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DOI
10.1145/2764464
Publication date
2015
Document Version
Final published version
Published in
ACM Computing Surveys

Energy-Efficient Networking Solutions in Cloud-Based Environments: A Systematic Literature Review

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The energy consumed by data centers hosting cloud services is increasing enormously. This brings the need to reduce energy consumption of different components in data centers. In this work, we focus on energy efficiency of the networking component. However, how different networking solutions impact energy consumption is still an open question. We investigate the state of the art in energy-efficient networking solutions in cloud-based environments. We follow a systematic literature review method to select primary studies. We create a metamodel based on the codes extracted from our primary studies using the Coding analytical method. Our findings show three abstraction levels of the proposed networking solutions to achieve energy efficiency in cloud-based environments: Strategy, Solution, and Technology. We study the historical trends in the investigated solutions and conclude that the emerging and most widely adopted one is the *Decision framework*.

Categories and Subject Descriptors: A.1 [**Introductory and Survey**]: General; C.2.3 [**Computer-Communication Networks**]: Network Operations

General Terms: Survey, Energy, Networking, Data Center, Design

Additional Key Words and Phrases: Energy efficiency, networking, cloud, systematic literature review

ACM Reference Format:
Fahimeh Alizadeh Moghaddam, Patricia Lago, and Paola Grosso. 2015. Energy-efficient networking solutions in cloud-based environments: A systematic literature review. ACM Comput. Surv. 47, 4, Article 64 (May 2015), 32 pages.
DOI: http://dx.doi.org/10.1145/2764464

1. INTRODUCTION

Cloud-based environments provide the required physical resources to launch services and applications. At production scale, they are implemented mainly by a single data center or a network of multiple data centers. Therefore, the quality indicators of cloud-based environments, such as energy efficiency and performance, are driven directly from the data centers' profiling systems. Because of high electricity bills, energy consumption has a significant priority for data center operators. As data centers are used extensively every day, their energy costs will increase accordingly. The DatacenterDynamics 2012 Global Census [Venkatraman 2012] states that total power consumption

This research was sponsored in part by the European Fund for Regional Development under project MRA Cluster Green Software and by the NWO through project GreenClouds.
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DOI: http://dx.doi.org/10.1145/2764464

of data centers increased globally from 24GW to 38GW (63%) between 2011 and 2012. This sharp increase basically shows the growing demand on power requirements in data centers. The concern of energy savings is not to curb this growth but to improve on energy efficiency. On the one hand, statistics show that the average data center workload is only 30% of the load in peak hours [Kliazovich et al. 2010]. On the other hand, reliability and availability are two quality requirements that are concerning to data center operators. This leads to a demand for huge amounts of power to keep the nonutilized infrastructure up and running.

The distribution of energy consumption within a data center is not homogeneous: a large portion of power consumption (80% to 90%) goes to infrastructure, servers, and cooling, and the rest (about 10% to 20%) is spent on networking Heller et al. [2010]. Baliga et al. [2011] determined that these proportions will change in different scenarios. Based on specific traffic patterns or data computations, energy consumption of each component would vary. Our focus is on the energy efficiency of the networking component, which has received less attention compared to the energy consumption of the data computation component. Data transmission is not the major contributor to total energy consumption, but improvement in this area is still important for the following reasons:

(1) The network architectures of data centers typically are richly connected and ensure availability by using a lot of redundant network devices. Consequently, a large number of network devices are kept up all the time.
(2) As mentioned earlier, network devices are idle most of the time, which causes energy wastes and poor energy efficiency.
(3) The network devices currently used in data centers are not energy proportional. Based on Heller et al. [2010], network devices even at the low load or in an idle state consume around 90% of the power consumed in a highly utilized state.

In this article, we survey existing solutions in cloud-based environments that aim to improve the energy efficiency of the networking component. Contrary to other surveys in this research area, we adopt a systematic manner, namely the systematic literature review (SLR) research method [Kitchenham et al. 2009], to define the search strategy and identify our primary studies. We then analyze the primary studies using the coding analytical method [Strauss 1987] to collect and extract the results. The codes are analyzed and aggregated into a metamodel that illustrates the identified classification in the articles.

The rest of the article is structured as follows. After discussing related work in Section 2, we describe the steps taken for collecting the primary studies in Section 3. Then, Section 4 details the classification of collected information and indicates a corresponding metamodel. Section 5 focuses on the findings from the primary studies. Existing implemented energy-efficient networking solutions are further discussed in Section 6, and the threats to validity are explained in Section 7. The article closes by presenting emerging opportunities of research in Section 8 and our conclusions in Section 9.

2. RELATED WORK

Several studies in the literature have analyzed the existing energy-efficient solutions of various domains.

There are surveys focusing only on the network infrastructure and not including cloud-based environments. For instance, Zhang et al. [2010]] describes existing work done in the energy efficiency of optical networks, and Bianzino et al. [2012], and Bolla et al. [2011] provide the current perspectives and emerging technologies on the energy efficiency of network infrastructures in general. These studies are interesting from a general viewpoint, but they miss the specific characteristics of networks suitable for cloud operations.

The energy efficiency of cloud-based environments has been researched from different perspectives. Priya et al. [2013] concentrate on energy models of different components in data centers and illustrate energy-efficient solutions of cloud computing services (SaaS, PaaS, and IaaS). Beloglazov et al. [2011] survey some ongoing projects from different companies on energy-efficient solutions in data centers, which include the networking component and its energy efficiency.

Other surveys have collected solutions for energy efficiency in cloud-based environments split by different components. Therefore, the networking component has been included as well, but partially as one of the influencing factors in total energy consumption of data centers. General solutions for energy efficiency are gathered in Kulseitova and Fong [2013], Cavdar and Alagoz [2012], and Orgerie et al. [2014], which cover "green" metrics applied in data centers and how energy-saving solutions for servers and cooling are improving energy efficiency. Moreover, they discuss networking solutions as part of these solution sets. We emphasize only on energy-efficient networking solutions in data centers and provide a deep analysis of existing solutions. Our analysis goes further by including networking solutions investigated in large-scale cloud-based environments.

The original contribution of our work compared to the research presented earlier is that we specifically focus on the networking component of the data centers offering cloud services and present the energy-efficient networking solutions provided in different scales: intra–, inter–, and mixed–data center scales. We are interested in identifying the solutions proposed to reduce energy consumption of the networking component and the granularity of which they are applied. For the first time in this research area, we use an SLR method to select our primary studies in a systematic manner. Although this method is quite common in other research fields (e.g., software engineering and knowledge management), it is not much adopted in the field of computer networks. Using this method, we provide a fresh perspective of the state of the art in this research area.

3. SYSTEMATIC LITERATURE REVIEW

SLR is an emphasized research method to collect all relevant articles based on a predefined search query [Kitchenham et al. 2009]. As the name implies, all steps are taken via a systematic procedure, which provides a more objective process to select relevant studies compared to other review methods. There are four major steps in an SLR: (1) definition of the research question, (1) search strategy, (2) study selection, and (3) primary studies management.

Following the initial step of *definition of the research question*, an initial list of studies is created during the *search strategy* step.

The list is used as a starting point in the *study selection* step. Each article is examined to select only studies answering the original research question. This requires the definition of selection criteria that will be the only objective guidance in selecting primary studies. It is important to record all inclusion and exclusion rules. Inclusion criteria determine if one study can be a candidate for primary study; they are minimum set of conditions that have to be met by a primary study. After application of the inclusion criteria, the resulting relevant studies are evaluated according to exclusion criteria. The remaining articles are called *primary studies*. Primary studies are the output of the SLR method and the input for further analysis and discussion.

The *primary studies management* step facilitates the process of study selection.

Our concrete work in the SLR protocol is described next.

Research question. We set out to investigate the current solutions adopted in cloud-based environments to improve the energy efficiency of the networking component. Namely, we want to answer the following question: What are the energy-efficient networking solutions in cloud-based environments?

Search strategy. We use Google Scholar as the input data source because it is easily accessible and reproducible for others. We construct the search query based on our research question, which is a combination of several relevant keywords and Boolean AND's/OR's. The keywords are chosen to maintain the proper balance between generality and specificity at the same time. To make sure that the query we define is effective in finding relevant studies, we have to verify its sensitivity using a set of pilot studies.

Pilot study. Based on our knowledge of the field, we found a list of 15 pilot studies, which we expect to show up as primary studies. We trained the SLR protocol with these pilot studies to make sure that each one of them is retrieved by the query.

The resulting search query is formulated as follows:

Search Query: routing "data-center" network cloud (intitle:energy OR intitle:power) -intitle:mobile -intitle:telecom -intitle:wireless -intitle:hoc -intitle:radio -intitle:smart

The specific syntax keywords shown in the search query are related to our choice of input data source. The syntax would vary for different digital libraries. To make the search query more tangible, we hereby describe the search operators:

—intitle:*term*: It finds the articles that have *term* in their title.
—The - operator: It can be used before any word or operator to give a "NOT" meaning to that part of search query. For example, *-intitle:wireless* in our search query targets the articles that do not have the term *wireless* in their title.
—"*phrase*": Using quoted phrases, it is possible to search for articles containing the exact *phrase*. In our search query, we have put "data-center," and Google Scholar is able to collect articles containing either "data center" or "data-center."
—(): By using parentheses, it is possible to skip conflicts of operators. In our search query, all words and operators are put together with an implicit "AND" operator between them. Because we need to use the "OR" operator as well, we put it in parentheses.

Study selection. After running the preceding query on Google Scholar, we obtained the relevant studies.[1] We assessed each study for its actual relevance through two sets of selection criteria: inclusion and exclusion. Table I lists all inclusion criteria used to identify our primary studies. Table II lists all exclusion criteria that must not be seen in one of our primary studies. At the end of this phase, we get all relevant primary studies.

Instead of reading all of the articles at once, we completed the selection process in multiple stages to accelerate the entire procedure. We used the output set of studies from each stage as the input set for its next stage. In the first two stages, we processed the title and abstract of the relevant studies. Finally, we assessed the whole body of articles and considered the output of this stage as our primary studies, which will be used in the data analysis. Figure 1 represents the steps of SLR and the number of remaining studies for each step.

We started with 640 articles in the relevant studies list and ended up with 44 primary studies. Of 596 articles removed from the initial selection, around 45% were removed during stage 3 (selection by abstract). In most cases, reading the abstract eases the decision-making process, as it describes the main goal and the scope of the study.

Primary studies management. We used two applications in the process of obtaining primary studies and analyzing them: the study selection of different stages is done in

[1]The search query was run on November 13, 2013, in Google Scholar.

Table I. Inclusion Criteria

Number	Criterion	Description
1	The study is written in English.	There are some studies written in languages other than English, but because of providing an English title or abstract, they show up in our query result. Only studies written in English will be included for reasons of feasibility.
2	The study is peer reviewed.	To ensure a satisfying quality of primary studies, only peer-reviewed studies will be chosen, as they have been published by a professional scholarly society.
3	The networking component is considered.	There are plenty of energy efficiency techniques investigated in cloud-based environments that are not focused on the networking component, such as cooling technologies. Thus, it is necessary to specify the requirement to find studies that aim to improve energy efficiency of the networking component.
4	Data and services are in cloud-based environments.	To investigate the solutions provided specifically in cloud-based environments, we do not consider cases that data and services need to be transferred from the customer side to the cloud.

Table II. Exclusion Criteria

Number	Criterion	Description
1	The network infrastructure is not wired/optical.	We are not interested in wireless network infrastructure deployed in data centers. In the search query, some limitations on title are defined, such as not having "wireless.", "smart,", "mobile," and "ad hoc" in the title.
2	Energy efficiency is not the primary requirement.	According to our research question, the aim is to find energy-efficient solutions. Thus, the studies investigated to model and monitor power/energy consumption of components in cloud-based environments will not be the case, unless they provide energy efficiency solutions.
3	The main focus of the study is not the networking component.	Energy efficiency in cloud-based environments depends on several components, one being the networking component. Because of the high impact of servers on total energy consumption of data centers, most studies are focused on this part, and the energy efficiency issue in the networking component is considered implicitly. For example, virtual machine (VM) consolidation in data centers will effect the energy consumption of the networking component. However, if the study is only covering considerations of potential congestion in the network, then it will be removed from our list.
4	The study does not include the data center environment.	As mentioned earlier, we consider data centers as a cloud-based environment's infrastructure. Other types of cloud IT infrastructure will not be included.
5	There is a missing study source.	Some studies release their abstract publicly, but the body text cannot be found because of either nonpublic publications or other transfer issues. These studies will be removed in the selection process. However, it should be noted that with our university license, we can access most major scientific journals.

Zotero[2]; we then import the primary studies in ATLAS.ti,[3] which makes qualitative analysis of a large number of studies much easier.

4. DATA ANALYSIS

We use coding [Strauss 1987] as our analysis method, where each article is interpreted with a number of codes to summarize its valuable information with summative words/phrases. After collecting all coded data out of the primary studies, the codes are clustered together based on relations between concepts to make hidden patterns

[2]https://www.zotero.org.
[3]http://www.atlasti.com/index.html.

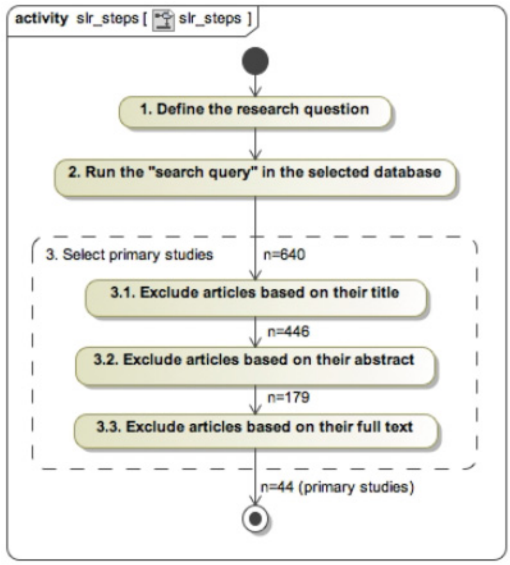

Fig. 1. The steps taken in our SLR, with *n* being the number of remaining studies in each step.

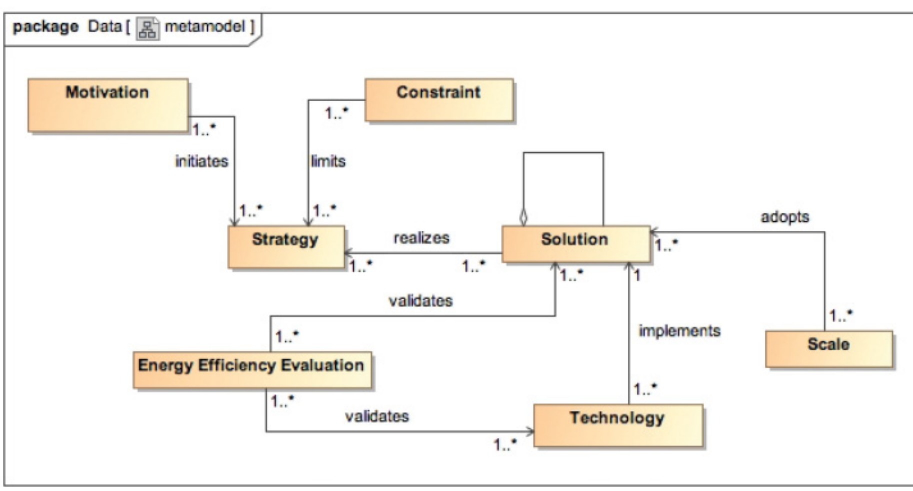

Fig. 2. The metamodel showing the summary codes extracted from the primary studies.

visible. Finally, each cluster is mapped to a more general code, which is shown in our metamodel as a class.

The metamodel has emerged from the identified codes in the primary studies. The aggregated codes are shown in the metamodel as classes, and they are related to each other based on the identified patterns in the primary studies. Figure 2 illustrates our metamodel and the elements necessary for providing energy-efficient solutions in all primary studies. In the following, we provide a more detailed description of each class:

(1) *Motivation*: This is the reason cloud providers think of energy-efficient solutions. The motivation can even be nonnetworking related but have effects on the energy consumption of the networking component. High electricity costs, using renewable

energy, and different energy policies are some of the example motivations in data centers.

(2) *Constraint*: In the service-provisioning process, the main objective has always been to meet quality requirements such as performance and network delay. However, due to the rapid growth of energy consumption in cloud-based environments, energy efficiency is also added to an efficiency factors list that must be managed with care. Optimum energy efficiency in a system might cause degradation in other efficiency factors. For example, aggregating network traffic into fewer numbers of network devices improves the energy efficiency of the networking component while introducing some increase in packet delivery delays. This class puts emphasis on the trade-off that has to be made between the required level of energy efficiency and other efficiency factors, such as network throughput.

(3) *Strategy*: A strategy introduces the plan in which the energy efficiency is achieved that it is realized by solution. For example, if the solution focuses on the *Device*, the strategy to improve energy efficiency could be "Replacing current devices with less energy consuming ones," or if the *Routing/Switching* solution is established, the strategy could suggest "Energy-aware routes." In essence, a strategy provides a high level of abstraction in this classification.

(4) *Solution*: A cloud-based environment, which is a data center or a network of multiple data centers, consists of a variety of components involved in energy consumption of the networking part. A solution is described as a method that aims to reduce energy consumption in one or more of these components.

(5) *Technology*: This is the specification of how a solution is implemented and deployed to satisfy the corresponding strategy, which is triggered by motivations and limited by constraints. It is the lowest level of abstraction in this classification, as technical details are covered in this class.

(6) *Scale*: The identified energy-efficient networking solutions are deployed in different scales of cloud-based environments. As shown in the metamodel based on the considered scale, the solution will be adopted. We have identified three different scales:
   —*Intradata center network*: This scale focuses on the solutions proposed within one data center.
   —*Interdata center network*: In this scale, the concentration is on the solutions implemented for data transmission between data centers. For example, in the case of virtual machine (VM) migration to another data center or moving data to remote data centers, the energy consumption of the networking component should be considered.
   —*Mixed-data center network*: The suggested solutions in this scale not only consider energy consumption within one data center but also take care of energy efficiency factors between data centers. Energy-efficient decisions have to be made while considering all effective factors. In this scale, cumulating the energy consumption within one remote data center with the energy consumption of transfer routing path to that data center has been tried.

(7) *Energy efficiency evaluation*: To find out how much improvement is gained or if it can be considered as an improvement at all, the proposed solution has to be evaluated with means of energy efficiency metrics. Each primary study provides theoretical arguments or statistical/testbed experiments to prove validity of the proposed solution and the deployed technology. Some primary studies use proposed energy models from previous studies as a reference to calculate energy consumption values. Some also generalize and simplify the energy models based on their scope and research question. Another way is to apply external power metering tools and equipments, which can profile more accurate measurements.

The metamodel not only introduces summarized classes but also their relations with an assigned name and multiplicity values. For example, we observed that *Motivation* plays the initiator role for the adoption of a certain *Strategy*, whereas *Constraint* limits it. The *Solution* class has an aggregation relationship with itself because of the *Decision framework* type, which can be derived from a set of other solutions. Depending on the *Scale*, one applicable *Solution* is adopted, which is then implemented by a specific *Technology*. The *Energy efficiency evaluation* class is meant to validate the proposed *Solution* and *Technology* to assess the improvements that they provide.

5. RESULTS

Each class presented in the metamodel shows the elements necessary for providing energy-efficient solutions. The *Motivation* and *Constraint* classes specify the scope of a solution. The diversity of identified items of these classes in the primary studies does not raise specific observations. Therefore, we skip these two and introduce the results of the *Strategy*, *Scale*, *Solution*, *Technology*, and *Energy efficiency evaluation* classes.

5.1. Results Rgarding *Strategy*

Table III lists all 11 strategies identified in the primary studies. The Description column provides a summary of for what the strategy is meant and how energy efficiency as the ultimate objective will be achieved. The primary studies realizing each strategy are listed and counted in the last column. We use the number of primary studies in the last column of all tables to sort the table rows.

The main goal with all strategies is to provide a plan for total energy consumption reduction of cloud-based environments, although they differ in their perspectives. For example, some try to shape the network traffic ("Traffic patterns" strategy), whereas others consolidate VMs in fewer numbers of physical machines ("VM consolidation" strategy). There are two types of relations identified between the networking component and energy efficiency achievement:

—One type starts from energy consumption reduction and then reflects that in the networking component. For example, in the "Heat minimization" strategy, the initiator point to make energy-efficient decisions is the temperature increment in different regions of the data center. If one region meets the heat threshold, then the networking-related decisions are brought up, such as putting network devices in the sleep mode.
—The other type starts from the networking component and then influences the energy efficiency factor. "Traffic consolidation" is an example of this type. Thus, first aggregating network traffic onto a fewer number of machines takes place. Then the effect on energy efficiency will be seen.

Overall, it can be said that the former type focuses on the desired effects, namely improvement in the energy efficiency, whereas the latter concentrates on the cause, which is the networking component.

As illustrated in Table III, "Sleeping mode/Switching off" is the most frequently used strategy. This strategy tries to make the collection of network devices in the data centers behave more energy proportional to the network traffic load. Studies show that the traffic load in data centers follows a relatively known pattern. For instance, at night, the traffic load drops dramatically. This can result in a considerable number of idle networking devices, which makes this strategy a good choice for application. Some strategies go further and target to increase the number of idle network devices. That is why some strategies, such as "VM consolidation" and "Traffic consolidation," are investigated in combination with "Sleeping mode/Switching off," which deactivates idle network devices to gain further improvements. Wang et al. [2012] introduce CARPO

Table III. Strategies Identified in Primary Studies

Number	Strategy	Description	Solutions	Layer	Primary Studies	OCR
1	*Sleeping mode / Switching off*	This strategy aims to improve the energy efficiency by deactivating idle network devices.	Routing/ Switching, Device, Decision framework, Network architecture	*Device*	[Shang et al. 2012; Si et al. 2012; Wang et al. 2013; Buysse et al. 2011; Wang et al. 2012; Liu et al. 2013; Heller et al. 2010; Thanh et al. 2012; Shang et al. 2010; Dong et al. 2013; Mahadevan et al. 2009; Leivadeas et al. 2013; Saha et al. 2012; Sun et al. 2012; Shang et al. 2013; Xu et al. 2013; He et al. 2012; Shirayanagi et al. 2013; Jin et al. 2013; Nguyen Huu et al. 2013; Fang et al. 2012; Mahadevan et al. 2011; McGeer et al. 2010; Huang et al. 2011; Kuribayashi 2012; Carrega et al. 2012; Mann et al. 2011; Fang et al. 2013]	28
2	*Traffic consolidation*	The idea with this strategy is to aggregate network traffic into fewer numbers of links and devices to utilize networking resources and result in higher energy efficiency.	Decision framework, Routing/ Switching, Device	*Network*	[Wang et al. 2012; Mahadevan et al. 2009; Sun et al. 2012; Shang et al. 2013; Shirayanagi et al. 2013; Kantarci et al. 2012; Szymanski 2013; Nguyen Huu et al. 2013; Mahadevan et al. 2011; Carrega et al. 2012; Fang et al. 2013]	11
3	*VM consolidation*	This strategy aims to aggregate VMs into fewer numbers of physical machines to reduce the total amount of energy consumption in data centers. The networking component will be involved at the stage of technical specification and implementations.	Decision framework	*App*	[Wang et al. 2013; Leivadeas et al. 2013; Sun et al. 2012; Shirayanagi et al. 2013; Jin et al. 2013; Mahadevan et al. 2011; McGeer et al. 2010; Mann et al. 2011; Fang et al. 2013]	9
4	*Optical devices*	The goal of this strategy is to replace current electrical networking devices with optical devices, which consume less energy and provide more throughput.	Device, Decision framework, Routing/ Switching, Network architecture	*Device*	[Tarutani et al. 2012; Kantarci et al. 2013; Cerutti et al. 2013; Kitayama et al. 2013; Ji et al. 2012; Glesk et al. 2013; Kantarci and Mouftah 2012; Kachris and Tomkos 2013, 2011]	9

(Continued)

Table III. Continued

Number	Strategy	Description	Solutions	Layer	Primary Studies	OCR
5	*Energy-aware routes*	Selection of the networking path is based on the energy consumption of switches. This can be applied in two ways: either the switches with less energy consumption will be on the path or the total energy consumption of the path will be kept in its minimum level.	Decision framework, Routing/ Switching	*Network*	[Peoples et al. 2012; Kantarci et al. 2013; Peoples et al. 2011; Cordeschi et al. 2013; Sun et al. 2012; Xu et al. 2013; He et al. 2012; Kantarci and Mouftah 2012]	8
6	*Traffic patterns*	This strategy takes the traffic patterns into account to discover behavior of applications and consequently make intelligent decisions.	Decision framework	*App*	[Wang et al. 2013; Tarutani et al. 2012; Wang et al. 2012; Liu et al. 2013; Heller et al. 2010; Thanh et al. 2012; Fang et al. 2012]	7
7	*Traffic locality*	To save the networking resources, one idea is to localize the traffic in some specific parts of data centers. This way, fewer networking devices will be involved in data transmission, which consequently consumes less energy.	Decision framework, Network architecture	*Network*	[Gyarmati and Trinh 2010; Huang et al. 2011]	2
8	*Energy-aware devices*	This strategy uses modified electrical switches that are able to increase their energy efficiency by aggregating the traffic into fewer number of ports and putting the idle ports into sleep mode.	Device	*Device*	[Si et al. 2012; Carrega et al. 2012]	2
9	*Heat minimization*	This strategy aims to reduce the total heat in data centers, which consequently will improve the energy efficiency of cloud-based environments. To mitigate the temperature growth in data centers, the load distribution takes place, which also needs involvement of the networking component.	Decision framework	*DC*	[Saha et al. 2012]	1

(Continued)

Table III. Continued

Number	Strategy	Description	Solutions	Layer	Primary Studies	OCR
10	*Traffic minimization*	The smaller network traffic becomes, the less energy will be consumed in the networking component. Using this strategy, the amount of traffic in cloud-based environment will be reduced, which involves either fewer numbers of networking devices or the same number of devices but for shorter duration.	Decision framework	*Network*	[Dong et al. 2013]	1
11	*Green energy*	Green energy has received more attention in cloud-based environments, as it is produced from renewable and nonpolluting resources. There are some studies doing path selections based on the availability of this type of energy.	Decision framework	*DC*	[Aksanli et al. 2012]	1

as an intra–data center scale decision framework, which focuses on network traffic engineerin (TE) to follow both "Sleeping mode/Switching off" and "Traffic consolidation" strategies.

The table also shows which solutions are used to realize each strategy. The *Decision framework* solution is able to realize all but one at different levels of granularity. Depending on the concentrated data center's component, it is possible for other solution types to realize specific strategies. For example "Energy-aware devices" is only realized by a *Device* solution.

For the sake of discussion, we classify the strategies into more general groups, which are shown for each strategy in the Layer column of the table. This classification is shown in *italic* format to differentiate it from the codes extracted out of the primary studies. Four groups of strategies have been identified based on the granularity of the target components as *Data Center (DC)* layer, *Application (App)* layer, *Network* layer, and *Device* layer. Within some strategy groups, there is no clear boundary between the areas that strategies touch upon. For instance, in the *Network* layer group, "Traffic minimization" and "Traffic locality" try to improve on the amount of network flows. The former makes static/dynamic decisions on VM allocations based on the network traffic between VMs, whereas the latter concentrates more on the network architecture of servers and switches in the data centers.

As shown in the table, both "Optical devices" and "Sleeping mode/Switching off" strategies are realized by all solution types. Replacing electrical switches with optical ones, which are more energy proportional and whose energy consumption is lower, fades out the need to shut down idle networking devices. Therefore, we have seen no primary study realizing these two strategies at the same time. "Energy-aware routes" is another frequently studied strategy that puts the emphasis on the energy consumption of routing paths. The energy-efficient routing paths are established by either selecting the switches that consume less energy or selecting the routing path with minimum total energy consumption. The energy-related decisions can be made through a centralized controller, or in a distributed manner, in which each stand-alone router/switch will select the next hop based on energy efficiency factors. The next interesting strategy is "Traffic patterns" with the idea of adapting the networking component to incoming traffic load of running applications in VMs. Setting the network devices as active/idle is done in a more intelligent way in this case, as the traffic load for time t can be estimated. Traffic patterns are taken into account in two ways: static and dynamic. The former uses initial traffic matrix, whereas the latter collects traffic information in real time.

5.2. Results Regarding *Scale*

We have identified three different scales in the primary studies. One is the intra–data center scale, which is concerned with all solutions and technologies implemented within one data center. The other two require to adopt solutions that are investigated on the data transfer network between data centers. We call them inter– and mixed–data center scales and point them out as large scales in this article. This appellation is not a comparison of the number of VMs running in the cloud-based environment, but rather it is referring to the number of data centers deployed in a cloud-based environment.

It is interesting to study the relation between the solution types and each scale. Table IV lists the solutions presented in inter–, intra–, and mixed–data center scales. As illustrated in the table, most of the primary studies (around 82%) have proposed intra–data center network solutions. The *Network architecture* and *Device* solution types are not investigated for larger scales. Considering that different areas of administration and ownership exist in multidomain transfer networks, these solution types cannot be deployed in a centralized consistent way. We have identified two primary studies

Table IV. Solutions Provided for Different Data Center Scales

Number	Solution	Primary Studies	Occurrence
		Scale: Intra–Data Center (81.8%)	
1	*Decision framework*	[Wang et al. 2013; Tarutani et al. 2012; Wang et al. 2012; Liu et al. 2013; Heller et al. 2010; Thanh et al. 2012; Cordeschi et al. 2013; Dong et al. 2013; Mahadevan et al. 2009; Leivadeas et al. 2013; Saha et al. 2012; Sun et al. 2012; Shang et al. 2013; Xu et al. 2013; Shirayanagi et al. 2013; Jin et al. 2013; Nguyen Huu et al. 2013; Fang et al. 2012; Mahadevan et al. 2011; McGeer et al. 2010; Huang et al. 2011; Kuribayashi 2012; Mann et al. 2011; Fang et al. 2013]	24
2	*Network architecture*	[Shang et al. 2012; Wang et al. 2013; Tarutani et al. 2012; Cerutti et al. 2013; Liu et al. 2013; Heller et al. 2010; Thanh et al. 2012; Shang et al. 2010; Kitayama et al. 2013; Dong et al. 2013; Ji et al. 2012; Shirayanagi et al. 2013; Gyarmati and Trinh 2010; Jin et al. 2013; McGeer et al. 2010; Huang et al. 2011; Kachris and Tomkos 2013, 2011; Carrega et al. 2012; Mann et al. 2011; Fang et al. 2013]	21
3	*Routing / Switching protocols*	[Shang et al. 2012; Si et al. 2012; Wang et al. 2013; Thanh et al. 2012; Shang et al. 2010; Kitayama et al. 2013; Cordeschi et al. 2013; Dong et al. 2013; Leivadeas et al. 2013; Glesk et al. 2013; Sun et al. 2012; Shang et al. 2013; Xu et al. 2013; He et al. 2012; Fang et al. 2012; Mann et al. 2011]	16
4	*Device*	[Si et al. 2012; Tarutani et al. 2012; Cerutti et al. 2013; Kitayama et al. 2013; Ji et al. 2012; Saha et al. 2012; Glesk et al. 2013; Kachris and Tomkos 2013, 2011; Carrega et al. 2012]	10
		Scale: Inter–Data Center (11.3%)	
5	*Decision framework*	[Aksanli et al. 2012; Buysse et al. 2011; Peoples et al. 2011; Kantarci and Mouftah 2012]	4
6	*Routing / Switching protocols*	[Aksanli et al. 2012; Buysse et al. 2011; Peoples et al. 2011; Szymanski 2013; Kantarci and Mouftah 2012]	5
7	*Device*	[Kantarci and Mouftah 2012]	1
		Scale: Mixed–(Inter– & Intra–) Data Center (6.8%)	
8	*Decision framework*	[Peoples et al. 2012; Kantarci et al. 2013, 2012]	3
9	*Routing / Switching protocols*	[Peoples et al. 2012]	1
10	*Device*	[Kantarci et al. 2013]	1

covering large-scale cloud-based environments and providing the *Device* solution type. They concentrate on the "IP over wavelength-devision multiplexing" (WDM) optical networks as their backbone transfer network.

From Table IV, it can be concluded that the *Decision framework* is the most widely adopted solution type in all scales. The table also shows how decision frameworks make use of other solutions. For example, Wang et al. [2013] use an intrascale decision framework that makes use of both solution types: *Network architecture* and *Routing / Switching*. The permutations of applied solution types in decision frameworks vary in different scales. Extracted from the table, a decision framework for an inter–data center scale is more likely to make the *Routing / Switching* solution type involved rather than the *Device* type.

5.3. Results Regarding *Solution*

We studied all of the primary studies to determine proposed solutions for energy efficiency improvement in cloud-based environments. The classification of suggested solutions in the primary studies includes the following:

—*Device*: This solution type is provided when the focus of the solution is to improve energy efficiency of networking devices. Only network switches and links are put in this category, excluding servers because they are not considered to be part of the networking component.
—*Routing/Switching protocols*: The main focus of this classification is to answer the following question: How can the energy efficiency be improved in network connections, namely routing and switching? Redesigning *Routing/Switching* algorithms and using current protocols but in more intelligent ways are some of the provided suggestions with regard to this type.
—*Network architecture*: Another component that is investigated in the primary studies is the network architecture. The data center network architecture specifies how large numbers of servers and switches are interconnected. Regarding the use of "richly connected" network architectures in data centers, which solves reliability and availability issues on the one hand, it is also required to consider the improvements that can be gained from an energy efficiency point of view.
—*Decision framework*: This can be a combination of other solution types or implemented as a stand-alone solution. It provides a framework to make static/dynamic decisions based on the information collected from the data center through a centralized/distributed method.

5.4. Results Regarding *Technology*

The ideal situation for a primary study is to propose a solution with high level of generality that can be applied to any cloud-based environment. For the most part, our primary studies have suggested a general solution. Following studies have evaluated the proposed idea with a specified IT infrastructure, such as a certain type of device or network architecture. We define technology as the implementations used to make the solution perform, not the specification details in the evaluation phase. Tables V through VII detail the technologies that implement the *Device*, *Routing/Switching*, and *Network architecture* solution types.

5.4.1. Device Technologies. Table V indicates the technologies implementing the *Device* solution type. The Type column illustrates the device methods in *italic* to be unlike other columns showing the primary studies codes. Two methods are suggested for the network devices: either replacing the current devices with optical ones or improving the current ones to be energy aware. Optical devices are used in 8 out of 10 technologies. Optical networks are recognized as a remarkable alternative to traditional transfer networks; thus, in cloud-based environments, benefitting from the energy efficiency features of optical devices has been attempted. Different kinds of optical routers, optical switches, and other optical devices are examined to explore the potentiality of data centers to be more energy efficient. For example, Cerutti et al. [2013] has suggested space-time interconnection optical devices for data center network architectures. The applied optical technologies are not invented by our primary studies, but they are adapted in a smart way to minimize the energy consumption of data centers in different scales.

There are two implementations focused on improving the current electrical switches (#9 and #10). The main idea with these technologies is to make use of fewer numbers of ports in a switch to reduce energy consumption. The incoming traffic load can be distributed into fewer numbers of output ports according to their utilization factors.

Table V. Technologies Implemented for the *Device* Solution

Number	Technology	Scale	Description	Type	Primary Studies	OCR
1	*Optical interconnect devices*	Intra	This technology refers to all devices used in optical networks, such as Couplers, SOAs, WSSs, and MEMS-switches.	*Optical*	[Glesk et al. 2013; Kachris and Tomkos 2013]	2
2	*Using optical switches for "IP over WDM" backbone network*	Inter, Mixed	This technology is used to reduce the energy consumption of transfer networks. "IP over WDM" networks make use of optical bypasses, which aggregate the incoming traffic from access routers and send it to light paths. This technology is suggested for inter–data center networks.	*Optical*	[Kantarci et al. 2013; Kantarci and Mouftah 2012]	2
3	*Hybrid optoelectronic router*	Intra	The "Hybrid optoElectronic router" performs a combination of optical and electrical switching technologies. It contains a shared buffer, which can be investigated to provide different services in optical packet switched networks, such as multicast and QoS. This technology is used in combination with other solution types, such as *Network architecture* and *Routing / Switching*.	*Optical*	[Kitayama et al. 2013]	1
4	*Cyclic arrayed waveguide grating (CAWG)*	Intra	CAWG plays the role of aggregation switches in the optical network architecture. It routes the incoming wavelengths to the output ports.	*Optical*	[Ji et al. 2012]	1
5	*WDM-OFDM ToR Switches*	Intra	These switches are used in optical network architectures as an alternative to conventional switches.	*Optical*	[Ji et al. 2012]	1
6	*STIA*	Intra	Space-time optical interconnection architectures introduce new optical switching technologies. They are more scalable and more energy efficient than other optical switches. They do the switching procedure using space and time domains.	*Optical*	[Cerutti et al. 2013]	1

(Continued)

Table V. Continued

Number	Technology	Scale	Description	Type	Primary Studies	OCR
7	*Using optical devices for WDM PON*	Intra	To create a "passive optical network," extra optical devices are needed to keep the network up and running. Optical WDM Transceivers and arrayed waveguide grating routers (AWGRs) are some examples of deployed optical devices.	*Optical*	[Kachris and Tomkos 2011]	1
8	*Optical cross connects (OXCs)*	Intra	In some layers of network architectures in data centers, this technology is used to implement an optical network. OXCs primarily are used to reconfigure the wavelengths according to bandwidth demands.	*Optical*	[Tarutani et al. 2012]	1
9	*eAware Ethernet switch*	Intra	Using this technology, switches and their ports are put in the idle state based on their queue length and utilization percentage of the device to save energy.	*Electrical*	[Si et al. 2012]	1
10	*"Merge network" switch*	Intra	This technology emphasizes on the traffic aggregation into fewer numbers of output ports based on the utilization rate of ports.	*Electrical*	[Carrega et al. 2012]	1

The idle ports, and gradually the switch itself, can be put in sleeping or low-power mode. The *Merge Network* switch (#10) not only deactivates idle ports but also tries to increase them by traffic aggregating methods. The advantage of these implementations is that energy awareness is distributed all over the data center network, and each switch makes locally optimum decisions (performing as greedy algorithms). In addition, there is no single point of failure in this system. However, from a distributed and holistic perspective, these local optimizing solutions might introduce some overhead in delay and other efficiency factors and might not end to the most energy-efficient set of active ports in the data center. These two technologies are suggested as stand-alone solutions, but other device technologies can be used in combination with other solution types, such as decision frameworks. In total, 14% of the primary studies propose a stand-alone device solution.

5.4.2. Routing/Switching Technologies. Table VI describes all of the technologies regarding the *Routing / Switching* solution type. Primary studies investigated on this solution type propose algorithms/protocols by which data center VMs will be able to communicate in an energy-efficient manner. There is a diverse range of ideas displayed in the table that differ in several aspects, such as the target network layer and the purpose of use. For example, Green VLAN (#7) is a specific implementation for layer 2 in the OSI model, whereas ECMP (#2) details a multipath routing protocol for layer 3 in the OSI model. Most technologies go for layer 3 rather than layer 2, and only two out of eight technologies are implemented for layer 2 (Green VLAN and ExP).

Two types of *Routing / Switching* technologies are proposed in the primary studies. They are shown in the Impact column of the table in the *italic* format to show their dissimilarity to other columns, which illustrate the codes emerged from the primary studies:

—*Direct*: The *Routing / Switching* technology is not used along with other solutions and it provides energy efficiency improvement in the networking component itself as a stand-alone solution. The improvement may come from either the least energy consuming routes or transferring the traffic through fewer numbers of network devices.
—*Indirect*: The *Routing / Switching* technology is used in combination with other solutions, and it does not necessarily need to be an energy-aware protocol. For example, the energy consumption–related decisions can be delegated to a decision framework, and the routing protocol performs as it did before. That is why we see ECMP in the table, which is a non–energy-aware routing protocol. Our primary studies show that *Routing / Switching* technologies have been used in combination with the *Device* and *Decision framework* solution types.

Another reason to make use of non–energy-aware *Routing / Switching* algorithms is because they are so widely used in the cloud-based environments. In this case, the primary study aims to increase the energy efficiency of a cloud-based environment while having existing non–energy-aware technologies deployed. Therefore, an energy-aware decision-making component is added to the system as a decision framework, which manages all energy efficiency–related concerns.

Moreover, the best energy-efficient route set is always changing because of real-time changes in the incoming load traffic. Some primary studies, such as the one proposed by Fang et al. 2012], make use of traffic patterns, which include information regarding the traffic flows in the data center to make energy efficiency–related decisions.

EAR technology [Shang et al. 2010] is one of the most frequently deployed algorithms in our list. This algorithm makes a trade-off between energy efficiency and other efficiency factors based on the quality requirements. The idle networking devices are

Table VI. Technologies Implemented for the *Routing/Switching* Protocols Solution

Number	Technology	Scale	Description	Impact	Primary Studies	Occurrence
1	*Energy-aware routing (EAR)*	Intra	In the EAR protocol, the number of switches and links will be minimized. Considering that the energy efficiency and other efficiency factors (e.g., performance and network delay) have an inverse relationship, in this protocol the eliminating process of network devices goes on until the network throughput decreases to a prespecified threshold value. Thus, the energy efficiency in the data center networks is achieved, and the network throughput threshold is not violated.	*Direct*	[Shang et al. 2012, 2010, 2013]	3
2	*Equal-cost multipath (ECMP)*	Intra	The ECMP routing protocol's focus is to make use of several routing paths that have equal costs. The forwarding decisions on sending the data through more output ports, are made by each routers. In data centers, which provide richly connected network architectures, ECMP is used to distribute the load over multiple paths and also increase the total bandwidth for that flow.	*Indirect*	[Si et al. 2012; Fang et al. 2012]	2
3	*Shortest path*	Intra, Inter	According to this routing algorithm, the shortest path between two nodes is always selected.	*Indirect*	[Dong et al. 2013; Buysse et al. 2011]	2
4	*Energy-efficient routing (EER)*	Intra	The idea with the EER algorithm is to use the minimum number of aggregation/core switches in a data center based on the traffic load at a specific time interval. In addition, by using multipath routing, the traffic flows will be load balanced among chosen network devices.	*Direct*	[Wang et al. 2013]	1
5	*Max-Flow Min-Energy*	Inter	Using this technology, the data transfer among remote data centers is done by aggregating the traffic flows as "trunks" and then routing them through the least energy consuming paths.	*Direct*	[Szymanski 2013]	1
6	*High-performance routing (HPR)*	Intra	The key idea behind HPR is to provide the highest network throughput for each flow. The procedure is done in steps. First, the routing paths for each flow are identified. Then, the paths with the lowest number of assigned flows will be selected. Thus, depending on the order of processed flows, the final set of routing paths will vary.	*Indirect*	[Shang et al. 2012]	1

(Continued)

Table VI. Continued

Number	Technology	Scale	Description	Impact	Primary Studies	Occurrence
7	*Green VLAN*	Intra	This technology tries to organize VLANs in a more energy-efficient way. It starts by checking out each VLAN's impact on energy consumption according to some constraints (e.g., the number of hosts belonging to that VLAN and the load of broadcast traffic in that VLAN). If they do not satisfy the requirements, they will be split into several VLANs. Therefore, each two hosts are ranked based on the amount of traffic between them and the path linking them together. According to calculated rankings, new VLANs are categorized.	*Direct*	[He et al. 2012]	1
8	*Express path (ExP)*	Intra	ExP is a routing method introduced for optical networks; the routing process takes place based on flows, not packets. Considering that all packets of a same flow contain the same values of identification parameters, such as source address, source ports, destination address, and destination ports, routing only the first packet of each flow would be sufficient and the rest of the packets would follow the same route.	*Indirect*	[Kitayama et al. 2013]	1

eliminated gradually in steps; in each step, checks are made to determine whether or not the output network still responds to the expected throughput.

As shown in Table VI, the *Routing / Switching* technologies are mostly targeted for the intra–data center scale; the however, inter–data center scale has received attention as a stand-alone *Routing / Switching* solution recently. *Max-Flow Min-Energy* technology [Szymanski 2013] is an example of an inter–data center solution.

5.4.3. Network Architecture Technologies. Given the high number of servers and switches in data centers, it is important to design a network architecture in a flexible way, which makes the environment able to provision services even in the presence of a quick bursty incoming load. Table VII presents the network architectures studied in our primary studies.

Currently, many richly connected network architectures are deployed in data centers, such as FatTree, BCube, VL2, and DCell. As the table shows, FatTree is the most widely investigated topology in our primary studies. It is a popular, regular, symmetric, and scalable network architecture. The organization of network devices in FatTree is based on a switch-centric approach, providing three layers of switches: core, aggregation, and ToR. Figure 3 shows a FatTree network architecture with four-port switches.

The primary studies illustrate that both *Device* and *Decision framework* solution types are implemented in combination with the *Network architecture* solution. FlattenedButterfly and Hybrid WDM PON network architectures [Cerutti et al. 2013; Kachris and Tomkos 2011; Carrega et al. 2012] are examples of the *Network architecture* solution types used in the *Device* solution type. The *Network architecture* solution type most commonly is used as a supporting role along with the *Decision framework* solution type. Only two primary studies focus on network architecture as a stand-alone solution [Cerutti et al. 2013; Ji et al. 2012]. Extracted from the table, 6 out of 14 network architectures are specialized for optical interconnections. Although this number is almost half of the total number of identified technologies for this solution type, this ratio is not seen in the number of primary studies providing optical technologies, because the energy efficiency in optical data center networks is nearly optimum, which is difficult to exceed. The *Network architecture* technologies are proposed only for the intra–data center scale because of different ownerships and maintenance methods in each domain.

5.4.4. Decision Framework Technologies. The *Decision framework* solution type can be a combination of other solution types or implemented as a stand-alone solution. The main idea with decision frameworks is to control energy consumption of the networking component by collecting relevant information from different components. Each decision framework follows a specific approach, and other solutions and technologies are selected accordingly. In addition, decision frameworks differ in the permutations of other selected solution types. We categorize the approaches taken by decision frameworks as follows:

—*Traffic engineering*: To minimize the energy consumption of the networking components, decision frameworks following this approach try to shape the network load. Decision frameworks collect and correlate context-dependent information as a basis for making static/dynamic decisions. Based on how the TE is done, different types of strategies would be realized. For example, Ji et al. [2012] propose a decision framework that collects the statistical information from network switches. Then, with regard to the utilization rates, a network subset with minimum number of networking devices and minimum needed capacity is selected to transfer the traffic. In this case, the traffic is consolidated and the idle networking devices are deactivated, which means that “Sleeping mode/Switching off” and “Traffic consolidation”

Table VII. Technologies Implemented for the *Network Architecture* Solution

Number	Technology	Scale	Description	Primary Studies	Occurrence
1	*FatTree*	Intra	The FatTree network architecture is a switch-centric physical topology, richly connected, and scalable. In this architecture, the network switches are classified in three tiers: core, aggregation, and ToR. If n shows the number of ports in a switch, in a FatTree architecture there will be $(n/2)^2$ core switches with n ports and n pods with n switches having n ports ($n/2$ aggregation switches + $n/2$ ToR switches) [Gyarmati and Trinh 2010].	[Shang et al. 2012; Wang et al. 2013; Cerutti et al. 2013; Liu et al. 2013; Heller et al. 2010; Thanh et al. 2012; Shang et al. 2010; Dong et al. 2013; Shirayanagi et al. 2013; Gyarmati and Trinh 2010; Jin et al. 2013; McGeer et al. 2010; Fang et al. 2013]	13
2	*BCube*	Intra	The BCube network architecture is a server-centric physical topology that can easily be extended in a recursive manner. If k shows the level number and n shows the number of ports in a switch, then BCube(k) consists of n BCube(k –1) architectures that are connected by n switches having n ports [Ling et al. 2012].	[Shang et al. 2012; Gyarmati and Trinh 2010; Huang et al. 2011]	3
3	*VL2*	Intra	The VL2 network architecture is a switch-centric physical topology. There are bipartite-like connections between core and aggregation switches in this topology. VL2 uses load balancing techniques (valiant load balancing) to distribute the load from aggregation switches to core switches.	[Mann et al. 2011; Fang et al. 2013]	2
4	*FlattenedButterfly*	Intra	The main idea with this network architecture is to minimize the number of hops for each route. It is scalable and can be extended in a recursive manner. As noted previously, this topology is recognized to be more energy efficient than FatTree [Carrega et al. 2012].	[Cerutti et al. 2013; Carrega et al. 2012]	2
5	*DCell*	Intra	DCell is an example of a server-centric data center network architecture that can be extended in a recursive way. If k shows the level number and $n(i)$ shows the number of servers at the ith level, then DCell(k) consists of $(n(k-1)+1)$ DCell(k –1) architectures that are connected only through servers.	[Gyarmati and Trinh 2010]	1
6	*BalancedTree*	Intra	In BalancedTree, there is only one switch, as root have n ports. The idea behind this architecture is to distribute the servers between switches uniformly, which all are similar in number of ports. The resulting topology looks regular and symmetric, but it has the possibility of a single point of failure.	[Cerutti et al. 2013; Gyarmati and Trinh 2010]	2

(Continued)

Table VII. Continued

Number	Technology	Scale	Description	Primary Studies	Occurrence
7	*VL2N-Tree*	Intra	The VL2N-Tree network architecture is a combination of traditional network architecture 2N-Tree and VL2. Thus, there is a bipartite graph between core switches and aggregation switches, and the rest of the connections (among aggregation switches and ToR switches and servers) follow the rules of a 2N-Tree data center network architecture.	[Fang et al. 2013]	1
8	*Generalized Flattened Butterfly*	Intra	Generalized flattened butterfly is a hierarchical extendible network architecture that tries to benefit from the "minimum hop" feature of the FlattenedButterfly network architecture and the "high bandwidth" feature of the DCell network architecture.	[Tarutani et al. 2012]	1
9	*Hybrid WDM PON*	Intra	The main focus of this network architecture is to replace all interrack links with optical interconnects in a FatTree architecture. In this scenario, aggregation switches are set as Optical Link Terminators, and ToR switches are used as Optical Network Units.	[Kachris and Tomkos 2011]	1
10	*MIMO OFDM optical*	Intra	In a MIMO OFDM data center network architecture, traditional ToR switches will be replaced with WDM-OFDM ToR switches and all aggregation switches will be replaced with one CAWG, which does the routing procedure in a cyclic manner.	[Ji et al. 2012]	1
11	*Torus*	Intra	Torus provides a three-dimensional network architecture; in each dimension, all switches are connected together. It is linearly scalable and has low latency.	[Kitayama et al. 2013]	1
12	*AWG-based architecture*	Intra	The AWG-based architecture is a kind of optical network architecture that makes use of AWG to route incoming wavelengths to output ports. Different versions of this architecture have recently been introduced.	[Kachris and Tomkos 2013]	1
13	*WSS-based architecture*	Intra	Each ToR switch sends out its traffic using optical transceivers to upper layers, namely MEMS switch.	[Kachris and Tomkos 2013]	1
14	*Broadcast and select (B&S) architecture*	Intra	The B&S architecture is another example of an optical data center network architecture that provides low delays.	[Kachris and Tomkos 2013]	1

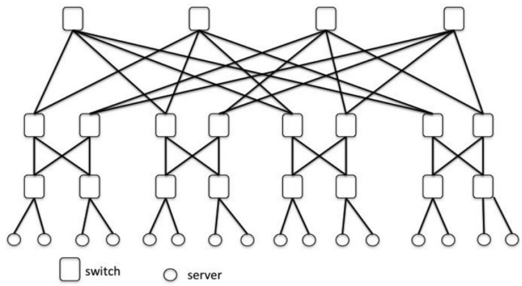

Fig. 3. A FatTree network architecture with four-port switches.

strategies are realized. In a different manner, in NESS [Fang et al. 2012] we see that network devices are put into sleeping mode according to prelearned traffic patterns, which shows that "Sleeping mode/Switching off" and "Traffic patterns" strategies are realized.

—*VM assignment/migration*: Using this approach, decision frameworks try to place/reallocate the VMs to aggregate them into fewer numbers of physical machines. In the VM migration process, the networking component is involved by decision frameworks. The "VM consolidation" strategy is realized by these types of decision frameworks. To provide an energy-efficient networking solution, this approach is used along with TE and routing.

—*Routing*: According to this approach, decision frameworks try to choose the best routing paths, which are the routes with the minimum energy consumption based on the big picture received from the collected energy information. The routing decisions can also be made using an overlay virtual network, which abstracts physical links in virtual links to provision network services at maximum energy efficiency. This approach is aligned with the "Energy-aware routes" strategy. For instance, DCe-CAB [Peoples et al. 2011] is a decision framework for the inter–data center scale and places VMs in different data centers. A data center is selected if not only the energy consumption of the data center satisfies quality requirements but also the routing path to that specific data center has the minimum number of networking devices involved and the maximum efficiency in quality requirements (minimum delay, minimum energy consumption).

Decision frameworks can follow more than one approach. One more remark is that decision frameworks can be scaled up for large-scale cloud-based environments. Intra–, inter–, and mixed–data center scales can be supervised by decision frameworks from an energy efficiency perspective. Overall, in the case of large-scale cloud-based environments, the *Decision framework* is an excellent choice because of its management possibilities for a network of heterogeneous data centers.

5.5. Results Regarding *Energy Efficiency Evaluation*

Each proposed energy-efficient networking solution has to be evaluated and analyzed. Primary studies present the energy-saving results for each solution while calculating the impact on other efficiency factors, such as network delay and network throughput. It is not a trivial task to measure, model, and optimize energy consumption of large-scale data centers. Therefore, 72% of experiments have been done in simulations. Table VIII represents all of the methodologies used for energy efficiency evaluation process and also specifies the corresponding scale of the studied cloud-based environment.

Every evaluation method has its limitations and advantages. Using more than one evaluation method could help derived conclusions be more concrete. For instance, Jin

Table VIII. Energy Efficiency Evaluation Methods Identified in Primary Studies

Number	Energy Efficiency Evaluation Method	Scale	Description	Primary Studies	Occurrence
1	*Simulations*	Intra, inter, mixed	There are plenty of simulators used to simulate cloud-based environments. Simulations become even more convenient when the implementation of a solution does not yet exist. For example, in the case of improving current network switches, it can be programmed in simulational experiments first.	[Shang et al. 2012; Si et al. 2012; Wang et al. 2013; Tarutani et al. 2012; Peoples et al. 2012; Aksanli et al. 2012; Wang et al. 2012; Liu et al. 2013; Peoples et al. 2011; Shang et al. 2010; Kitayama et al. 2013; Cordeschi et al. 2013; Dong et al. 2013; Mahadevan et al. 2009; Leivadeas et al. 2013; Saha et al. 2012; Sun et al. 2012; Shang et al. 2013; Xu et al. 2013; He et al. 2012; Shirayanagi et al. 2013; Gyarmati and Trinh 2010; Kantarci et al. 2012; Jin et al. 2013; Szymanski 2013; Fang et al. 2012; Mahadevan et al. 2011; McGeer et al. 2010; Kantarci and Mouftah 2012; Huang et al. 2011; Kachris and Tomkos 2011; Carrega et al. 2012; Mann et al. 2011; Fang et al. 2013]	34
2	*Empirical experiments in small scale*	Intra, inter	In this methodology, the experimental setup is prepared in hardware testbeds in small scales. The number of nodes and links in this kind of setup is much lower than what is being used in reality.	[Cerutti et al. 2013; Buysse et al. 2011; Wang et al. 2012; Heller et al. 2010; Thanh et al. 2012; Jin et al. 2013; Nguyen Huu et al. 2013; Mahadevan et al. 2011]	8
3	*Numerical analysis*	Intra, inter	In numerical analysis, the output results from literature study are used as a reference for the reasoning process.	[Glesk et al. 2013; Kachris and Tomkos 2013; Kuribayashi 2012]	3
4	*Empirical Experiments in production data centers*	Mixed, intra	The best way of evaluating a solution is to implement it in real-world scenarios. By using data centers to analyze the solution, the results would be more realistic and accurate. However, it is not always easy to get a production data center for this purpose.	[Kantarci et al. 2013; Ji et al. 2012]	2

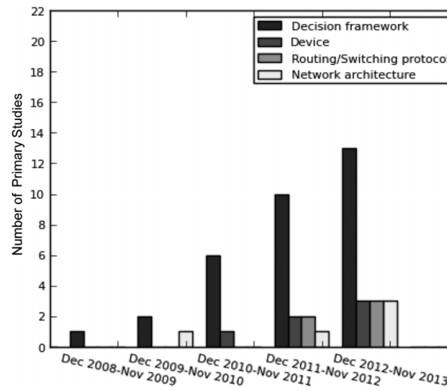

Fig. 4. Yearly distribution of each solution type from December 2008 to November 2013.

et al. [2013] evaluate their decision framework in both simulations and empirical experiments.

Primary studies also have shown how much they have gained in terms of improvement in energy efficiency. eAware [Si et al. 2012], as a modified version of the Ethernet switch and as an example of the device solution type, can save the total energy consumption of network switches from 30% to 50% while introducing only a 3% to 20% increase in the end-to-end packet delay. The proposed MIMO OFDM DCN architecture [Ji et al. 2012] has been evaluated by means of large-scale empirical experiments, and it can provide up to 25% energy efficiency improvement compared to the equivalent network architecture with commodity electrical switches. The GreenDCN decision framework [Wang et al. 2013], an intra–data center scale solution, introduces the energy savings of the networking component up to 50%.

The ElasticTree decision framework [Heller et al. 2010], a pioneer in making use of the OpenFlow technique in 2010 for energy efficiency improvements on the networking component (more detail in Section 6), is able to save the energy consumed by the networking component by 25% to 40%.

6. DISCUSSION

To discover the trends in energy-efficient networking solutions, we have split the articles into five yearly periods (the last period being "Dec 2012-Nov 2013").

As seen in Figure 4, the topic has been brought up from late 2008, with an increasing number of primary studies each year to testify to a growing interest. We can also see that the greatest attention has been paid to decision frameworks. Although the other three solution types (*Device*, *Routing/Switching*, and *Network architecture*) are proposed less often, they still have an increasing trend.

The very first article on this topic is a decision framework from the first time period for the intra–data center scale [Mahadevan et al. 2009]. Initially, decision frameworks were the most natural solution: they simply required extensions to existing optimization frameworks, where the energy efficiency was an additional quality requirement. The continuous attention to decision frameworks in the course of the years is due to their flexibility: they provide a global insight and collect relevant information from all over the data center. They allow one to make accurate energy-related decisions according to correlated information.

Figure 5 shows the yearly distribution of solutions at different scales. We see that the research done within one data center is still the main focus of studies, partly due to the easier manageability of these environments. Research on the inter–data

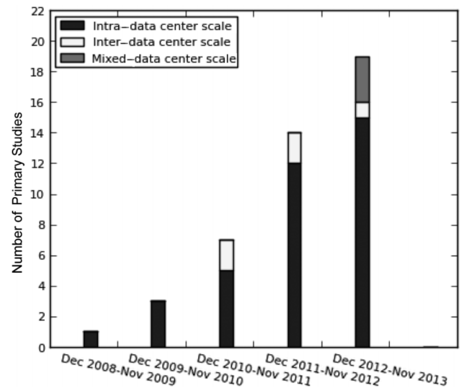

Fig. 5. Yearly distribution of solutions in different scales from December 2008 to November 2013.

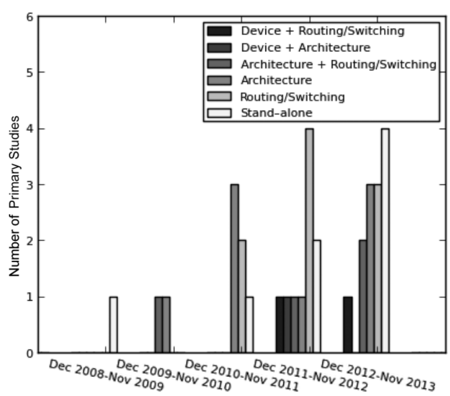

Fig. 6. Yearly distribution of solution types used in decision frameworks from December 2008 to November 2013.

center scale started in December 2010, whereas solutions for the mixed–data center scale were introduced in December 2012. Achieving energy efficiency in these scales is basically more challenging. Due to the emergence of new business models and new requirements for energy efficiency, we expect to see a growing interest in large-scale solutions, especially mixed–data center scale, in the coming years. This will likely result in a decreasing interest in pure interdomain solutions; this trend is already visible in Figure 5.

Decision frameworks can use other solution types in their implementation. We determine different permutations of solution types used by decision frameworks. Figure 6 shows that over the course of years, decision frameworks become more diverse. We also see that *Routing / Switching* is the most widely deployed solution type, both individually and in combination with others. The next most frequent solution type is the *Network architecture* solution, usually with FatTree implementation. The *Device* solution type is instead adopted in only three decision frameworks. The combination of *Device* and *Routing / Switching* solutions appears twice in our studies, and it is used in large-scale cloud-based environments, concentrating on optical “IP over WDM” backbone networks.

There are some decision frameworks that are not a combination of other solution types. We call them “stand-alone” decision frameworks. Stand-alone decision

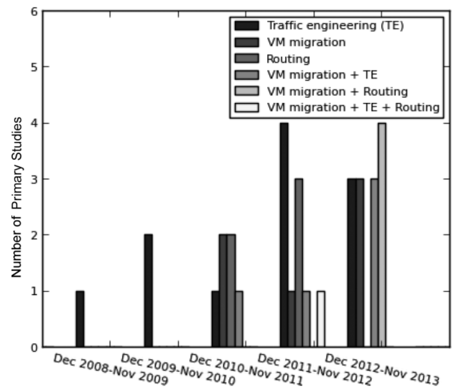

Fig. 7. Yearly distribution of approaches used by decision frameworks from December 2008 to November 2013.

frameworks target non–energy-aware infrastructures. They deploy other techniques to collect the required information and take action.

For example, they might use traffic pattern information to make more accurate decisions on putting network devices in sleep mode. Figure 6 shows an ascending trend for stand-alone decision frameworks in previous years.

Figure 7 displays how decision frameworks use different approaches to improve the energy efficiency of data centers. We recall from Section 5.4 that decision frameworks can use different approaches: TE, VM assignment/migration, and routing. From the figure, we see that the TE approach is the one used most frequently, both individually and with others. In addition, VM migration frequently is used, as minimizing the network traffic by grouping VMs into fewer numbers of physical machines implicitly reduces the energy consumption of the networking component. The VM migration process can include application dependencies as well.

Using the approaches only focusing on the networking component or the computation domain has a risk of missing all required information. Combination of the VM migration approach and one or two of the networking-related approaches (either TE or routing) in decision frameworks provides a broader view of changes that need to be made in cloud-based environments. That is why the combination of “TE + VM migration” and “Routing + VM migration” recently have been the most widely used approaches. Interestingly, the number of decision frameworks using only the routing approach dropped to zero in December 2012, when the combination of “VM Migration + Routing” approaches were introduced.

Decision frameworks additionally make use of other supporting techniques to implement approaches. Supporting techniques help them extend their collected information domain and improve the efficiency of taking action. Programmability of the networks and traffic pattern discovery are some of the example techniques used by decision frameworks. The network traffic originating from applications will produce a traffic pattern. By taking this collectable information into account, it will be clear at any given time what decision would fit the best according to the distribution of traffic load.

Decision frameworks benefit from programmability of the software-defined networks. These networks can be programmed because the data plane and control plane of the network switches are separated. An external controller will do the “updating flow table” process for each switch. Software-defined networking protocols, namely OpenFlow, make the communication between the controller and the OpenFlow-enabled switches possible. Using OpenFlow, the controller is able to schedule flows dynamically/statically

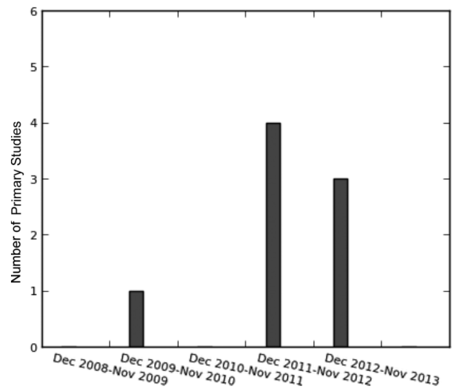

Fig. 8. Yearly distribution of the OpenFlow technique adoption by decision frameworks from December 2008 to November 2013.

between the network switches. Decision frameworks deploy the OpenFlow technique to apply required dynamic changes in data center networks by means of the OpenFlow controller.

We have eight primary studies providing solutions for the intra–data center scale that investigate the OpenFlow technique to flexibly control the traffic and operate the flow scheduling. The TE approach is followed in six out of eight decision frameworks, and the rest investigate the routing approach. Figure 8 shows that decision frameworks made use of the OpenFlow technique for the first time in early 2010. Recently, the use of this technique has increased remarkably, and we expect it to grow even more in coming years.

7. THREATS TO VALIDITY

There are some uncontrolled elements that could change the conclusions that we draw and threaten the accuracy and validity of our findings. The potential validity threats to our study are as follows:

(1) *Subjective analysis*: Since the study selection phase primarily is conducted by one researcher, there might be possibilities of biased subjectiveness in finding primary studies. Defining extensive and clear selection criteria through a systematic protocol helps to mitigate this threat.
(2) *General applicability*: Another threat to our study is the generality of identified solutions and the extent that they can be applicable to cloud-based environments. We included peer-reviewed and published research. Of course, this does not mean that works from industry are not relevant; on the contrary, we are planning a follow-up study using the same research question to survey the state of practice to discover if both domains are aligned together. Despite our academic focus, we have observed that 17% of the primary studies have authors from industrial affiliations. This suggests some nonnegligible mingling of academic research and industrial solutions. On the other hand, the evaluation phase of our primary studies most commonly makes use of industrial-driven datasets.

8. EMERGING RESEARCH DIRECTIONS

We have analyzed the primary studies to discover the direction of current research. Next, we list some of the future challenges and opportunities that we have identified:

—*Decision frameworks*: Our findings show that there has been an increasing focus on this solution type, and we expect to see even more evolvement of decision frameworks in the coming years. Not only are they able to apply other solution types, but they also can benefit from information collected by higher-level components in the data center. For example, decision frameworks can make energy-efficient decisions based on the behavior of applications in the environment. In addition, we have seen more attention paid to stand-alone decision frameworks recently, and expect even more because of the accurate data that can be collected from the application layer.

It is interesting to note that decision frameworks have evolved from one-aspect approaches to multiple-aspect approaches to get data as accurate as possible from the components. Therefore, the combinations of "TE + VM migration" and "Routing + VM migration" approaches have higher chances of be investigated.

—*Large-scale cloud-based environments*: Large-scale environments have increasingly been getting attention. However, energy-efficient solutions in large-scale environments are challenging to implement and evaluate. Therefore, academia and industry can collaborate more on the infrastructure provisioning aspect.

—*Software-defined networking*: According to the Gartner report, which has provided emerging trends in *Telecommunications Industry* [Bhatia 2014], the SDN field is in the "Sliding into the Trough" phase of *Hype Cycle*. As the author defines this phase, there is still time for SDNs to become mature. Our results show the increasing importance of SDNs in data centers, as SDN is the key to shorten the distance between hardware and software in cloud-based environments. This feature can help decision frameworks to significantly gain accurate information from the networking component and running applications.

9. CONCLUSION

This literature review outlines the state of the art in energy-efficient networking solutions in cloud-based environments. An original contribution of our effort is that for the first time in this research field, we have followed an SLR method to be as objective as possible in our selection of primary studies. By including the SLR protocol, the article provides the necessary instruments to replicate the study in the future or eventually extend it to cover new research, such as "smart green networks." In the latter case, it would require extending the query. For the example research identified earlier, this would require the inclusion of "smart" as a keyword.

All of the primary studies that we have analyzed clearly demonstrate a growing attention to the problem and a lively and dynamic research space. Our findings show that the *Decision framework* is the most frequently investigated solution type to accomplish the energy efficiency goal. Decision frameworks that have emerged over the years reflect a continuous increase in number and diversity. The most promising approaches used by decision frameworks are combinations of the VM migration computation-related approach and the TE and routing network approaches. The main advantage of decision frameworks compared to other solutions is their ability to use other supporting techniques, such as programmability of networks and traffic pattern discovery.

Another important observation is that although most of the primary studies target solutions for the intra–data center scale, we have seen an increase in the number of large-scale solutions, namely inter– and mixed–data center solutions.

We expect that the focus on using network programmability in large-scale environments will continue to grow in the coming years as a response to the increasing size of cloud-based environments. According to Gartner research in 2014 [Bhatia 2014], the SDN field will be at the phase of "Plateau of Productivity" in 5 to 10 years, which is a confirmation of our conclusion about the growing attention to this topic. However, it needs to be investigated and proved whether SDNs can provide higher energy efficiency in the data centers.

As future work, we aim to examine to what extent SDNs can be deployed in large-scale data transfer networks (mixed– and inter–data center scale) to make accurate energy-related decisions.

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Received July 2014; revised December 2014; accepted February 2015