing the system boundaries. Biophysical flows must be accounted for in units of energy (J) or mass (kg) preferentially, while monetary flows must be accounted for in currency (USD). Then, all flows are converted into solar emjoules (seJ) by using the UEVs. (3) Finally, calculating emergy indices to support a discussion about the system emergy performance. Fig. 2 provides the traditional indices considered for an emergy accounting.

Differently from other works using emergy environmental accounting to assess alternatives towards sustainability, the indicators used in

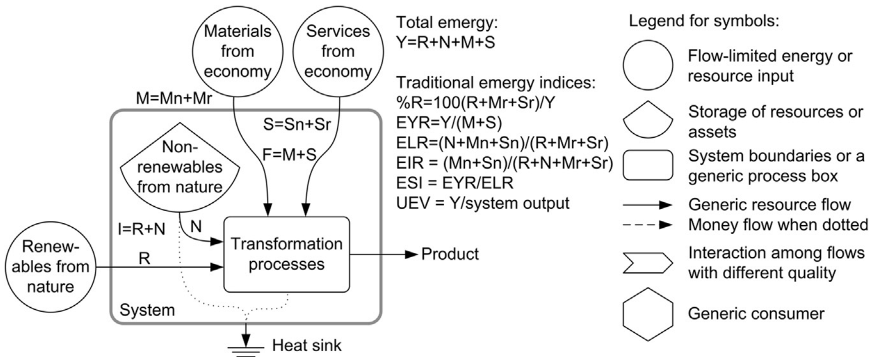

Fig. 2. Generic energy systems diagram. Legend: M = materials; S = services; R = renewable resources from nature; N = Non-renewable resources from nature; I = Total resources from nature; F = Total resources from economy; suffixes "r" and "n" means renewable and non-renewable respectively; %R = renewability; EYR = emergy yield ratio; ELR = environmental loading ratio; EIR = emergy investment ratio; ESI = emergy sustainability index; UEV = unit emergy value.
Adapted from Brown and Ulgiati [30] by considering the emergy symbols available in Odum [27].

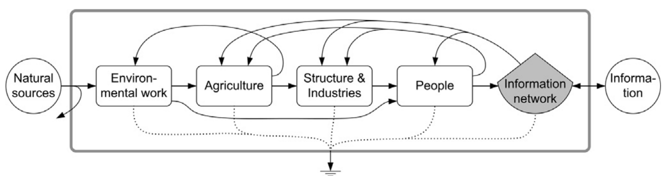

Fig. 3. System diagram separating the hierarchy into units in order of decreasing energy flow and increasing energy "quality" from left to right. The center with concentrated information is on the right.
Adapted from Odum and Odum [43].

this work are not the traditional ones, as described on Fig. 2. Eco-efficiency and energetic efficiency indicators are used herein, a detailed description of which is presented in the sub-items that follow. The option for using different emergy indexes is justified by the fact that the systems assessed here (Legacy and Cloud DCs) are spatially located in the far right extreme of the hierarchical energy scale, distant from natural and agricultural systems (Fig. 3) where "R" and "N" natural resources are abundant and allow for the use of traditional emergy indices. Thus, it is algebraically difficult –not to say impossible, in several cases – to calculate the traditional emergy indices for those types of systems, since they are supported exclusively by resources from the economy.

Rather than being projected, implemented and operationalized aiming its own sustainability, the main function of a DC is usually considered as to receive, store, manipulate, and transmit information. According to Odum [27], the sustainability of transmitted information is much more important than the sustainability of carriers, i.e. the sustainability of DCs – insights about this topic are provided in Section 3.2. of this paper. Thus, a priori, there is no sense in discussing the sustainability of DCs as its main goal is to make the transmission of high quality information possible, which can help society to develop itself and survive within its natural environment for long periods of time. However, the increasing amount of DCs being projected and used due to computational advancements raises concerns about the sustainability of DCs infrastructure that demands material and energy during their life cycle.

2.3. Selecting functional units

Comparing ICT infrastructures is a complex task, especially when the study objects have different purposes. Garg et al. [44] put forward a framework that classifies CC services after analyses of several indicators, such as scalability and service response time. However, such proposition could be not suited for comparisons between systems that are different, such as the ones considered in this work, i.e. CC v.s. traditional DCs. Stiel and Teuteberg [45] point out that, unlike ICT systems, functional units can easily be found in other areas of knowledge, such as the kilowatt/hour (kWh) considered in the evaluation of electricity generation systems, the time unit (hour, minute, etc.) to evaluate flows of any type, or mass (g, kg, etc.) when studying materials, and so on. On the other hand, Ardito and Morisio [46] argue that there are no such specific functional units for ICT, where the most common ones are the Floating Point Operations Per Second (FLOPS) and the Millions of Instructions Per Second (MIPS), both of which do evaluate the computers processing power. Measuring these functional units quantitatively requires the use of specific applications (e.g. the Linpack, which evaluates the performance of a computational system based on linear algebra operations), a difficult task due to access restriction in the DCs studied in this work.

In order to overcome this operational problem, an alternative route is the use of functional units which relate to data storage (i.e., bytes), since they are easily quantified, based on the existing equipment within the ICT structures. Another potential functional unit is the number of virtual machines (VM), defined by Popek and Goldberg [47] as an efficient and isolated replica of a real machine. Despite the fact that VM do not directly represent the processing power of a DC, it expresses the benefit for the user in adopting certain technologies instead of others.

Considering all existing operational barriers in choosing standardized and widely recognized indicators able to assess the energetic-environmental performance of data centers, this work uses bytes and VM as functional units because they are affordable and have an easy-to-understand interpretation.

2.4. Eco-efficiency and energy efficiency indicators

According to the WBCSD [48], eco-efficiency is reached by delivering goods and services at competitive prices, fulfilling human needs, and progressively reducing the impact on the environment. Thus, one can infer that the ratio between the total emergy required (seJ) by the studied systems and the computational services available to users (bytes and VM) meets the above definition of eco-efficiency, as far as the environmental load resulting from providing a resource is concerned (seJ/byte and seJ/VM).

Additionally to the eco-efficiency evaluation, the DCs energetic efficiency is also considered as an important index towards a higher "green" degree. A high level of uncertainty exists in the scientific literature as for calculating the DCs direct electricity consumption. Some efforts have been made towards this, as, for example, the two approaches proposed by Castañé et al. [1]. The first one considers the nominal power of every piece of equipment connected to the system in order to estimate the total consumption in an aggregate fashion – in this case, the maximum energy demand is estimated. The second one consists of using multimeter equipment connected directly into the mother-board of the equipment, so as to measure real-time consumption by every device connected to it. Anyway, there is a lack of a common denominator that will enable for a comparison among DCs, regarding their energy efficiency.

Garg et al. [44] introduce two energy efficiency indexes that can be used for comparisons among DCs. One of them is the Power Usage Effectiveness (PUE), which considers the ratio of the energy consumed by the system (infrastructure + equipment) and the energy consumed by the equipment. The other one is the Data Center Infrastructure Efficiency (DCiE), obtained from dividing the energy consumed by the equipment by the total system energy (infrastructure + equipment). They are both similar and assess the influence of the equipment on the total electricity consumption of a DC, that is, the DCiE is calculated by the expression 1/PUE. Besides being the most acknowledged indicator by the international community working on energy consumption in ICTs, the PUE is currently used by The Green Grid (www.thegreengrid.org) to classify the 500 most efficient DC's regarding direct electricity usage.

In this work, direct electricity consumption is calculated for both DCs studied by using the first method as presented by Castañé et al. [1]. Thus, the calculated value represents the DC maximum consumption, that is, the energy consumed by all machines operating at full capacity. Besides consumption by equipment, the electricity required for cooling was also considered, since it is an item with a large potential for influencing a DC total energy consumption – this explains why large companies are moving their DCs to cold regions [24]. Lighting and other equipment such as fire and humidity controllers are not considered for lack of detailed information, but they are believed to account for but a small percentage of the total electricity consumed in the DC. In order to obtain efficiency indicators that will establish a relationship between input and output, the electricity consumption is divided by the same functional units considered in the eco-efficiency indicators (bytes and VM). Finally, Table 2 presents the eco-efficiency and energetic efficiency indicators used in this work.

The analysis of indicators results is based on the assumption that they all are given the same weight and importance during the decision-making process. An integrated view supported by a radar diagram is considered for results analysis. In order to draw the diagram, all the indicators obtained for Legacy were considered as the reference parameters and their values were set equal to "1". Then, each individual indicator of Cloud was divided by its equivalent Legacy indicator and the obtained ratio diagrammed. The graphical reading shows how much better or worse performance than the Legacy indicator the Cloud indicator has, and which system has the best overall performance by looking at all indicators as a whole. Under the procedure adopted, a smaller area would be interpreted as having a better performance.

Table 2
Description of the functional units, energetic efficiency indicators, and eco-efficiency indicators used in this work.

Index	Description	Category
Functional units		
VM	Virtual Machine. It is the number of virtual machines available to users at every assessed DC. The total amount varies, according to the configuration of each VM and with the resources available at every DC.	Functional unit
Bytes	Bytes. It is the amount of available space for storage of information by the DC.	Functional unit
Eco-efficiency and energetic efficiency indexes		
seJ/VM	Emergy/VM. It is the ratio of the total system emergy (Y) to the number of virtual machines (VM) offered. The lower this index, the higher the efficiency in the use of emergy to provide virtual machines.	Eco-efficiency
seJ/byte	Emergy/byte. It is the ratio of the total system emergy (Y) to the amount of space provided the system (bytes). The lower this value, the higher the efficiency in the use of emergy per storage unit.	Eco-efficiency
kWh/VM	Kilowatt-hour/VM. It is the ratio of the DC electricity consumption (kWh) to the number of the number of virtual machines provided (VM). The lower this value, the higher the efficiency, i.e. lower electricity consumption required to feed virtual machines.	Energetic efficiency
kWh/bytes	Kilowatt-hour/bytes. It is the ratio of the electricity consumption by the DC (kWh) to its storage capacity. The lower this value, the higher the efficiency, i.e. lower electricity consumption per storage unit.	Energetic efficiency

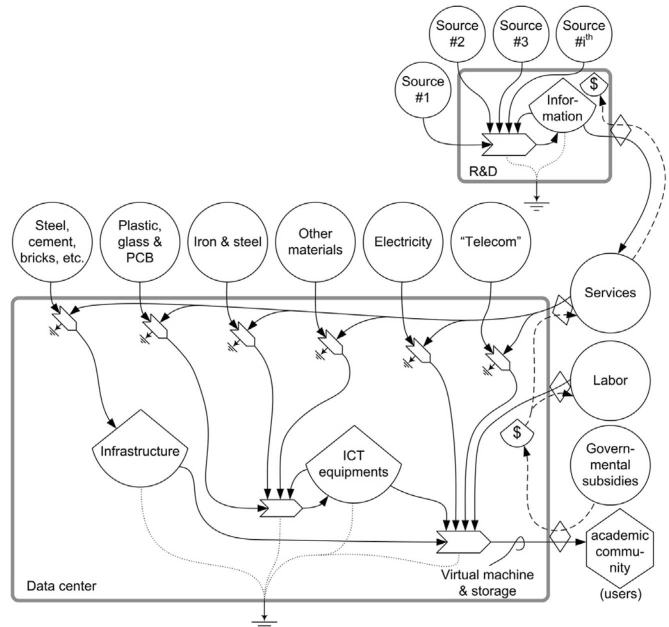

Fig. 4. Energy diagram of the studied Data Center. Upper-right diagram represents the demanded emergy by research and development activities necessary for the Data Center system.

3. Results and discussion

Fig. 4 shows the energy diagram of both studied systems, Legacy and Cloud. Since both systems are conceived for the same purpose (i.e. data processing, storage, and information transmission), the energy and, materials flows crossing the system border are similar, however, in different quantities. The internal elements of the diagram are divided, basically, into two parts: one showing the relations and dependencies of the energy and mass inflows to form an infrastructure stock; the other one representing the ICT equipment stock. While the infrastructure stock requires energy and materials for building construction (including refrigeration and all other facilities) to support and maintain the DCs, the stock of ICT equipment uses other energy and materials to support and maintain the equipment and electronics operating properly. Electricity is a necessary high quality energy input, which interacts with other system inputs, such as Telecom services (i.e. routers and switches) and Labor, and the internal storages of infrastructure and equipment to provide the final users with processing and storage power. The financial support for the acquisition and maintenance of the DCs under study is subsidized by the state and federal governments, and other funding agencies for research, since they belong to a public university. The outputs of the systems studied are the computational storage resources (measured in bytes) and virtual machines made available to academic community use.

Fig. 4 shows a smaller system located outside the main system boundaries, in the upper right position. It represents the relations and emergy demanded to provide the services input to the main system. In this work the approach by Ulgiati and Brown [40] to accounting for Labor and Services inputs was considered, in which the services item is measured in currency and includes all hidden costs related to Labor and Services required to make the primary resource available. In this case, the biophysical amounts of energy and materials crossing the system boundaries are accounted for by using UEVs values excluding Labor & $2 Services, then, the market values of the same system inputs are accounted for as their value in currency. This is a very interesting accounting approach– and its use is increasing among emergy analysts – especially when no information regarding the local/regional production of those primary products is available. Indirectly, the services category also includes the emergy used by ICT companies for Research and Development (R & $2D) of new technologies. A priori, these investments are embedded in the market value of high-tech equipment. In spite of some uncertainties involved in this approach (i.e. since other factors such as profits, brand appeal, consumers' wish, among others, are already accounted for in the cost of a device), it was considered due to a lack of information about high-tech equipment production – this was expected, since industrial secrecy is involved in this highly profitable business.

Tables 3 and 4 show the emergy evaluation of "legacy" and "cloud" respectively. Both tables have been divided into categories that include infrastructure, computers, electronic and telecommunication equipment, operation, and services. Such division allows for a clearer understanding of which category influences most on the total emergy budget. The two last far-right columns in the tables show the influence by each inflow on the system; while the first column indicates the percentage values without including services, the second column includes services and it represents all the emergy used by the system as a whole. Both approaches were considered in this work due to related uncertainties in accounting services as currency (as previously described), thus the reader can interpret results under different views.

When comparing both systems disregarding the services category, one observes that the total Cloud emergy is about 5.02E+18 seJ/yr, a figure about nine times lower than the amount demanded by Legacy (4.40E+19 seJ/yr). When assessing the categories individually, one verifies that both systems behave similarly, as the operation category is the most representative one of the systems, contributing about 98% of the total emergy budget. This category includes the items electricity and labor, the latter representing 93.6% of total emergy for Legacy and 72.5% for Cloud. In absolute values, the labor used by the Cloud is about eleven times lower than the labor used by Legacy (1.07E+06 USD/yr vs. 1.21E+07 USD/yr). These values corroborate one of the advantages of cloud-computing presented by Sultan [56], in that the cost of migration from a traditional infrastructure to the cloud can reduce labor costs since there is less demand for labor in the Cloud. Electricity is the second most representative item of all in both systems

Table 3
Emergy evaluation table of "Legacy" data center.

Item	Category and description	Unit/yr	Amount[a]	UEV[b] (seJ/Unit)	Reference for UEV	Emergy[c] (seJ/yr)	Emergy without services (%)	Emergy with services (%)
Infrastructure								
1	Lime	g	7.98E+05	1.68E+09	[27]	1.34E+15	& $2lt;1	& $2lt;1
2	Cement	g	1.15E+07	3.04E+09	[49]	3.50E+16	& $2lt;1	& $2lt;1
3	Crushed stone	g	2.66E+07	1.68E+09	[27]	4.48E+16	& $2lt;1	& $2lt;1
4	Sand	g	3.70E+07	1.68E+09	[27]	6.21E+16	& $2lt;1	& $2lt;1
5	Brick	g	1.23E+07	3.36E+09	[27]	4.14E+16	& $2lt;1	& $2lt;1
6	Steel	g	8.72E+06	3.16E+09	[50]	2.76E+16	& $2lt;1	& $2lt;1
Computers								
7	Computer	g	6.56E+06	8.90E+10	[51]	5.83E+17	1.3	1.1
Electronics								
8	Plastic	g	3.61E+05	9.68E+09	[52]	3.50E+15	& $2lt;1	& $2lt;1
9	Steel	g	5.18E+05	3.16E+09	[50]	1.64E+15	& $2lt;1	& $2lt;1
10	Glass	g	4.81E+04	2.77E+07	[42]	1.33E+12	& $2lt;1	& $2lt;1
11	Copper	g	3.61E+04	3.00E+09	[53]	1.08E+14	& $2lt;1	& $2lt;1
12	Circuit board	g	2.41E+05	3.00E+09	[54]	7.22E+14	& $2lt;1	& $2lt;1
Telecommunications								
13	Plastic	g	1.96E+05	9.68E+09	[52]	1.89E+15	& $2lt;1	& $2lt;1
14	Steel	g	3.44E+04	3.16E+09	[50]	1.09E+14	& $2lt;1	& $2lt;1
15	Copper	g	1.85E+04	3.00E+09	[53]	5.55E+13	& $2lt;1	& $2lt;1
16	Circuit board	g	1.59E+04	3.00E+09	[54]	4.76E+13	& $2lt;1	& $2lt;1
Others								
17	Steel rack	g	4.58E+06	3.16E+09	[50]	1.45E+16	& $2lt;1	& $2lt;1
Operation								
18	Electricity	J	3.39E+13	5.87E+04	[54]	1.99E+18	4.5	3.8
19	Labor	USD	1.21E+07	3.40E+12	[55]	4.12E+19	93.6	79.7
Emergy without Services =						4.40E+19	100.0	–
Services								
20	Infrastructure[d]	USD	4.71E+04	3.40E+12	[55]	1.60E+17	–	& $2lt; 1
21	Equipments[e]	USD	1.28E+06	3.40E+12	[55]	4.35E+18	–	8.4
22	Electricity[f]	USD	9.41E+05	3.40E+12	[55]	3.20E+18	–	6.2
Emergy with Services =						5.17E+19	–	100.0

[a] Raw data available at Appendix C
[b] All UEVs are based on a global emergy budget of 15.83E+24 seJ/yr [42] and do not include Labor and Services
[c] Emergy (seJ/yr) = Amount (Unit/yr) * UEV (seJ/Unit)
[d] It includes items 1–6
[e] It includes items 7–17 (Computers, Electronics, Telecommunication and Others)
[f] It includes item 18

Table 4
Emergy evaluation table of "Cloud" data center.

Item	Category and description	Unit/yr	Amount[a]	UEV[b] (seJ/Unit)	Reference for UEV	Emergy[c] (seJ/yr)	Emergy without services (%)	Emergy with services (%)
Infrastructure								
1	Lime	g	9.85E+04	1.68E+09	[27]	1.65E+14	& $2lt;1	& $2lt;1
2	Cement	g	1.42E+06	3.04E+09	[49]	4.32E+15	& $2lt;1	& $2lt;1
3	Crushed stone	g	3.29E+06	1.68E+09	[27]	5.52E+15	& $2lt;1	& $2lt;1
4	Sand	g	4.56E+06	1.68E+09	[27]	7.66E+15	& $2lt;1	& $2lt;1
5	Brick	g	1.52E+06	3.36E+09	[27]	5.11E+15	& $2lt;1	& $2lt;1
6	Steel	g	1.08E+05	3.16E+09	[50]	3.40E+14	& $2lt;1	& $2lt;1
Computers								
7	Blade Server200/230	g	8.36E+05	8.90E+10	[51]	7.44E+16	1.5	& $2lt;1
Electronics								
8	Plastic	g	7.80E+05	9.68E+09	[52]	7.55E+15	& $2lt;1	& $2lt;1
9	Steel	g	1.12E+06	3.16E+09	[50]	3.53E+15	& $2lt;1	& $2lt;1
10	Glass	g	1.04E+05	2.77E+07	[42]	2.88E+12	& $2lt;1	& $2lt;1
11	Copper	g	7.80E+04	3.00E+09	[53]	2.34E+14	& $2lt;1	& $2lt;1
12	Circuit board	g	5.20E+05	3.00E+09	[54]	1.56E+15	& $2lt;1	& $2lt;1
Telecommunications								
13	Plastic	g	1.79E+05	9.68E+09	[52]	1.73E+15	& $2lt;1	& $2lt;1
14	Steel	g	3.14E+04	3.16E+09	[50]	9.92E+13	& $2lt;1	& $2lt;1
15	Copper	g	1.69E+04	3.00E+09	[53]	5.07E+13	& $2lt;1	& $2lt;1
16	Circuit board	g	1.45E+04	3.00E+09	[54]	4.35E+13	& $2lt;1	& $2lt;1
Others								
17	Steel rack	g	2.80E+06	3.16E+09	[50]	8.86E+15	& $2lt;1	& $2lt;1
Operation								
18	Electricity	J	2.14E+13	5.87E+04	[54]	1.26E+18	25.1	3.5
19	Labor	USD	1.07E+06	3.40E+12	[55]	3.64E+18	72.5	10.1
Emergy without Services =						5.02E+18	100.0	–
Services								
20	Infrastructure[d]	USD	5.81E+03	3.40E+12	[55]	1.97E+16	–	& $2lt;1
21	Equipments[e]	USD	8.49E+06	3.40E+12	[55]	2.89E+19	–	80.3
22	Electricity[f]	USD	5.96E+05	3.40E+12	[55]	2.03E+18	–	5.6
Emergy with Services =						3.59E+19	–	100.0

[a] Raw data available at Appendix D.
[b] All UEVs are based on a global emergy budget of 15.83E+24 seJ/yr [42] and do not include Labor and Services.
[c] Emergy (seJ/yr)=Amount (Unit/yr)*UEV (seJ/Unit).
[d] It includes items 1–6.
[e] It includes items 7–17 (Computers, Electronics, Telecommunication and Others).
[f] It includes item 18.

(4.5% in Legacy and 25.1% in Cloud) in relation to the total emergy. The 4.5% obtained for Cloud could be considered as high, but its electricity consumption – in absolute units, i.e. J/yr – is about 37% lower than that of Legacy (2.14E+13 J/yr vs. 3.39E+13 J/yr). This result corroborates the studies of Accenture [57], by which cloud-computing can reduce direct energy consumption by 30–90% compared to traditional computing. All other categories show similar behavior, contributing around 2% to the total emergy of both systems, a negligible value as compared to the Operation category values, which includes electricity and labor items.

In an evaluation considering the services category, an increase in the total emergy of both systems is observed (5.17E+19 seJ/yr for Legacy and 3.59E+19 seJ/yr for Cloud), the sevenfold increase in the Cloud emergy being expressive, as compared to the 1.2 times increase for the Legacy emergy. The Cloud formerly demanded about 9 times less emergy than Legacy, however, in this new scenario, the difference is 1.4 times smaller, indicating the influence of the services category over the total Cloud emergy. When analyzing the behavior of the categories, one observes that the operation category continues to be the most representative one as for the Legacy, reaching 83% of its total emergy. However, a different behavior is noticeable in the Cloud, as the Services category is now the most representative of total emergy, reaching 87%. The operation category, which formerly represented about 98% of the total Cloud emergy, now represents around 14%. When assessing the items that integrate the Services category of Cloud, the huge impact of its acquisition costs can be observed (computers, electronics, telecommunications and others) which represents about 80% of the total system emergy. In absolute numbers, such figure is about seven times the money invested in the Legacy (8.49 vs. 1.28 million USD). This suggests that, under the approach considered in this work, the Cloud indirectly requires higher investments than Legacy in R & $2D to provide high-technology equipment, or even that market values of the existing equipment in the Cloud are overestimated, due to the existing subjectivity in the willing-to-pay quantitative metric. The remaining categories contribute with less than 1% of total emergy, therefore their behavior remains unchanged, regardless of considering or not considering the Services category. It is worth it pointing out that, should the Services category be measured under currency units by a willing-to-pay approach, these figures can change over time as a result of economy-related circumstances. This emphasizes the importance of making and presenting both calculations, i.e. considering and not considering the category Services.

3.1. Eco-efficiency and energy efficiency indicators

Figs. 5 and 6 present the graphic comparison between the assessed systems considering the total emergy, energy efficiency, and eco-efficiency indicators. As for total emergy (seJ/yr), the Cloud indicates

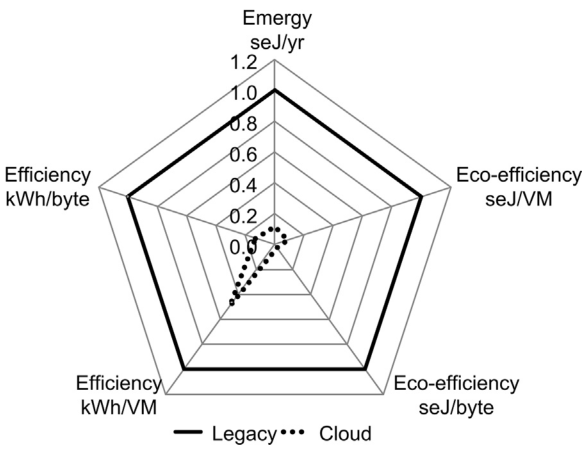

Fig. 5. Comparison between the Legacy and Cloud, disregarding the Services category.

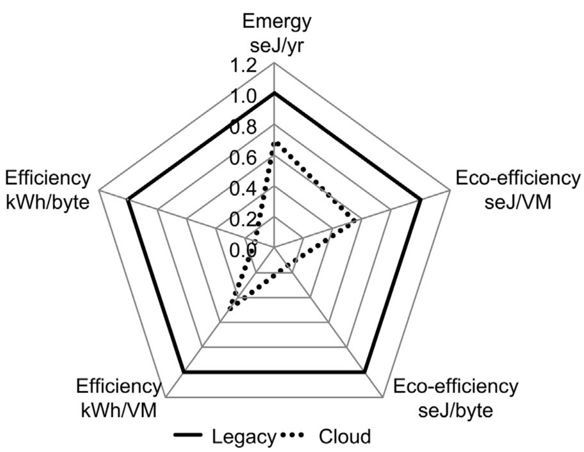

Fig. 6. Comparison between the Legacy and Cloud considering the Services category.

better performance than Legacy by both approaches: disregarding and considering the category Services. When disregarding Services, the Cloud demands about 89% less emergy than Legacy, whereas with Services included, this percentage reduces to 31%. The comparison between the structures considering the emergy demand indicates which system lays a heavier burden on the environment by consuming higher amounts of energy and materials in a global scale, under a donor's perspective – disregarding information input and the renewability rate of each system input. However, as stated by Murugesan et al. [23], evaluating green computing should also consider the systems output, i.e. the virtual machines and bytes functional units adopted in this work. This is fundamental when assessing efficiency – which, by definition, is a ratio of systems inputs and outputs –, since one system could demand a higher amount of inputs, which potentially indicates worse performance, while producing a higher amount of outputs, which could eventually increase the overall efficiency. Due to this, the efficiency indicators are also taken into account in supporting discussions about how green the studied systems are.

As for the eco-efficiency indicator (seJ/VM), setting up a VM in Cloud takes 91% less emergy than doing likewise in Legacy (Fig. 5). This figure changes when considering the Services category (Fig. 6), as a VM available in the Cloud still shows better performance, but now demanding 45% less emergy rather than 91%. The same behavior was observed when considering the eco-efficiency in seJ/byte: the Cloud demands 98% less emergy than Legacy to store 1 byte of information when disregarding the Services category, and 85% less emergy when Services are accounted for.

Regarding the energy efficiency indicators, Fig. 5 shows that 1 VM provided by Cloud demands 51% less energy than Legacy when the category Services is disregarded in the calculation. To store 1 byte, the Cloud's energy efficiency is even higher since it requires about 87% less emergy than the Legacy does. Fig. 6 shows that numbers are maintained when including the Services category. This behavior is observable because the energy efficiency analysis, performed the way it was in this work, does not consider the Services category the way it is considered in emergy accounting; only direct kWh of electricity usage during the operation phase is considered in the energy efficiency evaluation.

Numbers show that, regardless of Services category being considered in the calculations or not, the Cloud is better energy-efficiency and eco-efficiency-wise than Legacy as for the two functional units considered in this work (VM and bytes). These results corroborate Steenhof et al. [12], Markovic et al. [13], and Williams et al. [14] statements that a series of benefits to the environment (i,e., the efficient use of computational resources and energy consumption reduction) result from operating a DC based on cloud computing techniques, in lieu of a traditional DC.

Even considering all favorable indicators calculated for the Cloud studied in this work, labeling it as green could be considered as premature. The main issue here concerns a lack of a threshold indicating what can and what cannot be considered as green. The definition by Murugesan et al. [23] of what green computing is – please, see the Introduction section - can be useful at directing strategies towards energy and materials reduction usage under the life cycle of equipments, but it is still subjective, whereas quantitative values are needed in the evaluation. In this sense, the Cloud studied in this work could be considered as greener than Legacy. This is especially true because of the lower environmental cost per virtual machine provided and per byte stored. These results meet Marston et al. [58] findings, by which the efficient use of computational resources is one of the ideas within the concept of Green ICT. In order to further strengthen the argumentation that Cloud is greener than Legacy, it is suggested: (i) to include equipment disposal of each DC; (ii) to include the indirect energy consumed, besides the direct energy consumed to provide the existing equipment in the DCs; (iii) to consider other functional units so a multicriteria evaluation can be performed.

3.2. Complementary insights regarding the sustainability of information systems evaluated under emergy accounting

The main difficulty faced while developing this study relates to the use of the traditional emergy accounting indicators, which evaluate the sustainability of the studied systems and, consequently, how green they are. For instance, the renewability index (%R) and the environmental sustainability index (ESI) are taken as the most representative ones; for more details please see Odum [27] and Brown and Ulgiati [30]. Both indexes can be used to evaluate the sustainability of anthropic systems, since natural systems are sustainable by definition. To calculate these indexes, emergy flows are used when comparing the use of renewable natural resources to the use of non-renewable ones, the use of economy resources to the use of environmental resources, and so forth. A priori, these indicators could be considered as more appropriate for evidencing which Data Center could be considered the greenest, since %R and ESI consider a donor's side perspective of energy quality instead of a receiver's side. Furthermore, these indicators are calculated under a global scale view, which is recognized as an important approach by Murugesan et al. [23] when defining green computing. However, operationally speaking, calculating %R and ESI for the Data Centers studied in this work was not possible, since they are systems located in the extreme right side of a hierarchical energy chain (Fig. 3), therefore they do not use natural resources directly; instead, they are basically dependent on resources from the economy.

An alternative would be to include partial renewability of each input going into the evaluated data center systems; such approach has been proposed by Tiezzi and Marchettini [59], and further assessed by

Ortega et al. [60], Ulgiati et al. [61], Agostinho et al. [32], Agostinho and Ortega [62,63], Ulgiati and Brown [40], among others. However, although this approach can be used in emergy accounting of several different systems such as agriculture, industry, and even urban systems, its use in information systems such as the ones studied herein is rarely found in literature. This is so because the partial renewability of the inputs going into the information systems is negligible, as the renewability fraction of inputs was reduced when transferred from the far left side beginning systems of a hierarchical energy chain to the far right side information system (Fig. 3).

At this point, the following question emerges: considering that emergy accounting is a powerful tool in evaluating systems sustainability (or how green the system is), how can emergy accounting be used to evaluate the sustainability of systems located farther to the right side of the energy hierarchical chain? Eco-efficiency indicators based on emergy accounting were considered in this work, rather than the traditional emergy sustainability indicators. This is due to the methodological difficulties mentioned earlier, and also to the fact that, currently, the green label of ICTs is usually evaluated by exclusively considering their energy efficiency and CO_2 emissions. For instance, the most used indicators to assess the sustainability degree of ICTs are those proposed by Atrey et al. [64]: (i) Power Usage Effectiveness (PUE); (ii) Carbon Usage Effectiveness (CUE); (iii) Energy Reuse Factor (ERF); (iv) Space and Wattage Performance (SWaP). The eco-efficiency and energy efficiency indicators shown in Table 2 are considered as sufficient in order to accomplish the proposed objectives of this work, however, at no time the sustainability of data center was evaluated. The indicators used point out which system does better at efficiently using direct energy to provide services for users (virtual machine and bytes storage), as well as efficiently demanding emergy to provide the same outputs. The difference between the indicators (energy vs. emergy) is based on a scale of analysis (please see Agostinho and Pereira [29] on this regard), in which emergy accounting considers a larger scale and, therefore, it can account for all hidden costs not considered in an energy analysis.

At this point, another concern arises: how important is to calculate the sustainability of information carriers (e.g. data center)? First and foremost, the most relevant aspects related to information are on the quality of it, and not in its carrier's sustainability. What really matters is that the transmitted information be sustainable and allow for societal progress [24,43]. Thus, the sustainability of information carriers could be taken as a secondary goal. This raises the hypothesis that information carriers are not designed to be sustainable. However, this does not imply that they must be inefficient in converting inputs into outputs, mainly because they are exclusively dependent on electricity energy sources, which is a high quality energy due to their high Unit Emergy Value (UEV). For instance, the UEVs for hard coal and diesel (1.32E5 seJ/J and 1.81E5 seJ/J respectively; [65]) are, in average, 3.7 times lower than the one for thermal electricity (5.69E5 seJ/J; [66]). Thus, the high quality energy feeding the DCs must be efficiently used. This is also recognized by Servaes [67] who argues that there is a growing consensus that ICT not only can contribute to the reduction of anthropogenic greenhouse gas (GHG) emissions by increasing its own energy efficiency, but can also contribute as a guidance for more efficient energy production and consumption patterns – the latter can be interpreted as the information transmitted by the ICT.

In brief, the use of traditional emergy indicators to assess sustainability of information carriers is operationally difficult, since those systems are located on the right side of a hierarchical energy chain. However, assuming that the environmental load of information carriers correspond to a tiny fraction of the environmental load of a larger system receiving good information that allows for its sustainable development, then we would say that it seems that information carriers do not have to be sustainable; rather than that, the information transmitted must be sustainable. Information carriers that efficiently use energy and materials inputs must be identified, recognized, and promoted, since they are able to use resources in a more efficient way than other carriers are. Albeit efficient, the methodological approaches used in this work do not allow for granting the information carriers evaluated a green label.

4. Conclusions

Focusing on the direct energy consumption in the data centers operational phase, results show that Cloud demands 37% less electricity than Legacy (5.96E+06 kWh/yr vs. 9.41E+06 kWh/yr). Considering the functional units that represent the energy efficiency, the Cloud demands 51% less energy to provide a Virtual Machine than Legacy does (0.83E+03 kWh/VM vs. 1.65E+03 kWh/VM), and it consumes less energy than Legacy to store a byte (0.57E−09 kWh/byte vs. 4.30E−09 kWh/byte).

Similar behavior was observed under an emergy accounting approach. The Cloud demands less annual emergy than Legacy (3.59E19 seJ/yr vs. 5.17E19 seJ/yr), which stands for better performance. When the functional units are considered, results evidence that Cloud demands 45% less emergy to provide a Virtual Machine than Legacy does (4.99E+15 seJ/VM vs. 9.07E+15 seJ/VM), and it demands 85% less emergy to store a byte (0.34E+04 seJ/byte vs. 2.36E+04 seJ/byte).

Analyzing in absolute terms (i.e. under kWh/yr and seJ/yr units), the Cloud proved to achieve a better performance than Legacy did, by causing a lower load on the environment due to demanding a lower amount of global resources (directly or indirectly) for its implementation and operation phases. This is important in a world with reduced availability of energy resources. In fact, these indicators can be considered as more closely related to sustainability and/or green concepts than the ones expressing efficiency, however, they are still unable to indicate from where the amount of used resources comes from; i.e. whether they come from renewable or non-renewable sources, resulting in either a sustainable or in an unsustainable system, respectively.

Although recognizing that indicators of energy efficiency and eco-efficiency evidence the better performances by the Cloud, no conclusion on labeling it as green ever stands. The reason is that the equipment disposal phase was not considered in the study, and because there is a lack of a threshold that would allow categorizing a good or service as green, when those efficiency indicators are being used as parameters. Thus, the indicators of energy efficiency and eco-efficiency used in this work do allow to conclude that the Cloud can be considered as greener than Legacy.

The effectiveness of using environmental accounting metrics to assess sustainability or how green is the ICT systems claims for more efforts in operationalizing and defining the origin of energy and material inputs used to implement, operate, and dismantle the ICT system. However, assuming that the environmental load from information carriers corresponds to a tiny fraction of the larger systems receiving high-quality information, it can be said that ICT does not need to be necessarily as green as the information transmitted does. In other words, a priori, the ICT must allow for the transition of that secondary system dependent on the services provided by the ICT to a green label. Society should use ICTs to promote its progress, however, ICTs should not damage the environment in which humans live. This claim for a cost-benefit relation under a large-scale view, i.e. if using the ICT will indirectly allow for higher environmental benefits, then using it is justifiable, even if the ICT actually burdens the environment the way it has been doing.

Acknowledgements

Authors are grateful for the financial support from Vice-Reitoria de Pós-graduação da Universidade Paulista (UNIP), and to Instituto Federal de Educação, Ciência e Tecnologia do Sul de Minas Gerais

(IFSul). Thanks also to CNPq Brazil (proc. no. 307422/2015-1) for the fellowship provided to second author. The effort of José Hugo de Oliveira in the English version revision is also acknowledged.

Appendix A. Calculation procedure for virtual machine amount integrating the “Cloud”

Step #1 – Available memory size in each server =512 GB RAM
Step #2 – Memory size considered for calculations =480 GB RAM (A)
Step #3 – Memory size per virtual machine =32 GB RAM (B)
Step #4 – Number of available virtual machines per server =(A) $(B)^{-1}$ =15 virtual machines (C)
Step #5 – Total number of available servers considered in “Cloud” =480 servers (D)
Step #6 – Total number of available virtual machines =(C) (D) =7200 virtual machines

Appendix B

See Table B1.

Appendix C. Primary data used for the emergy evaluation of “Legacy” system (Table 3)

Item #1 (Lime) – Amount =9.98 kg/m^2 [68]; Constructed area per individual datacenter =16 m^2 per datacenter; Legacy datacenter number =150 datacenter; Assumed lifetime =30 years; Conversion =(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =798.40 kg $year^{-1}$
Item #2 (Cement) – Amount =144 kg/m^2 [68]; Constructed area per individual datacenter =16 m^2 per datacenter; Legacy datacenter number =150 datacenter; Assumed lifetime =30 years; Conversion =(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =11,520 kg $year^{-1}$
Item #3 (Stone) – Amount =333 kg/m^2 [68]; Constructed area per individual datacenter =16 m^2 per datacenter; Legacy datacenter number =150 datacenter; Assumed lifetime =30 years; Conversion =(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =26,640 kg $year^{-1}$
Item #4 (Sand) – Amount =462 kg/m^2 [68]; Constructed area per individual datacenter =16 m^2 per datacenter; Legacy datacenter number =150 datacenter; Assumed lifetime =30 years; Conversion =(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =36,960 kg $year^{-1}$
Item #5 (Clay) – Amount =154 kg/m^2 [68]; Constructed area per individual datacenter =16 m^2 per datacenter; Legacy datacenter number =150 datacenter; Assumed lifetime =30 years; Conversion =(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =12,320 kg $year^{-1}$
Item #6 (Steel) – Amount =10.9 kg/m^2 [68]; Constructed area per individual datacenter =16 m^2 per datacenter; Legacy datacenter number =150 datacenter; Assumed lifetime =30 years; Conversion =(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =872 kg $year^{-1}$
Item #7 (Computers) – Computers refer herein to servers; Amount =1,425 computers (data collected in situ); This amount covers all 150 data centers; Average value of computer weight assumption based on current equipment available in the market =23 kg $computer^{-1}$; Assumed lifetime =5 years; Conversion =(computers) (g $computer^{-1}$) $(year)^{-1}$; Input flow =6,555 kg $year^{-1}$
Item #8 (Plastic) – Percentage of plastic in electronics equipment =30% [69]; Amount of electronics present in the 150 datacenters =6,094,5 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =366 kg $year^{-1}$
Item #9 (Steel) – Percentage of steel in electronics equipment =43% [69]; Amount of electronics present in the 150 datacenters =6,094,5 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =524 kg $year^{-1}$
Item #10 (Glass) – Percentage of glass in electronics equipment =4% [69]; Amount of electronics present in the 150 datacenters =6,094,5 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =48 kg $year^{-1}$
Item #11 (Copper) – Percentage of copper in electronics equipment =3% [69]; Amount of electronics present in the 150 datacenters =6,094,5 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =36 kg $year^{-1}$
Item #12 (Printed board) – Percentage of printed board in electronics equipment =20% [69]; Amount of electronics present in the 150 datacenters =6,094,5 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(20%) (kg) $(year)^{-1}$; Input flow =244 kg $year^{-1}$
Item #13 (Plastic) – Percentage of plastic present in telecom equipment =74% [69]; Amount of telecom equipment present in the 150 datacenters =1376 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =204 kg $year^{-1}$
Item #14 (Steel) – Percentage of steel in telecom equipment =13% [69]; Amount of telecom equipment present in the 150 datacenters =1376 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =35.8 kg $year^{-1}$
Item #15 (Copper) – Percentage of copper in telecom equipment =7% [69]; Amount of telecom equipment present in the 150 datacenters =1376 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =19.3 kg $year^{-1}$
Item #16 (Printed board) – Percentage of printed board in telecom equipment =6% [69]; Amount of telecom equipment present in the 150 datacenters =1376 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(%) (kg) $(year)^{-1}$; Input flow =16.5 kg $year^{-1}$
Item #17 (Rack) – Amount (refrigeration and generator considered) =23880 kg (data collected in situ); Assumed lifetime =5 years; Conversion =(steel) (g $steel^{-1}$) $(year)^{-1}$; Input flow =4,776 kg $year^{-1}$
Item #18 (Electricity) – Total power including computers, electronic equipment, and telecom equipment =740 kW (data collected in situ); Total power refrigeration (assuming 24,000 BTUs based on equipment and other thermal load sources existing in datacenter) =348 kW; All this equipment is essential for the datacenter functioning, thus all must be connected full time, i.e. 24 h day^{-1} at 365 d

Table B1
Amount of devices and part number integrating the assessed “Cloud”.

Part Number	Item	Quantity
FAS6200	Storage netApp	8
DS4243	NetApp Disk Shelves and Storage Media	242
N7K-C7010	Chassi - Switch	4
N7K-SUP1	Cisco Nexus 7000 M1-Series 48-Port Gigabit Ethernet Modules	8
N7K-C7010-FAB 2	Cisco Nexus 7000 Switches Fabric−2 Modules	4
N7K-F132XP−15	Cisco Nexus 7000 F1-Series 32-Port	8
N7K-M132XP−12 L	Cisco Nexus 7000 F1-Series 32-PortCisco Nexus 7000 M1-Series 32-Port 10 Gigabit	16
N7K-M148GS−11 L	Cisco Nexus 7000 M1-Series 48-Port Gigabit Ethernet Modules - SFP module	4
N7K-M148GT−11 L	Cisco Nexus 7000 M1-Series 48-Port Gigabit Ethernet Modules	4
UCS-FI−6296UP	Cisco UCS 6296UP 96-Port Fabric Interconnect	6
UCS-FI−6140UP	Cisco UCS 6140UP 40-Port Fabric Interconnect	4
n.a.	Cisco ASR 9006 Router	2
n.a.	Cisco Firewall ASA5585-SSP−40	4
n.a.	Blade Server 200/230	512

n.a. = not available

$year^{-1}$; Conversion =(kW) (h day^{-1}) (day $year^{-1}$) (3,600,000 J kWh^{-1}); Input flow =3.39 10^{13} J $year^{-1}$
Item #19 (Labor) – Number of technical staff members needed for maintaining the Legacy =576 (144 with high level graduation and 432 with technical level; data collected in situ); Wages for staff with high level graduation =32,424 $ yr^{-1}; Wages for staff with technical level graduation =17,232 $ yr^{-1} per month (values estimated from [70]); Conversion =((144 persons)*(17,232 $ yr^{-1})) +((432 persons)*(32,424 $ yr^{-1})) Input flow =12,113,280 $ $year^{-1}$
Item #20 (Services of infrastructure)–Amount =588.35 $/$m^2$ [71]; Constructed area per individual datacenter=16 m^2 per datacenter; Legacy datacenter number=150 datacenter; Assumed lifetime=30 years; Conversion =($ m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=47,068 $ $year^{-1}$
Item #21 (Services of computers, electronics, and telecom)– Amount=6,327,674 $ (data obtained from current market prices of computers, electronics and equipments existing in the Legacy); Assumed lifetime=5 years; Conversion =($) $(year)^{-1}$; Input flow=1,265,535 $ $year^{-1}$
Item #22 (Services of electricity) – Amount=9,530,880 kWh $year^{-1}$ (from Item #19); Current market price of electricity=0.10 $ kWh^{-1}; Conversion=(kWh $year^{-1}$) ($ kWh^{-1}); Input flow =953,088 $ $year^{-1}$

Appendix D. Primary data used for the emergy evaluation of "Cloud" system (Table 4)

The acronym "DC1″ refers to actual Cloud Computing infrastructure located in São Paulo city, while "DC2″ refers to backup DC1 located in Barueri city.

Item #1 (Lime) – Amount =9.98 kg/m^2 [68]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime=30 years; Conversion=(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow =98.45 kg $year^{-1}$
Item #2 (Cement) – Amount =144 kg/m^2 [68]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime=30 years; Conversion=(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=1420 kg $year^{-1}$
Item #3 (Stone) – Amount=333 kg/m^2 [68]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime=30 years; Conversion=(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=3,285 kg $year^{-1}$
Item #4 (Sand) – Amount=462 kg/m^2 [68]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime=30 years; Conversion=(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=4558 kg $year^{-1}$
Item #5 (Clay) – Amount=154 kg/m^2 [68]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime=30 years; Conversion=(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=1,519 kg $year^{-1}$
Item #6 (Steel) – Amount=10.9 kg/m^2 [68]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime =30 years; Conversion=(kg m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=107.55 kg $year^{-1}$
Item #7 (Computers) – Computers refers herein to servers; Amount=512 computers (data collected in situ); Computer weight based on model =8160 g $computer^{-1}$; Assumed lifetime=5 years; Conversion=(computers) (g $computer^{-1}$) $(year)^{-1}$; Input flow=835,584.00 g $year^{-1}$
Item #8 (Rack) – Amount=74 racks (data collected in situ); Rack weight based on model =115,66 kg $rack^{-1}$; Assumed lifetime=5 years; Conversion=(racks) (g $racks^{-1}$) $(year)^{-1}$; Input flow =1711 kg $year^{-1}$
Item #9 (Plastic) – Percentage of plastic in electronics equipment=30% [69]; Amount of electronics present in cloud (DC1+DC2) =12,995.8 kg (data collected in situ); Assumed lifetime=5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=780 kg $year^{-1}$
Item #10 (Steel) – Percentage of steel in electronics equipment =43% [69]; Amount of electronics present in cloud (DC1+DC2) =12,995.8 kg (data collected in situ); Assumed lifetime =5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow =1,118 kg $year^{-1}$
Item #11 (Glass) – Percentage of glass in electronics equipment=4% [69]; Amount of electronics present in cloud (DC1+DC2) =12,995.8 kg (data collected in situ); Assumed lifetime=5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=104 kg $year^{-1}$
Item #12 (Copper) – Percentage of copper t in electronics equipment=3% [69]; Amount of electronics present in cloud (DC1+DC2) =12,995.8 kg (data collected in situ); Assumed lifetime=5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=78 kg $year^{-1}$
Item #13 (Printed board) – Percentage of printed board in electronics equipment=20% Amount of electronics present in cloud (DC1+DC2)=12,995.8 kg (data collected in situ); Assumed lifetime=5 years; Conversion=(20%) (kg) $(year)^{-1}$; Input flow=520 kg $year^{-1}$
Item #14 (Plastic) – Percentage of plastic in telecom equipment=74% [69]; Amount of telecom equipment present in cloud (DC1+DC2)=1208 kg (data collected in situ); Assumed lifetime=5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=179 kg $year^{-1}$
Item #15 (Steel) – Percentage of steel in telecom equipment=13% [69]; Amount of telecom equipment present in cloud (DC1+DC2) =1208 kg (data collected in situ); Assumed lifetime =5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=31 kg $year^{-1}$
Item #16 (Copper) – Percentage of copper in telecom equipment=7% [69]; Amount of telecom equipment present in cloud (DC1+DC2)=1208 kg (data collected in situ); Assumed lifetime =5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=17 kg $year^{-1}$
Item #17 (Printed board) – Percentage of printed board in telecom equipment=6% [69]; Amount of telecom equipment present in cloud (DC1+DC2)=1208 kg (data collected in situ); Assumed lifetime=5 years; Conversion=(%) (kg) $(year)^{-1}$; Input flow=14 kg $year^{-1}$
Item #18 (Steel) – Amount (refrigeration and generator considered) =10,928 kg (data collected in situ); Assumed lifetime=10 years; Conversion=(steel) (g $steel^{-1}$) $(year)^{-1}$; Input flow=1093 kg $year^{-1}$
Item #19 (Electricity) – Total power including computers, electronic equipment, and telecom equipment=340 kW (data collected in situ); Total power refrigeration (assuming a chiller refrigeration machine with 50 tr based on equipment and other thermal load sources) =340 kW; All this equipment is essential for the datacenter functioning, thus all must be connected full time, i.e. 24 h day^{-1} at 365 d $year^{-1}$; Conversion=(kW) (h day^{-1}) (day $year^{-1}$) (3,600,000 J kWh^{-1}); Input flow=2.14×10^{13} J $year^{-1}$
Item #20 (Labor) – Number of technical staff members needed for maintaining the Legacy =48 (16 with high level graduation and 32 with technical level; data collected in situ); Wages for staff with high level graduation=32,424 $ yr^{-1}; Wages for staff with technical level graduation=17,232 $ yr^{-1} per month (values estimated from [70]); Conversion=((32 persons)*(17,23 $ yr^{-1})) +((16 persons)*(32,424 $ yr^{-1})) Input flow =1,070,208 $ $year^{-1}$
Item #21 (Services of infrastructure) – Amount =588.35 $/$m^2$ [71]; Total constructed area=296 m^2 (120 m^2 DC1 and 176 m^2 DC2); Assumed lifetime=30 years; Conversion=($ m^{-2}) (m^2 $datacenter^{-1}$) (datacenter) $(year)^{-1}$; Input flow=5,805.00 $ $year^{-1}$
Item #22 (Services of computers, electronics, and telecom) – Amount=42,444,821 $ (data obtained from current market prices of computers, electronics and equipment present in the Cloud); Assumed lifetime=5 years; Conversion =($) $(year)^{-1}$; Input flow=8,488,964 $ $year^{-1}$
Item #23 (Services of electricity) – Amount=5,956,800 kWh $year^{-1}$ (from Item #20); Current market price of electricity =0.10 $ kWh^{-1}; Conversion=(kWh $year^{-1}$) ($ kWh^{-1}); Input flow=595,680 $ $year^{-1}$

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Glossary

ICT: Information and Communication Technology
DC: Data Center
VM: Virtual Machines
seJ: Solar emjoules
CC: Cloud Computing