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Optimizing energy consumption for data centers

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ABSTRACT

Big data applications have become increasingly popular with the appearance of cloud computing and green computing. Therefore, internet service providers (ISPs) need to build data centers for data storage and data processing under the cloud service pattern. However, data centers often consume a significant amount of energy and lead to pollutant emissions. In recent years, the high energy consumption and environmental pollution of data centers have become a pressing issue. This paper reviews the progress of energy-saving technologies in high-performance computing, energy conservation technologies for computer rooms and renewable energy applications during the construction and operation of data centers. From multiple perspectives of energy consumption, cost reduction, and environment protection, a comprehensive set of strategies are proposed to maximize data centers' efficiency and minimize the environmental impact. This paper also provides energy-saving trends for data centers in the future.

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1. Introduction

1.1. Energy consumption outlook for data centers

Data centers are computer warehouses that store a large amount of data for different organizations in order to meet their daily transaction processing needs [1]. Data centers may be considered as a collection of different servers and network infrastructures, where servers are used to collect data, network infrastructures are used to utilize, keep and update servers' data and users can access the data center servers by network.

Recently, digital information has been enjoying an explosive growth and the information scope also has a vast expansion. Data centers are the core infrastructure to support such a trend. Along with the development of cloud computing and proposals for green computing, data center technologies have become the battlefield of "Information contest" for IT giants in cloud computing area. The high performance is not the only requirement for data centers deployment. People begin to pay more attention to data centers' energy consumption [2].

According to the statistics in Ref. [3], U.S. data centers consumed almost 61 billion KWH in 2006, which accounts for approximately 1.5% of the total energy consumption in the United States. The energy consumption of U.S. data centers increased to more than 100 billion KWH in 2011[4]. From a global perspective, the energy consumption of global data centers accounted for 1.1–1.5% of the total global energy consumption in 2011, which is equivalent to the average amount of energy consumption in 25,000 American households [5].

With the constant expansion of the global economy, energy consumption and carbon emissions will keep increasing in coming years. Fig.1 shows an estimate of CO_2 emissions of data centers for each information and communication technology (ICT) category from energy efficiency and low carbon enabler. According to Ref. [6], CO_2 emissions from ICT are increasing at a rate of 6% per year, and with such a growth rate, they will account for 12% of worldwide emissions by 2020.

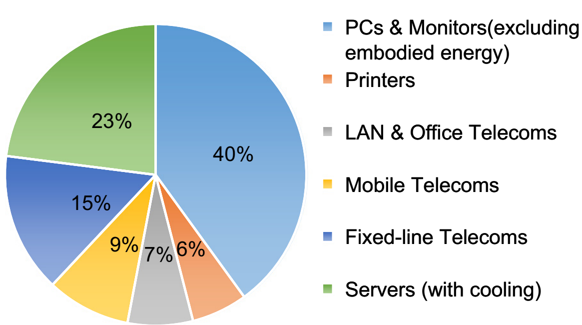

Fig. 1. Estimated ICT CO_2 emissions.

The energy consumption of data centers may be divided into two categories: computing resources and physical resources. The statistics in Ref. [7] shows that the energy consumption of computing resources accounts for about 50% of the total energy consumption. The servers' computation takes about 40% of energy consumptions; the communication equipment' energy consumption accounts for roughly 5%, and the storage devices consume about 5%. On the other part, the energy consumption of refrigeration systems is a major part of energy consumption by physical resources, which accounts for about 40% of the total energy consumption; In addition, power supply systems and other miscellaneous factors account for about 10%, as shown in Fig. 2.

From Fig. 2, we can conclude that servers and cooling systems are the most substantial energy draining facilities in data centers. They account for a dominant portion of the total operating costs. Therefore, reducing energy consumption for servers and cooling systems is the key issue of the sustainable development of data centers.

In general, energy consumption of data centers restricts the expansion of data centers with a high electricity cost, and at the same time, the rapid growth of "carbon footprint" aggravates the damage to the environment [8]. The energy consumption issue of data centers has caused widespread concerns in both the academia and the industry.

1.2. Energy conservation framework and key contributions

From the above discussion, we can conclude that the energy consumption of data centers is concentrated in the following aspects of high-performance computing, low-power servers, energy conservation of computer rooms and renewable energy application. In this paper, we summarize a general framework of energy conservation for data centers from the main aspects, shown in Fig. 3.

Some composite energy-saving strategies are proposed maximize the efficiency of data centers and minimize the impact on environment dynamically according to user expectations and other constraints. Our key contributions are summarized as follows:

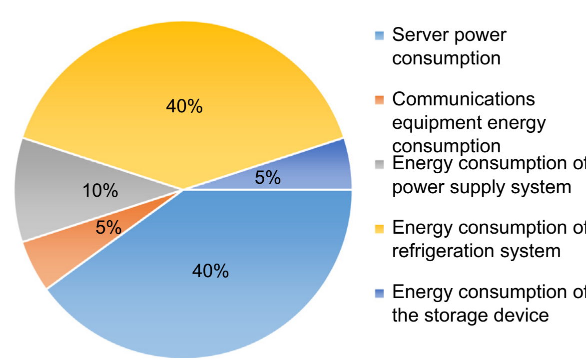

Fig. 2. Energy consumption distribution of data centers.

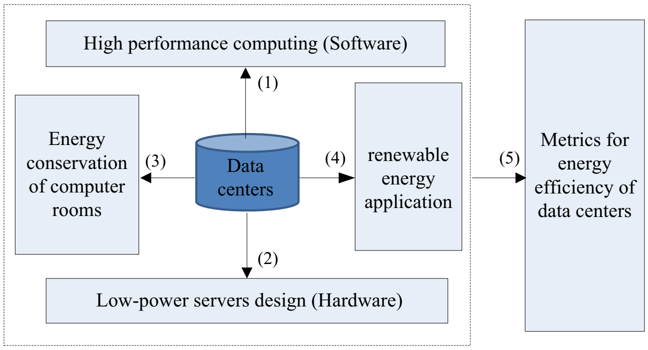

Fig. 3. The energy conservation framework.

(1) We present a general energy-saving framework for data centers that mainly focus on the most influential factors, which allows us to find more optimization opportunities and find some constrains for achieving the most profit under the conditions to meet user expectations.
(2) We review the main progress about our proposed energy conservation technology and strategy for data centers. Then, from multiple perspectives of energy consumption, cost reduction and environment protection, a comprehensive set of strategies are presented to maximize data centers' efficiency and minimize the environmental impact.
(3) By introducing popular energy consumption evaluation methods and conducting side-by-side comparison for their accuracy and efficiency, we consider that these proposed aspects of high-performance computing, low-power servers, energy conservation of computer rooms and renewable energy application have a greater impact on energy conservation of data centers.

The rest of this paper is organized as follows: In Section 2, we introduce the high performance computing technologies and strategies, which is proved to greatly reduce the energy consumption through resources scheduling and optimization. Section 3 focuses on energy saving technology from hardware design and management, and we achieve energy conservation through components configuration of low-power. Section 4 reviews the overall energy-saving technologies and strategies of computer rooms from the layout and ventilation patterns of computer rooms and rational utilization of natural cold source. Section 5 discusses the green energy supply with full of opportunities and challenges for data centers, followed by Section 6, which introduces the energy consumption evaluation methods. We summarize the energy-saving technologies with different contribution to the energy conservation at different stages of data centers, and then conclude the paper in Section 7.

2. High performance/efficiency computing

High performance computing (HPC) is a leading branch of computer science, which focuses on supercomputer architecture, parallel algorithms and parallel software development. Although the data centers always consume huge amounts of various energy per year, while the utilization rate of server resources is not so efficiency, furthermore, some server and internal processors are completely idle [9,10]. The energy consumption will be greatly reduced through high performance computing of resources scheduling and optimization.

2.1. Resources scheduling and optimization

2.1.1. Processor resources scheduling and optimization

Currently, the technique of power-aware task scheduling (PATS), based on dynamic voltage scaling (DVS), has been most widely used in the energy-saving research field of processors. This technique may reduce the power consumed by processors through reasonable task scheduling.

In 2001, P. Padmanabhan et al. proposed a series of classic real-time DVS algorithms RT- DVS oriented to a periodic task collection [11], and their experiment results show that these algorithms can reduce the energy consumption of embedded platforms by 20–40%. Then, the research on a single processor scheduling has become popular. Three years later, S. Martin further performed this research and revealed that at the threshold value of 100nm for the integrated manufacturing technology of complementary metal oxide semiconductor (CMOS) processor, if higher than this threshold value, the leakage power may be ignored in terms of the relative dynamic energy consumption; or lower, it can not. Almost the same time, the technique of dynamic voltage scaling-adaptive body biasing (DVS-ABB) is proposed and contributes significantly to reduce the leakage power [12]. Based on this, R.Jejurikar et al. applied the calculation method based on the key rate to simultaneously reduce leakage and dynamic energy consumption [13]. Furthermore, L.Yan et al. adopted and improved the technology of DVS-ABB to solve the difficulties of PATS in distributed heterogeneous real-time systems [14].

Subsequently, with the platform equipment and application with multicore and multiprocessor being widely used, there are more and more works about the PATS technology based on multicore and multiprocessor platform. Based on symmetric multiprocessor with a DVS support, H. Aydin, et al. designed an algorithm to reduce real-time energy consumption of periodic tasks, and analyzed the function of heuristic classification method by using earliest deadline first (EDF) algorithm [15]. In order to achieve the energy-saving purpose, D. Zhu, et al. used the spare time recovery technology to adjust dynamically the run speed of real-time tasks in multiprocessor systems [16]. Furthermore, a kind of approximate optimal scheduling algorithm was proposed by Ref. [17] based on multi-core processor platform, and this algorithm found the approximate optimal solution of each task running frequency by analyzing the dependencies of multi-tasks to achieve energy saving.

With a global DVS support and leakage power in current multi-core embedded processor sheets of CMOS, the PATS technique based on hard real-time task also has been studied in a multi-core embedded environment [18], and this achieves the overall energy consumption reduction by three steps: (i) static task partitioning based on greedy method, (ii) dynamic load balancing based on global resources recycling and task migration, (iii) dynamic nuclear scale.

Recently, there are works which analyze the link between the dynamic voltage & frequency scaling (DVFS) versus CPU application, and their findings revealed that there is almost a linear relation of power and frequency them [19,20,21]. According to their works, the average power consumed by a free server accounted for 70% of energy consumption with full speed running server, and this fact proved that total energy consumption should be reduced by exchange technology of idle servers. A.J.Younge did experiments in multi-core environment and found that the curve of energy consumption is not a growth by ratio with an increasing of processor cores[22], while the truth is that the increment of energy consumption will be reduced with each additional nuclear. In other words, if the total of server resources allocation does not exceed that of resources in a multi-core environment, it will be more energy-saving to assign more virtual machine to servers and

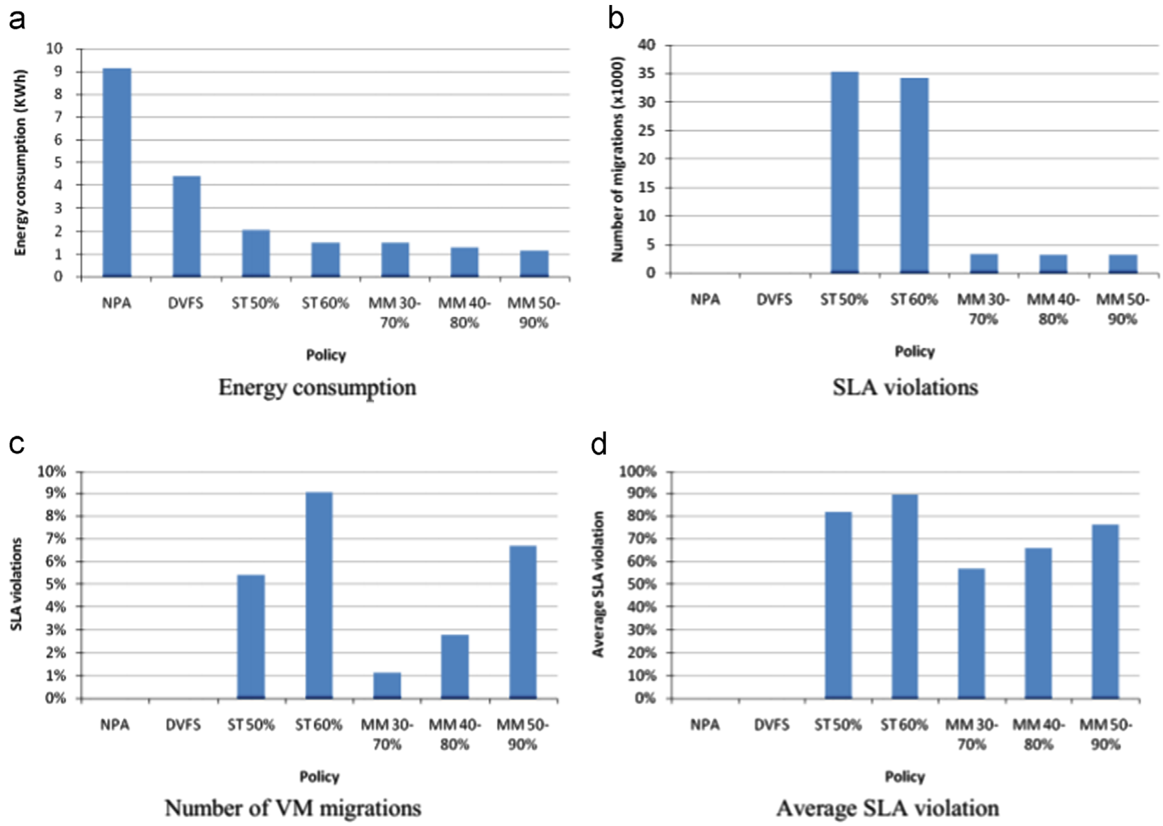

Fig. 4. The final simulation results.

shut down some idle servers than to assign averagely. Mishra A et al. constructed a model of multi-core processors with software controlled DVS that has a finite set of discretely available core speeds [23], and their findings revealed the mechanism of voltage scheduling to minimize the energy consumption given a computational load to process and a deadline to qualify. There are also other researches who presented a modeling framework for controlling and optimizing the energy management in the emerging multi-core servers with speed scaling capabilities. Buyya R, etc. presented the final results comparing all the policies with different values of the thresholds [24], as shown in Fig. 4.

The results show that dynamic reallocation of VMs according to current utilization of CPU provides higher energy savings compared to static allocation policies, and the flexibility of the algorithm, as the thresholds can be adjusted according to SLA requirements. Strict SLA (1.11%) allows the achievement of the energy consumption of 1.48 KWh. However, if SLA is relaxed (6.69%), the energy consumption is further reduced to 1.14 KWh.

The authors presented a framework for controlling and optimizing the energy management in the emerging multi-core servers with speed scaling capabilities [25]. And they proposed different strategies for adapting the multi-core processor speeds based on the observable buffer content, so as to optimize objective functions that balance energy consumption and performance. We reconsidered some constraint conditions needed to get such results, with a focus on the specific strategies that we evaluate. It is noted that fluid models keep track of the system *workload*, not of the number of active jobs. This strategy does not necessarily find the objective function's global minimum; this problem can be remedied by starting the conjugate gradient method at different initial values. After performing extensive tests, it turned out that the conjugate gradient algorithm provided us with correct results.

It is noted that we have to impose specific constraints on the parameter space for getting the stated results. Beyond the last threshold level the matrix $D^{-1}Q$ must have at least one negative eigenvalue, to ensure stability; s_{min} is the minimum value of service rate to make sure that this is the case. The matrix $D^{-1}Q$has always a zero eigenvalue, but if $s=s_{min}$ it has at least two zero eigenvalues while all other eigenvalues are positive; this case leads to a minor technicality and is dealt with separately. The (trivial) constraints $0<B_1 \leqslant B_2 \leqslant \ldots \leqslant B_N$ and $0<s_0 \leqslant s_1 \leqslant \ldots \leqslant s_N<r$ must be imposed explicitly.

2.1.2. Server resources scheduling and optimization

The utilization rate of server resources only reaches about 20% of overall performance [26,27]. Apparently, resources scheduling and optimization of the server cluster can effectively reduce the server idle rate and energy consumption, as well as improve the use efficiency of server resources [28]. It is proved to be an important means to reduce the energy consumption of the server by scheduling and optimizing the resources of server cluster.

Energy-saving solutions for servers mainly include two categories of virtualization-based and non-virtualized solutions. For non-virtualized solutions, there are three kinds of technologies including load concentration (LC), DVFS and idle time management (Powernap). And the virtualized technology utilizes the four features of the virtualized platform: (i) The independence between the underlying hardware and upper layer application can support multiple running VMs in the same hardware platform; (ii) The VM can dynamically start, hang, and turn off; (iii) The resources assigned to VM can be dynamically adjusted; (iv) The VM can support a dynamic migration. These features of virtualized technology provide the technical means and new ideas for flexible resource management and optimization.

(i) Non-virtualized resources scheduling scheme

LC technology, as an earliest non-virtualized scheme, was presented almost the same time by E.Pinheiro team and J.S.Chase team [29], which distributes task requests to a dynamic servers set through the gateway or agency control. This solution adopts an energy-aware strategy that makes task loads to focus on a small number of servers as much as possible, so that some servers are idle and then turned off to save energy. Furthermore, this strategy was verified in a web environment by Chase JS et al. [30], and their experimental results revealed that the LC technology can achieve more than 29% energy saving.

Subsequently, there are some works which compared three different decision models including independent voltage scaling (IVS), Coordinated Voltage Scaling (CVS) and Vary-On Vary-Off (VOVO) [31]. There are different mechanisms among the three models: (i) The server only adjusts the speed of processors according to the load condition of itself in IVS model; (ii) a global control device is designed to determine the speed regulation scheme of processor through the load analysis of all servers in this system, in CVS model; (iii) some idle servers are always shut down and only opened when the system needs in VOVO model. According to the final experiment results, both CVS and VOVO achieve a good effect of energy saving, and the combination of CVS and VOVO is proved to be the best way of energy saving, in practical application.

In 2009, D.M Eisner [32] proposed a server energy-saving method called Powernap. According to his study, the energy consumption and CPU resource utilization are basically a linear correlation in spite of the server being supported or not by DVFS technique, and the overall energy-saving effect exerted by DVFS technique is not so obvious. Based on this, the authors established a new model of energy consumption, and proposed an energy-saving method by fast switching between the active state of high performance and the idle state of low power, and the experiment results show this method achieves energy saving by 74% on average. A new green energy-saving scheduling algorithm about cloud computing is proposed in Ref. [33], which achieves energy deduction by 72.2% through reducing the number of running servers with the idle servers being closed. Subsquently, Rizvandi NB proposed an algorithm with linear combination of the minimum and maximum frequency of processors to optimize energy consumption [34], which achieves energy saving by 13.5% according to the experimental results.

According to Ref. [33], both energy consumption and CPU utilization are almost linear correlation between two machines with different levels of CPU utilization ranging from 10% to 100%, and the energy consumption of four core and dual core machines are increased about 6.5% and 3.0 % respectively with CPU utilization increased by 10%.

Additionally, you can observe the idle state machine consumes a lot of energy, reaching as much as 62% in case of the quad-core machine, and 78% in the case of the dual-core machine, of the peak power. So, a great deal of power reduction may be achieved by transferring idle servers to low-power states.

(ii) Virtualization technology scheduling scheme

According to Gartner research report of well-known consulting firm, the current server resource utilization of data centers around the world does not exceed 20%, and a great deal of idle resources is wasted. By virtualization technology, multiple servers may be integrated to one virtualized server to improve server resource utilization.

Along with virtualization technology being widely used in data centers, as an important part of the system software, the virtual machine manager software in a single calculation system also has an urgent need to introduce energy-saving measures. Presently, research on energy conservation oriented to virtual machine manager mainly includes the management interface support of energy consumption, management framework of energy consumption and virtual machine energy saving of desktop level [35]. The above energy-saving management mechanism only provides a close interface channel for the energy saving of full virtualization system, but how to realize the energy saving of the virtual machine environment still need a further study. Stoess J et al. [36] proposed an energy management framework under multi-module and multi-level virtualization architectures based on the virtual machine of L4. Virtual Power is a research project on energy-saving technologies based on virtual machine manager, which integrates the energy-saving technologies of both hardware and software into virtual machines, and thus has local and global energy conservation strategies [37]. In 2008, a two layer control structure from RTSS was designed by Ref. [38], where the upper layer ensure the performance of each virtual machine qualify the application requirements, and the lower layer achieves the purpose of reducing energy consumption by controlling CPU frequency based on the performance of the upper level.

Temperature-aware workload scheduling (TAWS) is one of the common solutions before the large-scale applications of virtualization technology. After that, energy-saving resources management solutions of data centers focus more on improving resource utilization through integrating VMs, as much as possible, and closing idle servers in order to realize the energy saving. This is opposite to the principle of TAWS, because the server running with a high-load will cause a sharp rise of operating temperature, while it is necessary to improve the air conditioning frequency to cool these servers as there being no single cooling solution for server unit in air-cooled and water-cooled data centers, which can result in an increased consumption of refrigeration systems. An energy-saving strategy based on power and temperature management (PTM) engine was proposed to solve the above problems [39], and PTM engines make timely decisions to turn on server parameters of data centers, control router strategy and refrigeration frequency through a real-time load monitoring. F. Ahmad and TN Vijaykumar [40] designed a fusion technology solution called PowerTrade & SurgeGuard, which achieves the lowest energy consumption of overall server energy consumption and cooling systems by calculating server energy-efficient saving and refrigeration system; and this program also proposed a strategy of resources "over deliver" to guarantee for QoS through considering the system overhead and performance impacted by server status switch.

The promotion of virtualization technology makes server resources management more flexible. Energy-efficient solutions, based on virtualization technology currently receive more attention from around the world research institutions and enterprises. In 2007, J.s. toess et al. [41] designed a two- layer structure virtualization management platform based on Hypervisor for implementing an application-specific, fine-grained control of energy consumption. K.H. Kim et al. [42] investigated a new strategy combining resources allocated dynamically and DVFS VM, for achieving the energy saving of server. D. Kusic et al. [43] found a more comprehensive energy-saving solution and presented better experimental results with an energy consumption reduction of 22%. There are other works which constructed a VM migration model oriented to energy efficiency and service level agreement (SLA), and this model adopts first fit decreasing (FFD) algorithm to select the optimal physical servers for VM placement with a consideration of migration cost to reduce energy consumption [44]. Furthermore, Refs. [45,46] are also involved in discussing the problems of VM integration in cloud data centers, and proposed a heuristic method for energy saving.

Subsequently, as for data center resources, an energy-aware allocation provision was proposed to client applications in a way improving energy efficiency of data centers, under the premise of qualifying the quality of service (QoS) [47]. An uncertainty-aware scheduling architecture is designed for a cloud data center, and a novel scheduling algorithm RPS was proposed to make trade-offs

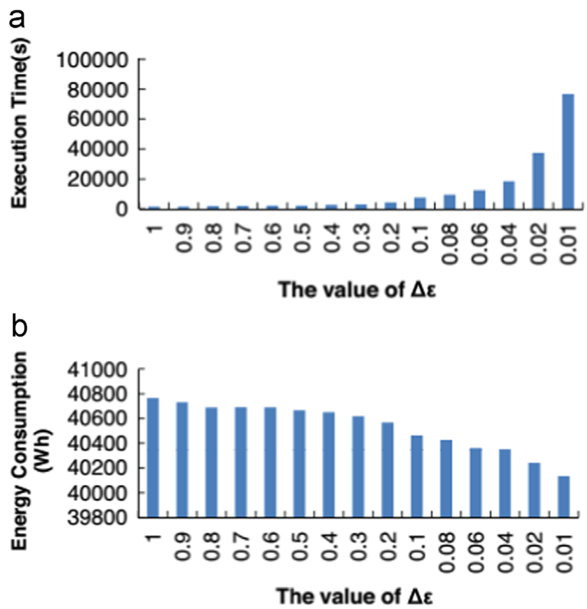

Fig. 5. Execution time and energy consumption of IPAC: a greater Δε means a shorter execution time. (a) Total execution time in 7 days. (b) Solution Quality.

among tasks guaranteeing ratio, system resource utilization, system energy consumption and stability [48].

There are other works which presented a performance-controlled server consolidation solution for virtualized data centers to achieve power efficiency and application-level performance assurance. Ref. [49] presented the change in the execution time and the energy consumption of IPAC when the value of Δε changes from 1 to 0.01 while the number of VMs is fixed at 5, 415, and the execution time of IPAC increases quickly as Δε increases, as shown in Fig. 5. In general, existing solutions rely on DVFS or server consolidation in a separate manner, their solution integrates feedback control with optimization to utilize both DVFS and server consolidation for maximized energy savings with performance guarantees.

Currently, another challenge faced by data center operations is how to minimize energy consumption and prevent the business income loss at the same time by balancing IT resources supply and SLA violations minimization. Once specific IT services based on pre-defined targets of SLA and QoS are difficult to provide, data centers will face a penalty with a business income loss. Amazon, for example, will bear the 1% loss of their sales with every delay of increase 100 ms, while Google found its search traffic will be reduced 20%, with the search page response time being more than 500 ms [50]. Therefore, how to correctly configure IT equipment is an important problem in the data center resources management, so as to avoid SLA standard violation and energy consumption minimization. Ref. [51] proposed a hybrid approach to server configuration by tracking work load history to determine demand patterns of long-term work load. The experiment results show that the above method has a significant improvement on energy saving and supply costs reduction, up to 35% of power savings completed and 21% of SLA standard violation reduced than other approaches.

2.1.3. *Workload management methods*

The workload management method has low-cost and energy-efficient advantages, especially for data centers distributed geographically. According to the works of Refs. [52,53], the same loads are distributed to different servers in the same row rack, while the temperature increments of the servers are inconsistent. The servers are closer to the floor, the increments are smaller, conversely higher. Because the server, near to the floor, is also near air conditioning and the refrigeration effect is the best, so the temperature increment is lower and conversely away from the floor. Based on this discovery, they proposed a method called zone-based discretization (ZBD) based regional division of the load scheduling algorithm that greatly improves cooling efficiency and reduces energy consumption. Meanwhile, they also proposed another algorithm of minimization heat recirculation (MinHR) that reduces heat emissions of the entire data center through load dispatch and reduces the impact of thermal cycling effects on the cooling, thereby improving the methods of cooling efficiency. Experimental results show the two methods have good efficiency of energy saving, while MinHR is more energy efficient than ZBD, unfortunately, the computation time of MinHR method is too long to qualify the needs of practical application, only may be used under certain circumstances.

Subsequently, one similar method by reducing the heat emission for the entire data center was proposed [54], thus reducing the effect of thermal cycle on the refrigeration efficiency. In Ref. [55], by simulating real-world electricity prices and historical temperature data, the researchers proposed a distributed m-block ADMM algorithm based on the classic 2-block algorithm, and then conducted a simulation of cooling efficiency model. Experimental results show that this algorithm can achieve energy saving by 15%-20% of the refrigeration equipment and reduce the overall cost by 5%-20% of the data center.

Tridib Mukherjee [56] utilized the thermal mass and relaxation tributes of the device to indicate the coordinated scheduling of thermal perception and time job collaboration will produce good effect of energy saving; Different solutions are also presented from the income and balance of energy consumption aspects of data centers [57,58]. Subsequently, a new application-aware approach was proposed, resulting in data center resources scaled for striving to minimize energy consumption and maintain the end-to-end performance simultaneously [59]; According to the works of Ref. [60], a Platform-as-a-Service model of server cluster was designed, which can lease servers to tenant under the benefits maximization, and has a better solution for the conflict between user needs maximization and energy consumption minimization. Zahra Abbasi [61] constructed a two-tier model of data centers management with a comprehensive considering of service quality issues and the balance between the server energy consumption and the cooling energy consumption, which can reduce the energy consumption as much as possible; According to Ref. [62], a data center may be regarded as a CPS system, and a network model and thermal network model were established to assess the CPS coordination strategy, the corresponding scheduling strategy are presented by coupling method.

2.2. *Network optimization*

With the constant expansion of data centers, the internal network infrastructure (including routers, switches etc.) also has a corresponding rapid increase, and the research on the energy efficiency of network has become a popular topic [63].

2.2.1. *Energy saving of network environment*

In energy saving of network environment, the green agent technology combined with dormancy mechanism, as the international frontier research field, reduces and optimizes energy consumption by adjusting network topology structures. In 2009, Christensen K and Nordman B [64] began to introduce green agent technology that will wake up the nodes need to work through a proxy client, it neither affects network performance, but also reduces the energy consumption. In all types of private networks, the relationship between the topology and energy consumption has been widely studied, such as multi-hop Ad Hoc networks.

Other related works of Refs. [65, 66] are also involved to investigate a distributed topology and cooperative algorithms to maintain the topology structure for energy saving. In addition, there are some other studies on wireless sensor network, car network, wireless multicast network, et al.

(i) Link state adaptation (LSA) technology: The energy consumption of network ports is independent from their loads, but only related to the forwarding rate of data packets, which is the basis of proposed LSA method. IEEE 802.3 committee proposed ALR (Ethernet Adaptive Link Rate) technology standards in 2006, which allows the network port to adjust automatically the packet forwarding rate by itself and supports current rate of 10Mbps, 100Mbps and 1Gbps [67]. According to Ref. [68], the energy consumption of 1Gbps network ports is 4Watt higher than that of 100Mbps ports, while the energy consumption of 10Gbps network ports is 10Watt higher than that of 1Gbps network ports according the test results for mainstream network equipment.

(ii) Network traffic consolidation (NTC) technology: This technology mainly integrates the network traffic into a small number of links and closes some free links off to save energy by using routing control methods. Gupta and Singh [69] first proposed a sleep function design for network equipment to achieve energy efficiency, and improved the existing network protocols, which was verified in a LAN environment in Ref. [70]. Ref. [71] discussed the problem that when and how long network components begin to sleep to reduce energy consumption.

(iii) Server load consolidation (SLC) technology: This achieves energy saving by using task scheduling or VM scheduling methods and making tasks run on a few servers to perform, with corresponding network links reduced. Ref. [72] presented a scheduling approach combined with DENS in 2013. The DENS methodology balances the energy consumption of data centers, individual job performance, and traffic demands and optimizes the trade-off between job consolidation (to minimize the amount of computing servers) and distribution of traffic patterns (to avoid hotspots in the data center network)

2.2.2. Energy saving of network protocol

Because the energy factor has not been considered as a constraint at the beginning of Internet construction, then many network protocols and algorithms do not qualify the requirements of energy saving, such as TCP retransmission mechanism, CSMA/CD and CSMA/CA in wireless networks and so on. Some scholars and researchers made a lot of improvements of energy efficiency goals based on existing network protocols [73,74]. In collaboration services, a dynamic network services reconfigurable framework was proposed [75], which can effectively reconstruct services based on key computing tasks in the case of certain services unavailable. Fuzzy theory is introduced to implement adaptive matching among services during studying context-aware mobile computing and middleware [76].

With the rapid development of network services and their application scope, there are works on the integrated services management which received a wide spread attention and become current research hotspots, such as the adaptive collaboration mechanism of intelligent service discovery [77], the management mechanism of service state supporting migration and remodeling [75] and the integrated services management mechanism based on transparent computing theory [78]. Subsequently, Urgaonkar B et al. [79] firstly proposed an adaptive optimized architecture from multi-layer network server application systems, and analyzed the adaptive supply of resources under the conditions of network steady-state for improving efficiency and reducing energy consumption. At the same time, Urgaonkar B designed [80] a series of mechanisms of supplying virtual machines services agilely to provide resources supplies for reducing energy consumption in the dynamically environment. Later, Choi J et al. [81] proposed energy forecasting model and other methods to achieve energy-aware.

Internet data center (IDC), as a common form carrying cloud computing, has brought huge benefits in today's society, we also found that the rated power of the center server has been increased 10-fold over the past decade. Thus, it becomes currently an urgent need to design and deploy energy-efficient IDC. Now, researchers have made many efforts to improve the energy efficiency of IDC. In Ref. [82], a mixed integer programming was used to optimize routers power in a wide area network by configuring the parameters of *chassis* and *linecard* for best qualifying expected demands. Ref. [83] proposed a kind of network-wide power management model of *Elastic Tree*, which can dynamically adjust the settings of active network elements (links and switches), in order to qualify changing traffic loads needs of data centers. According to experimental results, *Elastic Tree* model can save 50% of energy consumption for data center workloads, while maintain an ability to handle the traffic surge. At the same time, the works of Ref. [83] also shows how to configure *Elastic Tree* for a network administrator, in order to qualify their needs of performance and fault tolerance. However, Evaluating Elastic Tree requires infrastructure to generate a small data center's worth of traffic, plus the ability to concurrently measure packet drops and delays. To this end, we have implemented a NetFPGA based traffic generator and a dedicated latency monitor.

2.3. Power optimizing compiler technology

Tiwari [84] proposed some basic concepts of energy consumption analysis for the embedded software and constructed an instruction-level power model, and practiced low-power compilation techniques in Intel 486 dx and Fujitsu SPARClite processors in 1994. Then, many researchers have carried out a variety of improved research with traditional compiler technology being applied to low-power consumption, and the main work focuses on the branch prediction, circulation structure optimization and cache memory allocation optimization, etc.

2.3.1. Energy-aware compiler optimization

Some representative work of energy-aware compiler techniques includes: Edwin H.M. Sha [85] proposed a comprehensive technical combined data transfer scheduling algorithm between cores and interconnected network design methods, which can minimize energy consumption during data transfers between cores. Shirako J et al. proposed an energy-saving scheme of multicore processors controlled by a static compiler [86]. This scheme can reduce energy consumption of granularity parallel processing environment by controlling the supply voltage of each nuclear. Huang et al. [87] investigated a compilation technology combined with DVS and Adaptive Body Biasing (ABB), which can effectively reduce energy consumption of application running on processors, and optimize dynamic and leakage energy consumption, with a reduction of about 26% of the energy consumption from embedded applications. Shao Zili [88] presented a real-time task scheduling with feedback control mechanism of energy perception, which can effectively reduce energy consumption based on the scheduling mechanism of earliest deadline first. According to Ref. [89], the energy-saving goal may be achieved by using compiler analysis program and providing cache, and this strategy can make the program accessing registers in a single cycle with a power reduction under the performance guarantee.

2.3.2. Software power optimization

Recently, it is one of the effective energy-saving strategies to achieve system energy consumption reduction of data centers by optimizing software design and coding ways, and current optimization technology of software power has made some progress. In Ref. [90], the researcher analyzed the generation and constitute of software energy consumption, and conducts structured-based power optimization by code structure transformation, Loop unrolling, Loop blocking (Loop tiling), Loop fusion, Function in lining for C code, and then compared optimization results. According to Ref. [91], by decreasing the instructions and memory access times, the system energy consumption could be efficiently reduced based on the symbolic algebra (symbolic algebra) technology for specific MP3 decoder algorithm software. In Ref. [92], the software architecture graph (SAG) method was adopted to carry out a multi-process and embedded Linux application architectural transformation, and the system power savings can be up to 66.1%. According to the works of Ref. [93], the energy consumption of data centers would be effectively reduced with the constraints of computing power and utilization through rational design of software architecture; Ref. [94] presented an multi-objective optimization (MOO) framework to design, document and realize multi-objective optimization in embedded control software, and their proposed approach can lead to an increase in productivity by 20%, and it can decrease the energy consumption by 10%.

Software prefetching is a technique of inserting prefetching instructions into codes for memory reference that are likely to miss in the cache [95,96]. The code optimization techniques will lead to performance improvement and energy savings from earlier studies. The prefetching instruction is introduced to a cache of pre-processor before the data used at run time, and then overlap the processor calculation and the memory access. Software prefetching techniques eliminates cache misses and promotes the performance improvement. However, it also increases the energy consumption, so this leads to a problem of power-performance tradeoff for software prefetching programs.

2.4. The comparison for selected HPC methods

After the above review on high performance computing, we select some typical energy-saving methods to compare their features, evaluation and constraints, energy efficiency ratio and so on, shown as in the following Table 1.

3. Low-power servers design

Low-power servers reduce server energy consumption and improve performance mainly through the components configuration of low-power server including some core components optimization of processors, storage structure and disks.

3.1. Processor architecture optimization

The energy efficiency of early processors was improved by two hardware means: (i) DVS technology, based on the principle of non-linear relationship between the processor and voltage dynamic power, adjusts dynamically the processor voltage and makes the processor computable speed "slow" [97]; (ii) Dynamic power management (DPM) technology improves energy efficiency mainly through dynamically closing some members on processor chips [98].

Then, in the case of processor design, low-power processors are usually adopted to build high-performance computer systems for reducing system energy consumption. The low-power cluster

Table 1
The comparison of selected HPC methods for energy conservation.

Methods	Features	Energy efficiency	Constraints	Literature
1. A new power-aware scheduling algorithm (GRR&CS)	dynamic load balance and dynamic core scaling	almost 14.8–41.2%	the power saving was achieved by specified steps	[18]
2. EAGLE algorithm	reducing energy by balancing the utilization of multi-dimensional resources	as much as 15%	based on proposed multi-dimensional space partition model	[28]
3. Energy-aware allocation and scheduling algorithm	energy-efficient resource allocation and scheduling considering QoS and power usage characteristics	a significant cost savings and energy efficiency	conducting a performance evaluation study using the CloudSim toolkit	[47]
4. A performance controlled power optimization algorithm	a novel multi-input and multi-output controller is designed to achieve the desired performance for applications spanning multiple VMs	reducing 165W power and leading to a power saving of 69.6%	evaluating the response time controller and examining the power optimizer on hardware test bed	[49]
5. A hybrid provisioning approach	the combination of predictive and reactive provisioning achieves a significant improvement in meeting SLAs	35% savings in power consumption and reducing SLA violations by as much as 21%	both trace driven simulations and real implementation	[50]
6. CPU gradients approach	CPU gradients are can be automatically constructed using runtime measurement techniques	as much as 57% energy savings	using extensive experiments on multiple multitier applications	[59]

architecture FAWN for large-scale data-intensive applications was designed in Carnegie Mellon University, and this structure showed excellent performance and a low-power consumption [99]. Subsequently, Caulfield A M et al. [100] proposed a fast, low-power consumption cluster system *Gordon* based on flash memory, which may satisfy the demand of highly data-centric concurrent applications. Ref. [101] discussed the future energy consumption issues and trends of high-capacity network nodes, proposed a dynamic circuit exchange or a hybrid switching approach, which effectively combines the packet, circuit and burst-switched core network, and can reduce significantly the complexity of core nodes and the overall energy consumption.

In Ref. [102], the researchers proposed the concept of cluster-based mapping operation / command and the new high efficiency related resources (operator, multiplier, and shifter) method to reduce energy consumption. The experimental results show that this design can achieve energy consumption greatly reduced (35%-94%) with only relatively small additional hardware, also improve the performance. Ref. [103] introduced a single-ISA heterogeneous multi-core architecture as a mechanism to reduce energy consumption of processors, and designed a heterogeneous core representing different power / performance design space. Ref. [104] analyzed the feasibility of building servers based on low power computers through an experimental comparison of server applications running on x86 and ARM computer architectures. They found that the use of ARM based systems has shown to be a good choice when power efficiency is needed without losing performance.

Presently, a number of international mainstream processor manufacturers have raised their related technologies for improving their energy efficiency, such as SpeedStep technology of Intel Xeon processor series [105], PowerNow technology of AMD Opteron ™ processor [106], Power processor technology of IBM et al. Per Watt technology has more effective load management, virtualization technology support, and is able to run at a higher temperature environment [107].

3.2. Disk storage system optimization

Storage system is the core component of the data centers, energy consumption of storage systems accounts for a large proportion of the entire data centers, so the memory structure optimization of data centers will have a positive impact on high energy consumption, and receive more and more attention from researchers [108]. The current research focus, on the one hand, is to explore new storage application technologies with high-speed and low-power, on the other hand, to explore a balancing strategy between energy saving and performance in high-power mode with full load and low power mode with lighter load.

3.2.1. Low-power disk storage technologies

With the advances in solid state technology of Not AND (NAND), flash memory has rapidly developed over the past few years. NAND flash memory is widely used in solid state drives (SSD) and provides innovative ways for enterprise and client computing. The adaptive error correction code (ECC) and SSD for integrating storage class memory (SCM) and NAND flash memory have been proposed [109]. The energy consumption, rising time, and circuit area of the program-voltage generator are 88%, 73%, and 85% less than those of a program-voltage generator with a conventional charge pump, respectively. The total energy consumption of each NAND flash memory is reduced by 68%.

Recent studies have proposed information processing language (IPL) approach to overcome the "erase before write" weakness of log-based file system NAND flash memory [110]. Unlike traditional log-based file system, IPL method is used to update records of data log page instead of directly copying the entire data page. In IPL approach, only the updated data log sectors can be written to flash memory, and the data page use is more efficient than that of traditional flash memory based on log. As phase-change random access memory (PCRAM or PRAM) technology being improved, PCRAM technology with in-place update and fast access speed shows that it has the greater potential advantages to replace the NAND flash memory.

The author proposed a hybrid structure NAND flash memory (PCRAM). PCRAM memory has the highest cell density in these emerging technologies [111,112]. Second, the capacity of the up-to-date PCRAM production is qualified for the log region of NAND flash memory that works as massive storage [113]. Previous research has also proven that integrated PCRAM and the feasibility of replacing NAND flash memory [114,115].

According to Ref. [116], the PRAM includes the s-PRAM and d-PRAM, the former represents the hybrid architecture using the basic static log assignment and the latter represents the hybrid architecture using the basic dynamic log assignment. It means that there are no hot unit queue or merge threshold for optimizations of merge operations. The PRAM method based on log area shows that, the performance of the flash memory can also be significantly improved if in-place update allowed in log area even without the support of multistage storage. The results also show that this method can reduce the overhead of read operations and increases the life span of the storage. In addition, this method can reduce the energy consumption during read and write operations than the IPL method. More importantly, the in-place update feature of PRAM provides a more flexible management policy, resulting in further optimization of the performance and life [116], as shown in Fig. 6.

The change of the whole system architecture needs to make full use of SSD advantage with performance, reliability and energy consumption. Especially the emerging SCMs, such as PCRAM test, FeRAM, RRAM and MRAM, are becoming a used storage body that can be used to replace often used volatile and nonvolatile memory.

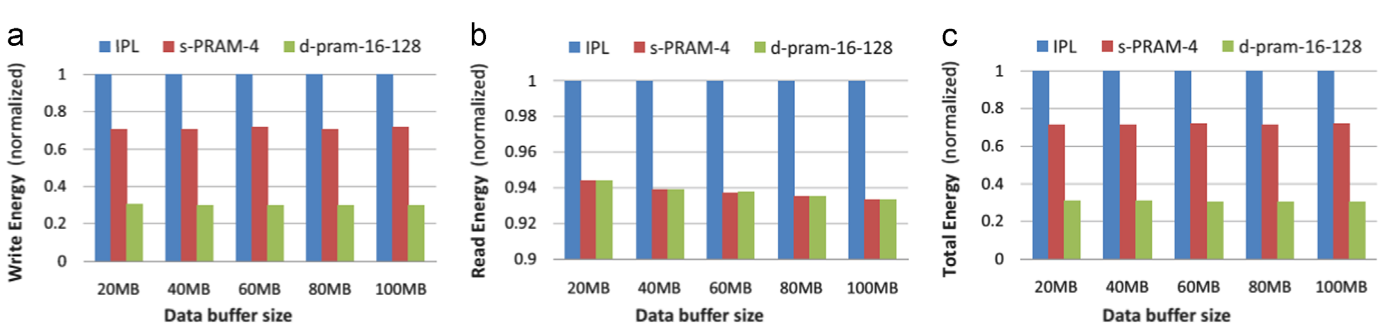

Fig. 6. (a) The comparison of write operation energy; (b) The comparison of read operation energy; (c) The comparison of total energy consumption.

SSD and intelligent SSD, may reduce the storage errors by 95%, and reduce energy consumption by 43%.

In order to overcome the reliability and power crisis of SSD, two kinds of technology are proposed in Ref. [117]: Asymmetric Coding improves by 95% of the storage unit reliability, and there will be no loss of access time. Stripe Pattern Elimination Algorithm shown eliminates the worst program data pattern and decreases the power during the program by 43% without circuit area or access time overhead.

3.2.2. Energy optimization of disk array management

Disk array management can easily store data, reduce overall energy consumption of data centers through integrating multiple disk devices into a unified disk space, reducing the access area and centralizing the access frequency.

In 2004, Pinheiro and Bianchini [118] proposed a technology solution known as popular data concentration (PDC). This technique reorganizes the file data according to the access frequency and put together the file data frequently accessed, while the other part can be placed in the rest of the disk, which can be transitioned to a low-power mode to conserve energy consumption. Subsequently, a hybrid strategy based on a storage power management system of Hibernate was proposed by Zhu et al. [119]. This system supports data migration between different disks and adjusts the each disk speed through the coarse-grained decision-making mechanism for achieving energy saving, and provides a performance guarantee of the storage system at the same time.

Then, J. Chou et al. [120] presented an approach based on power-aware scheduling techniques of magnetic head to achieve energy. In this scheduling strategy, we firstly obtain the data request of read and write, and determine the read order by analyzing these data requests and the data location on the disk, then reduce disk consumption by minimizing the moving distance between the disk rotation and the needle extending and retracting.

Many modern file systems achieve fault tolerance and disaster recovery through data copy, such as Hadoop distributed file system (HDFS). Based on this fact, Weddle et al. [121] proposed a power-aware technical solution of RAID management, called power-aware RAID management (PARAID). PARAID allows running part of the disk while the other part is dormant in the system, unlike the previous all RAID disks running simultaneously. The key of this technology is to determine how many disks need to run or dormancy through the current system load, and the technology may be extended to support multiple RAID field to qualify the needs of mass data storage and access in data centers [122]. The researchers designed an adaptive energy-saving scheme in parallel disk systems, and achieved the adaptability in energy conservation through the integration of a dynamic disk scheduling scheme and power management [123]. According to experimental results, the scheme can achieve up to 70% energy savings compared with standard parallel disk systems with fixed supply voltage.

However, to evaluate the performance of the DCAPS strategy in an efficient way, we simulated a parallel disk system with all the functions that are necessary to implement our system and give some important parameters used to resemble real world disks. In addition, we implemented a data-partitioning algorithm to optimize parallelism degrees of large disk I/O requests.

3.2.3. Energy saving based on cache management

As we know, not all data access will read the disk. The system checks the cache firstly. If the cache contains the data block, it will directly read and return the data. Modern storage systems will be equipped with large-capacity cache to improve the cache hit probability, such as 10-50TB capacity of EMC Symmetric storage systems, which can be equipped with 128 GB cache [124]. Different cache management strategy can make a difference in disk access request sequences, which directly affects the energy consumption of storage systems. If we can improve data block hit rate of in the cache, the background disk have a longer time being in a low-power state. This gives a chance to reduce the energy consumption of storage systems and also provides a research space for cache management technique.

According to the works of Ref. [125], the offline and online PA-LRU (Partition-based LRU) algorithm (Power-aware Cache Replacement) was proposed to achieve the energy saving of storage systems. Based on this algorithm, they proposed a replacement algorithm of PB-LRU based on cache partitioning strategy [126]. This method will divide cache into several areas, corresponding to the disk partition of storage arrays. According to the data access frequency in different disk partition, the method will dynamically change the size of each buffer zone to improve the overall hit rate of data block and the energy efficiency. In Ref. [127], a cache management strategy of offline write was proposed, and unlike data reading, data writing needs to wake up all of the data stored in the disk, and all data copies need to be updated. Alves et al. [128] investigated a technique for saving cache leakage and dynamic energy and this technique predicts the usage pattern of the sub-blocks of a cache block, which includes which sub-blocks of a cache line will be actually used and how many times it will be used. A technique for saving cache energy was proposed in QoS systems, and this technique allocated cache at granularity of cache colors [129]. Meanwhile, the technique predicts the cache energy and program performance for multiple cache configurations by using auxiliary tag structure for different cache configurations. Ref. [130] increased the cache hit rate and reduced the cache-access energy consumption by developing a new cache architecture known as a single linked cache (SLC) that stores frequently executed instructions. SLC has the features of low-power consumption and low access delay, similar to a direct mapping cache, and a high cache hit rate similar to a two way-set associative cache by adding a new link field.

3.3. The comparison of selected methods for low-power servers

After the above review on low-power servers, we select some typical energy-saving methods to compare their features, evaluation and constraints, energy efficiency and so on, shown as in the following Table 2.

4. Energy conservation of computer rooms

The full load running of air conditioning system in computer rooms and some other unreasonable conditions lead to higher energy consumption of data centers, and the average energy consumption of air conditioning systems accounts for about 40% of overall energy consumption of data center, some data centers are even close to or over 50% [131]. As the high-density servers and mixed-mode with low-density of large data centers appears, the generated heat is uneven distribution because the server density is not balanced. So, the cooling method of traditional data centers has been difficult to qualify current needs, the overall energy-saving technologies and strategy of computer rooms are receive more and more attentions.

4.1. Layout and ventilation patterns of computer rooms

4.1.1. Location and layout of computer rooms

Currently, reducing the costs of cooling system brought by server fever is one of focuses of data centers. Canbing Li et al. found that air condition will worsen city micro weather (heat

Table 2
The comparison for selected energy-saving methods of low-power servers.

Methods	Features	Energy efficiency	Constraints	Literature
1. An automated, fine-grained approach	selecting per-loop processor clock frequencies	up to 7.6% on an 8-core Intel Xeon E5530 and 10.6% on a 32-core AMD Opteron 8380	on an 8-core Intel Xeon E5530 and on a 32-core AMD Opteron 8380	[106]
2. A hybrid architecture for the NAND flash memory storage	significantly improving the usage efficiency of log pages by eliminating auto-date log records	substantially improve the performance, energy consumption, and lifetime of the NAND flash memory storage	the log region is implemented using phase change random access memory (PRAM)	[116]
3. An adaptive energy-saving scheme or DCAPS in parallel disk systems	the data partitioning mechanism allowing DCAPS to adjust the parallelism degrees of write requests	up to 70% energy savings	the integration of a dynamic disk scheduling scheme and power management based on dynamic workload conditions	[123]
4. The Dead Sub-Block Predictor (DSBP)	predicting sub-blocks of a cache line that will be actually used	Almost 24% energy reduction for the whole cache hierarchy	averaged over the SPEC2000, SPEC2006 and NAS-NPB benchmarks	[128]
5. CASHIER, a Cache Energy Saving Technique	using dynamic profiling to estimate the memory subsystem energy and execution	the average saving by using Cashier being 23.6%	allowed slack may be specified either as percentage of baseline execution time or as absolute slack	[129]
6. A multiple linked caches (MLC) approach	reducing the power consumption by avoiding unnecessary cache accesses when the requested data is absent from the cache	MLC consumed 66%, 78%, and 85% of the power consumption by selective compression, traditional cache, and filter cache, respectively	simulation with selective compression, traditional cache, and filter cache in terms of the hit rate, power consumption and execution time	[130]

island effect) [132]; at the same time, the micro weather will further lead to greater energy consumption of air condition. Therefore, the location of computer rooms could result in more energy consumption. An appropriate location with natural cooling conditions is worthy of priority consideration in data centers solutions, so, data centers' location is an important part of solutions. Water-cooled data centers will usually be constructed in water-rich areas, such as grand rivers, sea side, or even on a ship. Google will invest 200 million euros in the construction of the data center in northern Europe, where cold natural conditions are the unique advantages for reducing the energy consumption of data centers on the cooling systems [133]. Similarly, Facebook will also build green data centers in Sweden, where the cold air throughout the year is used for cooling servers, with additional refrigeration equipment saved.

The building structure and parameters selection of computer rooms play an important role in airflow organizations. Sorell et al. [134] analyzed the impact of the room ceiling height on overall airflow organization by numerical simulation; Gildera et al. [135] presented a detailed demonstration for the airflow uniformity factors of the floor with a hole: Floor openings should be in the right position, where the outlet distance from the air condition being too close or too far away is inappropriate; If the distance from the air conditioner is too close, the moving pressure of will be very large and the static pressure is very small, which makes cold air getting no out, when the cabinet should not be opened from the air conditioning vents too; Once the outlet is too far away the air conditioning unit, the cold wind does not come out. Patankar [136] analyzed the affecting factors between the two floor spaces of air flow up and down on the airflow organization of computer rooms, such as the height of raised floor, overhead layer pipeline layout, floor openings location and opening rate.

In the design process of some large scale data centers, as one-time investment, the consideration of the computer rooms layout and the ventilation system usually costs almost 8-10% of the total expense, which is usually compensated by energy saving in almost two or three years. Obviously, this strategy and investment may be said to be very meaningful for data centers.

4.1.2. Ventilation patterns of computer rooms

The energy consumption of air conditioning systems may be effectively reduced through optimizing the airflow distribution and layout of computer rooms, which, on the one hand it makes air circulation smoother, reduces the interaction between hot and cold air, improves dramatically the use efficiency of cold air and reduces the circulation wind amount of air condition; On the other hand, the reasonable airflow and cabinet layout make room temperature more uniform, eliminate local hot spots and properly increase the operating temperature of air conditioning. Ref. [137] suggested that the temperature of data center should maintain from 20 °C to 25 °C.

The early construction of the data room cabinet does not consider the airflow factor, it generally adopts unified toward arrangement, as shown in Fig. 7. In this arrangement, the hot air of front cabinet and the cold air of rear ones are mixed with each other, increasing the inlet air temperature of rear cabinets, and greatly reducing the cooling efficiency of air-conditioning. Currently, the factors of airflow in cabinet arrangement play an important role and the face to face or back to back arrangement usually are selected [138], as shown in Fig. 8.

Under this arrangement, cooling channel and thermal channel are formed between cabinets, where the cold airflow from the air conditioning system flow into the cabinet from the cold aisle and the hot air after cooling servers flow into the hot aisle with a return to air-conditioning system from the cabinet back. The cold and hot air channels separate the hot air from the cold one, which

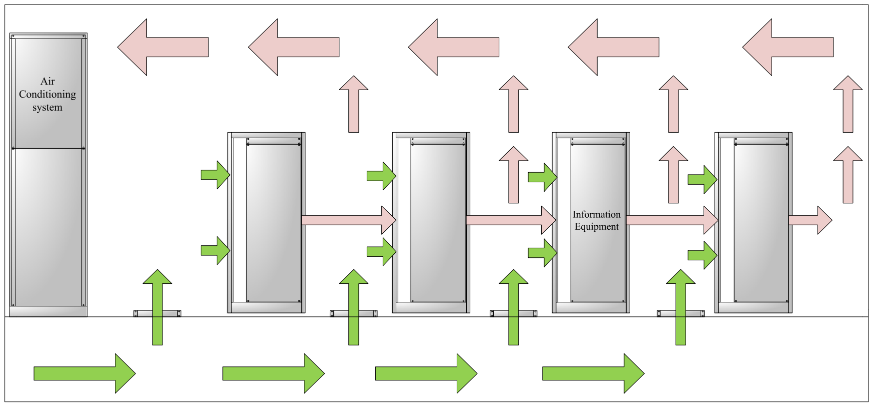

Fig. 7. Toward unity cabinet arrangement.

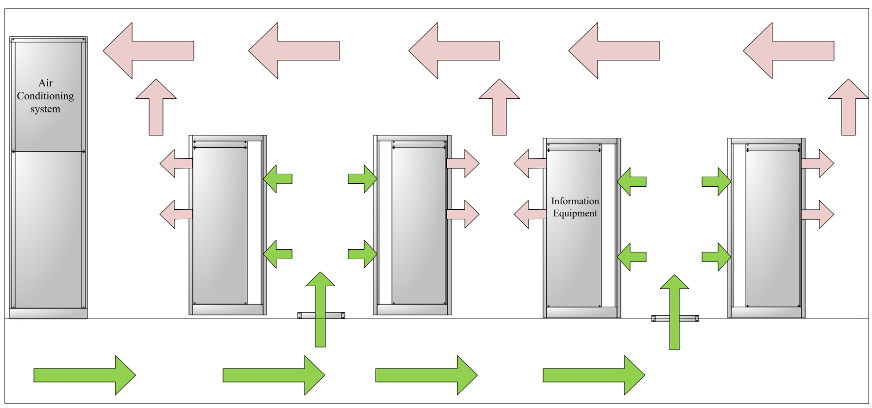

Fig. 8. Face to face and the back to back of rack configuration.

effectively inhibits the mixing of the hot and cold air, reduces the inlet air temperature of the cabinet and improves the cooling efficiency. In order to better isolate the hot air from the cold one, some baffles should be arranged in the cold aisle or hot aisle under the cabinet arrangement with face to face or back to back, or one channel should completely be closed up, which can achieve an efficient use of cold airflow.

Vishwas Bedekar et al. found the best position of CRAC and air volume through CFD simulating 80 different positions and three different air volumes in data centers [139]. From the results, they found that the performance of data centers mainly depends on the location and the corresponding airflow and the best cooling effect may be achieved with the air volume taking 10000 cfm nearing the rack location.

The airflow distribution mode of data center rooms can be mainly divided into two kinds, supply air upward and supply air down. The way of air supply upward is to put the cold air disposed by the air conditioning unit to the upper information equipment through air supply outlet. This method takes away heat of information equipment and computer rooms and then back into the air conditioning unit for cooling treatment through the lower space of computer rooms. The air supply down forms a overhead layer by raising the engine room floor, the cold air treated by the air conditioning unit is sent to an aerial layer from the bottom of the air conditioner, and the cold air enters the engine room and information equipment through the floor with opening hole at the device bottom, comes back into the air conditioning units after taking the heat through the upper space, resulting in cooling temperatures, and then begin the next cycle.

The floor design of current data center computer rooms is divided into two categories of the hard floor and overhead floor, and the wind pattern includes three types of open mode, a local pipeline or full pipeline, and can be derived from a variety of air supply through the different combination between them. A typical air-cooled data center is designed in Fig. 9. First, the data center will need to raise the floor for wiring and cool air distributed to the racks of data centers. Cold air flows into the rack from cold channel through the perforated floor. Cold air flows the servers and cools them and becomes hot air by absorbing heat, and is finally discharged from the hot aisle. Hot air flow is sent to air cooling unit and re-converted to cold air due to air flow.

Researchers do some experiments on different types of air supply through numerical simulation and experimental measurements and other means. Rasmussen [140] carried out a study whereby three basic methods are used to convey air between the CRAC and the IT server: flooded supply/return, locally ducted supply/return and fully ducted supply/return. The requirement to deploy high-density servers within single racks is presenting data center managers with a challenge. Vendors are now designing servers which will demand up to 20kW of cooling if installed in a single rack. With most data centers designed to cool an average of no more than 2kW per rack, some innovative cooling strategies will be required. Ref. [141] provided a ten-step approach on how to increase the cooling efficiency, the cooling capacity, and the power density of existing data centers. According to the works of Ref. [142], different ventilation patterns of outside air could determine the optimal local distribution of the outside air in a non-homogeneous data center.

4.2. Rational utilization of natural cold source

The conventional temperature of data centers should maintain in (23 ± 1) °C, but the north outdoor environment temperature is lower than the required temperature most of the time, so if we can

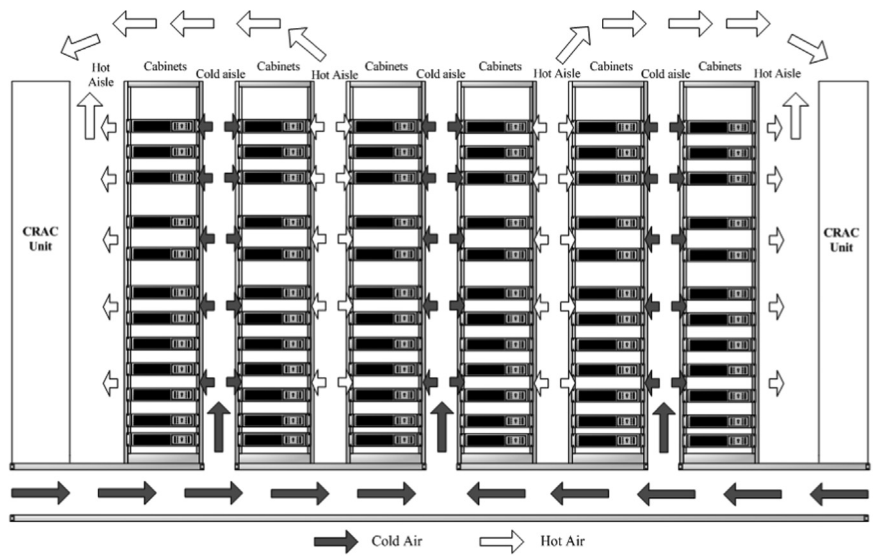

Fig. 9. Air-cooled data center.

Table 3
The comparisons of electric power saving effect applied the two types of heat exchangers.

	The electric power consumption in air conditioning mode (kWh)	The electric power consumption in the mode of air conditioning combined with heat exchanger (kWh)	Annual electric power saving (kWh)	Annual electric power saving rate (%)
Installed the plate heat exchanger	5694.6	4045.7	1648.9	29.0%
Installed the heat pipe heat exchanger	5694.6	4381.1	1313.5	23.1%

take advantage of the cold source outdoor environment and relying on the outdoor cold air taking away the heat in the data center, the air conditioning running time will be shortened greatly. Meanwhile, it will reduce energy consumption and extend the life of air conditioning equipment.

The utilization of natural cold source can be divided into two broad categories: direct use and indirect use. Outdoor air is introduced directly into the data center for cooling in direct use, taking away heat from devices to the outdoor. Due to the data center being strict requirements for humidity and cleanliness, so the control of humidify and filtering should be processed before outdoor air pulls into the data center. The indirect use of natural cold source achieves the cold and heat exchange between the outdoor air and indoor air through the heat exchange equipment, which will reduce indoor cycle airflow temperature in the case of assuring indoor humidity and cleanliness meanwhile and. The difficulty of natural old source indirect use lies in how to efficiently implement heat exchange between indoor and outdoor air change.

Many scholars made some research on the natural cold source utilization in data centers. Brandemuehl et al. [143] concluded energy savings should be achieved using an airside economizer in buildings and this could achieve an energy saving of 6% (Denver) to 25% (Miami). Sloan [144] proposed a new design for the airside economizer system. A novel approach for separating the hot aisle and the cold aisle with a physical barrier was proposed. The surrounding air was brought into the server room after filtration. Intel Corp. recently reported large energy savings (40%) by implementing wet side economizers system in data centers [145]. A recent report published by Rumsey Engineers in collaboration with Pacific Gas & Electric Company discussed a new design of a data center with economizer [146]. A small-scale (130 m^2) data center located in a large office building was considered. Ref. [147] conducted a survey and simulation-based estimation toward their introduction. The estimation results have shown that the water-side economizer requires doubling the capacity of the cooling tower and consideration of the installation space and cost, while the air-side economizer increases the humidifying power, which requires the relaxation of indoor humidity specifications. According to the simulation comparison results, the package type air-conditioning unit with an expanded scope of low pressure ratio control has the lowest energy consumption per year. According to the works of Ref. [148], when the outdoor temperature was low enough, a communication base station, equipped with a plate exchanger, discharged excess heat, which could cool the station instead of air conditioning for about 5014 hour each year, and the corresponding electronic power saving rate reached up to 29%, shown as in Table 3. Thus, rational utilization of natural cold source will contribute to energy saving greatly.

5. Renewable energy demand in data centers

At present, the electric energy consumed by data centers is mainly from fossil fuels, while recent researches on renewable energy never stop and this trend also extends to data centers with the advent of cloud computing. A large number of servers not only consume power, but also produce worrisome environmental pollution resulting from its energy consumption. These contaminants will cause serious damage to urban environment. Faced with huge energy demand from data centers' construction and operations, Greenpeace organizations promote and encourage data centers to use new energy through rating the clean energy of data centers in global IT companies. Meanwhile, governments have also developed energy conservation regulations and policies.

Usually, the available power is unstable and changeable with time due to the wind and solar power generation being closely related to environmental conditions, such as wind speed and sunshine intensity. Accordingly, their capacity factor is far lower than traditional power plants (capacity factor is the ratio of actual output to the rated maximum output) The traditional power plant capacity factor is up to 80% or even higher for there being a stable supply of fossil fuels. According to the most optimistic estimate by IEA, the renewable energy share in the electricity generation could increase from 18% in 2004 to 39% in 2050 [149].Thus, when a new energy is introduced for reducing energy consumption, energy saving and emission reduction in new data centers construction or upgrading, data centers also face following new issues: How to plan the energy portfolio of whole data center system? How to choose a variety of rated power quota of new energy? This needs to consider different sources of new energy (wind or solar energy, new energy directly available or indirectly), different costs of different energy and unit carbon emissions, storage devices, load, weather conditions, incentive policy, the service agreements of SLA, tax, grid power factors and so on. This makes the development of the energy portfolio and quota planning more challenging according to local conditions.

The energy quota plan of data centers is mainly related to research about constructing a new data center or how to choose the best combination of energy costs, carbon emissions and energy consumption when a new energy added. In Ref. [150], a general, optimization-based framework was proposed to minimize datacenter costs in the presence of different carbon footprint reduction goals, renewable energy characteristics, policies, utility tariff and energy storage devices (ESD). This framework can achieve the purpose of optimizing the new energy mix and match, minimizing the costs of data centers depending on the carbon footprint target, new energy characteristics, policies, taxes, and energy storage devices, modeling optimization. And the authors expect their work can help datacenter operators make informed decisions about sustainable, renewable energy powered IT system design. In Ref. [151], the researchers presented a kind of management plan of energy consumption, which makes the data center load match the energy demand and supply. This method uses DVFS and server consolidation techniques to adjust CPU energy consumption and the number of servers, and set the upper limit to control the energy consumption requirements. Ref. [152] constructed a system model of optimal energy mix. This model could consider the reliability of the power grid, power cost, and the health effects of pollution, the impact on the built environment, the impact on the scenic spots and local wealth and environmental. Moreover, it can simulate the interaction between these factors, and provide decision-making information to design the best combination of electrical energy.

For more efficient utilization of new energy, Ref. [153] discussed a problem that faces the algorithms aiming at fostering a better utilization of renewable energy in data centers: the lack of information about the running applications at a macroscopic level. Janacek S et al. [154] believed data centers may make profit from local renewable energy, and reduce carbon dioxide emissions. They proposed a data center simulation concept and constructed two independent smart grids, and then created a comprehensive simulation through both combinations. Special focus is placed on a new surrogate data center model (SDCM) and its functionality and requirements. This SDCM, as a data center, can accommodate its architecture and itself at the case of different energy status to obtain the best synergies between the data center and the smart grid use in energy exchange and infrastructure aspects, ultimately improving the utilization efficiency of the new energy.

eBay decided to use the fuel cell power of 30 Bloom Energy to supply energy for its data center in Utah [155]. In April 2012, the green peace organization published a report named "How Clean is Your Cloud?" which made an assessment on the green energy utilization for those data centers of famous IT companies [156]. Among them, Dell topped with a ratio of 56.3% of clean energy, Google and Facebook lined up second and third place with 39.4% and 36.4% ratio respectively. In other indicators such as data centers site selection, energy efficiency and greenhouse gas emissions, energy use secondary recovery, and few companies can reach A and B level on behalf of green. In addition, most IT companies have more difficult to adopt new energy due to financial and technical reasons. Obviously, the green energy supply is full of opportunities and challenges for data centers and is also still a long way to go.

6. Metrics and trends for energy efficiency of data centers

As we know that the different evaluation indicator could reflect the different tendency of energy conservation and provide a guide to select air condition, power supply and distribution system and so on. Therefore, we consider employing popular indicators, for example, PUE (Power Use Efficiency), DPPE of Japan (Data center Performance per Energy) including IT equipment usage and energy efficiency, SWaP (Space, Watts and Performance) and DCeP (Data Center energy Productivity).

6.1. PUE

Christian Belady [157] proposed the concept of PUE (Power Use Efficiency) for data centers and presented a following formula:

$$PUE = \frac{\text{Total Facility Power}}{\text{IT Equipment Power}} \tag{1}$$

The ratio value of PUE formula is smaller, the higher the energy efficiency of the data center, and the data center is more in line with low-carbon, energy-saving standards. Today, PUE has developed into global energy consumption standards of data centers. If we want to reduce the PUE value, we should reduce the energy consumption of the air conditioning system, power system and other supporting equipment according to the calculation formula. The energy consumption of air conditioning systems accounts for the biggest proportion, so the energy-saving potential is also the biggest.

According to evaluation index of computer rooms' energy saving, the most energy-efficient data center is "chicken coop" of Yahoo (PUE = 1.08). This data center is located Niagara Falls near the north of New York, the entire building has a large skylight and dampers to control airflow in order to better "breathing". Each building itself is an air handler and looks like a giant chicken coop. PUE value ranked second is the data center of Facebook (PUE = 1.15), where new distribution design is adopted and the uninterruptible power supply (UPS) and power distribution units (PDUs) of traditional data centers are eliminated, and the UPS and battery backup functions are transferred to the data center racks. Meanwhile, Facebook is also using fresh air for natural cooling. The third is the data center of Google in Belgium (PUE = 1.16), where the climate almost support year-round free cooling except only 7 days per year. Even the maximum temperature of Brussels reaches 66-71 degrees F (19–22 °C) in summer, the temperature of Google data center is almost 80 Fahrenheit degrees (27°C).

6.2. DPPE

In Japan, the Green IT Promotion Council established DPPE (Datacenter Performance per Energy) as a new indicator of energy efficiency at data centers [158], which includes IT Equipment Usage, IT Equipment Energy Efficiency, PUE, and Green Energy Coefficient. There are high hopes that DPPE will be an indicator that allows comprehensive evaluation of the energy efficiency of factors such as ICT devices and facilities, operating conditions of ICT devices, and the amount of green power introduced. While this indicator is still being reviewed, it has a unique point, as compared with the existing techniques: the capability to comprehensively evaluate both a data center's energy-saving efforts and the attempt to incorporate green energy use. The indicator is intended to promote green energy use in the future and reward data center operators' efforts to use green energy. They hope it will be established at an early date so that Japan can take the initiative in this field. The indicator of DPPE may be calculated as the following formula [158]:

Energy efficiency (DPPE) = (Actual consumption energy of IT equipment) / (IT equipment rated energy consumption) $\times$ (IT equipment rated capacity) / (IT equipment rated energy consumption) $\times$ (Energy consumption of IT equipment) / (Energy consumption of datacenter) $\times$ (Energy consumption of datacenter) / (Non-green energy consumption) = ITEU $\times$ ITEE $\times$ (1/PUE) $\times$ (1/(1 - GEC)) (2)

According to this formula, in addition to increasing the energy efficiency of air condition and other facilities, the energy efficiency of data centers can be achieved by improving the scheduling algorithms, enhancing the server energy efficiency, utilizing the green energy. According to the measurement results of various data centers by the DPPE indicator [159], it can be learned that it is important to evaluate these items holistically, as shown in the following Table 4.

Presently, the Green IT Promotion Council is committed to building an international standardization of DPPE. This will be a new metric starting from Japan to measure the performance of the overall data centers.

6.3. SWaP

The metric of SWaP (Space, Watts and Performance) is used to evaluate energy efficiency of data centers by defining three parameters including space, energy and performance together. The SWaP is calculated as follows [160]:

$$\mathrm{SWaP} = \frac{\mathrm{Performance}}{\mathrm{Space} \times \mathrm{PowerConsumption}} \tag{3}$$

In the foregoing equation, the performance means using industry-standard benchmarks, the space is described as measuring the height of the server in rack units (RUs), and the power denotes determining the watts consumed by the system, and using data from actual benchmark runs or vendor site planning guides.

The SWaP metric will present an effective cross-comparison and a total view of server energy efficiency. Users are able to accurately compare the performance of different servers and determine which ones deliver the optimum performance for their needs. The SWaP can help users better plan for current and future needs and control their data center costs.

Table 4
DPPE Measurement Results.

Data Center	A	B	C	D	E	F	Vietnam	Singapore
ITEU	0.57	0.26	0.42	0.36	0.42	0.31	0.40	0.74
ITEE	2.14	1.08	0.48	3.68	1.32	1.41	0.84	3.59
PUE	1.89	1.42	1.76	2.12	1.82	1.71	1.77	2.2
GEC	0	0	0	0.004	0	0	0	0
DPPE	0.64	0.20	0.11	0.63	0.31	0.26	0.18	1.2

6.4. DCeP

The DCeP (Data Center energy Productivity) is proposed to characterize the resource consumed is energy for useful work in a data center. The DCeP is calculated as follows [161]:

$$\mathrm{DCeP} = \frac{\mathrm{Usefulworkproduced}}{\mathrm{Totalenergyconsumedtoproducethatwork}} \tag{4}$$

Useful work is the tasks performed by the hardware within an assessment window. The calculation of total energy consumed is the kWh of the hardware times the PUE of the facility.

Among these indictors, The DPPE method tried to establish the metrics which could evaluate not only the data center infrastructures, but also to improve the IT efficiency and introduction of the Green energy source. Therefore, the DPPE is comprehensive and efficient measurement method and becomes increasingly popular besides Japan.

6.5. Trends for energy efficiency

From the energy-saving perspective of software, the high-performance computing technologies are always the effective methods. We can be confirmed from the Greens500 List in the energy efficiency systems over the years. Fig. 10 shows the energy efficiency of all the HPC systems for recent Green500 List [162].

This figure clearly illustrates that the gap between the most energy-efficient systems and the rest gradually widen the gap every year. In the last four lists, we may find outliers at the top end of the list, and BlueGene/Q systems have been largely responsible for this. In general, these systems ranked by top ten possess energy efficiency with more than 2.0 GFLOPS/watt in the last two editions of the Green500 List. From this way, we can find that the HPC technology contribute to the energy conservation with an increasing share for the supercomputers of Green500 List, and it has become an important aspect of energy efficiency.

For disruptively boosting the energy efficiency of low-power servers, the hardware enhancements of design and craftsmanship must be updated and integrated with the chip technology. Therefore, the current server deployment with high-end processors of low power becomes the main stream, and especially the System-on-Chip (SoC) designs with low power are impressive. Recently, there has been an alternate architecture—Thin Servers with Smart Pipes (TSSP). It couples an embedded-class core with low power to a memcached accelerator that can process GET requests entirely in hardware, offloading both network handling and data look up [163]. This technology emerges for cost effective

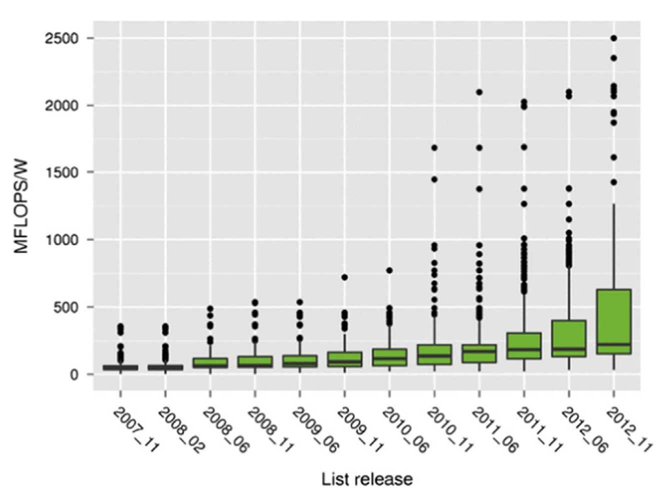

Fig. 10. Energy Efficiency in Green500 Lists.

and high performance and it will be the development trends of low-power network equipment.

In addition, faced with huge energy demand from data centers' construction and operations, the energy-saving strategies for data centers have evolved from the original ventilation cooling systems to the air conditioning cooling and renewable energy application. Moreover, the future research trends and opportunities for energy-saving systems lie in the utilization of the latest energy-saving technologies for reducing energy consumption and emissions. Above all, the sustainable and renewable energy is far from being widely used, and the green energy supply is full of opportunities and challenges for data centers.

7. Conclusion

This review paper focuses on the available energy-saving technologies for data centers. Those technologies are very useful for the energy conservation.

Energy-saving technologies have different contribution to the energy saving at different stages of data centers from a global perspective. In the site selection of data centers, proper site selection through scientific and rational utilization of natural energy can reduce probably 30% of computer room air conditioning (CRAC) consumption, while the energy consumption of CRAC usually accounts for 40-50% of total energy consumption, so the reasonable site selection may lead to almost 12-15% off in total energy consumption. In the construction of data centers, it may effectively reduce energy consumption probably by 25-30% to choose low-power servers and auxiliary energy-saving devices. The operators of data centers can save about 10-15% of the total energy consumption by optimizing resources scheduling algorithm and management strategies. The rational use of renewable energy also can effectively reduce overall energy consumption of data centers, during the construction process of data centers.

It's a desirable goal to achieve a tradeoff between the maximum benefits of data centers and the minimum environmental impact by considering various aspects such as cost, energy consumption and environment. Now, with the building pace and scale of data centers increasing greatly, we should integrate various energy-saving technologies into data centers to better improve resource utilization and reduce energy consumption, and truly build "breathing" green data centers.

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