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Energy-efficient Techniques in SDN: Software, Hardware, and Hybrid Approaches

Vikas Verma* and Manish Jain

Department of Computer Science and Engineering,
JECRC University, Jaipur, Rajasthan 303905 India

In recent times, software-defined networking (SDN) has garnered significant attention due to its approach of separating the control plane from the data plane. This abstraction allows managers to have a centralized perspective on the network, which in turn enables them to control traffic flow and routing policies dynamically without configuring individual devices. The increased adoption of SDN has resulted in the need to optimize energy consumption without compromising network performance. Creating an energy-efficient solution presents a challenge due to the intricate process of finding the right equilibrium between network performance and energy conservation. This article examines various techniques for achieving energy efficiency in SDN and classifies them into three categories – software-based, hardware-based, and hybrid approach. These categories are further divided into their subcategory. Furthermore, a comprehensive exploration will be conducted to delve into the benefits and drawbacks of each energy efficiency approach, followed by an in-depth comparative analysis. The article also discusses the research issues and challenges associated with each technique. Finally, the paper provides future prospects for investigating energy efficiency approaches in SDN, which are expected to yield substantial benefits for upcoming researchers in this domain.

Keywords: energy consumption, energy-efficient, hybrid approaches, routing, SDN

INTRODUCTION

Software-defined networking (SDN) has gained popularity and attention around the world recently. A non-profit organization specializing in the creation and standardization of SDN is called the Open Networking Foundation (ONF 2022). According to ONF, SDN can be defined as a network engineering that isolates the elements of a network into two distinctive planes – the control plane and the information plane. The control plane deals with the progression of data between network gadgets, whereas the information plane is answerable for sending the information packets themselves. This separation of any network infrastructure from the applications that use it enables more programmability and automation in the control of network behavior and policies. SDN centralizes the network's intelligence and state, allowing for more efficient and flexible management of the network. This, in turn, enables organizations to better optimize their network resources, improve network security, and support new applications and services with ease (Narmanlioglu and Zeydan 2017).

SDN introduces programmability to networking, a capability that is not achievable in traditional networks. It simplifies network management, reduces costs, enhances flexibility, and empowers organizations to adapt and innovate in the rapidly evolving world of networking. Unlike traditional networks, SDN allows for global management of the network, meaning it is not

*Corresponding author: vikasverma1988@gmail.com

limited to specific vendor policies (Rout *et al*. 2021). This adaptable controller grants administrators enhanced authority in directing the flow of network traffic, thereby facilitating improved overall network administration and optimization. Through SDN, network regulations can be readily established and modified, thereby liberating them from the constraints or limitations imposed by particular vendors. Despite the many advantages of SDN technology, it also has some drawbacks. One important issue is the management of energy utilization, which can impact the SDN (Assefa and Özkasap 2019; Molina and Juárez 2018; Rout *et al*. 2018; Son *et al*. 2017; Liao and Wang 2018; Hu *et al*. 2017; Zheng *et al*. 2014). To address this issue, various techniques have been suggested to minimize unnecessary energy consumption in SDN. It is essential to fully utilize network components to ensure optimal network performance. Underutilized components can contribute to energy consumption, and the energy consumption factor may vary depending on incoming traffic patterns (Galán-Jiménez *et al*. 2018; Leng *et al*. 2017). Efficient utilization of the programmable controller is crucial in addressing energy consumption in SDN (Rout *et al*. 2021). Diverse strategies have been employed to mitigate avoidable energy consumption, with a specific focus on managing the inefficient use of network components that are not fully utilized. It is important to consider the incoming traffic patterns as energy consumption may vary. Tailoring energy-saving strategies based on traffic patterns helps optimize network performance while minimizing energy consumption in SDN networks. Numerous surveys have been conducted by different researchers to identify and evaluate energy-efficient methods in SDN (Assefa and Özkasap 2018a; Rout *et al*. 2021; Agg and Johanyák 2021; Xie *et al.* 2018; Tuysuz *et al.* 2017; Rawat *et al.* 2016).

The study by Rout *et al*. (2021) delved deeper into various energy-efficient techniques by providing a thematic taxonomy of SDN. Scientific categorization relies on previous research and encompasses three distinct sub-divisions – traffic awareness, end-host awareness, and rule placement. Each of these subcategories incorporates intricate objective functions, parameters, and constraints to offer a comprehensive analysis. Agg and Johanyák (2021) conducted a comprehensive literature review to evaluate different SDN-based energy-saving solutions. The authors acknowledged the challenge of directly comparing these solutions based solely on existing literature – owing to the differences in parameters, network topologies, conditions, and simulation tools employed across various studies. However, through their analysis, the study was able to qualitatively evaluate the efficiency of the methods and identified heuristic rule space modification as the most effective approach, considering the limitations of wired networks. The author emphasized the importance of further research on rule placement to optimize routing and network performance, which directly impacts energy efficiency. The proposed survey (Rout *et al*. 2021) also highlighted the need for addressing security concerns in the communication of control data and control applications, stressing the requirement for further development in secure communication protocols. Furthermore, the author suggested the exploration of fuzzy techniques as a potential avenue to enhance energy savings and called for future investigation in this area.

In a survey carried out by Assefa and Özkasap in 2019, an analysis was presented, classifying energy efficiency approaches within SDN. This classification segregated the approaches into two categories: software-based solutions and hardware-based solutions. Within the software-based solutions, there were further subdivisions – namely, traffic awareness, end system awareness, and rule placement. Each of these subdivisions was underpinned by optimization models that established specific objectives, parameters, and limitations. The study also delved into hardware-based solutions that aimed at enhancing the efficiency of network switches. Further, the survey identified unresolved issues in the field and proposed directions for future research endeavors aimed at enhancing energy efficiency within SDN.

The energy-centric SDN approaches proposed by Tuysuz *et al.* (2017) so far have mostly utilized a single technique to save energy. The authors emphasized that numerous techniques can be employed independently or in conjunction to further enhance energy efficiency. They achieved this by comparing and summarizing the features, differences, and expected energy benefits of various methods. In summary, the paper serves as a valuable reference for researchers and practitioners seeking to enhance energy efficiency within SDN and those interested in optimization in this domain.

The work by Rawat and Reddy (2016) provided a thorough examination of SDN and its implications on both network security and energy efficiency. The primary emphasis of the article was to investigate the interplay between energy efficiency and security within the context of SDN. The authors thoroughly examined various approaches to improve the energy efficiency of SDN and explored the delicate balance required between optimizing energy consumption and maintaining network security in such environments. The article provided a comprehensive overview of the techniques used and compared them directly to highlight their similarities and differences. The article also provided a comprehensive understanding of SDN architecture and its influence on security and energy efficiency.

Our survey is focused on conducting a thorough analysis of energy-efficient methods in SDN. The proposed survey contributes by examining existing survey papers in this area, offering deep insights into the effectiveness and limitations of various techniques. Furthermore, we provide a classification to categorize energy-efficient approaches in SDN software-based, hardware-based, and previously unexplored hybrid approaches, which combine software-based and hardware-based methods. A hybrid approach for energy saving in SDN involves the use of a combination of different strategies and techniques like dynamic resource allocation, virtualization, energy-efficient hardware, traffic engineering, sleep mode, *etc.*, to reduce energy consumption. This survey explores various hybrid approaches and categories further into three categories – network function virtualization (NFV), topology optimization, and hybrid switch. Hybrid approaches in energy-saving aim to find a middle ground between flexibility and efficiency. They can quickly adapt to changing network traffic using software while also achieving long-term energy savings by improving the hardware.

We explored the fundamental concepts, advantages, and limitations of three energy-efficient approaches. After categorizing them, we provided a brief comparison of the potential energy-saving ratios associated with these established methods.

This study identifies research gaps and challenges in SDN's energy efficiency, providing guidance for future research directions. Importantly, this survey distinguishes itself from prior work by incorporating the unique hybrid approach, summarizing these contributions in Table 1.

The survey is outlined as follows. Section 2 furnishes foundational knowledge about the SDN paradigm – including its definition, classification, and operational processes. In Section 3, the significance of conserving energy within the SDN context is underscored. The subsequent section, Section 4, introduces a structured categorization of energy-efficient strategies in SDN. This segment studies the underlying principles, advantages, and limitations of different SDN approaches. Section 5 conducts a comparative analysis of existing approaches, mainly focusing on their energy-saving benefits. Finally, Section 6 explores contemporary challenges and issues pertinent to the domain of energy efficiency within SDN. Further, the section offers recommendations and outlines potential research directions that can be pursued in the future to address these challenges and enhance energy efficiency in SDN environments.

MATERIALS AND METHODS

SDN is a networking architecture that can effectively handle the increasing demands of network components by providing a flexible way of managing traffic and network devices. The segregation between the control plane and the data plane stands as a pivotal attribute within SDN.

Architecture of SDN

The data plane is accountable for transmitting network traffic, whereas the control plane governs the flow of network traffic streams. The distinct separation of the data plane and control plane facilitates centralized network control, thereby simplifying the implementation of novel services and applications, adaptation to evolving network circumstances, and the augmentation of the overall network. As a result, SDN is becoming increasingly popular in both enterprise and service provider networks. SDN also offers simplified network management and automation, making it a highly efficient and effective solution for modern networking needs (Singh and Janghel

Table 1. Analysis of existing survey on energy-efficient approaches for SDN.

Ref.	Year	Background	Performance	Traffic aware	Rule placement	End-system aware	Objective model	Hardware	Hybrid
Rout *et al*.	2021	✓	✓	✓	✓	✓	✓		
Agg and Johanyák	2021	✓		✓	✓				
Assefa and Özkasap	2019	✓	✓	✓	✓	✓	✓	✓	
Xie *et al*.	2018	✓	✓	✓			✓	✓	
Tuysuz *et al*.	2017	✓	✓	✓	✓	✓		✓	
Rawat and Reddy	2016	✓	✓	✓	✓	✓			
This survey	2023	✓	✓	✓	✓	✓		✓	✓

2017). Figure 1 shows the architectural components of each plane and their interactions and detailed information on these three components.

Data plane. It is the bottom layer of SDN architecture. It is also called an infrastructure plane. This plane has physical sending devices like switches and routers. In SDN, switches are of two types – physical and virtual. A physical switch is a hardware device that connects and directs data traffic between devices on a local network, whereas a virtual switch is essentially a software program that functions as a switch and can operate on common operating systems such as Windows or Linux.

Control plane. The control plane acts as a "heart" of SDN frameworks, which can control all system assets, utilizing a program, updating, and sending rules progressively that depend on the organized state and make arranged organization adaptable and nimble.

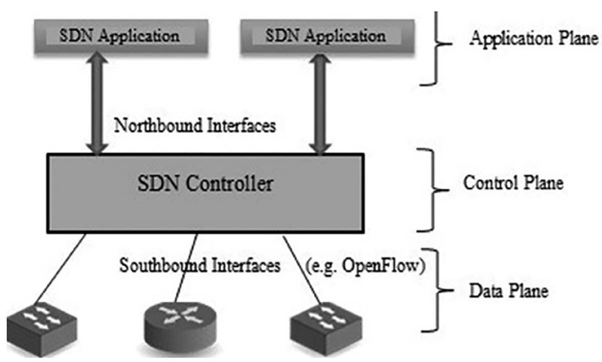

Figure 1. Architecture of SDN.

The control layer is liable for dealing with the organization utilizing open APIs (application programming interfaces) and programming programs. It provides oversight for the network and enables network administrators to implement customized policies for infrastructure devices (Habibi *et al*. 2020).

Application plane. The application plane, which is fundamentally integrated with enterprise applications, represents the top layer of an SDN's design. Business management and various services can be achieved through these applications. The northbound interface, a crucial element, provides all the necessary information about the network state. Applications can then adjust or modify established processes based on this data and the specific requirements of a particular business application (Ndlovu *et al.* 2020).

Need of Conserving Energy in SDN

The escalation in energy usage within networking has emerged as a substantial apprehension, influenced by a multitude of factors. One of the primary reasons for this increase is the rapid advancement of information technology. With technologies like cloud computing gaining popularity, there has been an exponential rise in the amount of data generated by individuals and networks. As a result, data centers need to operate continuously to ensure uninterrupted and reliable services, leading to a substantial surge in energy consumption (Tuysuz *et al*. 2017). The inefficiency of data centers further contributes to the energy consumption challenge. Since the growth of data traffic continues, data centers need to find ways to manage energy usage more efficiently. The rapid expansion of data centers has brought forth a notable surge in energy expenditures. To put this into context, according to a report published by the New York Times in 2012, these digital storage units collectively consume approximately 30 billion watts of electrical power worldwide, a scale comparable to the output of 30 nuclear plants (Glanz 2012). In the United States (US) alone, data centers consumed an estimated 91 billion kilowatt-hours of electricity in 2013, akin to the consumption of approximately 34 power plants. Predictions indicated that by 2020, this energy consumption would escalate to 139 billion kilowatt-hours, equivalent to the output of 51 power plants, signifying a 53% increase from the 2013 levels (Delforge 2014). The concerning rise in energy consumption highlighted the need for more sustainable solutions in the data center industry. The global internet energy consumption experienced a notable 19% increase in 2022 (Tuysuz *et al*. 2017).

The cloud allows for efficient allocation of computing resources, benefiting both individuals and businesses by reducing energy consumption. For example, research by Lawrence Berkeley National Laboratory in 2013 suggested that shifting US office workers to cloud services could cut IT-related energy consumption by 87% (Masanet *et al.* 2013). In a case involving Google Apps, the US General Services Administration reduced office computing expenses and carbon emissions by 65– 90%. Additionally, using Gmail for email services can result in up to 98% environmental savings compared to local email servers (Google 2023)

Facebook's US data centers – totaling 13 – have had a substantial impact on the economy, environment, and communities from 2017–2019. They contributed approximately USD 18.6 billion to the US gross domestic product, mainly through upfront construction investments, and supported numerous jobs. Facebook's community development efforts included donations and a focus on technology for community benefit and STEM (science, technology, engineering, and mathematics) education. In terms of the environment, the data centers reduced greenhouse gas emissions by over 3 million tons since 2011 and saved 4.6 billion gallons of water in 2019. Additionally, Facebook invested significantly in renewable energy, adding 987 megawatts of wind and solar capacity during this period (Vanlear *et al.* 2020).

Back in 2011, it was approximated that the information and communication technology (ICT) sector contributed to approximately 6% of the total worldwide energy consumption, and this figure is projected to continue rising due to the increasing energy demands of data center equipment (Lambert *et al*. 2008). The substantial growth in data traffic and energy consumption by data centers presents a significant sustainability challenge. Therefore, finding and implementing energy-saving solutions is crucial to address this issue, as failure to do so may have severe environmental, economic, and social consequences (Katal *et al*. 2022). The energy consumption and CO_2 emissions in the ICT sector as a whole pose significant sustainability concerns. Studies have shown that energy consumption and emissions continue to grow worldwide, despite improvements in energy efficiency. The expanding usage of ICT services and technologies contributes to this increase. As a result, it becomes essential for the ICT sector to take proactive measures to decrease energy consumption and reduce its environmental impact (Gelenbe and Caseau 2015).

The SDN controller plays a pivotal role in optimizing energy consumption. It can put idle switches into sleep mode for predefined periods, reducing their power consumption. However, this approach may introduce trade-offs such as increased bandwidth and packet reception delays. Additionally, the controller can dynamically adjust data rates to minimize energy consumption. Lower data rates result in reduced energy usage, as transmission power is directly related to data rates according to Shannon's formula (Davoli 2013).

Various components of the SDN framework can be flexibly modified to conserve power. One strategy entails the dynamic adjustment of network traffic flow and the activation of sleep mode for underutilized devices. In instances of reduced traffic, specific ports can be placed in a low-power state rather than the entire device. Traditionally, network routing data is stored in flow tables, usually housed in a power-intensive and costly ternary content addressable memory (TCAM) (Tuysuz *et al*. 2017). By reducing the size of these tables, energy consumption can be minimized. By carefully managing TCAM usage, the controller can reduce unnecessary energy consumption. Additionally, virtualization in SDN enables the consolidation of multiple systems into a single virtual machine (VM), leading to more efficient energy usage.

Energy consumption within SDN can be categorized into three key components – the controllers, the switches, and the network links. The SDN controllers comprise both software and hardware elements. Notably, most controllers in the market are designed using versatile programming languages and can function on various operating systems. Similar to any software application, they have the potential to harness the multi-core processing capabilities of the underlying platforms. Given that most operating systems are designed to cater to a wide array of tasks, there exists an opportunity for optimizing the hardware and software specifically for the unique demands imposed by SDN controller operations, thus streamlining energy consumption in this critical network component (Oliveira *et al.* 2021). The increased adoption of graphics processing units (GPUs) in servers has garnered significant attention, especially in the context of computational methods like machine learning. However, it is important to note that as of 2016, servers equipped with GPUs accounted for just a small fraction – approximately 5% – of the total global server shipments (Agg and Johanyák 2021). No significant change in server energy consumption due to GPUs through 2020. This assumption is based on the fact that GPUs were not widely represented in servers at that time, and there was a lack of data to predict their future adoption and energy impact accurately.

Nonetheless, considering the potential for increased GPU usage in various emerging applications (Dean *et al.* 2018) and the evolving landscape of chip and processor technology, it introduces uncertainty when making long-term projections for annual global data center traffic. These projections can vary considerably, with estimates differing by up to 80 zettabytes by 2030. This variation, in turn, leads to estimates of global data center energy consumption as high as 8 petawatt-hours per year (Andrae and Edler 2015). Therefore, Dean *et al.* (2018) included the GPU scaling factor in our model to underscore the importance of monitoring and revisiting estimates related to GPU penetration in the server infrastructure for future assessments of server power usage.

Network virtualization provided an effective solution to combat the ossification of the Internet by enabling multiple virtual networks to coexist on a shared infrastructure (Wang *et al.* 2014b; Gharbaoui *et al.* 2014; Jin *et al.* 2013). The concept of virtual network embedding or assignment deals with the allocation of physical resources to these virtual networks. In a similar vein, server virtualization can also play a role in reducing energy consumption in SDN.

Classification of Approaches for Energy-efficient SDN

For an energy-efficient SDN, a number of approaches can be employed in SDN architecture. In this article, approaches are typically divided into three types –

software-based, hardware-based, and hybrid solutions – as illustrated in Figure 2. Software-based solutions primarily involve the controller of SDN and may be algorithmically applied to achieve energy savings. This approach refers to techniques that focus on optimizing the software components of the SDN infrastructure to achieve energy efficiency. These strategies aim to curtail energy usage by enhancing the efficiency of network resource usage, all the while upholding a commendable level of service quality. Techniques such as resource management and network virtualization techniques provide effective solutions for energy efficiency (Narmanlioglu and Zeydan 2017). In our survey, three main techniques for energy optimization in SDN have been identified – traffic awareness, end-system awareness, and rule placement. These techniques will be discussed in detail in the following sections.

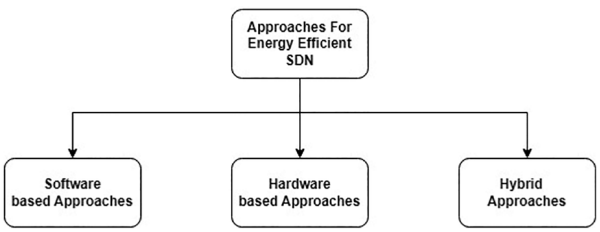

Figure 2. Methods to enhance energy efficiency in SDN.

To mitigate power consumption in network devices like servers, routers, and switches, researchers have been using hardware-based approaches. These methods are designed to optimize the devices' performance while consuming less power (Singh and Sharma 2021). Energy-saving processors and memory modules are used in these strategies for power utilization. Dynamic voltage and frequency scaling (DVFS) is a notable strategy that effectively adjusts voltage and frequency settings and frequency of the processor in view of responsibility, permitting it to work at lower voltage and frequency levels during low workload periods, which results in lower power consumption (Lee *et al.* 2007). Another hardware-based technique is the minimum use of TCAM, which serves as a type of memory utilized by network devices for swift packet lookup. This method minimizes the use of TCAM by utilizing alternative lookup methods such as hash tables, which consume less power (Mahendra *et al.* 2020). Sleep mode techniques are also effective in reducing power consumption in network devices. This involves putting the devices into sleep mode when they are not in use, which can significantly reduce their energy consumption. Wake-on-LAN is a technique that can be used to wake up the devices when they are needed, thereby minimizing the impact on network performance (Vu *et al.* 2014).

Our survey identifies another category of approaches for achieving energy efficiency in SDN as the hybrid approach, which is a mixture of hardware and software techniques. In recent years, researchers proposed several techniques for energy-efficient SDN, which combine hardware-based and software-based forwarding methods (Rezaeipanah *et al.* 2019). Hybrid switches (Xu *et al.* 2017), field-programmable gate arrays (FPGAs) (Suresh *et al.* 2021), virtualized network functions (VNFs) (Duan *et al.* 2017), and smart NICs are well-known methods for energy-efficient SDN.

This article examines the benefits and limitations of each approach and highlights the potential for synergistic effects when they are combined. The objective of this article is to provide insights that can guide the selection of the most appropriate approach or combination of approaches for a given SDN deployment scenario.

Software-based Approaches

Software-based methods can be classified into three categories – traffic-aware, end-system-aware, and rule-based approaches (Assefa and Özkasap 2019) – as shown in Figure 3.

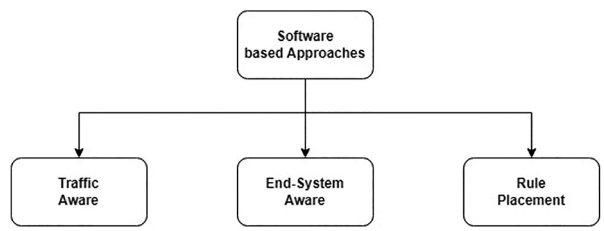

Figure 3. Software-based approaches for energy-efficient SDN.

Traffic-aware

Network traffic over a network includes various types of information such as files, emails, web pages, and streaming media. Traffic management is a useful approach for addressing network congestion, load balancing, bandwidth management, energy usage, security enhancements, and other related issues. One of the key benefits of traffic management is its ability to analyze network traffic, which can significantly enhance network performance (Rawat and Reddy 2016). Traffic classification is also one of the main key aspects for solving various issues in SDN (Verma and Jain 2019).

In the study by Jiménez-Lázaro *et al.* (2022), an artificial intelligence (AI) approach to logistic regression was used to predict energy utilization in SDN. This technique eliminates the requirement for heuristic or optimal solutions, which can result in longer computation times. The study involved conducting experiments on realistic network topology, and the results showed that this approach can accurately predict network configurations with a more than 95% feasibility rate. Moreover, the proposed solution was found to improve the amount of energy saved by a genetic algorithm-based benchmark heuristic. Additionally, this approach significantly reduces computation time by more than 500,000 times.

In the study by Assefa and Özkasap (2018), an innovative machine-learning framework named MER-SDN was introduced to optimize energy-efficient routing within the SDN domain. This framework was structured around three key phases – feature extraction, training, and testing. During the experiment, an authentic network topology and dynamic SNDlib traffic trace were employed on Mininet and POX controllers. The outcomes indicated the effectiveness of this approach in forecasting parameters for an energy-efficient heuristics algorithm with an accuracy rate surpassing 70%, coupled with a substantial reduction of 65% in feature dimensions. Furthermore, when contrasted with the brute force approach, the heuristics algorithm's anticipated values exhibited convergence to optimal parameter values at speeds up to 25 times quicker.

In the study by Ibrahim *et al.* (2022), EARMLP is an energy-efficient routing algorithm designed for SDN, which aims to minimize power consumption by considering system configuration and traffic demand. The algorithm can reorganize traffic to satisfy provisioning criteria using capacity-aware design. Experimental results demonstrated that when compared to other approaches, EARMLP can conserve up to 70% of energy.

In the study by Lu *et al.* (2019), a traffic load satisfaction ratio was proposed. This research endeavor explored the possibilities of energy conservation. The study aimed to enhance the energy efficiency of SD-DCN through the utilization of an integer linear programming model and the minimum energy consumption heuristic algorithm. This approach strategically balances the maintenance of quality of service (QoS) satisfaction while optimizing energy consumption. The algorithm demonstrated proficient energy savings, particularly in scenarios characterized by low to moderate traffic levels. Furthermore, it showcased superior performance compared to existing methods in terms of upholding QoS requisites for data flow, especially under high-traffic conditions.

The study by Verma and Jain (2019) proposed a hybrid approach that utilized machine learning techniques for traffic flow classification. The framework utilizes supervised machine learning techniques to classify network flows and detect elephant flows, which are exceptionally large flows in terms of total data volume, within a network. A routing algorithm was proposed that utilizes the Dijkstra calculation to calculate the most reasonable path founded on the basis of the QoS necessities of the elephant flow. The simulation results showed that the system identified elephant flow with a precision pace of 80% and figured a minimal expense path for every elephant flow in light of an actual internet data set.

The research study by Masood *et al.* (2019) proposed a dolphin echolocation algorithm to optimize routing decisions in wireless sensor networks (WSNs). The algorithm utilized a meta-heuristic approach with an objective function that considers the residual energy of the nodes to choose energy-saving routes. The result of the proposed algorithm was contrasted with a few meta-heuristic calculations in view of energy utilization and network throughput boundaries.

An online scheme proposed by Ba *et al*. (2018) called multiple topology switching with data plane forwarding path rerouting (MTSDPFPR) for energy saving in networks. The scheme dynamically switches links to sleep mode based on network traffic demands to achieve energy efficiency. The author evaluated the proposed scheme using the GEANT network and real traffic matrix, demonstrating up to 30% energy savings can be achieved.

The traffic-aware energy-efficient methods focus on minimizing the number of active links primarily and switches secondly or both. Testing energy-efficient methods in real time on actual network equipment is not timely and economically feasible. That is the main reason why researchers resort to creating small-scale test beds or using simulation/ emulation environments (Assefa and Özkasap 2018).

One significant issue that may arise with traffic-aware approaches is the lack of consideration for network security's impact on energy efficiency. While optimizing traffic load can lead to energy savings, it is crucial to balance this with network security requirements. Overemphasizing traffic load as the primary optimization parameter may compromise network security, leading to vulnerabilities and potential attacks. Additionally, the generalizability of traffic-aware solutions to different network scenarios can be limited. What works well in one context may not be applicable or as effective in another, making it challenging to develop a one-size-fits-all approach. Furthermore, the heuristic nature of some traffic-aware algorithms may not always guarantee the best solution in all situations, as their performance depends on various network conditions and parameters.

End-system-aware

End-system-aware techniques, on the other hand, optimize energy usage by taking into account the characteristics of the end systems such as servers, switches, and routers. These methods utilize the power of end frameworks by placing them into low-power modes when they are inactive. In SDN, the controller is used to determine the path for all incoming flow and decides the usage of every node and connection. The controller decides whether a switch should be active or inactive based on information received about the incoming packet flow. However, in sleep mode, the power consumption of a switch is almost zero. Similarly, links connected to multiple switches share the same power profiles. In sleep mode, a link uses no power and uses the most power when it is active. In order to conserve more power, it is preferable to turn off a switch or link that has been idle for an extended period of time. The number of active network components is reduced by this method, which ultimately leads to energy savings in the network (Jiang *et al.* 2018).

Shudhanshu *et al*. (2022) focused on addressing the challenges in handling complicated networking challenges caused by the recent changes in the networking industry. They proposed the challenges by applying the concept of the Internet of Things (IoT) with SDN to handle performing tasks at high speeds and engaging in complex problem-solving efficiently. The main problem tackled was assigning the VMs to end devices, which is a challenging optimization problem. A method called "ServerCons" has been proposed that allocates VMs by considering CPU and memory usage to enhance energy consumption. This approach reduces the count of live migrations and also the count of nodes used while maintaining energy efficiency comparable to other advanced algorithms like FFD (first-fit-decreasing), BFD (best-fit-decreasing), and MBFD (modified-best-fit-decreasing). Overall, the authors' contribution lies in proposing a solution that efficiently manages IoT implementations with SDN, thereby improving network performance, security, and energy consumption.

The authors in the papers by Liao and Wang (2018) and Hu *et al*. (2017) presented joint optimization efforts for efficiency of energy and migration of VM in cloud data centers. They view the arrangement of VM and migration challenge as an MVBPP (multidimensional vector bin packing problem), which can be challenging for heuristics to find optimal solutions due to the increasing vector dimension. To address this, a mathematical representation was introduced and a hybrid single-parent (partheno-genetic) algorithm was suggested to address the issue of virtual migration integration. The results of the simulation demonstrated that their approach reduces migration duration in comparison to comparable techniques, although the scalability issue remains partially unresolved.

In the paper by Neghabi *et al*. (2019), the authors compared various SDN meta-heuristics algorithms for load balancing. Different metrics were proposed – including online migration, throughput, energy efficiency, and migration time – to evaluate the performance of these meta-heuristics algorithms. Examples of such algorithms include particle swarm optimization, genetic algorithm, greedy and simulated annealing, and ant colony optimization. The main motivation for using meta-heuristics algorithms was that formal solutions for load balancing in SDN are time-consuming and might only converge effectively under limited scenarios involving physical and VMs. Therefore, meta-heuristics algorithms are employed to find sub-optimal solutions that are computationally more feasible but might still be far from the optimal solution in some cases. These algorithms offered a trade-off between efficiency and optimality, making them suitable for addressing SDN load-balancing challenges.

In the study by Molina and Juárez (2018), the authors proposed the fair share routing (FSR) algorithm to achieve a uniform distribution of network traffic in SDN. The algorithm ensures equal load sharing across the entirety of switches and links within the network. A portion of links was chosen, and the overall traffic was uniformly allocated to avoid delays. However, one limitation of the FSR algorithm is that it does not achieve 100% link utilization of its total capacity. The authors argued that fully utilizing links and turning off unused links would boost the consumption of energy, which they sought to avoid. The proposed algorithm relied on the centralized controller to manage all processes. Despite its intentions, the FSR algorithm is not suitable for fault tolerance in normal network operation. It might not handle unexpected faults or failures effectively, potentially leading to disruptions and suboptimal performance in such scenarios.

The paper by Son *et al.* (2017) presented a dynamic energy-saving optimization scheme for networks that aimed to avoid modifying the transmission route of traffic that has not finished when new traffic arrived to prevent route oscillation. The issue was framed as a mixed integer linear programming (MILP) problem in order to identify the best energy-saving solution. However, the authors proposed an improved constant weight greedy algorithm (ICWGA), which is a heuristic routing algorithm used to find a near-optimal solution for a complex problem. The results of the simulation demonstrated that ICWGA effectively saves energy in a way that comes close to the ideal solution, thereby increasing the network's energy efficiency.

Rule Placement

The rule placement approach aims to utilize energy consumption by strategically placing rules in the network. These techniques enable the consolidation of network functions thereby reducing energy consumption. By utilizing rule placement techniques, it is possible to replace some flow entries with either wildcard entries or default rules. Rule placement techniques are utilized in SDN to cut down the flow inputs and, therefore, the reconfiguration cost and energy consumption.

Nouho and Ndie (2022) proposed an effective approach for optimizing energy consumption in software-defined wireless community networks by placing routing rules in routers and switches based on network characteristics. Their goal was to minimize total energy consumption while taking into account the remaining energy and available memory capacity of nodes. The authors addressed the challenging issue of energy-efficient routing, which involved finding optimal paths to relay flows from source to destination. The approach was particularly useful in energy-sensitive areas with limited or irregular power supply, as it extended the network and nodes' lifetime, outperforming Dijkstra's algorithm in their evaluation experiments.

Hu *et al.* (2017) dealt with a dynamical energy-saving optimization scheme for networks that preserves the paths of uncompleted flows upon the arrival of new traffic. The authors modeled the energy-saving problem as a MILP problem to determine the best possible outcome. Recognizing the increased complexity of the problem, they proposed an improved heuristic routing algorithm (ICWGA) to discover a sub-optimal solution. The outcomes of the simulation demonstrated that ICWGA achieved energy conservation capability approaching the optimal solution, thereby leading to significant improvements in the network's energy efficiency.

Ashraf (2017) presented the minimum rule application (MIRA) model, which minimized the number of rules installed while using MILP to dynamically recalculate flow distribution. Due to the NP-hard nature of the proposed model, this implies that achieving the best solution through computation is difficult (Ryan 2003). An NP-hard problem is one for which if a polynomial-time solution exists, then every problem in the complexity class NP can also be solved in polynomial time (Erickson 2019). Essentially, solving an NP-hard problem efficiently implies the ability to solve a broad class of seemingly difficult problems efficiently as well. The paper introduced a well-organized heuristic-based greedy algorithm. Additionally, the authors proposed rule-aggregation optimization to minimize rule installation, referred to as MIRA-RA. In addition, the study also introduced a multi-objective optimization model (PARETO) that used the constraint approach to achieve Pareto-optimality while simultaneously minimizing the competing goals of rule installation and link utilization.

Kosugiyama *et al.* (2017) addressed the performance limitations of SDN switches when managing application flows dynamically. SDN switches can only handle a certain number of forwarding rules per second, which hinders their ability to efficiently manage dynamic and scalable application flows. To overcome this bottleneck, the authors focused on reducing the count of flows within the network while ensuring that all flows meet their permissible delay as part of the service level agreement (SLA) or QoS. The main contribution of this paper was the proposal of a technique to aggregate flows, which effectively reduced the total count of flows in the network. The author also presented a heuristic algorithm to tackle this problem since it falls under the category of NP-hard. To evaluate their proposed method, the authors conducted simulations on four different network topologies. The results demonstrated that their algorithm successfully decreased the count of flows while satisfying the allowable delay requirements for all flows. This approach could potentially improve application flow management and reduce delays in SDN-based networks.

Hardware-based Approaches

In the current interest, we have observed that a majority of researchers in the field of energy-efficient techniques for SDN have primarily focused on software-based approaches. In our survey, a detailed classification of energy-efficient techniques is provided in SDN, encompassing not only software-based but also hardware-based approaches. The hardware approaches primarily concentrate on reducing power consumption by optimizing the utilization of hardware resources such as network switches and routers, exploiting their capabilities to perform specific functions more efficiently. These approaches typically employ techniques like DVFS and TCAM, which lower the power consumption of hardware components by adjusting their operating frequency and voltage based on workload demands. Another strategy is sleep mode, which allows hardware components to be turned off or placed into a low-power state when it is not in use. In order to save energy, the DVFS method is used in SDN. In an SDN network, this method can be used to adjust the processing speed of switches and routers based on the traffic load. These approaches modify the processor's operating frequency and voltage in accordance with the workload. It can also be used to minimize the consumption of energy in servers and VMs by tuning the CPU frequency and voltage based on the processing workload. This survey classifies the discussed approaches into three categories – DVFS, TCAM, and smart sleep methods – as shown in Figure 4.

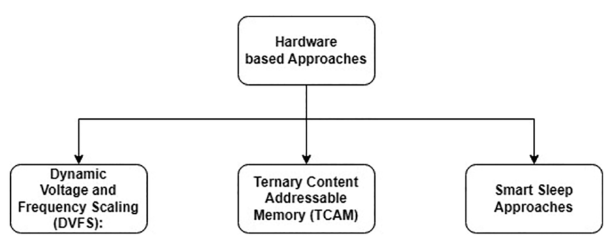

Figure 4. Hardware-based approaches for energy-efficient SDN.

Table 2. Evaluation and Analysis of proposed work on software-based approaches.

Ref.	**Protocol name**	**Simulation environment**	**Energy efficiency level achieved**	**Parameter used**	**Capabilities**	**Scalability**	**Security**	**Complexity**	**Issue that may arise**
Jiménez-Lázaro *et al.* (2022)	OpenFlow	Mininet	High	No. of clusters	Notable reductions in power consumption and computation time compared to energy-efficient *ad hoc* solutions.	Yes		Simple	ML model could be overly optimized for that specific network setup
Assefa and Özkasap (2018)	OpenFlow	Mininet	High	Traffic load	Traffic-aware routing	Yes			Lack of consideration for the effect of network security on energy efficiency, reliance on traffic load as the primary optimization parameter, and limited generalizability to different network scenarios
Ibrahim *et al.* (2022)	Energy-aware routing	SDN-based network	Significant	Number of controllers, end-to-end network delay, and path costs	Formulated energy-aware routing algorithm			Highly complex	As NP-hard is an issue, the heuristic approach used for finding optimal solutions might not always guarantee the best possible results
Lu *et al.* (2019)		SD-SDN	High	Smallest demand first (SDF), biggest demand first (BDF), and random-order demand (RD)	The optimization of the energy consumption problem is represented using an integer linear programming (ILP) model	Yes		Moderate	The algorithm's heuristic nature means it may not always provide the best solution in all situations, as its performance is influenced by network conditions and parameters
Verma and Jain (2019)	OpenFlow	Mininet	Fair	Traffic classification and link bandwidth	Traffic-aware routing proposed			Simple	Different types of traffic may require different types of QoS parameter
Masood *et al.* (2019)		Matlab	Average	Number of iterations, number of runs, and optimal values		Yes		Highly complex	Open issues related to SDN energy efficiency that require further research and exploration
Ba *et al.* (2018)	GEANT network	Mininet	High	Link sleeping and rate adaptation	Multiple topology switching with data plane forwarding path rerouting (MTSDPFPR)			Moderate	Implementing the switching of links to sleep mode and data plane forwarding path rerouting may introduce additional overhead and latency in the network
Shudhanshu *et al.* (2022)		Matlab	Average	No. of used VMs and no. of used nodes	Minimization of live migrations and turning off underutilized devices	Yes		Moderate	Dynamic network conditions: SDNs are highly dynamic, with changing traffic patterns, VM demands, and network conditions; the algorithm's ability to adapt and respond to these dynamic changes is crucial for its success
Liao and Wang (2018)			High	VM migration integration	Energy-saving optimization and VM migration integration	High complexity		Average	Network dynamics: cloud data centers are dynamic environments with changing workloads, traffic patterns, and resource demands; the proposed methods may need to adapt and respond efficiently to these dynamic changes
Neghabi *et al.* (2019)			Moderate	Traffic data and QoS parameters	Global view of the network for optimized load balancing and efficient load distribution among multiple resources		Adequate	Moderate	Lack of specific QoS parameter determination, energy efficiency, and failure management

Table 2. Cont.

Molina and Juárez (2018)		SDN-based CPS	High	Bandwidth, latency, redundancy, and safety	Adaptive and flexible network control		Strong encryption and authentication mechanisms	Moderate	Integration challenges and resource allocation in dynamic environments
Son *et al.* (2017)		CloudSimSDN	Moderate	SLA violation and resource allocation		Yes		Moderate	Data sensitivity: the correlation analysis and learning algorithm heavily rely on historical utilization data and flow rates
Naho *et al.* (2022)	Multicore SDN controller	Data center network	High	CPU utilization and frequency	Minimizes energy usage by splitting the load of the controller among multiple cores	Yes	Secure implementation	Moderate complexity	Implementation challenges and optimizing CPU utilization for different workloads
Hu *et al.* (2017)	Improved constant weight greedy algorithm (ICWGA)	Mininet	High	Number of hops, propagation delay, and average bandwidth utilization	Dynamical energy saving optimization and improved energy efficiency of SDN			High complexity	The high complexity of the problem may limit real-time applicability
Ashraf (2017)	DEDCA	PowerNetS	Medium	CWmin value	QoS management	Yes	Not specified	Moderate	Parameter tuning for optimal QoS
Kosugiyama *et al.* (2017)		Mininet	Medium	End-to-end delay	Aggregating flow according to end-to-end delay in SDN			Simple	Bypassing on weak topology

Dynamic Voltage and Frequency Scaling (DVFS)

By utilizing DVFS, SDN networks can save energy and reduce operational costs while maintaining network performance and QoS.

Javadpour et al. (2023) presented a novel approach that included the development of a task prioritization algorithm based on execution deadlines, the utilization of DVFS for energy-efficient processing of low-priority tasks, and the implementation of job migration techniques for workload balance and machine class adaptation. The proposed method demonstrated substantial improvements, achieving a 12% reduction in energy consumption [which refers to the total amount of energy used over a period of time and measured in kilowatt-hours (kWh)] and a 20% decrease in power consumption [which represents the rate at which energy is used and measured in watts (W)]. The proposed method employed job migration strategies to ensure workload balance among machines and adapt to changes in their class according to their scores. This dynamic allocation and migration of tasks helped in optimizing energy and power consumption.

An innovative approach named SDN-DVFS was introduced by Mahmoudi *et al*. (2022). SDN-DVFS utilizes DVFS and takes into account factors such as VM overload, host machine efficiency, and user load to achieve traffic load balancing in the network. This technique operates effectively with dynamic traffic patterns, addressing on-demand requests without requiring advance knowledge of future arrivals. SDN-DVFS skillfully manages the distribution of traffic loads, leading to enhanced utilization of network resources, even when dealing with a substantial number of VMs. Furthermore, it manages to decrease the synchronization overhead between the data and controller layers, ultimately resulting in improved response times. On the energy consumption front, this novel approach outperforms a comparable method named PSOAP by achieving a noteworthy 48.7% reduction in average energy usage. Specifically, SDN-DVFS records an energy consumption of 1.53 kWh, whereas PSOAP consumes 2.99 kWh. Through simulation outcomes, SDN-DVFS's superior performance becomes evident as it excels in terms of energy efficiency, latency, and packet delivery rate in comparison to recent similar methods. These outcomes underscore the method's potential in enhancing the overall performance of SDN systems.

The publication presented an extensive review and examination (Mishra and Khare 2015) of DVFS strategies employed to augment the energy efficiency of GPUs. The main objective was to present a detailed interpretation of different power management methods that have employed DVFS over the past few years. The analysis included a comparison of different DVFS schemes utilized during this period. The investigation uncovered that DVFS methodologies operate not only in isolation but also in tandem with other power optimization approaches such as load balancing and task mapping. The performance and energy efficiency of these techniques were influenced by factors like platform variations and benchmark characteristics. The paper provided a thorough examination of various DVFS schemes that aimed to contribute to the advancement of further research in this field, hence fostering a better understanding and utilization of DVFS for improved energy efficiency in GPU systems. The authors concluded that future studies in the area of DVFS should be strengthened by building on the thorough analysis of various schemes presented in this paper. By understanding the potential of DVFS techniques and their impact on energy efficiency and performance in SDNs, researchers can develop more effective power management techniques that are tailored to specific network configurations and use cases.

GPUs are advantageous in SDNs for their impressive parallel processing and energy efficiency in handling parallel workloads. However, they have high energy consumption when running at full capacity and can waste energy during lighter tasks or idle periods, prompting the need for energy-saving measures.

Mishra and Khare (2015) conducted a comprehensive survey and in-depth analysis of DVFS techniques aimed at enhancing the energy efficiency of GPUs over the past decade. It offers a detailed examination of these schemes, emphasizing the evolution of DVFS methods over the years. The primary objective was to provide a comprehensive understanding of power management techniques that leverage DVFS within the last decade. Throughout this study, it becomes evident that DVFS does not function in isolation but also interacts with other power optimization strategies such as load balancing and task mapping, where changes in the platform and benchmarks impact both performance and energy efficiency. The paper's thorough analysis of various DVFS schemes aims to facilitate further advancements in the DVFS research domain.

Oliveira *et al.* (2021) introduced an innovative approach to enhance energy efficiency, mainly focusing on the control plane of networks and complementing existing data-plane solutions. The method leverages the capabilities of contemporary multicore processors to distribute controller tasks across cores. By delegating these tasks evenly among homogeneous cores, the frequency of operations is reduced, resulting in decreased overall energy consumption while maintaining consistent service quality. The research demonstrates that a multicore controller, implemented on an off-the-shelf multicore processor, can significantly conserve energy while upholding service levels. Empirical assessments, employing standard network performance indicators like latency and throughput, along with established data center energy efficiency metrics like communication network energy efficiency reveal notable energy savings – up to a 28% reduction in processor energy consumption – when compared to the traditional single-core approach.

Ternary Content Addressable Memory (TCAM)

TCAM is used in networking devices, including SDN switches, to perform high-speed table lookups. It is often used to store forwarding rules and match packets against those rules, making it an essential component for fast packet processing in SDN environments. One of the benefits of using TCAM in SDN is its ability to perform parallel search operations, which allows it to quickly find the matching rule for incoming packets. This helps in achieving fast and efficient packet forwarding, which is crucial for real-time and high-performance network applications. High-speed table lookups are possible with these types of memory. However, TCAM is power-hungry and consumes significant amounts of energy. To resolve the problem of TCAM power consumption in SDN, researchers have proposed several approaches.

The study by Ghiasian (2016) showed that the quantity of TCAM can influence the network's power effectiveness, and this work identified an optimal TCAM capacity that can maximize power efficiency. The author explored the effect of TCAM capacity on power consumption in OpenFlow switches and presented a model for TCAM-based power consumption. The authors have identified an optimal TCAM capacity and demonstrated that it can significantly improve energy efficiency. Simulation results showed that their proposed solution outperforms existing methods such as the MNO (minimal node on) approach and the MLO method by reducing average power consumption by 24 and 11.5%, respectively. The results suggested that better power efficiency can be achieved by supplying each memory with an appropriate amount of power. A messaging protocol like Open Flow is used to send the decision vector to switches after the decision-making process has been completed in the controller. Subsequently, the switches adjusted the capacity of their TCAM memory and flow tables to attain the optimal power profile while efficiently managing the movement of network traffic between source and destination points.

Chuang *et al*. (2016) made a significant contribution by addressing the scalability issue in SDN architecture deployed in data centers. They introduced an innovative policy centered on rule reduction aimed at diminishing the utilization of resource-intensive and energy-consuming TCAM in SDN switches. This reduction in TCAM usage proved instrumental in easing the workload on the SDN controller, which can be overwhelmed by the frequent replacement of rules caused by escalating data center traffic. The researchers incorporated 60-GHz wireless technology into the data center environment and formulated a problem of minimizing routing rules under a hybrid architecture, incorporating both wired and wireless links. The primary objective was to minimize the count of rules installed in switches. To address this, the authors introduced an effective algorithm that factored in TCAM limitations and flow sizes, thereby successfully solving the optimization problem. The outcomes of their simulations underscored the supremacy of their algorithm when compared to existing solutions for both wired and wireless data centers. These results not only provided valuable insights but also served as guidelines for the development of scalable SDN-based data centers.

Sridhar and Ramapackiam (2018) presented an FPGA implementation of a TCAM that used SRAM (static random-access memory), a type of volatile computer memory that provides fast data access but requires continuous power to retain data for higher energy and resource efficiency. They proposed a scalable TCAM architecture by utilizing look-up table RAM (LUTRAM) with dual outputs in Xilinx FPGAs, along with slice registers and carry chains. This design has mapped an 8 × 1 TCAM, doubling the utilization density compared to the conventional 8 × 5 TCAM. The use of in-slice registers and carry-chain logic for match reduction improves logic utilization and throughput, resulting in better power area (PA) compared to existing approaches. The proposed solution achieved 3.34 and 8.4 times better energy efficiency and PA, respectively, compared to other FPGA-based TCAM solutions. The authors emphasized that, despite the magnitude of TCAM emulation on SRAM-based FPGAs, their approach surpasses existing alternatives in terms of dynamic power usage.

Smart Sleep Approaches

SDN can be leveraged to implement smart sleep mechanisms in networks and devices to save energy. Smart sleep refers to a technique where network devices dynamically adjust their sleep and wake-up times depending on the demands of network traffic. In SDN architecture, a centralized controller can monitor network traffic and identify which devices can be turned off without compromising the performance of the network. The controller can send commands to the devices to initiate sleep mode and wake them up as necessary when traffic demands increase. This approach can significantly reduce energy consumption in networks, especially during low-traffic periods.

The article by Jiang *et al.* (2018) proposed an SD-WSN (software-defined wireless sensor network) model in which multiple zones or clusters are managed by the controller of SDN. The controller was responsible for identifying the most energy-efficient pathway between any source and destination, regardless of whether they were located within or outside the source's zone. These SDN controllers possessed an understanding of the network's structure and the remaining energy of individual nodes. This awareness enables one to continually update flow tables, thus avoiding the unnecessary broadcasting of route requests. The strategy put forward also incorporated a "sleeping" mechanism, whereby nodes with depleted energy levels could enter a sleep state using a request-grant mechanism. This approach yielded substantial energy conservation benefits. Through simulations, it was demonstrated that the proposed technique led to a substantial reduction in energy consumption when compared to conventional methods.

The paper by Wang *et al*. (2015) proposed a novel energy-efficient approach called SDN-ECCKN for managing energy in WSNs. The main focus was on the sleep scheduling (SS) mechanism, which effectively prolongs the overall lifespan of the network by efficiently managing the energy of each node. The proposed algorithm utilized SDN to implement the SS strategy. EC-CKN operates as the foundational algorithm upon which SDN-ECCKN builds. Unlike traditional EC-CKN, where computations are performed on individual sensors and broadcasting between nodes occurs, SDN-ECCKN shifts all computations to the controller and eliminates broadcasting between nodes. This strategy yielded numerous benefits in energy management such as prolonged network lifespan, augmented count of active nodes, and decreased instances of isolated nodes within the network. The results of applying SDN-ECCKN demonstrated its effectiveness in improving energy efficiency and overall network performance in comparison to traditional methods.

The article by Zheng *et al*. (2014) highlighted the issue of the consumption of energy and its effect on the environment with reference to data centers. The high density of ICT facilities in data centers leads to the generation of significant heat, which requires cooling units to maintain operational temperatures. The energy usage of these cooling units added to the overall energy consumption of the data center, thereby leading to a substantial carbon footprint. The article emphasized the need for energy-efficient practices in data centers such as adopting renewable energy sources, improving cooling techniques, and reducing power consumption through workload consolidation and virtualization. The article also discussed several research ideas and industry-adopted techniques to tackle energy efficiency concerns in data centers and emphasized the urgent matters that demand focus within this domain.

Hybrid Approaches

Hybrid approaches are characterized by the integration of software- and hardware-based approaches. This integration is a promising area of research and holds the potential to bring about a revolutionary transformation in the field by enhancing performance, reducing costs, and increasing flexibility. As such, it represents an important avenue for further investigation and development. The proposed hybrid approaches offer promising solutions for optimizing energy consumption in SDN systems while maintaining network performance. SDN enables network administrators to dynamically manage and control network resources, thus providing opportunities for optimizing energy consumption. Here are some hybrid approaches to save energy in SDN. In our survey, we categorize the various approaches into three main categories shown in Figure 5. Firstly, NFV involves the virtualization of network functions, allowing them to operate as software on standard hardware, which enhances network flexibility and resource utilization. Secondly, topology optimization focuses on refining network layouts and interconnections to improve network performance and efficiency. Lastly, hybrid switching encompasses the integration of different switching technologies such as circuit and packet switching to effectively handle diverse network traffic types, thereby ensuring optimal data transmission and network management.

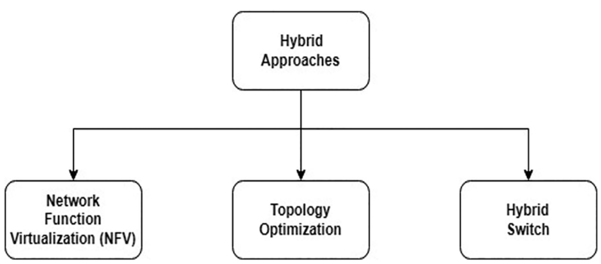

Figure 5. Hybrid approaches for energy-efficient SDN.

Network Function Virtualization (NFV)

Mai *et al.* (2021) proposed a solution to enhance both enhancing both energy efficiency and service availability in the context of NFV. The article introduced green orchestration NFV architecture and a novel algorithm for energy-efficient NFV placement that guarantees end-to-end service availability. The authors also suggested exploring dynamic optimization strategies that can balance achieving energy efficiency while ensuring service availability in real-time and investigating trade-offs between conflicting network performance objectives. Their contribution provided a comprehensive approach to optimizing network performance while reducing energy consumption in NFV-enabled networks. Xu *et al.* (2022) proposed a hybrid approach called NBACO-SS (N-base coding-based ant colony optimization for SFC deployment) to enhance the efficiency of service function chain (SFC) deployment within NFV setups. Through the utilization of N-base coding and ant colony optimization techniques, the approach effectively transformed intricate SFC deployments into streamlined digital codes, thereby achieving a 20% improvement in time efficiency without compromising network service traffic. This hybrid approach combines multiple techniques, hence making it a valuable contribution to the field.

Topology Optimization

Guo and Yuan (2021) made noteworthy contributions through their paper by introducing a hybrid strategy that melds AI and big data technology within an SDN context. Their primary objective was to attain intelligent network control and traffic optimization tailored for

Table 3. Evaluation and analysis of proposed work on hardware-based approaches.

Ref.	Protocol name	Simulation environment	Energy efficiency level achieved	Parameter used	Capabilities	Scalability	Security	Complexity	Issue that may arise
Javadpour *et al.* (2023)		CloudSim simulator	Medium	CPU and memory utilization plus load balancing algorithm	Using the DVFS approach, it reduces the energy used by the machines doing low-priority jobs	Yes		Simple	While this method can effectively reduce energy consumption, it may also impact the performance of the tasks by slowing down the processing speed; this may affect the user experience and the overall quality of service
Mahmoudi *et al.* (2022)		Mininet	High	Network traffic and QoS parameters		Yes		Moderate	The distribution of traffic in SDNs can create several challenges such as unbalanced load distribution and increased delays
Mishra and Khare (2015)	Dynamic voltage frequency scaling (DVFS)	GPU-based simulation	Moderate to high	Frequency and voltage settings	Improves energy efficiency of GPUs	Yes		Moderate	Variation in performance based on platform and benchmark
Ghiasian (2016)	OpenFlow	Mininet	Moderate	No. of active links and switches plus flow table size (TCAM)	TCAM power model for energy optimization	Yes, with the proper TCAM size	Yes, secure communication	Moderate	Performance and power degradation due to inappropriate TCAM size

Table 3. Cont.

Chuang *et al.* (2016)	SDN with TCAM-based rule reduction	Wired and wireless data centers	High	TCAM entries, flow sizes	Fast flow table lookup and rule reduction	Improved scalability	Yes, secure communication	Moderate	Massive flow setup requests causing real-time controller overload
Sridhar and Ramapackiam (2018)	FPGA-based TCAM emulation	Networking applications with AI	High	slice carry chains, LUTRAMs, and flip-flops	Simultaneous rule mapping and deeper pipelining	Improved resource utilization	Yes	Moderate	Potential challenges in handling TCAM emulation on SRAM-based FPGAs
Jiang *et al.* (2018)	OpenFlow	Mininet	High	Network topology, power consumption of links, and sleep interval	Energy-aware routing in SDN			High	Link failures may cause increased energy consumption
Wang *et al.* (2015)			High	EC-CKN algorithm	Energy management, prolonged network lifetime, and count of live nodes and solo nodes				No broadcasting between nodes, controller-based computation, and traditional EC-CKN comparison
Zheng *et al.* (2014)		NS-2	High	Network topology, packet arrival rate, sleep interval, and link utilization	Energy-efficient data center networks with link sleeping technique	Yes		Moderate	Potential increase in latency due to link sleeping

telecommunications operators. This endeavor led them to formulate an intelligent network control architecture that combined SDN and AI, thus encompassing three core modules – network status collection, AI-driven intelligent analysis, and SDN controller. The paper also delved into a range of routing calculation and optimization algorithms – including greedy, top-k-shortest paths, particle swarm optimization, simulated annealing, and genetic algorithms. Within the scope of operator networks, the authors presented three distinct optimization algorithms – network congestion control, resource preemption, and network traffic balancing. To validate the efficacy of their approach, the authors conducted extensive large-scale experiments. The outcomes demonstrated the heightened efficiency achieved by integrating SDN and AI in realizing intelligent network control and traffic optimization for operator networks. Altogether, this work stands out as an exemplar of how multiple techniques have synergistically integrated, thus offering a valuable hybrid approach to elevate network performance within the telecom domain.

Hybrid Switch

A hybrid switch refers to a network switch that supports both traditional, hardware-based forwarding and SDN-based forwarding. This approach is particularly useful in scenarios where certain network functions or flows require high-performance handling, whereas other parts of the network benefit from the programmability and dynamic control provided by SDN. By integrating hardware acceleration and SDN capabilities into a single switch, network administrators can achieve a more optimized and flexible network infrastructure.

A framework was proposed by Xu *et al.* (2017) called STREETE (segment routing-based energy-efficient traffic engineering) to improve the backbone networks' energy efficiency by controlling network flow pathways to reduce over-provisioning. STREETE enables the automatic management of links and line cards, thereby putting them to sleep during off-peak hours and quickly activating them when there is a need for more network capacity. The authors have also proposed a load-balancing technique to extend the STREETE framework to handle high network loads that require fine-grained management of flows. The combination of STREETE and the load balancing technique is evaluated based on the performance of disabled links and its potential to prevent network congestion.

Issues and Challenges in Various Approaches

Software-based approaches for energy-efficient networking can significantly reduce energy consumption in networks and improve network performance. By utilizing techniques such as traffic analysis, machine learning, and end-host optimization, organizations can achieve greater energy efficiency and reduce their carbon footprint.

Traffic-aware approaches aimed to optimize network performance by analyzing network traffic and utilizing this information to reduce energy consumption (Verma and Jain 2019; Rezaeipanah *et al.* 2019; Jiménez-Lázaro *et al.* 2022; Assefa and Özkasap 2018 ; Ibrahim *et al.* 2022; Lu *et al.* 2019). This can include techniques such as traffic classification, load balancing, and bandwidth management to reduce network congestion and improve energy efficiency. Machine learning algorithms and optimization techniques also hold the potential to predict network configurations that are energy-efficient and reduce computation time. Several research issues in traffic-aware energy efficiency need to be addressed such as scalability, flexibility, and security. In particular, traffic-aware methods must be able to handle increasing traffic loads and support scalability in multi-domain SDN scenarios, where multiple controllers manage different networks.

An ascendible solution is required for energy efficiency across all controllers. Additionally, security and flexibility should also be considered in these methods. End-host-aware approaches focus on optimizing energy consumption at the end systems such as servers, switches, and routers. This can involve putting devices into low-power modes when they are idle or reducing power consumption during periods of low network activity (Molina and Juárez 2018; Akbar *et al.* 2019; Son *et al.* 2017; Liao and Wang 2018; Hu *et al.* 2017). In order to come up with an effective solution, it is important to regularly monitor and analyze the status and structure of the end systems and traffic. Additionally, there are two distinct issues to consider regarding end system awareness – server consolidation and network optimization – which are typically approached as separate problems. However, incorporating multiple objectives in the solution can be computationally intensive, and formal methods may not be practical for larger networks. Rule-based approaches involve setting rules or policies for network behavior such as turning off certain devices during low traffic periods or adjusting network settings based on the time of day (Naho *et al.* 2022; Ashraf 2017; Kosugiyama *et al.* 2017). These approaches can be effective in reducing energy consumption but may not be as flexible or adaptable as other approaches. The optimization of rule space in SDN involves a network-wide problem that requires the placement of rules on switches throughout the network. This optimization aims to minimize energy usage while satisfying various constraints.

However, this problem is difficult to solve, as it falls into the NP-hard category. To address this, it is essential to have a solution that efficiently represents rules and leads to energy savings. Additionally, this optimization should consider both the network's end-point and routing policies. In SDN, optimizing energy consumption through DVFS techniques is a key research challenge due to variations in power consumption among different physical machines (Javadpour *et al.* 2023; Mahmoudi *et al.* 2022; Mishra and Khare 2015) across all types of machines. Another challenge is developing sophisticated load-balancing algorithms that can manage the dynamic traffic loads in SDN networks. The algorithm must be able to distribute the traffic load evenly across the network, even when there are a large number of VMs. Another important research issue is taking into account the influence of additional aspects like security and dependability during the utilization of DVFS. The use of DVFS techniques can sometimes lead

Table 4. Evaluation and analysis of proposed work on hybrid approaches.

Ref.	Protocol name	Simulation environment	Energy efficiency level achieved	Parameter used	Capabilities	Scalability	Security	Complexity	Issue that may arise
Xu *et al.* (2022)		Novel network architecture (NFV)	High	0-1 integer linear programming and N-base coding	SFC deployment optimization, continuous digital coding, solution space composition, and ant colony optimization	Yes	Yes	Moderate	The complexity of mapping complex SFC deployment to digital coding and finding optimal solutions in large solution spaces
Mai *et al.* (2021)	NFV-based service orchestration	Not specified	High	Green orchestration NFV architecture energy model service availability model Energy-efficient VNF placement	Energy efficiency, optimal VNF placement, service chaining, and service availability guarantee	High	Not specified	Not specified	Balancing energy efficiency and service availability, service level agreement (SLA) fulfillment, and open research problems and technical problems in NFV-enabled networks
Guo and Yuan (2021)	SDN-based network traffic optimization with AI	Not specified	Not specified	Resource preemption and network traffic	Intelligent network control, traffic optimization, SDN and AI integration, routing algorithms, optimization algorithms, network scalability, flexibility, and resource utilization	Not specified	Not specified	Not specified	Limited evaluation on synthetic data, application to actual networks needed, more network control scenarios to be explored, flexibility and scalability enhancement, network equipment load reduction, and real data problem-solving in future work
Zu *et al.* (2017)	OpenFlow	Mininet	High	Traffic demand, network topology, link bandwidth, and flow table entry	Reduced energy consumption while maintaining QoS by optimizing traffic engineering in SDN	Yes		Moderate	Possible QoS degradation due to network congestion or insufficient bandwidth, which may affect network performance and user experience

to performance degradation, and it is important to ensure that such techniques do not compromise network security or reliability. Providing specific guidelines for selecting and implementing DVFS techniques in practical SDN deployments is another challenge. The standard must take into consideration the specific characteristics of the network – including the types of physical machines, traffic patterns, and the required QoS.

As SDN switches make use of TCAM for the upkeep of flow tables within the framework of hardware-oriented solutions, TCAM presents several challenges for organizations that are implementing SDN networks (Ghiasian 2016; Chuang *et al.* 2016; Sridhar and Ramapackiam 2018). These challenges include cost, power consumption, limited capacity, limited write endurance, and security vulnerabilities. To deal with these challenges, organizations may need to consider alternative memory technologies or develop new techniques to mitigate these issues. The use of TCAM in SDN poses several challenges and issues – including high costs, power consumption, limited capacity, and low flexibility. Various techniques such as power gating and voltage scaling have been proposed to enhance these issues and refine the energy efficiency of TCAM. However, these techniques also come with their own limitations and trade-offs such as increased design complexity and reduced search speed. Additional research is required in these areas to overcome these problems and to develop more efficient and scalable TCAM-based solutions for SDN. One research issue when implementing smart sleep techniques is ensuring that the network devices can be quickly and reliably woken up when they are needed. This requires careful consideration of the sleep duration and the process of waking up devices (Jiang *et al.* 2018; Wang *et al.* 2015; Wang *et al.* 2014a), as well as ensuring that wake-up times are predictable. Another challenge is optimizing the sleep patterns for different network devices and usage scenarios. Different devices have different energy consumption profiles, and the optimal sleep pattern for one device may not be optimal for another. Additionally, different network usage patterns may require different sleep patterns to minimize energy consumption while maintaining performance. Hybrid approaches represent a combination of software and hardware techniques that aim to enhance energy efficiency in SDN. To the best of our knowledge, we are the first to provide a comprehensive classification for energy-efficient approaches for SDN, including hybrid approaches. One of these is NFV, an emerging technology that has gained popularity due to its potential for enabling more agile and cost-effective network service deployment. NFV involves the virtualization of network functions and deploying them on standard servers or cloud-based platforms, which can reduce power consumption and increase network service flexibility and scalability. One of the primary challenges is the effective allocation and management of resources – including computing power, storage, and network bandwidth. Efficient resource allocation algorithms are needed in order to reduce energy use and maximize resource utilization. The placement of network functions is another significant challenge in NFV-based SDN environments (Xu *et al.* 2022; Mai *et al.* 2021). Placing network functions in the right location can reduce energy consumption, but determining the optimal location requires a thorough understanding of the network topology and traffic patterns. These approaches aimed to offload processing tasks from the central processing unit (CPU) to specialized hardware (Suresh *et al.* 2021), which can provide significant energy savings while maintaining high performance. Despite the increasing interest in hybrid approaches to energy-efficient networking, several challenges remain. These difficulties include creating effective management of resources and allocation algorithms, the optimization of network function placement, the reduction of processing delays and overhead, and maintenance of network security and reliability. Furthermore, there is a need for standardization and interoperability between different vendors' solutions to enable the seamless integration of hybrid approaches into existing SDN environments (Xu *et al.* 2017).

Furthermore, hybrid switches can also play a role in implementing energy-aware load balancing. By distributing network traffic across multiple switches, hybrid switches can effectively manage resource allocation and minimize energy usage. During periods of low network traffic, these hybrid switches can consolidate traffic to a single switch, thereby reducing the number of switches that need to remain operational.

DISCUSSION

Energy conservation in SDN systems holds significant importance, with two primary avenues to achieve it – software- and hardware-based enhancements. These strategies target different levels of the network, spanning from the individual chip to network-wide infrastructure. Implementing these approaches can lead to enhanced energy efficiency in SDN systems, hence contributing to environmental sustainability (Assefa and Özkasap 2019). One recurring challenge in evaluating energy-saving techniques in SDN research is the lack of uniformity across studies (Rout *et al.* 2021). Different parameters, network topologies, conditions, and simulation software often hinder direct comparisons between results. Additionally, studies tend to focus on evaluating the effectiveness of their proposed algorithms within specific networking scenarios rather than comparing the efficiency of various energy-saving techniques comprehensively. Consequently, assessing the relative efficiency of these approaches in terms of energy consumption necessitates their step-by-step implementation within a unified platform for comparative analysis. Further complicating the matter is the absence of standardization in evaluating the effectiveness of energy-saving approaches in SDN. Numerous studies resort to designing and implementing their simulation environments – thereby resulting in variations in parameters, network topologies, conditions, and simulation software (Tuysuz *et al.* 2017). This lack of standardization makes it arduous to compare findings across different studies, especially when authors opt to compare their approaches exclusively against traditional networking scenarios, rather than benchmarking them against existing solutions.

We have observed that most works related to energy-efficient techniques for SDN in the literature focus on a single SDN domain. However, SDN domains consist of different content providers and ISP networks, each managed by their own controller according to different policies. Algorithms developed for energy efficiency in single-domain SDN environments might be inefficient in multi-domain SDN networks. In a nutshell, existing energy-aware SDN approaches mainly focus on a single issue such as link rate adaptation, load balancing among links, re-routing the traffic flow, turning a device on or off, rule placement, minimizing the TCAM, or network virtualization. Although it is not possible to apply load balancing among links and turn resources on and off simultaneously to gain energy, most of the other aforementioned techniques are independent of each other and can be applied simultaneously. Therefore, by gathering most of these techniques under a single or few roof(s), energy optimization can be achieved with a far-reaching solution proposal.

In the context of computer networks, SDN, the concept of consensus can be related to various aspects such as protocols, standards, and best practices. However, achieving a "general consensus" in the sense of a unified standard or benchmarking framework for testing and comparing different aspects of computer networks can be complex due to the diverse nature of network technologies and the rapidly evolving field (Table 1). To aid in this endeavor, we have categorized the expected energy gains into four levels – significant, moderate, fair, and acceptable (Tables 2, 3, and 4). While many of the suggested SDN solutions are built upon individual energy-saving methods, the potential exists to combine these techniques to achieve even higher levels of energy efficiency. Therefore, gaining a comprehensive understanding of the diverse energy-saving techniques proposed within this paper is pivotal for determining the most effective combination to attain desired energy savings while preserving an acceptable level of network performance. It is likely that in the realm of computer networks, and possibly even in the case of SDN, there exist various works and platforms for testing, comparing, and benchmarking software, hardware, or hybrid networks. For example, in the context of SDN, one such platform is Mininet – an open-source network emulator that allows users to create and experiment with network topologies in a controlled environment. Mininet has been widely used for conducting tests, benchmarks, and experiments in network research and education. A similar tool or components akin to those found in Mininet may also exist to assess energy efficiency and other aspects of traditional networks.

CONCLUSION AND FUTURE SCOPE

In modern networking, being aware of energy consumption is essential. Creating efficient solutions is challenging because it involves finding the right balance between saving energy and meeting network performance needs like ensuring good quality and adapting to changing network conditions. Our survey delves into the realm of SDN to investigate a range of strategies aimed at improving energy efficiency. In contrast to the surveys listed in Table 1, this particular survey adopts a distinctive classification framework for energy-efficient strategies within the context of the research. The survey also takes a comprehensive approach, examines the advantages and disadvantages of each energy efficiency technique, and subsequently conducts an in-depth comparative analysis. The evaluation criteria encompass parameters shown in Table 2, 3, and 4 like the achieved level of energy efficiency, the specific assessment metrics employed scalability, security considerations, and complexity. Existing research on energy-efficient SDN approaches primarily involves designing and implementing simulation environments to assess the effectiveness of proposed techniques. However, these studies often use different parameters, topologies, network conditions, and simulation software – making it challenging to compare the results across different studies. Furthermore, our exploration not only highlights the existing solutions but also underscores the ongoing areas of concern and the need for future investigation. In this article, we endeavor to provide readers with a comprehensive knowledge base, equipping them with insights into the strategies employed to optimize energy efficiency within SDN, a nuanced understanding of the critical attributes associated with each approach, and a structured framework for categorizing these methods. This holistic perspective not only enhances the reader's understanding but also paves the way for potential advancements in the field of energy-efficient SDN solutions. In essence, most proposed energy-centric approaches in SDN tend to focus on individual techniques for energy conservation. However, our survey reveals that many of these techniques are self-contained and can be simultaneously deployed to enhance energy efficiency significantly. This perspective opens the door for the development of integrated energy-saving mechanisms within the SDN framework.

Looking forward, our future research endeavors may involve the design and comparative assessment of innovative techniques geared toward enhancing energy efficiency in multi-domain SDN networks. Building upon the insights gained from single-domain solutions, this exploration aims to contribute to the evolution of energy-efficient practices within the broader SDN landscape.

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STATEMENT ON CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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