Energy Consumption Minimization in Data Centers for Cloud-RAN

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Abstract*—Data centers are to become a vital part of mobile networks when exploring new architectures such as cloud radio access network, which is seen as a more energy efficient alternative to today's mobile network installations. However, the scale of a data center affects its energy efficiency, with larger data centers having more resources for energy-saving measures but at the same time different challenges than those faced by data centers of smaller scale. Hence, this work analyzes and compares energy efficiency of small, medium, and large data centers, and explores the energy minimization opportunities for cloud radio access network data centers. When moving processing from the radio access network to a data center to save energy in the radio access network, the mobile network operator does not want to move the energy consumption from the radio access network to the data center. Hence, energy consumption must be reduced in all segments of the network, and not moved to another segment. In the case study provided, cloud radio access network data centers are categorized as mid-scale and small-scale depending on the size of area they cover due to strict latency requirements of mobile network traffic flow. Thus, even though larger DCs prove to be more energy efficient, other factors, which in the case of mobile networks will be latency, will impact the size of the data center. Hence, this is a major driver to consider how energy consumption can be minimized in small data centers.

Keywords-Data center; cloud; C-RAN; green RAN; energy efficiency.

I. INTRODUCTION

This work is an extended version of [1]. The Information and Communications Technology (ICT) sector, including Data Centers (DCs), communication networks and user devices, is accounted for an estimated up to 6% of global electricity use [2]. Thus, many initiatives aim at reducing the energy consumption of the various different sub-parts of the ICT sector. However, looking into solutions for reducing the energy consumption in one part of the sector should not just move the problem to another part of the sector. The solution must look at the ICT sector from a holistic perspective. A starting point is to trace the solutions and investigate what other implications they will bring. Mobile networks, are widely used communication infrastructure, and looking at their energy consumption, the Radio Access Network (RAN) plays a significant role [3]. One solution envisioned to reduce the energy consumption of the RAN, is to utilize the long time discussed Cloud RAN (C-RAN) architecture [4].

In C-RAN, the mobile network functions are divided into three functional units; the Radio Unit (RU), Distributed Unit (DU) and Centralized Unit (CU). The RU, is located in the antenna mast and contains part of the physical layer functions. Whereas the DU and CU, containing the upper layer baseband processing functions, can be virtualized and located in DCs. A C-RAN installation and a traditional RAN installation are compared in Fig. 1. The figure shows how all baseband processing is located on site in the traditional RAN in top of the figure, where baseband processing is divided into separate DU and CU and moved to DCs in the C-RAN installation. The concept is, to store processing from a number of sites in the same Data Center (DC), where they can share physical resources and exploit their different user movement patterns. This being users gathering in different areas at different times of day [4]. Hence, in order to make the RAN segment of mobile networks more energy efficient, much of the processing is moved into DCs.

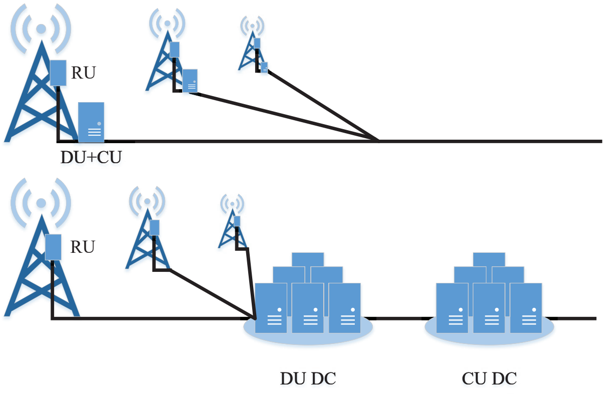

Figure 1. A traditional Radio Access Network (RAN) architecture [top] and a Cloud-RAN (C-RAN) architecture where data processing is moved to Data Centers (DCs) [bottom].

A DC refers to a number of servers located in the same building. Many different types of DCs exist and they are in this work categorized into three different sizes ranging from small, medium to large.

- *Small DCs* are categorized as having less than 1,000 servers, as well as less complex infrastructure, limited storage and thus; consume less power compared to larger DCs.
- *Mid-scale DCs* have a larger number of servers which ranges between 1,000 to 10,000 [5] with more complex infrastructure.
- *Large DCs* are defined as having more than 10,000

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servers with an even more complex infrastructure [5]. Large DCs are typically used by large companies or governments.

Energy efficiency in DCs is a crucial topic of modern DC operations, as it can help to reduce energy costs and environmental impact of the ICT sector. DCs are energy-intensive facilities that consume a large amount of electricity to power servers, storage systems and cooling equipment. The energy consumption of DCs has become an increasing concern for the industry, as well as businesses and organizations that operate these facilities, as DCs are responsible for approximately 1% of global electricity demand [2].

This paper investigates methods for energy efficiency in DCs, with a focus on state-of-the-art technologies and techniques, as well as how and why these are beneficial for DCs of different scale. Furthermore, it is investigated how DCs, handling mobile network data processing in the C-RAN architecture, can become energy optimized. Section II presents other related papers, research projects and features our contribution to the topic. Section III explains the typical components in a DC, to be used in section IV, which goes in-depth with modern and commonly used strategies for minimizing DC energy consumption. Section V elaborates on the use of DCs in C-RAN mobile networks, while section VI discusses what and why some methods are most commonly used in DCs of certain sizes and their potential. Finally, the conclusion closes this paper. A list of acronyms is provided after the conclusion.

II. STATE OF THE ART

This study combines two directions of energy efficiency studies, namely DCs and mobile networks. There have been several studies and research conducted on energy efficiency in DCs in recent years. However, numerous surveys regarding energy efficiency in DCs tend to be older than 5 years, such as the work in [6], which presents an overview of energy-aware resource management approaches with focus on basic architecture of cloud DCs and virtualization technology. The survey in [7] investigates the green energy aware power management problem for Megawatt-scale DCs and classifies work that considers renewable energy and/or carbon emission. In [8], authors discuss several state-of-the-art resource management techniques, that claim significant improvement in the energy efficiency and performance of ICT equipment and large-scale computing systems, such as DCs. The work in [9] conduct an in-depth study of the existing literature on DC power modeling, covering more than 200 models. The concept of C-RAN was first mentioned by companies IBM [10] and China Mobile [11] and later explored in numerous surveys including [4], [12] and [13]. However, the following section of related work will focus on research conducted within the latest years.

A. Related work

Recent related work in the field of greening DCs includes [14], where the approaches moving towards green computing are investigated and categorized to help researchers and specialists within cloud computing expand green cloud computing and improve the environment quality. The work in [15], gives a brief overview of the state-of-the-art in green cloud computing. Existing research in the area is examined and categorized into different themes. Furthermore, challenges and opportunities in the field are discussed to provide insights into future directions for research. The paper provides valuable background information and a significant understanding of the current landscape of green cloud computing. In the survey [16], the authors discuss different mechanisms for lowering the power utilization in DCs. The survey provides in-depth details about the various mechanisms that can be employed at the hardware level so that the utilization of energy by component can be reduced. Techniques that can be applied at network, cluster of servers' level along with the various dynamic power management measures that can be employed at the hardware or firmware level and can lead to energy efficient or green DCs are also studied in detail [16]. Table I lists relevant research in the field of energy improved DCs categorized into relevance regarding the different DC sizes.

TABLE I. DATA CENTER REFERENCES BY SIZE

DC Size	References
Large scale	[6] [7] [8] [9] [14] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27]
Mid scale	[9] [14] [16] [18] [21] [22] [23] [24] [25] [27] [28]
Small scale	[14] [16] [18] [21] [22] [23] [24] [25] [27] [28] [29] [30] [31]

C-RAN has recently been surveyed in relation to energy consumption improvements in [3], [32], [33], [34]. Which all highlights the energy saving potential of shutting down equipment not in use. Hence, in DCs, some equipment can be shut down in low traffic periods such as during the night. Another benefit of C-RAN is the opportunity to assign extra capacity where it is needed. In the perspective of users being in residential areas in the morning and evening, and goes to work areas during the day [4]. Thus, current trends in C-RAN research point in the directions of: Load consolidation [35], [36], [37]; coordinated transmission [38], [39]; and with a focus on the transport network [40], [41].

The work in [42] acknowledges the problem of low server utilization when mobile network traffic is moved to DCs, and proposes a framework for a higher utilization of the physical machines. In [43], various methods for DC load balancing was surveyed and compared not only for resource utilization, but also in other parameters such as power usage and reaction time.

The authors of this work have previously addressed the topic of energy minimization of DCs in [1]. Which examined various methods for minimizing DC energy consumption in various sizes of DCs. To the best of our knowledge the combination of C-RAN and energy efficient DCs has not yet been explored.

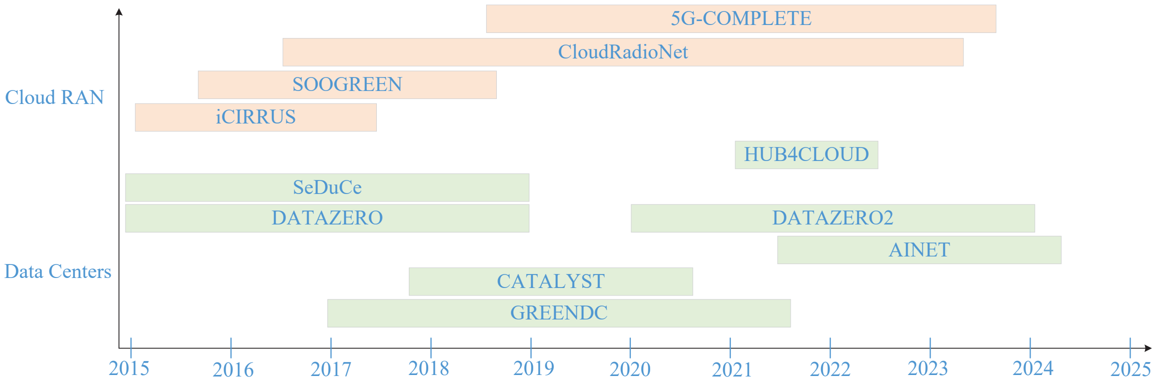

Figure 2. A timeline overview of various research projects within energy efficient Data Centers (DCs) and Cloud-Radio Access Networks (C-RAN).

B. Related research projects

DC energy consumption is a topic that receives broad attention. The European Commission has created the group ”Data Centres Code of Conduct”, to reduce DC energy consumption [44]. In the United States (US), Berkely Lab has a ”Center of Expertise for Energy Efficiency in Data Centers” [45]. Some of the recent past and ongoing research projects in DC energy efficiency are listed below, and summarized in Fig. 2.

- The ”Greening Datacenters”, GREENDC project, is a recently finalized project where knowledge of DCs operations was transferred from industry to academic partners, where simulation based optimization for best practice of energy demand control was examined [46].
- The ”Converting DCs in Energy Flexibility Ecosystems”, CATALYST project, investigated how to combine existing and new DCs into flexible multi-energy hubs [47].
- The AINET project focuses on edge DCs to provide enablers and solutions for high-performance services by the use of Artificial Intelligence (AI), which also includes methods for minimizing energy consumption [48].
- The ”DATAcenter with Zero Emission and RObust management using renewable energy”, DATAZERO and DATAZERO2 projects, investigate how a DC only operated by renewable energies alone can work. Where the focus in DATAZERO2 is the operation and design of cooperating DCs [49].
- The ”Sustainable Data Centers: Bring Sun, Wind and Cloud Back Together”, SeDuCe project, aimed to design an experimental infrastructure dedicated to the study of DCs with low energy footprint. Resulting in a testbed for research on thermal and power management in DCs [50].
- The ”The European Cloud Computing Hub to grow a sustainable and comprehensive ecosystem”, HUB4CLOUD project, aimed to magnify the impact and relevance of cloud computing research, innovation, and policy-driven efforts in Europe with the ambition of environmentally sustainable cloud technologies and solutions [51].

For the sake of C-RAN, some of the recent past and ongoing research projects are listed below, and summarized in Fig. 2.

- The ”Service-oriented optimization of Green mobile networks”, SooGreen project, investigated how to reduce the energy consumption of services in light of the traffic evolution and exploit new network architectures including hybrid C-RAN [52].
- The ”intelligent Converged network consolIdating Radio and optical access aRound USer equipment”, iCIRRUS project, proposed an intelligent C-RAN solution bringing together optical fibre technology, low-cost but highly flexible Ethernet networking and wireless resource management [53].
- The ”Cloud Wireless Networks: An Information Theoretic Framework”, CloudRadioNet project, aimed at developing novel information theoretic concepts and techniques and their usage, to identify the ultimate communications limits and potential of different C-RAN structures [54].
- The ”Computational and stOrage resource Management framework targeting end-to-end Performance optimization for secure 5G muLti-tEchnology and multi-Tenancy Environments”, 5G-COMPLETE project, utilizes the C-RAN architecture to build an unified ultra-high capacity converged digital/analog fiber-wireless transport network for the RAN [55].

C. Our contribution

This current work explores numerous strategies for improving energy efficiency in DCs, while taking the different sizes of DCs into consideration. Furthermore, we examine the size of DCs to be used for C-RAN, to explore how these can become the most energy efficient, which is a major additional contribution of this paper compared to [1], as well as the extended overview of related work. Thus, we provide an in-depth overview of key challenges, opportunities and methods for improving energy efficiency in all types of DCs, but with a major focus area in DCs for C-RAN. Hence, we:

- Provide insights into effective ways to improve energy efficiency in DCs by synthesizing the state-of-the-art technologies and techniques for DCs of different sizes.

- Analyze previous surveys and papers on energy efficiency in DCs, and provide an overview of current research projects.
- Offer engineering guidelines for DCs in C-RAN mobile networks.
- Examine recommendations towards achieving minimized energy consumption in DCs for C-RAN.

III. DATA CENTER BASICS

This section introduces various types and components of a typical DC, before exploring the energy minimization opportunities in the next chapter. Two types of DCs include private enterprise DCs and public cloud DCs. As illustrated in Fig. 3, the end-users gain access to the DCs to store and process data through a network of computers, wireless Access Points (APs), switches/routers and the Internet. The computers are connected to both DCs through a switch or router, which directs the data traffic between them.

An enterprise DC is located inside the same local network as the users, while a cloud DC is located outside of the local network. Cloud DCs are typically managed and owned by third-party service providers and the services they provide are accessed through the Internet. Users can access both types of DCs by authenticating themselves and then proceed to transfer data through the nodes in the network. Fig. 3 gives an overview of a basic network architecture where users have access to both an enterprise DC and a cloud DC. The benefits of connecting to both a cloud DC and an enterprise DC for data access and exchange are:

- The cloud DC enables remote, on-demand access to data and application services from other providers through the Internet.
- The enterprise DC provides more secure, local access to other types of data and applications, which is beneficial for vulnerable data.

The architecture of a DC plays a crucial role in its overall energy efficiency. Several components make up a typical DC architecture, including [18]:

- *Server Racks:* The servers themselves, as well as the physical stations that house the servers in a DC and consume energy for processing and cooling. Server racks are designed to organize, store and manage numerous servers, while optimizing floor space at the same time.
- *Top of the Rack (ToR) Switches:* Switches connected to every server in a server rack and connects those to the network. A ToR switch can be located at the top of each server rack to provide the connection between the servers and the network. They are responsible for forwarding data packets between servers and the rest of the network. This is however; depending on the chosen DC architecture [56].
- *Aggregation Switches:* A centralized connection point for assigned ToR switches. Responsible for collecting data traffic from multiple servers and forward it.
- *Load Balancers:* Devices responsible for distributing network traffic evenly across several servers, reducing the probability of network failures by lowering workload of overwhelmed servers.
- *Access Routers:* A secure connection point for external network traffic.
- *Core Switches/Routers:* Devices responsible for forwarding traffic at a high speed within nodes of a DC network.
- *Edge Routers:* Handles incoming and outgoing network traffic by routing data from and to the DC.

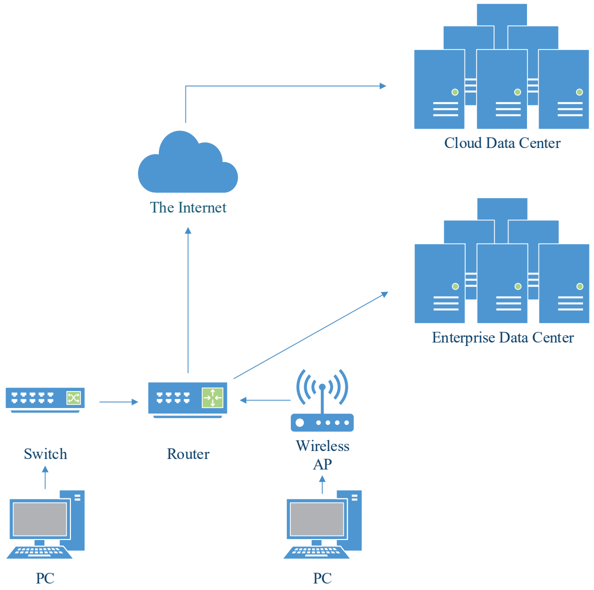

Figure 3. A basic network with computers connecting to both a cloud Data Center (DC) and an enterprise DC.

The various components cooperate to distribute, forward and transmit data traffic stored in a DC, and understanding the purpose and role of each device is key when optimizing energy efficiency in DCs. Fig. 4 illustrates the basic elements of a DC architecture, designed to efficiently process and manage data. It includes server racks connected to ToR switches which forwards traffic to the aggregation switch. The data is then directed to the load balancer which distributes the traffic between the servers. The access router controls access to the DC network and the core switch/router forwards to the edge routers which serve as the bridge between the internal DC network and the external network, being the Internet.

Table II provides an overview of the various DC components and their appearance in the different DC sizes. Furthermore, the table provides an overview of the energy consumption of the various elements using numbers from [56]. However, comparing these numbers to the work in [57], then the energy consumption of servers, storage and communications equipment only account for approximately 50% of the total DC energy consumption. The cooling systems require 40% and the power supply system require the remaining 10% [57]. Thus, in light of the total DC energy consumption the servers will consume 35%, aggregation switches 5%, access routers 7.5% and core switches 2.5%. The break down of energy consumption figures are illustrated in Fig. 5.

TABLE II. DATA CENTER COMPONENTS BY SIZE

Component	Small scale	Mid scale	Large scale	Energy consumption
Servers	<1,000	1,000-10,000	10,000<	70% [56]
ToR switches	<50 [58]	50-500	500<	Expected to be part of the aggregation switch energy consumption
Aggregation switches	<25 [59]	25-250	250<	10% [56]
Access routers	<25 [60]	25-250	250<	15% [56]
Core switches	<12 [59]	12-120	120<	5% [56]

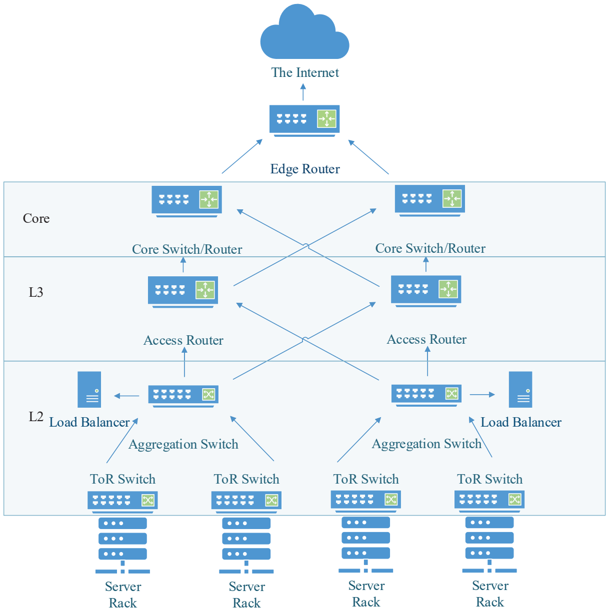

Figure 4. Key components of a basic data center architecture separated into different layers.

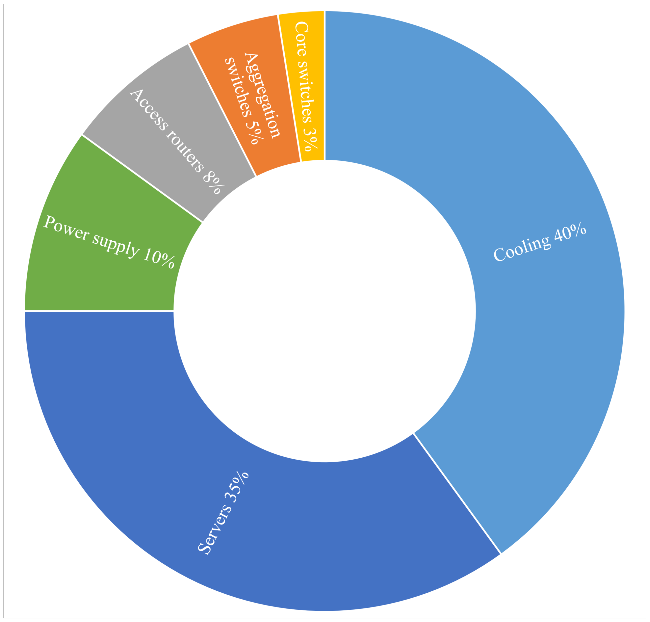

Figure 5. Data Center (DC) key components' energy consumption in relation to the total DC energy consumption.

IV. ENERGY MINIMIZATION METHODS

Energy minimization methods refer to the numerous strategies used to reduce the energy consumption of DCs with the goal of minimizing energy consumption while maintaining high levels of performance and reliability. Server utilization in DCs are found to be under 20% most of the time and with the servers still running fully, this results in very low energy efficiency since servers still consume a significant amount of energy even when not fully utilized [21]. A common tool for measuring energy efficiency in DCs is the Power Usage Effiectiveness (PUE) metric. It is calculated by dividing the total amount of energy used by a DC, including all systems and components, by the energy used by the IT equipment within the DC [61].

This section will give a brief overview of multiple technologies and techniques as well as going in-depth with some subcategories of these strategies, being: sleep state methods and resource utilization in their own subsections. Fig. 6 illustrates where in a DC certain methods are utilized and what components are involved by highlighting the energy efficiency strategies with different colors:

- Green for load balancing and scheduling
- Blue for cooling systems optimization
- Yellow for sleep state methods
- Pink for Data Center Infrastructure Management (DCIM) tools

Figure 6 can be used as an overview of in which components the various energy consumption minimization strategies belong. The strategies will be further elaborated below.

A. *Trending methodologies*

Energy efficiency in DCs can be achieved through a variety of strategies. Examples of current research directions are:

- Advanced cooling systems
- Server virtualization
- DCIM tools
- Edge computing
- AI-driven DC Management
- Quantum computing

Advanced cooling systems are innovative technologies used for mainly cooling servers and can result in notable energy savings. Liquid cooling, free cooling and indirect cooling are some of the advanced types of cooling systems [30]. However, opportunities to place DCs underwater are also being investigated [62]. Another relevant method in this category is

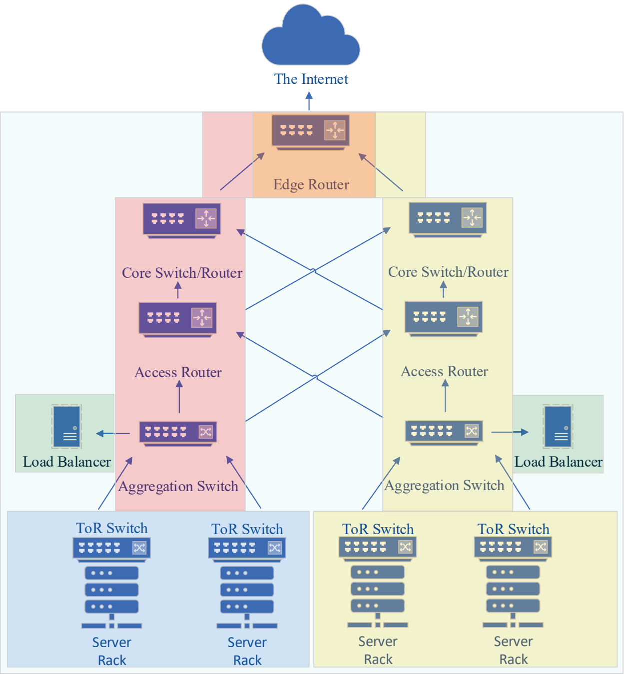

Figure 6. Energy minimization strategies highlighted in color for involved key components of a Data Center (DC). Hence, some of the components benefit from more than one strategy and thus; they are represented in different colors. The green colored components benefits from load balancing and scheduling. The dark blue components benefit from cooling systems optimization. The yellow components benefit from sleep state methods. The pink components benefit from DC Infrastructure Management (DCIM) tools.

heat re-use, which refers to the process of utilizing waste heat generated from one process or system and using it for another purpose, rather than letting it go to waste [3]. Such purposes could be to heat up greenhouses in cold regions [63] [64] [65], houses or whole cities [64] [66], also swimming pools and even laundries can make use of the heat generated in DCs [64].

Server virtualization can lower the number of needed servers in a DC by running multiple virtual servers on a single physical server, resulting in lower power consumption [22]. The technique is an enabler of methods to improve resource utilization, which will be examined later in this chapter [43]. Servers can be virtualized by realizing the functions in software by the use of either Virtual Machine (VM) or container systems. Thus, they need an integrator between the hardware and software, which can be a hypervisor for VMs or a container engine for containers.

DCIM tools are used to monitor, measure, manage and/or control DC utilization and energy consumption of DC equipment such as servers, storage systems and network switches/routers. This helps identify power-related issues and improve DC performance and energy efficiency [67].

Edge computing refers to a range of networks and devices at or near the users and enables processing data closer to where it is being generated. Edge computing can reduce the amount of data traffic that needs to be transmitted to a central DC, resulting in potential energy savings [23]. However, this represents a trade-off between centralization benefits for larger DCs and energy savings in the transport infrastructure. Hence, more centralized traffic in one DC will open up for more opportunities for sharing existing resources, but the cost is a comprehensive transport network, which is examined in [41], [68]. Edge computing however, might prove to be most beneficial for smaller DCs. Large DCs are much more centralized and have a much greater power density which counteracts the whole principle of edge computing. However, egde computing results in more and smaller DCs rather than one or a few large DCs and thus, if considering the amount of data processed, then the potential for higher resource utilization increases by the number of servers in the DC. Hence, more traffic will bring a larger potential for utilizing the servers at different times of the day. On the other hand, not all traffic can be transported to distant DCs, including time critical operations for mobile networks.

AI-driven DC Management is a method for automating control and monitoring of DC resources. By improving DC operations, energy efficiency improves as well [69].

Quantum computing defines super powerful computers that uses quantum technology to create a 3D reference model that significantly increases the computational performance compared to a normal computer. Quantum computing has the potential to increase energy efficiency in DCs by solving complex problems at an incredible speed compared to traditional computing methods. However, it is a new technology and still in its early stages [70]. Furthermore, the quantum computing requires extremely low temperatures and thus; the energy consumption of the cooling system is expected to be higher than the energy consumption of the computers [71].

B. *Sleep states*

Sleep states can be implemented to shut down several server components for a short period of time to reduce energy wasted on un-used server capacity. Fig. 6 illustrates the components in a DC that can be impacted by sleep state methods, being both switches, servers and routers at various levels. When utilizing sleep state methods, the components that are being powered down are the Central Processing Unit (CPU), cores of the CPU, memory and storage devices [21]. The devices and nodes that are involved when utilizing this method are highlighted in Fig. 6, marked by yellow. Modern processors support multiple types of sleep states, primarily:

- Core C-states
- Package C-states
- P-states
- Dynamic Random-Access Memory (DRAM) power mode

Core C-states work by stopping executions on the core. They range from C1-C6 and the differences between those being the varied amounts of power savings and exit latency costs, which will here be referred to as wake up time. C0 is the active state, with no CPU power savings. C1 is the state with the least power savings but with the shortest wake up time whereas C6 is having the longest wake up time at a 133μs transition time [21], however; this number is depending on

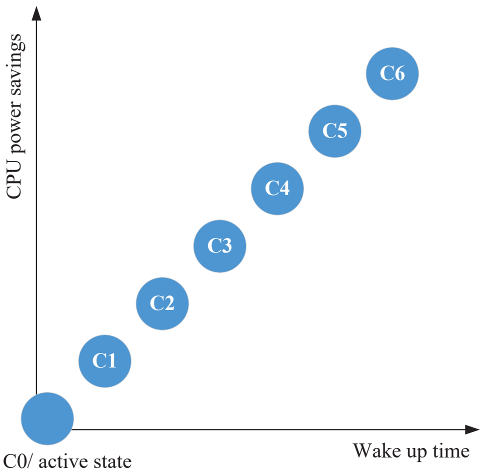

Figure 7. Illustration of the 6 Core C-states according to wake up time and opportunities for power savings.

the protocol used. The core c-states and their relation between wake up time and CPU power savings are illustrated in Fig. 7.

Package C-states are used when all cores are in state C1 to C6, hence; the entire CPU is idle. In this state a whole package of components turns off, such as shared caches, integrated Peripheral Component Interconnect Express (PCIe), memory controllers, and so on [24]. However, the concept is that additional power is saved compared to the power saved with the sub-components individually [24]. Package C-states can significantly reduce energy consumption but has the side effect of increasing the latency for cores going to or from low power states [21]. Furthermore, package C-states can be problematic because of high response times during re-activation when handling traffic spikes. Additionally, having the memory and/or storage of all servers to be available, even during times of light load, can be very beneficial. Lower latency can be achieved by AgileWatts (AW) [21] which is a deep idle core power-state architecture that reduces the transition latency to/from very low power states. AW has been proven to result in up to 71% power savings per core with a less than 1% end-to-end performance decrease [21].

P-states changes the frequency and voltage of a part of the system. This being the cores or other components such as a shared Layer 3, the network layer (L3) cache [24]. P-state is a module state affecting a collection of cores that share resources [24]. The concept of P-states is that a CPU running at lower frequencies requires lower performance and longer latency to complete a certain amount of work. Thus, under some circumstances, for example in low traffic periods, it is possible to complete a required amount of work with lower energy [24].

The DRAM power mode consists of two power-saving methods which are the Self-refresh function and the Clock Enable (CKE) mode. CKE sends a signal from the Memory-Controller (MC) to the DRAM device, and when this signal is no longer being sent, the DRAM is free to enter a low power state. In the Self-refresh function, the MC sends the refresh signal to the DRAM to ensure that the data is valid. DRAM has the ability to start the Self-refresh process itself, which can reduce the power consumption in the MC [72].

C. *Resource utilization*

DCs' load rises when more requests are received, and these requests can be received seasonally. Thus, the workload demands of the servers are changing dynamically and are determined by a real-time workload status. By balancing the load on the servers carefully and properly, it is possible to increase the energy efficiency of components in a DC. Fig. 6 illustrates resource utilization techniques within a DC, highlighted as green. This work examines two different ways of increasing the resource utilization:

- Load balancing
- Scheduling

Load balancing can be explored using various methods. Dynamic Time Scale based Server Provisioning (DTSP) is a method which takes the variability of workloads into consideration when providing servers for workload demands. For DTSP to load balance properly, key information is gathered constantly so that DTSP can accurately estimate workload requirements on servers and specify the appropriate number of servers for the dynamic workloads [19]. Irregular arrivals of requests impact the accuracy of the expected workload. To increase the estimation, the gathered information of incoming requests is standardized before it is used in later calculations. When it comes to workload, the algorithm looks at the three factors; arrival rate of previous requests, the arrival rate of current requests and the mean service time of current requests. With these factors, the algorithm is able to figure out the intensity of previous workloads and reflect the available remaining capacity for the unfinished waiting workloads, as well as measure the intensity and time needed for current workloads to complete. These factors are also used when calculating the workload demand of incoming requests and to determine how many servers are needed to finish current and remaining workloads while satisfying the Quality of Service (QoS) requirements [25]. DTSP has been proven to be able to estimate the workload demands of servers in a DC. By periodically adjusting service resources to match workload demands, DTSP significantly improves and maintains the system energy efficiency under an acceptable QoS level [19]. The work in [43] explores five different load balancing methods, the dynamic, predictive, energy-conscious application scaling, energy efficient and generic algorithm with population reduction. Results show that each of the investigated methods have individual pros and cons when evaluating them based on various parameters.

Scheduling can be used to prioritize which machines that run what jobs or are higher utilized. A cloud system uses virtualization technology to provide cloud resources such as CPU and memory to users in the form of virtual machines.

Tasks and job requests are assigned on these VMs for execution. The technique known as job scheduling is a method used to assign a job to a VM based on classification. By allocating jobs based on types and availability, it is possible to increase energy efficiency by making better use of available resources. Minimizing the number of hosts used when allocating resources reduces energy consumption. The Energy Aware VM Available Time (EAVMAT) scheduling algorithm does exactly this [26]. By categorizing jobs into three types and then assigning jobs based on a predefined policy with the earliest available resource. Energy consumption is then reduced since less hosts are in an active state and resource utilization is higher. This method has been tested and was able to achieve up to 46% energy savings [26].

V. DATA CENTERS FOR CLOUD-RAN

The C-RAN mobile network architecture centralizes the baseband processing of a number of sites in DCs, as illustrated in Fig. 1. Hence, for each RU the associated baseband processing is divided into DU and CU functions, which can remain on the cell site or be centralized in a DC. The potential maximum number of sites associated with one DC, will depend on several factors, being:

- Cell density in covered area
- Type of installations in covered area
- Latency limit in transport network
- DC efficiency

The *cell density* is an important parameter when estimating the amount of DUs and CUs in an area, and it requires knowledge about the Inter-Site Distance (ISD) in the current area. Hence, the ISD in an urban area is expected to be much shorter than the ISD in a rural area, due to the higher capacity requirement and more obstacles. More sites are equal to more installations and thus; more CUs and DUs.

The *type of installations* will vary based on the specific area. In an urban area more equipment is installed compared to a rural area due to the higher capacity requirement.

The *transport latency* limit is set by the requirements of the current network segment. The network segment connecting the RU to the DU is referred to as the fronthaul network, where the network segment connecting the DU to the CU is referred to as the midhaul network. The functions located respectively in the DU and CU, referred to as the high layer functional split or High Layer Split (HLS), is already standardized by 3rd Generation Partnership Project (3GPP) in [73]. However, the low layer functional split or Low Layer Split (LLS), separating the functions of the RU and DU is still a discussion topic amongst various industry alliances and standardization bodies [74].

The *efficiency of the DC* is also a parameter, since more efficient equipment can handle higher traffic loads, and on the contrary, if the capacity of the DC is not enough, it might not be able to handle traffic from all of its potential coverage area. Hence, if it is a private DC it will require more effort to upscale than using a public cloud solution where capacity is rented on demand. This is also a more difficult parameter to evaluate since it will vary based on vendor capabilities, and because this is an area in continuous development.

A. Engineering guidelines

In the light of the implementation factors mentioned, then in order to determine the size of a DC for C-RAN, the Mobile Network Operator (MNO) must be mindful about several conditions:

- On-site installation
- Number of basebands or DU and CUs in the current area
- Server efficiency
- Size of area to deploy C-RAN

The on-site installation defines what equipment in terms of RU, DU and CU are installed at the cell site. The type of RU is defined by the LLS used. Following 3GPP recommendations, for the HLS and a variety of LLSs, including the one used in today's installations; then the fronthaul transport delay must be < 250 μs [73] and the midhaul transport delay must be < 10 ms [73]. Thus, assuming a fiber propagation delay of 10 μs/km [3], then the maximum distance from the farthest site position and RU is 25 km to the associated DU DC and up to 1000 km to the associated CU DC [3]. These distances provides an approximation of how large an area a DU DC and a CU DC can cover, by assuming the DC covers a circular area with the maximum distance as the radius. Hence, this is corresponding to 1900 km^2 for the DU DC, which is the size of the Hawaiian island of Maui. On the other hand, the CU DC can cover more than 3 million km^2, which is larger than the country of Argentina, or approximately 1/3 of Europe. A MNO has three potential placement scenarios if they want to centralize their processing in DCs:

- Scenario A: To leave the DU on the cell site and move CU functions to a DC.
- Scenario B: To centralize the DU functions in one DC closer to cell sites and centralize CU functions from multiple DU DCs in one CU DC.
- Scenario C: To centralize both DU and CU in the same DC.

The three scenarios are illustrated in Fig. 8, where the various latency requirements are stated too. Hence, if the MNO wants to install CU functions in the same DC as the DU, then the DU transport latency requirements must be met.

The number of basebands will determine the size of the DC. This number is depending on the type of area, since an area with higher population or frequent visits by many people, like a huge train station or a concert hall, require more equipment and capacity. Thus, since more capacity can be added to an area by deploying more sites, then areas requiring high capacity will have a shorter ISD compared to areas with lower capacity requirements.

The server efficiency is difficult to measure and is an area in continuous development. In order to be able to compare the efficiency of a COTS server and a proprietary baseband installation, the performance must be measured. The performance can be quantified by examining the number of jobs executed in

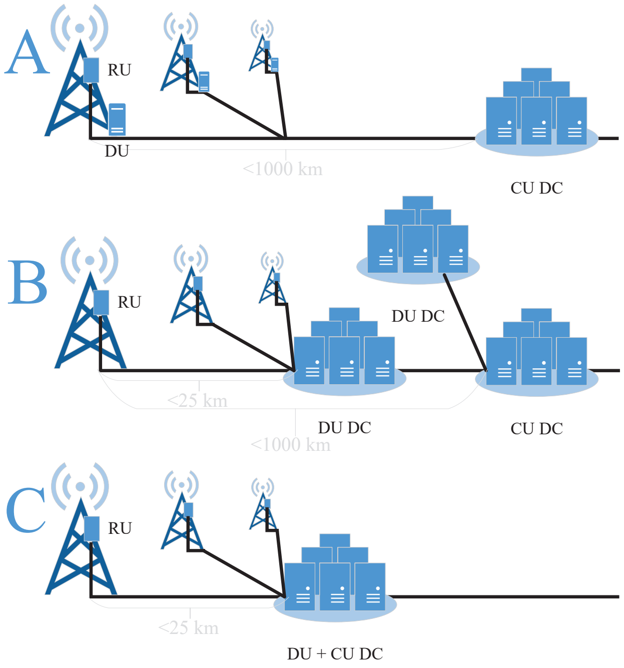

Figure 8. Three Cloud-Radio Access Network (C-RAN) installation options: Distributed Unit (DU) on the cell site and Centralized Unit (CU) centralized in a Data Center (DC) [A], DU and CU in different DCs [B] and in the bottom, DU and CU in the same DC [C].

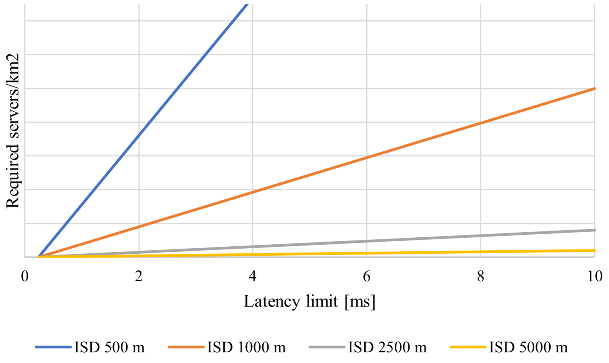

Figure 9. The figure shows the capacity in terms of required servers as a function of the latency required by the fronthaul network.

a certain time interval and the maximum load of one unit. In order to make an estimate for this work it is expected that one onsite DU+CU will correspond to one server, with the traffic distribution 2/3 to DU and 1/3 to CU. This is a topic that leaves room for further investigations, because how efficient is a Commercial off the Shelf (COTS) server actually compared to a proprietary baseband? However, if the efficiency of the proprietary baseband and the server(s) running the DU and CU functions are not 1:1 efficient then the number of COTS servers required might be less or (more likely) more than the proprietary installations in the traditional RAN. Hence, the server efficiency will affect the number of servers in the DC. The relationship between latency and capacity in terms of required servers in the DC is explored in Fig. 9. The figure shows the required number of servers for various ISDs when complying with different requirements to fronthaul latency.

The size of the area determines how many DCs are required to cover the current area in order to comply with the RAN latency requirements. Furthermore, the placement scenario selected will also determine the need for multiple smaller or one larger DC.

B. *Case study*

This case study, investigates the number and sizes of DCs required for the Danish MNO TDC Net [75] to convert to a C-RAN installation in their mobile network. Thus, real life numbers and approximations are used to evaluate the sizes of required DCs. TDC Net provides 99% geographical 5G coverage in the country of Denmark and utilizes approximately 4000 sites. The country of Denmark can be seen in Fig. 10. The country of Denmark is approximately 43,000 km^2 and thus; only one DC can according to the transport latency requirements carry all CU data of the whole country. According to transport latency requirements, then at least 23 DCs are necessary to handle the DU traffic. In this case we assume 23+ DU DCs since more might be required due to practical implementation specifics. In order to explore the C-RAN DC opportunities for TDC Net two areas with a radius of approximately 25 km are selected. One urban area with high traffic loads and many users present at all times of the day, and one rural area with the complete opposite capabilities. Table III summarizes the parameters of the urban area, rural area and the whole country, utilizing the parameters stated in the engineering guidelines. As stated in the table, the capacity illustrated by utilized spectrum in the current area, differs a lot in the different areas. The capacity here includes both Long Term Evolution (LTE) and New Radio (NR) cells. The rural area chosen has a lower average capacity compared to the average capacity in the whole country, where the urban area used here have a much higher average capacity compared to the average capacity for the whole country. In the following subsections, scenarios A, B and C presented under engineering guidelines, will be explored in the light of the case study.

1) *Scenario A:* Only one CU DC, is necessary for covering all of Denmark's CU traffic. This DC shall be able to handle upper layer traffic from all 4100 sites covering the whole country, with a total of 7100 basebands. Thus, expecting 1:1 performance of current installations and DC servers, with 1/3 traffic handled in the CU as described under DC efficiency in chapter V. Then 2400 servers will be required to handle CU traffic, corresponding to a mid-scale DC. Data is summarized in Table IV.

2) *Scenario B:* 23+ DCs are nescessary to handle all DU traffic. The DU DCs' sizes will depend on the cell density and installation types of the current area. Thus, two areas will be considered, a rural and an urban area in Denmark. The areas are compared in Table V considering an urban area with a total of 900 sites (including macro, pico and indoor systems) and a rural area covered by 50 sites, both areas covering approximately 25 km from the area center. When expecting

TABLE III. AREA SPECIFICS

Parameter	**Urban area**	**Rural area**	**Denmark**
Type of RU	LLS8	LLS8	LLS8
Fronthaul latency limit	$< 250\ \mu s$	$< 250\ \mu s$	$< 250\ \mu s$
Total macro sites in area	900	50	4100
Total basebands in area	1400	100	7100
Average capacity per site	109 MHz	77 MHz	83 MHz
Estimated server efficiency	1:1	1:1	1:1
Approximated size of area	1900 km^2	1900 km^2	43,000 km^2

Figure 10. The country of Denmark. The image is a creative common under license CC BY-SA.

TABLE IV. CU DC

Parameter	**Denmark**
Assumed traffic distribution	1/3
Servers in DC	2400

1:1 performance of current installations and DC servers, and DU traffic corresponding to 2/3, then 940 servers will be required to handle DU traffic in the urban area, corresponding to a small-scale DC. For the rural case, only 60 servers will be necessary to handle DU traffic, corresponding to a minor small-scale DC. Data is summarized in Table IV.

3) Scenario C: If the DU and CU is both located in the same DC, then the covered area will be limited by the latency boundaries of the DU, and thus; 23+ sites are necessary to cover the whole country of Denmark. Table VI summarizes the required size of DC in a rural and an urban area. As the table shows, then the rural area is still covered by a small-scale DC. However, the urban area DC becomes a mid-scale DC with 1400 servers required to handle DU and CU traffic.

TABLE V. DU DC EXAMPLES

Parameter	**Urban**	**Rural**
Assumed traffic distribution	2/3	2/3
Servers in DC	940	60

TABLE VI. DU AND CU DC EXAMPLES

Parameter	**Urban**	**Rural**
Assumed traffic distribution	1/1	1/1
Servers in DC	1400	100

VI. DISCUSSION

DCs being responsible for approximately 1.5% of global carbon emission with an annual growth rate of 4.3% have become an area of focus within the last decade [28]. However, a lot of attention has been directed towards the larger DCs, which are only responsible for a small portion of the overall energy consumption of DCs in general, since small-/mid-scale sized DCs are responsible for approximately 50% of the energy consumption [28]. Due to the increased attention, large-scale DCs have therefore advanced more than small-scale DCs and have numerous energy efficient methods implemented already. It is shown in [28], that energy efficient strategies such as virtualization are adopted less in smaller DCs compared to large DCs. Small DCs are in general behind on the energy efficiency front with around 43% of them not having energy efficiency objectives in place at all [28]. When energy optimizing the mobile networks, the baseband processing of the RAN is moved into DCs categorized as small-or mid-scale. Thus, if the energy usage should not just be passed on to the next segment of the network, ie. the DC, it is important to consider methods for minimizing the energy consumption in DCs for C-RAN as well.

The benefits of different strategies used for energy efficiency in DCs varies depending on the size of the DC. Below is recommended a set of guidelines for optimizing energy efficiency in DCs and evaluated based on the three different sizes/categories; small-, mid- and large-scale. However, it is important to stress that techniques and technologies recommended for small-scale DCs are also excellent methods for larger DCs, whereas methods recommended for large-scale DCs are not always realistic/beneficial options for smaller

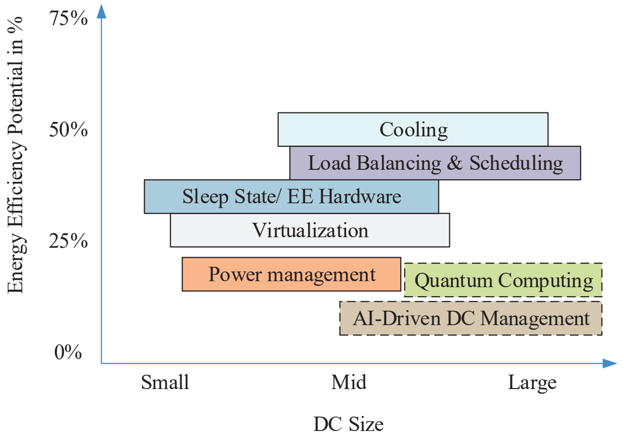

Figure 11. The graph compares the energy efficiency improvement percentages achieved through different energy efficiency strategies in DCs of different scale.

DCs because of price and other circumstances such as the scale. On the other hand, small-scale DCs might see greater improvements when utilizing some of these strategies, since they are size-wise easier to manage, which can result in energy-efficient technologies and practices being adopted more easily. Large DCs managing thousands of servers and hundreds of server racks will likely achieve greater power savings by investing in advanced cooling systems than small-scale DCs managing less than hundred servers. Here, small-scale setups might see greater benefits investing in other technologies and techniques as described in the next subsection.

A. *DC Strategies at Different Scale*

Many different factors are decisive for how effective certain strategies are when it comes to the energy efficiency for DCs of various sizes. This makes it difficult to generalize the different methods as all DCs differ in relation to infrastructure, scale and utilization, environmental factors and what energy efficient technologies are already in place. Some energy efficiency strategies can provide the best results for smaller DCs compared to larger DCs, since small-scale DCs have fewer resources available as well as generally not even having implemented any energy efficiency strategies at all [28]. Fig. 11 shows potential power savings of different strategies for varying DC sizes. Furthermore, below various opportunities for minimizing energy consumption in DCs of different scale are examined:

Small-scale and mid-scale DCs benefit from energy efficiency strategies such as sleep state methods and power management tools, as well as virtualization, load balancing and energy efficient hardware. Additionally, small-scale DCs can also benefit from design optimization including efficient cooling systems and energy efficient infrastructure.

Large-scale DCs have access to more resources and can allocate those towards many different energy-saving measures, including advanced cooling systems, server virtualization, load balancing as well as renewable energy sources. Having access to additional resources opens up for other strategies such as AI-driven DC management and quantum computing as large-scale DCs also have more data traffic to handle. Modern energy efficiency strategies such as advanced cooling systems have proven to potentially achieve energy saving of up to 50% [30], virtualization has proven possibilities of 30% [22], sleep state methods can provide up to 34% energy savings [27], and resource utilization methods can reduce energy consumption by up to 46% [26]. All these strategies are beneficial for DCs of all sizes but can vary in potential energy savings depending on multiple different factors. DCIM and PUE are also excellent methods for working towards more energy efficient DCs and can provide beneficial tools for analysing DCs of all sizes. That being said, as well as being able to utilize and implement the technologies and techniques mentioned for smaller DCs, large-scale DCs does also have other possible methods for achieving greater energy efficiency. AI driven DC management and quantum computing are both methods which will most commonly be seen in large-scale DCs since the owners are able to provide sufficient resources for these technologies to be implemented and these methods are therefore recommended for large-scale DCs, along the methods mentioned for smaller DCs.

Numbers provided in section III illustrate the energy consumption of the various components of the DC and table VII shows an overview of the various methods for energy savings examined throughout this paper and the savings they provide. Furthermore, the table shows how large a reduction in the overall DC energy consumption each of the proposed methods will bring, as well as which of the components will save energy by the current method. Finally, the table also shows whether the various DC sizes can benefit from the different solutions. The table leads to the clarification that small and mid scale DCs can potentially minimize their energy consumption by up to 23% by utilizing methods mentioned earlier in this section and in the table, where large DCs can save up to 34% energy consumption by utilizing the methods proposed.

B. *Energy Minimization potential for C-RAN DCs*

When moving baseband processing from mobile networks into DCs, the network functions are already virtualized, otherwise they could not operate on COTS hardware. Thus, multiple DUs or CUs can run on the same physical hardware. This opens up for opportunities in resource utilization including load balancing and scheduling. By utilizing these methods it is possible to shut down un-used hardware resources in low traffic periods. Mobile traffic does vary by time and is especially lower during the night, thus; this is a great potential energy saver. Hence, during the day the users of mobile networks will move around between different areas, for instance residential and work areas, leaving one area underutilized. The take away points from the case study is that even in urban areas, the C-RAN DC is still a minor mid-scale DC. Hence, the strategies for small-scale DCs energy minimization can be applied. By examining the strategies for small-scale DCs energy minimization, it is possible to utilize

TABLE VII. DATA CENTER ENERGY EFFICIENCY BY COMPONENT

Method	Saving	Reduction	Component(s)	Small scale DCs	Mid scale DCs	Large scale DCs
Cooling	50% [30]	20%	Cooling	Yes	Yes	Yes
Virtualization	30% [22]	10.5%	Servers	Yes	Yes	Yes
Resource utilization	46% [26]	23%	Servers, aggregation switches, access routers, core switches	No	No	Yes
Sleep states	34% [27]	17%	Servers, aggregation switches, access routers, core switches	Yes	Yes	Yes
Power management	20% [76]	2%	Aggregation switches, access routers, core switches	Yes	Yes	Yes

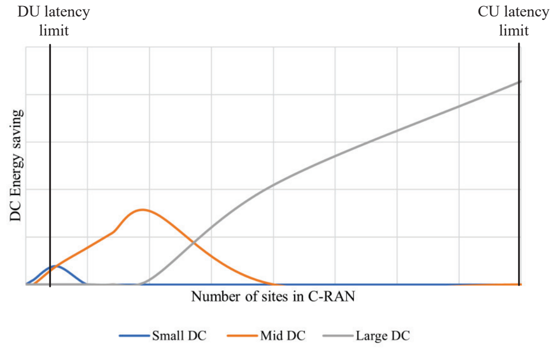

Figure 12. The graph illustrates the energy usage in small-, mid- and large scale Data Centers (DCs). The latency boundaries from Fig. 9 for a DU corresponding to ISD 0.5 km and a CU corresponding to ISD 5 km, are outlined in the graph.

sleep modes, where core C-states can be used in different ranges depending on the traffic pattern. Hence, the MNO must be aware of the exit latency, which increases with the CPU power savings. Furthermore, package C-states can be used for longer idle periods. However, since much mobile traffic is latency sensitive, P-states are not recommended.

Exploring how many DCs are actually beneficial to cover a certain area will depend on the size of the area as well as the chosen size of DC(s). From an energy efficiency perspective, both many small and one large DC have different pros and cons. Hence, looking at the various elements in the DC, as presented in Fig. 5, then some components will remain the same number when increasing the amount of DCs while others will increase, this is stated in table VII. Figure 12 shows how the various DC sizes are beneficial for different numbers of sites in C-RAN. In the figure, the maximum DC sizes stated in table II, are utilized, and when exceeding this number, more DCs of the current size are added increasing the number of cooling systems and power supplies, which are expected to be only one per DC. Thus, the figure outlines how latency requirements, as are a vital part of mobile network data flow, will be the limiting factor for re-routing DU traffic to larger DCs.

VII. CONCLUSION

This work investigated how the scale of a DC can impact its energy efficiency where large DCs in particular face opportunities in terms of energy minimization. On the other hand, the C-RAN trend in the RAN segment of mobile networks requires smaller and local DCs. Small and mid-sized DCs, can achieve notable energy-savings by improving design and infrastructure, as well as improving resource utilization. On the other hand, large-scale DCs can make use of the greater amount of available resources to increase energy efficiency in the same and other ways such as with AI driven resource management, new cooling methods and quantum computing. This work provided a set of engineering guidelines to be used for determining the size of a DC for C-RAN. These guidelines implicate the on-site installation, which particularly restricts the latency between the current site and the DC handling the mobile traffic. Furthermore, the size of the area and the number of installations in the current area affect the size of the C-RAN DC, and the server efficiency which is a yet greenfield area of exploration. Thus, when exploring the case study two candidate areas within the latency limit of one DU brought an insight in the size of DC required to support the C-RAN architecture if adopted in the mobile network, but highlighted the limitations within the mobile traffic latency requirements.

ACRONYMS

3GPP	3rd Generation Partnership Project.
AI	Artificial Intelligence.
APs	Access Points.
AW	AgileWatts.
C-RAN	Cloud RAN.
CKE	Clock Enable.
COTS	Commercial off the Shelf.
CPU	Central Processing Unit.
CU	Centralized Unit.
DC	Data Center.
DCIM	Data Center Infrastructure Management.
DCs	Data Centers.
DRAM	Dynamic Random-Access Memory.
DTSP	Dynamic Time Scale based Server Provisioning.
DU	Distributed Unit.

EAVMAT	The Energy Aware VM Available Time.
HLS	High Layer Split.
ICT	Information and Communications Technology.
ISD	Inter-Site Distance.
L3	Layer 3, the network layer.
LLS	Low Layer Split.
LTE	Long Term Evolution.
MC	Memory-Controller.
MNO	Mobile Network Operator.
NR	New Radio.
PCIe	Peripheral Component Interconnect Express.
PUE	Power Usage Effectiveness.
QoS	Quality of Service.
RAN	Radio Access Network.
RU	Radio Unit.
ToR	Top of the Rack.
US	United States.
VM	Virtual Machine.

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