Environment Friendly Energy Efficient Distributed Data Centers

Ahsan Ali and Oznur Ozkasap

Abstract Geographically distributed data centers form a significant technology used by the Internet users to fulfil the demand of storage, processing and large scale computations. Most of the operational cost of such data centers is due to the electricity cost, which affect both service providers and consumers. In this paper, we addressed the problem of energy consumption of data center entities and reviewed state-of-the-art solutions proposed to reduce the electricity cost. We present the full view of the problem by providing the widely used energy consumption and/or operational cost models. We identified key characteristics of efficient techniques proposed for reduction of the electricity cost, carbon emission and financial penalties in case of SLA violations. These techniques include environment friendly cost minimization, energy efficient load migration, job scheduling and resource allocation. We also identified open challenges as guidelines for future research.

Key words: distributed data centers, environment friendly, energy efficient.

1 Introduction

In the present era of technology, cloud data centers are becoming more popular due to the features such as on demand computing resources, user only pay for what they use, multiple users can use the same physical infrastructure, and high computational power. Cloud Service Providers (CSP) are responsible for managing and allocating resources, Scheduling of tasks, power consumption optimization and management of network traffic. The operational cost in data center is affected by the power consumption. A data center's 30-50% operational cost consists of electricity bills [1].

To reduce the energy cost, different techniques have been proposed, that includes use of energy efficient servers, server consolidation by moving virtual machines (VM), using renewable energy sources such as solar, wind, wave, tidal with traditional electricity grid power, exploiting the temporal and geographical variation of electricity prices. There are two different charging schemes being used in electricity market of US: retail pricing and wholesale pricing. In retail pricing, electricity prices are announced in advance and remain constant for a certain period, while in

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wholesale market electricity prices vary on 15 minutes to one hour basis. Different geographical locations and regions exhibit different price variations on daily as well as hourly basis. Therefore, geographically distributed nature of data centers and the spatio-temporal variation of prices is being used by researchers to minimize the energy cost.

We group cost minimization techniques for distributed data centers into four categories (Table 1), identify key characteristics in each category along with the proposed solutions, and discuss open challenges. These aspects distinguish our review in comparison to the previous studies. For instance, green energy aware power management problem for data centers is investigated in [2]. Another prior work [3] focuses mostly on reducing the losses and wastage of electricity by supporting subsystems in data center for minimizing the cost, while [4], [5] focus on energy consumption of data center networks.

Table 1 Characterization of cost minimization techniques

Category	Description
Environment Friendly Cost Minimization	Encouraging use of renewable energy sources for power generation
Energy Efficient Load Migration	Migrating load from higher electricity price to cheap electricity price data centers
Energy Efficient Job Scheduling	Utilizing spatio temporal variation of electricity prices
Energy Efficient Resource Allocation	Efficient allocation of data center resources and using energy efficient entities

2 Modelling of Energy Consumption

In the system model, we assume a CSP with M geographically distributed data centers consisting of N servers in each. There exist K regions generating λ requests with deadline restriction μ agreed in the SLA. Each request is initially received by a front-end server or scheduler, which assigns the request to a server in a particular data center. The unit price of the electricity in location of data center M_j is expressed as α_j. Total electricity consumed in M_j is the summation of energy consumed by the servers, energy consumed by the cooling systems and the energy consumed by the network elements. Electricity generation from carbon-intensive fossil fuels is expensive due to high fuel prices and carbon emission taxes. While green energy sources are cheap but highly unpredictable for the unexpected load spikes.

Power usage efficiency (PUE) is a benchmark for calculating the power efficiency of a data center, which is defined as the ratio of overall power consumption to power consumed for performing actual computation by different entities of data centers. Usually the value of PUE is between 1 and 2, the lower the value of PUE the better is the energy efficiency. [6] modelled the power consumption of a server S_i as:

$$Po_i = P_{idle} + (P_{peak} - P_{idle}) \text{ x } U_i$$

where P_{idle} is the average power consumed by the server when there is no operation being performed, P_{peak} is the power consumption of the server while running at full capacity and U_i is the utilization of S_i. The electricity cost of S_i can be calculated by the product of unit price of electricity and the total power consumed:

$$Es_i = Po_i \text{ x } \alpha_i$$

The cooling system of a data center is responsible for maintaining the temperature within a safety zone. [7] modelled the electricity consumption of a cooling system defined as the ratio of power consumed by active servers in data center M_j to the coefficient of performance (COP).

$$Ec_j = \frac{\sum_{i=1}^{i=N} Es_i}{COP}$$

Suppose the cost of transferring a single request from the scheduler to the data center is Rc. Electricity cost of network element for the data center M_j can be calculated as the product of the total number of requests being transferred to the data center and the cost of single request:

$$En_j = \lambda_j \text{ x } Rc$$

Total electricity cost of a data center with N servers can be calculated as the summation of individual electricity cost of all servers, network elements and overall cooling cost. Electricity cost of data center M_j can be represented as:

$$Etc_j = (\sum_{i=1}^{i=N} Es_i) + Ec_j + En_j$$

While providing the services, CSP needs to maintain the quality of service (QoS) mentioned in Service Level Agreement (SLA). QoS includes the fairness among users and the delay constraints. In case of any violation of the SLA, CSP faces a financial penalty which results in an additional cost for them.

3 Environment Friendly Cost Minimization

It is suggested that the carbon footprints in the process of electricity generation can be reduced by using the green reusable energy resources such as wind, solar, and hydro. Table 2 represents an overview of the research carried out to minimize the energy cost by using green energy sources with other constraints. *Workload prediction* techniques are being used to find out the future workload based on the previous requests and workload. *Latency* is also taken into consideration for SLA and QoS purposes, which refers to the time required to transfer the user request from user's end to the data center. *Queuing delay* refers to the time a user request waits before it is processed. As data centers host multiple users and applications, it is necessary that each user would get equal time for processing and *fair* resource allocation. *Server provisioning* is the technique to monitor the activities of servers in a data center to avoid overloading or under loading.

Table 2 Characteristics of Environment Friendly Cost Minimization

Methods	Workload prediction	Latency	Queuing delays	Fairness	Server provisioning	Carbon emission taxes
GLB [8]	×	✓	✓	×	✓	✓
FORTE [9]	×	✓	✓	×	×	✓
RHC/AFHC [10]	✓	✓	✓	×	✓	×
Green fair [11]	✓	✓	✓	✓	×	✓

The way geographical load balancing (GLB) can enhance the use of green renewable energy and minimize the use of carbon intensive fuels for electricity generation is explored in [8]. Two distributed algorithms for achieving optimal GLB are proposed and the feasibility of powering the data center entirely with on-site renewable energy source (i.e. wind or solar) is explored. It is shown that by efficient use of dynamic electricity pricing GLB provides significant reductions in brown energy use. This work jointly optimizes energy cost and delays keeping in consideration price diversity and network delay diversity. However, study of [8] ignores some aspects such as reliability and availability of on-site renewable energy sources.

A request routing framework named FORTE (Flow Optimization based framework for requesting-Routing and Traffic Engineering) is proposed in [9]. FORTE consists of three algorithms providing three way trade-off among electricity cost, access latency and carbon footprint. Although the work of [8] considered the cost for the carbon emission, [9] argues that the carbon emission taxes are negligible as compared to the overall cost of data center. However, the cost of carbon tax considered by [9] is less than 2% of overall electricity cost which is far less than the real carbon market [2].

On-line algorithms to minimize number of active servers in each data center to fulfill load requirement are suggested in [10]. Receding horizon control (RHC) is proposed to determine the minimum number of active servers by predicting the future workload for homogeneous data centers. It is shown that Performance of RHC is better for homogeneous environment, however it is also proved that in case of heterogeneous setting RHC performs poorly. Average Fixed Horizon Control (AFHC) is suggested for heterogeneous environment which guarantees good performance in such settings. This study also proposed the idea of powering the data centers entirely using green renewable energy sources.

A novel approach of using green renewable energy resources to minimize the queuing delays by scheduling the jobs to the data centers closer to the user is proposed in [11], which incorporates SLAs. The proposed green fair algorithm ensures fairness amongst the consumers providing the service capacity constraints and latency constraints. Optimal electricity, social and latency costs are sought within fairness constraints agreed in the SLAs.

4 Energy Efficient Load Migration

Techniques in this category investigate how much workload should be scheduled in the current time slot and how much to be put in a queue and move to another data center in a future time slot. In an event of price change of electricity, the user requests as well as VMs are moved to a data center with a cheaper electricity price. Table 3 characterises the main features of Energy Efficient Load Migration. Delaying the requests might lead to miss the deadline resulting an *SLA* violation and incurring financial penalty. The SLA penalties increase the overall cost for the CSP. *Bandwidth cost* is the network cost while transferring the user requests or VMs from one data center to another. *Load of data center* refers to the number of requests handled by the data center in the current time slot.

Table 3 Characteristics of Energy Efficient Load Migration

Methods	SLA Penalties	Workload prediction	Latency	Bandwidth cost	Load of data center
Efficient online algorithm [12]	×	×	×	✓	✓
Dispatcher/datacenter level sched. [13]	✓	×	✓	×	✓
CP-LNS [14]	×	✓	×	✓	✓
VR-HM [15]	✓	✓	×	✓	✓

An online algorithm for migrating batch jobs between data centers is proposed in [12]. The proposed solution considers multiple energy sources at each data center with continuous variation of prices and availability. Migration decision is based on current cost as well as the future uncertainty of electricity price and availability. Bandwidth cost, as an important factor in job migration is included in overall cost calculation.

A cost reduction off-line algorithm is proposed in [13] for assignment and migration of requests depending on the electricity price and load of data center. The theoretical information is then used to design an online algorithm for GLB, migration and error prediction. Performance of the suggested algorithm depends on the duration between price fluctuation and the quality of error prediction. This algorithm does not consider server provisioning, heterogeneity, and availability of the renewable sources.

By using the migration of VMs and outside temperature for reducing the cooling cost, a solution for cost minimization problem is proposed in [14]. Inter and intra data center migrations of VMs are used to reduce the cost by following the lowest energy price in the geographically distributed data centers. By using workload prediction, assignment of the VMs for the longer time frame is performed which reduces the migration cost.

A migration method for VMs, namely Virtual machine Resizing Heuristic Migration (VR-HM), to handle server failure and SLA is proposed by [15]. For tolerating the high failure rate in cloud environment, a heuristic migration model is presented for online migration of VMs between data centers by considering energy and deadlines constraints when failures occur. There is a local manager for each data center which monitors the utilization, fault occurrence and energy consumption of VMs, and issues orders for VM resizing and migrations.

5 Energy Efficient Job Scheduling

The aim of research in this category is to find the data center for processing user requests with minimum possible electricity cost. It is also necessary to meet the QoS constraint while scheduling the requests to data centers. Table 4 summarizes the main features of energy efficient job scheduling with the key common factors to maintain the QoS and minimize the cost. In order to reduce the cost, both *inter data center* and *intra data center* constraints should be considered. *Cooling cost* is also an important factor in the overall electricity cost of the data center.

Table 4 Characteristics of Energy Efficient Job Scheduling

Method	SLA Penalties	Data center load	Latency	Inter data center	Intra data center	Cooling cost
Distance constr. electr. price optimizer [6]	✓	×	✓	✓	×	×
Power trade / Surge guard [16]	×	✓	×	✓	×	✓
Brenner's alg. [17]	✓	✓	×	✓	×	×
Energy price driven dispatcher [18]	✓	✓	✓	✓	×	×
GreFar [19]	✓	✓	×	✓	×	×
Cheapest-DC/S [20]	✓	×	×	✓	×	✓
JET [7]	×	✓	×	✓	✓	✓

A latency and cost request dispatching policy is presented in [6]. This price aware optimizer observes the locational time-varying fluctuation of electricity prices and distributes the user requests to data centers with the cheapest price within a maximum radial geographical distance. While routing the requests to data centers, the algorithm uses two parameters: a distance threshold and a price threshold. Apart from reducing the electricity cost by dispatching the request to cheaper data centers, the scheduler also reduces the energy consumption.

Study of [16] optimizes the intra data center workload distribution for the efficiency of cooling system, and divides the data center into three temperature zones based on the airflow: hot, warm and cool. The hot zone requires more power to maintain the temperature as compared to the cool zone. Therefore, requests are assigned to servers accordingly to reduce the cooling cost. In order to reduce the overall cost, two schemes are proposed: power trade and surge guard. Power trade dynamically distributes the load between and within zones based on the temperature of each zone. Surge guard improves the response time of servers in case of an unexpected load spike, and uses server provisioning to meet the load requirements.

The electricity cost under multiple electricity market is aimed to be minimized in [17]. The problem is formulated as the minimum cost flow problem and Brenne's algorithm is used to find the solution in polynomial time. The algorithm assigns job requests according to the electricity prices, data center workload and it saves the energy consumption by keeping minimum number of active servers to meet the delay requirement.

An energy-price-driven dispatcher, that forwards the client requests to data centers with cheap electricity price and can meet the latency threshold, is presented in [18]. No request is assigned to the data center if the resource utilization exceeds 80% which is not being considered in [6]. The results are compared with the policy proposed by [6] and random dispatching policy, which show that in terms of cost the policy of [6] is more efficient but it may overload the cheapest data centers as it does not consider the load of data centers while assigning the requests.

GreFar algorithm is proposed by [19] that minimizes the energy cost and ensures fairness between data center consumers with keeping in consideration queuing delay. GreFar schedules requests based on the trade-off between cost-delay and energy-fairness. With the cost-delay parameter, the jobs are scheduled to avoid the queuing delay, to meet the delay constraint or when electricity prices meets the cost constraint. In the energy-fairness scheduling, all the resources are allocated based on a specific fairness weight. The energy cost marginally increases in energy fairness but the average delay decreases. If these two parameters are fine-tuned, this scheduling scheme will provide better fairness, minimum queuing delay and minimum cost.

A recent study [20] suggests using the outside temperature for the cooling of data centers along with temporal and spatial variation of electricity prices. Two types of algorithms for scheduling the batch jobs are proposed. Immediate scheduling algorithm schedules jobs on the basis of FCFS among the available cheapest data center. Delayed scheduling algorithm schedules the jobs in a future time slot where the electricity price is cheaper. Besides, the SLA penalties are also included in the cost calculation in case of any SLA violations.

As the scheme in [16] only focuses on workload management within data center and also does not consider electricity price variation in geographically distributed data centers, the recent work of [7] proposed a joint inter- and intra-data center workload management scheme called JET, which considers both electricity price variation among the distributed data centers and the efficiency of cooling system. It reduces the cooling cost by minimizing the number of active severs which results in reducing the electricity cost.

6 Energy Efficient Resource Allocation

In recent years, several efficient resource allocation techniques have been proposed which consist in multitasking on each server to reduce the energy consumption, efficient dynamic allocation of virtual machines, and adapting the rate of operations of active servers according to the load (DVFS). Resource allocation, when done efficiently, can save the cost for both the user and the provider as well as it can also improve the QoS in terms of response time and related parameters. Table 5 highlights the main features of energy efficient resource allocation. *Virtualization* is the technique of running more than one VM on a server. *Server provisioning* refers to monitor the activities of servers in a data center to avoid overloading or under loading. *DVFS* is the technique to control the CPU frequency according to the current processing and load.

Table 5 Characteristics of Energy Efficient Resource Allocation

Methods	SLA Penalties	Virtualization	Server provisioning	DVFS
ACES [21]	✓	×	×	✓
Meta scheduling [22]	✓	×	×	✓
ECE-CIS [23]	✓	✓	×	✓
Cost and deadline optimization [24]	✓	✓	✓	×
Fair [25]	✓	×	✓	×
Cloud aware scheduling alg. [26]	✓	✓	✓	✓
MPC [27]	✓	×	✓	×

An automated server provisioning system (ACES) proposed in [21] faces three way trade-off between cost, performance, and reliability to perform energy-aware server provisioning. It has two key components, load predictor and optimization framework, to reduce the energy consumption, meet the load requirement and minimize the reliability cost.

A scheduling scheme, taking into consideration electricity price, carbon emission rate, workload, server power efficiency and the deadline of the requests, is presented in [22]. Various meta scheduling policies are provided to maximize the profit, minimize the carbon emission and reduce the power consumption of servers by varying the CPU frequency (DVFS). The meta scheduler finds an optimum CPU frequency for servers in order to process as many requests as possible without missing request deadlines.

A carbon efficient heuristic for VM placement is presented in [23]. The users send their requests with the predefined requirements to the cloud provider. The heuristic places the VM in geographically distributed data centers taking into account the carbon footprint rates, energy sources, QoS and PUE in order to minimize the overall electricity cost.

A resource allocation model in which a CSP and CSC are encouraged to share the information for the efficient resource allocation is presented in [24]. The Asymmetry Algorithm is proposed for allocating the resources to different users according to the capacity and the load. VMs are migrated according to the server utilization and putting servers on standby mode or idle mode. If a requested job deadline is below a threshold, it is immediately scheduled, otherwise the job is not scheduled until it meets the cost constraints.

The cost minimization, fair request rate allocation problem with SLA constraints and spatio temporal variation of electricity price are studied in [25]. Distributed data centers and the scheduler with requests to be allocated are represented as minimum cost multi commodity flow problem. An algorithm named Fair is proposed that is based on the optimization framework, which determines the number of servers to be in active state in each data center to meet the workload and SLA requirements.

The intelligent scheduling is combined with DVFS to utilize cheap electricity as well as to reduce the electricity consumption of the servers in [26], that also considered server consolidation which helps in processing user requests before the defined deadlines.

The cost minimization problem from a resource buffering prospective is tackled in [27]. The novel idea of buffering electricity in batteries while the electricity cost is low and use this buffered power to operate the servers while the prices are higher is proposed. A power management controller per battery is used to make the decision of charging batteries or use them as a power source for servers. They adopt the model predictive control (MPC) for smart charging under the varying price of electricity. MPC predicts the future electricity cost of server by solving the current electricity price and the battery power levels.

7 Conclusions

In this study, we analysed different techniques used to reduce the electricity cost of geographically distributed data centers. First, we presented the model of energy consumption with some basic knowledge of data center infrastructure, energy sources, different electricity markets and carbon emission taxes. We classified the current research to reduce the data center operational cost into four categories and identified the key characteristics in each category. Open issues which need attention are optimizing the use of green energy sources for powering data center entirely and efficient methods for reducing delays along with the cost minimization especially for delay sensitive requests. Data center cooling systems need to be optimized to reduce the cooling cost. These problems have not been fully analysed and can be investigated as future research directions.

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