Energy-Efficient Information and Communication Infrastructures in the Smart Grid: A Survey on Interactions and Open Issues

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***Abstract*—Smart grid has modernized the way electricity is generated, transported, distributed, and consumed by integrating advanced sensing, communications, and control in the day-to-day operation of the grid. Electricity is a core utility for the functioning of society and for the services provided by information and communication technologies (ICTs). Several concepts of the smart grid, such as dynamic pricing, distributed generation, and demand management, have significantly impacted the operation of ICT services, in particular, communication networks and data centers. Ongoing energy-efficiency and operational expenditures reduction efforts in communication networks and data centers have gained another dimension with those smart grid concepts. In this paper, we provide a comprehensive survey on the smart grid-driven approaches in energy-efficient communications and data centers, and the interaction between smart grid and information and communication infrastructures. Although the studies on smart grid, energy-efficient communications, and green data centers have been separately surveyed in previous studies, to this end, research that falls in the intersection of those fields has not been properly classified and surveyed yet. We start our survey by providing background information on the smart grid and continue with surveying smart grid-driven approaches in energy-efficient communication systems, followed by energy, cost and emission minimizing approaches in data centers, and the corresponding cloud network infrastructure. We discuss the open issues in smart grid-driven approaches in ICTs and point some important research directions such as the distributed renewable energy generation capability-coupled communication infrastructures, optimum energy-efficient network design for the smart grid environment, the impact of green communication techniques on the reliability and latency requirements of smart grid data, workload consolidation with smart grid-awareness, and many more.**

***Index Terms*—Data centers, distributed generation, dynamic pricing, energy-efficiency, green communications, renewable energy, smart grid, sustainability.**

I. INTRODUCTION

INCREASING electricity prices, diminishing fossil fuels and rising concerns on GreenHouse Gas (GHG) emissions have called for the modernization of the power grid, in which Information and Communication Technologies (ICTs) are playing the key role. Smart grid adopts the cutting-edge technology in generation, transmission, delivery, consumption and storage of electricity. ICTs bring significant innovations in these areas, as sense, communicate and control functionalities are becoming the standard practice in smart grid deployments. Meanwhile, modernization of the grid brings forward new concepts such as Time of Use (ToU), real-time pricing, distributed generation, demand management which impact the Operational Expenditures (OPEX) and emissions of the information and communication infrastructure. In particular, communication networks and data centers, being the largest power consumers and GHG emitters among other ICTs, benefit from smart grid-driven techniques to enhance energy savings and emission reductions.

For the past decade, telecommunication companies have been seeking ways to reduce their electricity bills as well as their energy consumption and emissions. The research in the field of energy-efficient communications targets communication networks with less OPEX, less power consumption and less emissions with minimal service degradation. To this end, vast amount of research has been performed in energy-efficient wireless, wireline and optical communications. Nevertheless, ToU, demand management, renewable-dominated supply selection or briefly smart grid-driven techniques can further bring down the bills, reduce the amount of energy consumption and emission release of the operators.

Besides telecommunication companies, data center operators are impacted by high electricity prices and carbon costs. Combined electricity demand of telecommunication networks and data centers is reported to be equivalent to the demand of the fifth largest country [1]. Therefore, green data centers have been another major research track in the past several years. To this end, smart grid-driven techniques have been implemented through price- or emission-aware workload consolidation and migration as well as renewable powered data centers.

Implementation of wireless communications and data centers in connection with the smart grid is illustrated in Fig. 1 including the power flow in the grid. Electricity is transported to the consumers over the transmission and distribution system similar to the legacy grid, while in addition, consumers can become power generators and sell power the grid according to the novel distributed generation practices of the smart grid [2]. In the smart grid, all of the entities are connected through communications. In the figure only wireless technologies are presented but as will be discussed later on in this paper, using optical and wireline communications is also possible. In the figure, data collected from sensors and meters are fed into the utility headquarters and stored in cloud data centers.

Manuscript received November 10, 2013; revised May 17, 2014; accepted July 15, 2014. Date of publication July 22, 2014; date of current version March 13, 2015.

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Digital Object Identifier 10.1109/COMST.2014.2341600

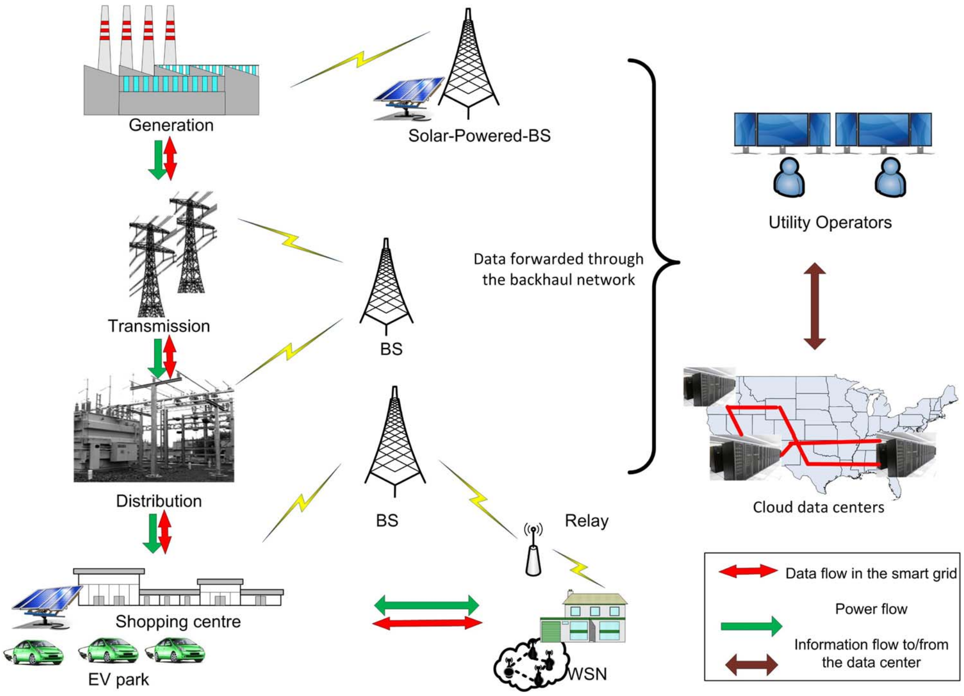

Fig. 1. Smart grid, wireless wide area solutions and Internet data centers. (Some links and flows have been omitted for the sake of clarity.).

In this paper, we take a closer look at the smart grid-driven research in energy-efficient information and communication infrastructures, in particular communication networks and data centers. The reason for focusing on communication networks and data centers is their large power intake that positions them as significant players in the power grid. Our survey differentiates from the other works in the literature, being the initial survey on smart grid-driven techniques in energy-efficient ICTs. There are a number of surveys solely on smart grid communications, each of which focus on different aspects of the topic. A comprehensive review of smart grid technologies in terms of infrastructure, management and protection is presented in [3]. In [4] the authors present an informative tutorial on data sensing technologies for the smart grid. In [5], the authors provide a comprehensive review on the applications of wireless technologies in the smart grid while [6], [7] discuss the challenges and feasibility of state-of-the-art wireless technologies in the smart grid domain. A broad review of communication technologies in smart grid can be found in [8]. Smart grid application requirements in terms of delay, reliability, bandwidth or more generally Quality of Service (QoS) and the ability of existing communication technologies to meet those requirements have been discussed in detail in [9], [10]. Furthermore, recent efforts on standardization can be found in [11] and [12]. In addition, surveys that solely focus on energy-efficient communications or green data centers are also available in the literature. Interested readers can refer to [13]–[16] for energy efficient wireless communications, [17], [18] for energy efficient optical communications, and [19], [20] for green data centers. In this survey, we focus on the works that enhance the energy efficiency of the information and communication infrastructures by making use of the concepts that have come under the spotlight with the emergence of the smart grid; such as dynamic pricing, distributed renewable energy generation, fine-tuned fault and disturbance monitoring and so on. We also point out open research directions, as we believe utilizing smart grid concepts for enhancing the energy-efficiency of communications and data centers is a research topic with significant potential. Looking from another perspective, communications is needed for the smart grid and energy-efficiency techniques that are employed in green communications are anticipated to impact the latency and the reliability of smart grid traffic. Further research is needed to analyze and quantify those impacts.

The rest of the paper is organized as follows. Section II provides background on the smart grid and introduces its fundamental concepts. Section III surveys the studies that use smart grid concepts to enhance energy-efficiency of communication networks including wireless, wireline and optical communications. Section IV surveys the works that benefit from price, renewable energy or emission awareness to improve the operational practices at data centers. Section V discusses the open issues and lessons learned in both fields with a taxonomy of surveyed papers. Finally Section VI concludes the paper.

II. AN OVERVIEW OF SMART GRID

Smart grid integrates advanced sensing, communication and control functionalities in the power grid's operation, for the purpose of enhanced efficiency, reliability, security and reduced emissions [21]. The legacy grid involved sensing, communication and control functionalities to some extend, however the advances in ICTs have necessitated bottom-up modernization of the cyber and the physical elements of the power grid. Smart grid aims to increase its efficiency by integrating renewables into the energy mix, employing smart demand management and by adopting techniques to reduce the losses over the power lines [22]. Meanwhile, smart grid aims to enhance its reliability without falling into the pitfalls of the traditional approaches,

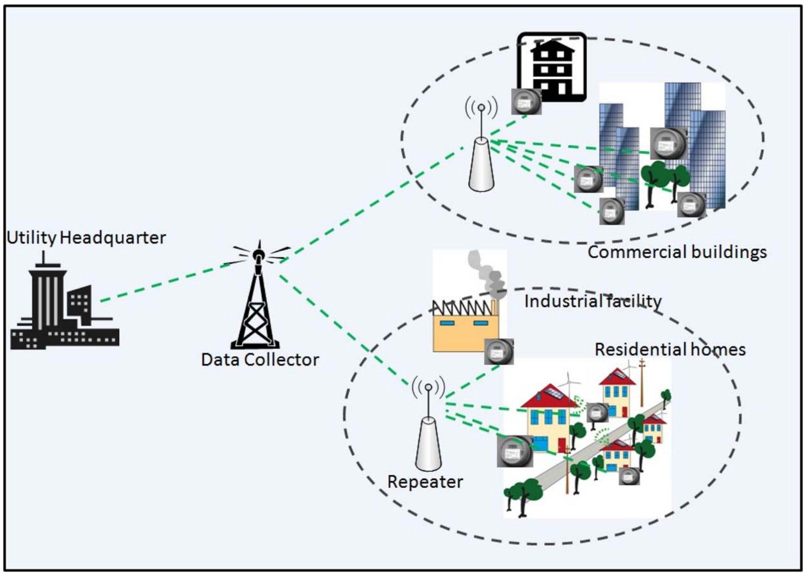

Fig. 2. A typical AMI network.

i.e. over provisioning of the resources. Reliability corresponds to 100% availability of the electricity as well as protection against power quality fluctuations and operation in isolated mode in unexpected circumstances such as natural disasters or terrorist attacks [23]. In addition, smart grid desires to have improved security. Security of the physical smart grid infrastructure refers to the security of the utility assets such as substations, overhead power lines, towers, generators, batteries, as well as the customer equipment, e.g. smart meters, smart thermostats that may be controlled by the utility while security in the cyber domain refers to secure communications and secure software tools that preserve the corporate, infrastructure and customer information. The readers who are interested on a detailed survey on smart grid security are referred to [24], [25].

Advanced communications enable smart grid to device variable pricing policies such as ToU and real-time pricing. The variable pricing of electricity can be either based on historical demand data or real-time demand and supply condition. In either options, electricity has higher price during high demand than the price set for low demand periods. ToU uses the seasonal and daily demand information collected over the years and real-time pricing uses the hour-to-hour market price of electricity [26]. With the installation of smart meters, variable pricing and corresponding billing actions have become feasible in the smart grid.

Variable pricing policies lead to price-following demand management. In legacy demand response programs, utility operators used to call large-scale customers such as industrial plant operators or building operators and ask them reduce their consumption during critical grid conditions by offering some incentives. This type of demand response is not convenient for small-scale customers nor for dynamic pricing, therefore in the smart grid price-following demand management has become the common practice. In this context, smart grid adopts diverse communication technologies to support remote smart meter reading and price-following demand management.

The network of smart meters is known as the Advanced Metering Infrastructure (AMI). AMI may be implemented using a wide variety of communication technologies that allow remote configuration, meter reading and appliance control. For instance, IEEE 802.15.4g is being developed for the utility-to-meter communications while IEEE 802.11b/g is another standard available in many smart meters. Cellular, Worldwide Interoperability for Microwave Access (WIMAX) and narrowband wireless communications are also among the utilized technologies for AMI. Furthermore, cognitive radio using TV white spaces has emerged as an alternative to costly cellular communications, especially for coverage in rural areas [27]–[32]. In addition, the technique known as Power Line Communications (PLC) emerges as a strong candidate for the AMI [33], [34]. A typical AMI using cellular communications is presented in Fig. 2. In a broader context, AMI is seen as an ideal application of Machine-to-Machine (M2M) communications while M2M communications will also become useful for self-organization of microgrids [35], remote control of home appliances, interaction of distributed renewable energy generation resources and so on [36], [37].

As for price-following demand management, the past several years have seen a tremendous interest in the development of residential demand management techniques. In general, based on prediction of consumption patterns, consumer demands are shifted to less expensive timeslots to reduce energy expenses of the consumers and to reduce the peak-to-average ratio of the grid. Several studies apply optimization models [38]–[40] while others use neural networks [41], [42] or game-theory [43]–[46]. Furthermore, sensor networking technology has been considered as an integral part of residential demand management [47]. As communication technologies are getting more and more integrated in the smart grid, reliability of communication and its impact of smart grid applications has been a relevant research direction as well [48], [49].

The novelties included in the developing smart grid is not limited to pricing policies and demand management. Energy flow from the customers to the grid [50] or energy transactions among communities [51]–[54] or advanced monitoring solutions for the transmission and distribution systems [55]–[59]

are among the new concepts of the smart grid. For instance, wide area measurement and situational awareness components are gaining large deployment opportunities. In the U.S., there is a momentum for dense deployment of phasor measurement units (PMUs) and other wide area measurement instruments in the power grid[1] [60]. Close to 1000 PMUs are planned to be up and running in substations and power plants in the U.S. in the near future [61].

Efficient integration of renewable energy, in parallel with the governments' targets of reducing GHG emissions, is another driving factor for an enhanced grid. The energy sector is one of the major GHG emitting sectors, therefore utilizing resources such as solar, wind, tidal or biomass will significantly reduce its emissions. Among those renewable resources, solar and wind power are available in most of the parts of the world while their contribution to the energy mix of today's power grids is fairly low. This is due to their intermittent nature since, without efficient storage or backup capacity, fluctuation in their generation output may risk the operation of the grid. According to a US-based independent system operator (ISO), 9000 MW of wind generation requires an additional of 1150 MW of capacity for regulation and ramping purposes [62]. Once again, advance sensing, communication and control functionalities help the integration of such intermittent energy resources [63]. For example, sensors collect weather-related data, feed them to the grid operators through near-real-time communications and control actions are implemented for dispatching more power from other sources, ramping or load shedding. Besides, the challenges of renewable energy generation, management of large-scale, distributed generators emerges as a significant problem where researchers from the NSF future renewable electric energy delivery and management (FREEDM) systems center seek solutions for [64], [65]. In relation to renewable energy integration, convenient energy storage is essential where advanced storage technologies are becoming an integral part of the smart grid [66]. Distribution automation is another important feature that will transform the legacy grid into a smart grid [67].

Finally, the smart grid technologies are closely related to Electric Vehicle Charging Infrastructure (EVCI) since Electric Vehicles (EVs) require a reliable and digitized grid for battery charging. The past couple of years have seen a significant amount of studies addressing the challenges of charging EVs from the power grid, as well as using EV batteries for the benefit of smart grid. The former is known as Grid-to-Vehicle (G2V) energy flow while the latter is called Vehicle-to-Grid (V2G) energy flow [68]. EV charging is challenging because it is expected to be aligned with the evening peak demand, adding to the stress on the grid that is already operating close to its operational limits. Thus, uncontrolled vehicle charging is overload transformers and harm utility equipment, degrade power quality, increase power losses and cause voltage problems [62]. The coordination of vehicle loads, and utilization of vehicle batteries for ancillary services have been studied in several works such as [69]–[74]. For a more complete survey of electrification of transportation interested readers are referred to [75]. The interaction of smart grid with the transportation industry is out of the scope of this survey.

III. ENERGY-EFFICIENT COMMUNICATIONS AND THE SMART GRID

Energy-efficiency has been an integral part of networks that consist of battery-run nodes such as sensor nodes or mobile phones while energy-efficiency of network equipment powered from mains such as base stations, switches, routers has not been under the spotlight until recently. In parallel to the increasing number of subscribers and their diverse demands, electricity bills of network operators have been skyrocketing. As a result, a significant amount of academic and industry efforts have been put into reducing the energy consumption of core and access network equipment. Along with the traditional electricity costs, large amount of GHG emissions of communication networks is foreseen to add more costs to the operators with the forthcoming carbon taxes and caps. Price-following demand management of smart grid can be employed by the communications infrastructure to reduce electricity bills where this can be also extended to emission-following load management of the equipment. On one side smart grid-driven approaches impact the way energy-efficient communication technologies are implemented, on the other side smart grid involves dense communications and it is impacted from energy-efficiency techniques. This section summarizes the works that study the mutual impacts of smart grid and energy-efficient communications. We have grouped these studies under wireless, wireline and optical networks and for each type of network, we focus on the appropriate smart grid domain. Energy-efficiency of battery-run, hand-held devices and Wireless Sensor Networks (WSNs) are beyond the scope of this survey since their energy-efficiency aims at increasing the lifetime of the network or the device considering their limited battery power.

The smart grid can be roughly divided into three domains in terms of communication coverage and functionality; Smart Grid Home Area Network (SG-HAN), Smart Grid Neighborhood Area Network (SG-NAN) and Smart Grid Wide Area Network (SG-WAN). SG-HAN is a single residential unit with smart appliances, an energy display, power consumption control tools, storage, solar panels, small-scale wind turbines, electric vehicles and a smart meter. A SG-NAN corresponds to a group of houses possibly fed by the same transformer. Advanced Metering Infrastructure (AMI) collects smart grid data from the premises in a SG-NAN and aggregates the meter data before they are sent to SG-WAN which connects SG-NANs to the utility operator. From the utility perspective, besides metering, equipment in the field needs to be monitored and controlled. Hence the equipment in the field are managed by a separate network which is called as Smart Grid Field Area Network (SG-FAN). The geographical scale of a SG-FAN is similar to SG-NAN therefore similar communication technologies are applicable for both. These network domains can be implemented using a variety of communication technologies. For instance,

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[1] PMUs provide timestamped and synchronized phasor measurements which demonstrate the direction of power flow in the grid. Monitoring the power flow is essential since excessive flow towards one direction may unstabilize the power grid while time synchronization provides a complete view of the grid at a specific time for interconnections covering multiple time zones.

due to their wide coverage fiber optic, UMTS, LTE/LTE-A may be more convenient for SG-WAN while IEEE 802.11, IEEE 802.15.4, PLC would be more suitable for SG-NAN and SG-HAN. In [76], the authors provide a comprehensive survey on routing techniques and applications in each of those domains. In the following sections, we will provide a survey of energy-efficient wireless, wireline and optical communications tailored for each smart grid domain.

A. Energy-Efficient Wireless Communications

Wireless communications can be employed in a wide range of smart grid applications including, meter data collection, demand management, substation and power line monitoring and protection. For the sake of clarity, in the next three sections, we present wireless communications that are used or planned to be used in SG-WAN, SG-NAN, and SG-HAN, respectively.

1) Energy-Efficient Wireless Communications for SG-WAN: In wireless communications, energy-efficiency is generally quantified by the "bits-per-joule" metric which corresponds to throughput versus unit energy consumption [13]. Here, the definition of throughput may include the whole transmitted bits or it may only refer to the actual data that excludes headers, signaling bits, duplicate packets and transmission errors. Furthermore, the majority of the studies in the domain of energy-efficiency focus on optimizing transmit power and ignore the circuit power and power needed for cooling the equipment. Although a holistic metric and an approach is not available in the literature, even focusing only on energy-efficient transmission has resulted in significant power savings.

Third generation (3G) and fourth generation (4G) cellular networks are expected to be densely used in the SG-WAN. They provide the convenience of using the existing infrastructure and wide coverage with high data rates. For instance, KEPCO KDN Co. [77] offers a transmission line surveillance system that uses laser scans to monitor the surroundings of power lines and sends an SMS notification in case of an alarm. Another industry example comes from Qualcomm Inc. and Echelon Inc. who are using Verizon's and T-mobile's infrastructures, respectively, to provide cellular connectivity for smart meters [78], [79]. Furthermore, with the adoption of high data rate Long Term Evolution (LTE) and LTE Advanced (LTE-A) technologies, the cellular networks will be able to carry the high-volume PMU data. The peak data rates for LTE is around 300 Mbps at the downlink and 80 Mbps at the uplink with 20 MHz channel bandwidth and 4 × 4 Multiple Input Multiple Output (MIMO) antennas. On the other hand, with 70 MHz channel bandwidth and 4 × 4 MIMO antennas, LTE-A's targeted peak downlink transmission rate is 1 Gbps and the uplink transmission rate is 500 Mbps. In addition to their high speed, LTE and LTE-A employs the relaying technique to extend the typical cell diameter. Relaying technique is specifically useful for connecting geographically spread smart meters in rural areas.

Relying technique is considered to be inherently energy-efficient since the transmitter and the receiver are close to each other, incurring less transmission power and interference [13]. Relaying allows for multiple links between a source and a destination pair which have different channel conditions. This diversity gain also contributes to energy-efficiency [14]. In particular energy savings increase for environments with higher path loss [80] making relaying technique ideal for enhancing the energy-efficiency of SG-WAN communications. In addition, using mobile relays instead of direct transmission under delay-tolerant data has been shown to be more energy efficient [81]. In smart grid, during off-peak hours smart meter data can be collected in a delay-tolerant manner since demand management will be less of an issue. In this sense, mobile relays become useful in SG-WAN to provide meter connectivity. Similarly, cooperative communications provide energy efficiency because they benefit from channel diversity [13]. Therefore, cooperative communications emerges as another alternative for energy efficient communication of smart meters. It is worth to mention that the potential savings from relaying and cooperative communications have not been exploited in previous research efforts.

In energy-efficient wireless communication literature, putting Base Stations (BSs) to sleep during low traffic volume has been the common approach to save energy. This is relevant since BSs account for 60–80% of the whole power consumption in a wireless network [82]. Gong *et al.* have proposed to switch on and off a BS based on a blocking probability threshold and holding the state of a BS for a certain amount of time to avoid the ping-pong effect [83]. Although this technique has not been employed in a smart grid environment, similar BS sleep/wake-up schemes can be useful in the smart grid. Nevertheless, the nature of the smart grid traffic will be different than human generated traffic and sleep/wake-up schemes need to take this into account. Besides traffic volume, QoS requirements of smart grid applications can interfere with energy-efficiency techniques.

In [84], the authors have proposed an energy-efficient resource allocation scheme for Code Division Multiple Access (CDMA)-based systems which maximizes each users' utility in terms of transmit power and rate while satisfying delay requirements. In the smart grid, asset monitoring and control of protection switches require strict delay guarantees while data collection from the smart meters during off-peak hours can tolerate delay to a certain extend. For this reason, coordination of smart meter reports with BS station sleep schedules can yield further energy savings. However, those coordination schemes are only convenient for off-peak hours because smart meters need to report more frequently during peak hours as the energy consumption data becomes crucial for demand management, protection and dispatch operations. Although a number of studies have considered putting BSs to sleep, its impact on smart grid communications is still an open issue.

Coordinated Multi-Point (CoMP) technology can be also utilized in SG-WAN applications. Energy-efficiency of Coordinated Multi-Point (CoMP) technology has been studied in the literature [85]. CoMP relies on separating the conventional BS into two parts as Baseband unit (BBU) and Remote Radio Unit (RRU). BBU is responsible for network management, resource allocation and so on. Multiple RRUs are scattered in the cell and they offer transceivers close to the users. BBUs and RRUs are connected via fiber. In [85], the authors explore the optimal placement of RRUs in terms of energy-efficiency. Furthermore,

[86] investigates energy-efficiency of CoMP and relaying under an average outage constraint. A use case of CoMP in the smart grid has been provided in [87]–[90]. In [88], [89], the authors blend smart grid provided real-time electricity price information in the decision of shutting down BSs. Once the selected BSs are shut off, CoMP is used to attain coverage for active users. In [90], a Heterogeneous Network (HetNet) environment has been considered using a dual cognitive approach where both the spectrum and smart grid resources are allocated in a cognitive manner. In [87] along with [91] are the seminal works that integrate smart grid concepts in energy-efficient communications. In [91], the authors discuss the utilization of renewable energy in wireless BSs and the implications regarding the uncertainties. The authors have proposed an adaptive power management scheme that optimizes the power consumption of the BS by taking renewable generation output, electricity price and wireless load profiles into consideration.

In addition to 3G and 4G networks, WIMAX stands as a strong candidate for SG-WAN communications. To this end, energy efficiency of Orthogonal Frequency-Division Multiple Access (OFDMA) which is the common multiple access scheme for all of those networks, has been studied in several works. In [92], the authors have proposed an energy-efficient rate adaptation and resource allocation scheme. Another technique that is common in 3G, 4G and WIMAX is Multiple Input Multiple Output (MIMO). MIMO increases throughput, however the circuit power required for multiple antennas incur high energy consumption. In [93], the authors claim that over short distances Single Input Single Output (SISO) provides higher energy-efficiency than MIMO. To this end, adaptively changing the number of active antennas has been proposed to provide energy efficiency for MIMO [94]. For instance, voice and data traffic volume is low during overnight hours, so is the electricity consumption data fed by the smart meters and protection related data fed by the sensors since at off-peak hours it is less likely to have overloaded transformers and circuits, hence sensors are expected to report less events. Thus, switching to SISO for overnight hours and then back to MIMO for daytime may reduce circuit power in SG-WAN communications. The implications of adaptively changing the number of antennas in a smart grid environment has not been explored yet. Its impacts on the QoS requirements of smart grid applications remains as an open problem.

Finally, cognitive radio technology as described in the IEEE 802.22 standard defines the access of unlicensed users to TV white spaces. According to the cognitive radio concept, a secondary user (unlicensed user) with a cognitive radio has the ability to sense the unused spectrum, use it and then vacate it as soon as the primary user (licensed user) arrives. The use of cognitive radio in SG-WAN has been motivated in [27] where the range of IEEE 802.22 standard is between 33 km and 100 km, which makes it suitable for the SG-WAN, especially for meter readings from remote regions. Furthermore, in [29], the authors have proposed a cognitive network that dually senses the radio spectrum and the smart grid environment. Operating cost of the cognitive network is optimized under real-time pricing where macro and femto cell base station adjust their power consumption based on electricity prices. Although energy conservation has not been the main focus of those studies, they are either proposing to use cognitive radio in the smart grid or utilizing smart grid concepts in cognitive networks. To this end, energy efficiency of CR has been studied in [95]. The authors focus on the joint optimization of the medium access and physical layers to maximize energy efficiency. Nonetheless, using cognitive radio as a part of smart grid-driven energy-efficiency efforts has not been considered in previous studies. Open issues in smart grid-driven approaches in energy-efficient wireless communications and the impacts of energy-efficiency techniques on the QoS of smart grid data will be discussed in more detail in Section V.

2) Energy-Efficient Wireless Communications for SG-NAN: SG-NAN is one of the crucial domains that glue utility networks with the customer networks. It carries a large volume of heterogenous data and supports a large number of devices [96]. Similar to SG-WAN, 3G, 4G and WIMAX can be utilized in the SG-NAN. In addition, IEEE 802.11 family of standards offers promising deployments for urban SG-NANs.

Recently, several IEEE 802.11 standards have adopted power saving mode (PSM) in their operations [97]. IEEE 802.11b and IEEE 802.11s utilize PSM to allow wireless nodes sleep when they are not receiving or transmitting. IEEE 802.11b is widely used for residential premises therefore it is also preferred for SG-HANs while IEEE 802.11s, the mesh standard has been considered as a promising candidate for the electric vehicle charging network. In [73], the authors study the performance of IEEE 802.11s in an admission control scenario for electric vehicles. PSM can be considered for IEEE 802.11 based SG-NAN communications however the drawback of the PSM is the additional delay which is the common tradeoff in all sleep-based schemes [98]. Delay-tolerant SG-NAN data may not be impacted from PSM however, communications for controlling real-time operations may experience service degradation. For instance, in an electric vehicle charging network connected via IEEE 802.11s, increased delay due to sleeping nodes can cause severe damages to the distribution system if a control command from the utility that restricts charging happens to be delivered with extensive delay. For this reason, the impacts of PSM over the smart grid operation needs to be further explored.

3) Energy-Efficient Wireless Communications for SG-HAN: Zigbee is one of the widely adopted smart home and smart energy standards in SG-HANs. Presently, there are various Zigbee certified products for home automation and several smart meter vendors such as Landis+Gyr, Itron and Elster have manufactured Zigbee-enabled smart meters. ZigBee Alliance has also developed Smart Energy Profile (SEP) to support the needs of smart metering and AMI, and provide communication among utilities and household devices.

Zigbee is a short-range, low-data rate wireless technology that is based on the IEEE 802.15.4 standard. Zigbee has been initially designed for power-constrained sensor networks, therefore energy efficiency is an intrinsic property of Zigbee. It employs duty-cycling to increase the network lifetime. In [47], the authors utilize a Zigbee-based WSN for demand management in the SG-HAN.

Wi-Fi is another strong candidate for wireless SG-HAN communications. Utilization of Wi-Fi based sensors in the smart grid has been studied in a recent work [99]. Particularly, newly emerging ultra low power Wi-Fi chips are expected to increase the adoption of Wi-Fi for WSNs and increase their interoperability at SG-HAN. Energy-efficiency in WSNs has been studied vastly in the literature, however those works are out of the scope of this survey since they are independent of smart grid concepts such as dynamic pricing, demand management, etc.

In addition to Zigbee and Wi-Fi, cellular technologies may provide connectivity to residential premises with the deployment of small cells. Indoor picocells and femtocells may be useful in reducing the energy consumption of the transmitters in SG-HAN as they are less prone to path loss than macrocells [100]. It has been shown that joint deployment of macro- and publicly accessible residential picocells can reduce the total energy consumption of a network by up to 60% in urban areas [101]. Furthermore, energy-efficiency increases as the density of small cells increase [102]. Thus, implementing SG-HANs with small cells may contribute to the overall energy-efficiency of the cellular network. To this end, optimal energy efficient network design in a smart grid environment has not been explored yet. Furthermore, a comparison of SG-HAN technologies in terms of their energy-efficiency has not been made.

B. Energy-Efficient Wireline Communications

Wireline communication technologies may be used to implement a SG-HAN and SG-NAN. In this context, PLC and Energy Efficient Ethernet (EEE) are among promising wireline communications.

PLC uses low voltage power lines as the communication medium for data. PLC is already being used by some utilities for load control and remote metering. Energy efficiency of the PLC has been studied in [103] and a spectrum sensing scheme has been introduced to reduce its power consumption. In [104], the authors have extended this work to include resource allocation. Transmission parameters have been selected carefully to mitigate interference in contrast to the former approach of passively avoiding interference. Interference mitigation relies on a signal detection function whose durations are optimized with a limitation on power budget. Another energy-efficient PLC scheme has been proposed in [105] where the authors have energy-efficiency as a bound for infinite transmissions and introduce a green resource allocation scheme. The scheme optimizes the quantity of information allocated to each channel when parallel channels are available. As a PLC standard tailored for smart grid applications, HomePlug Alliance has recently adopted power saving mode within its Green PHY 1.1 definition. A central coordinator is responsible for sleep/wake up schedules of connected devices in order to avoid devices waking up at different times [106].

Energy Efficient Ethernet is also among the wireline technologies that are being considered for SG-HANs. As described in the IEEE 802.3az-2010 standard, EEE uses low-power cycles to save energy. During the low-power mode, short periodic refresh intervals are defined to maintain alignment between the transmitter and the receiver. For a low link utilization of 25%, it has been shown that EEE reduces power consumption by 25% [107].

Although wireline technologies are promising and in particular PLC is considered to be a natural communication medium for smart grid, smart grid-driven techniques have not found its way into energy-efficiency approaches in PLC. PLC is known to be impacted by the disturbances in low-voltage network [108]. For instance, energy-efficient resource allocation with disturbance awareness has not been explored yet.

C. Energy-Efficient Optical Networks

Fiber optical networks offer high speed, large bandwidth and high degree of reliability that has enabled them to be widely deployed as the basic physical network infrastructure. Optical networks have been traditionally implemented in a hierarchical structure consisting of core, metro and access domains. In general, a core network provides nationwide coverage with a few hundreds to a few thousands kilometers of optical fibers. A metro network provides coverage for a metropolitan area with optical fibers of a few tens to a few hundreds of kilometers length. Meanwhile access networks reach the customer and run between the service provider and the customer which typically uses optical fibers of a few kilometers in length. Energy-efficiency has found its way into all of those three domains including energy-efficient components, transmission, network design or applications. Optical communications may be used in SG-WAN or SG-NAN where the former is implemented by core technologies and the latter with metro or access technologies. SG-HANs can be implemented by visible light technology which is a fairly new, high data rate communication technology [109]. However, this is out of the scope of this survey since energy-efficiency of visible light communications nor its use in smart grid have been explored so far.

1) Energy-Efficient Optical Communications for SG-WAN: A single core network equipment is one of the most power hungry elements of the telecom optical networks [17]. A core IP router port consumes approximately 1000 W, whereas the maximum power consumption of an optical network unit (ONU) operating in the access network is around 5 W [110]. Therefore significant research efforts have been put into addressing the energy efficiency of the core network.

In smart grid, information flow between ISOs in distant regions utilizes the core network infrastructure. For instance, wide area measurements taken under the control of an ISO, can be delivered to another ISO for protection purposes. Although smart grid data will be carried over the same core infrastructure with all other traffic and it is difficult to have smart grid specific energy-efficiency measures, energy-efficiency techniques will have direct impact on the QoS of smart grid applications. For this reason, this section will cover general energy-efficiency techniques in core optical networks and include several studies that consider the renewable energy and ToU-based energy-efficiency improvements. Since utilization of renewable energy and ToU are part of the big smart grid picture, those works stand out as examples of the interaction of smart grid and energy-efficient core optical communications.

In the core networks, there are several opportunities to reduce energy consumption of network equipment. Various studies have proposed turning off idle network equipment, such as switches, line cards or the links, during low traffic volume [111], [112]. The fundamental challenge in turning the equipment off is guaranteeing the same QoS with the case when all equipment are operational, as well as responding to the variations in traffic volume in a fast and an efficient manner. Recent research has shown that network design is one of the significant factors impacting the energy-efficiency of the core networks. Considering this, in [113], the authors have proposed optimizing the physical topology to increase energy-efficiency.

In IP-over-WDM networks, it has been shown that lightpath bypass technique is more energy-efficient than lightpath non-bypass technique [114]. In [115], the authors have addressed provisioning survivable demands with minimized power consumption in a Wavelength-division multiplexing (WDM) network using lightpath bypass approach. In [116], the authors have proposed a multi-path selection approach to minimize the energy consumption of the optical core network. Moreover, energy-efficient traffic grooming has been shown to reduce the core network energy consumption [117] while multi-granular switching has been claimed to provide further energy savings [118]. Finally, energy-aware routing has been proposed as an alternative to the traditional shortest path routing in [119]. The fundamental challenge of the previously proposed schemes is that they consider human-generated traffic when for instance turning off network equipment or taking energy-efficient routing decisions whereas smart grid traffic is mostly machine-generated and it may suffer from undesired QoS degradation. Although more research efforts are needed to investigate the impact of energy-efficient core optical networks on the SG-WAN traffic, smart grid related concepts such as ToU and distributed renewable energy generation have made their way through core optical networks.

The interaction of smart grid with energy-efficient communications appear explicitly in studies that make use of renewable energy and ToU. In [120], the authors have formed a Linear Programming (LP) model to optimize the use of renewable energy in the IP-over-WDM network which can be considered as a power grid-driven approach since it allows selecting the source of electricity. The authors' findings show that non-renewable energy consumption is further reduced when renewable energy is employed in the nodes at the center of the network rather than the nodes at the edge of the network. Similarly, in [121] network equipment is powered from renewable resources to reduce GHG emissions while routing is also performed accordingly. Nodes with better access to renewable energy are put on the preferred routes. Integration of distributed renewable energy generators to core optical networks and renewable energy-aware planning and routing has considerably reduced the amount of emissions [120].

In addition to utilizing renewable energy, reducing OPEX of the operators using TOU electricity prices is another aspect of the interaction between the smart grid and the optical networks networks. TOU-aware routing and wavelength assignment have been considered initially in [122]. The authors have proposed an ILP formulation to reduce the electricity bills of a large network covering multiple time zones. ToU-aware routing and wavelength assignment directly impact the OPEX of network operators and provide an opportunity to reduce their electricity bills. On the other hand, ToU-awareness implies using off-peak electricity generators which are generally less GHG emitting than on-peak generators. In power grids, base load supplying generators are a mix of nuclear, hydro or in some places coal while peak load supplying resources are diesel generators or alikes which respond fast to load variations but have high GHG emissions. It is worth to mention that ToU and energy-efficiency is loosely coupled, i.e. ToU-aware approaches shift the loads to off peak hours rather than conserving energy or using renewable energy. In this sense, ToU-awareness provides reduced electricity bills and it can also lead to reduced emissions if off-peak generators are cleaner than on-peak generators.

2) Energy-Efficient Optical Communications for SG-NAN: Most of the smart grid communications is within metro and access networks reach. Utility headquarters and offices are already connected via fiber optical networks while with the fast adoption of Fiber-to-the-Home (FTTH) technology, the number of residential subscribers are increasing. In addition, hybrid technologies are emerging as promising candidates for metro and access convergence. Thus, metro and access optical networks emerge as a strong alternative for SG-NAN communications.

Although a single access network equipment consumes much less power than a core router port, access equipment are large in quantity, hence they consume significant amount of power in total. According to [18], access networks contribute to 70% of power consumption of all networks. For this reason, energy-efficiency of access networks has been an active research area in the past several years. According to [123], Passive Optical Networks (PONs) and point-to-point optical networks have been found to be the most energy-efficient access technology in comparison to digital subscriber line (DSL), hybrid fiber coaxial (HFC) networks, fiber to the node (FTTN), Universal Mobile Telecommunications System (UMTS) using wideband wideband code-division multiple access (W-CDMA) and WiMAX. Further energy savings in Ethernet Passive Optical Networks (EPONs) have been studied in several works. The general approach has been putting ONUs to sleep similar to putting BSs to sleep in wireless networks. ONUs can be put to sleep either depending on the traffic volume or link speeds between ONUs and Optical Line Terminal (OLT) [124]. Gigabit PON (GPON) which is another PON technology, have seen energy-efficiency efforts as well, which have lead to standardization. Power conservation standard in [125], describes the implementation of sleep mode for ONUs. Furthermore, for a more general PON, a modified ONU architecture has been proposed in [126] which reduces the clock recovery overhead when waking up from sleep mode. EPON has been utilized for smart grid monitoring applications in [127]–[129] which will be covered later in this section.

Long-reach PON (LR-PON) technology which is another recent optical technology in metro and access consolidation, can provide a backbone for most high speed utility networking needs. Energy-efficiency of LR-PON has been initially studied in [130] where the authors have proposed to put transmitters to sleep that become idle upon a dynamic wavelength allocation scheme. In summary, putting an access unit to sleep completely or partially have formed the fundamental focus

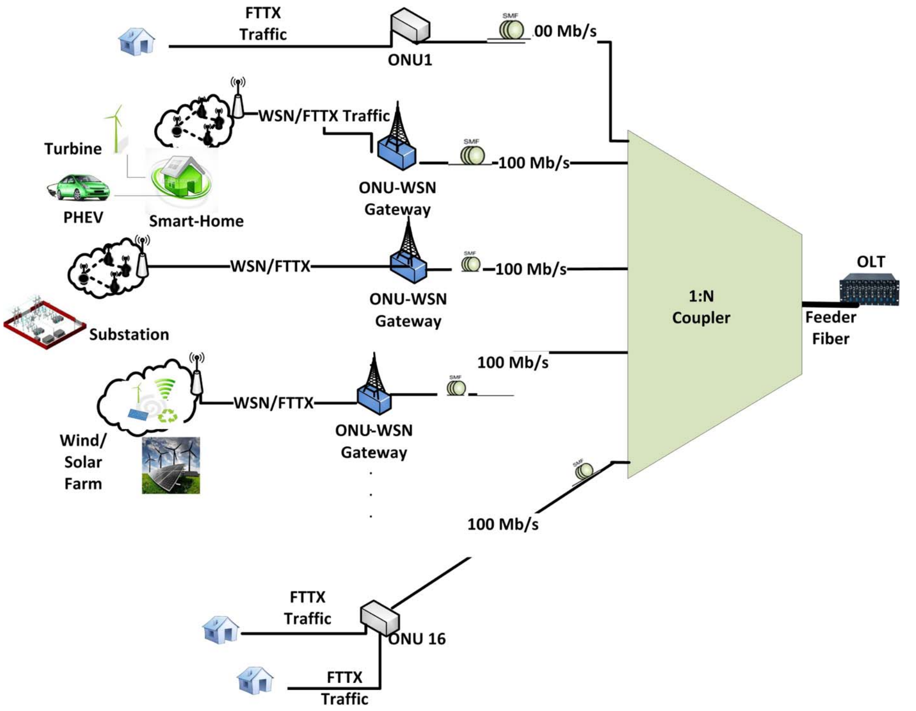

Fig. 3. Fiber-WSN Architecture [129].

of energy-efficiency in access networks in optical domain. Although the use of EPON in SG-NAN has been studied [129] before, to this end, the impact of energy-efficiency techniques, such as putting ONUs to sleep, on the SG-NAN traffic has not been researched. Similar to wireless networks and core optical technologies, more research is needed to explore how the machine-generated SG-NAN traffic is impacted under those energy-efficiency techniques.

In addition to pure optical networks, optical-wireless networks are also becoming strong candidates for SG-NAN communications. Optical-wireless networks combine the speed and the reliability of optical networks with the ubiquity, coverage and flexibility of wireless networks. In this context, Fiber-Wireless (Fi-Wi) networks are expected to be adopted in the SG-NAN. A comprehensive survey on energy-efficient Fi-Wi networks can be found in [110]. An interesting approach in Fi-Wi networks proposes to put ONU modules of a joint ONU-BS node to sleep, while the BS module forwards data to a peer ONU-BS node when the traffic volume is light [131]. Meanwhile the downlink traffic towards the standby ONU is buffered at the peer ONU-BS node. The authors have considered human activity profile while optimizing the sleep schedules of ONU-BS nodes, however SG-NAN traffic is machine-generated although coupled with human activity as well. Thus, it still remains as an open problem to study the degree of energy-efficiency under different types of smart grid traffic.

Very recently, Fiber-WSN technology has been explored for possible uses in the smart grid environment. Wireless sensor networking is a proven technology for monitoring indoor and outdoor facilities while fiber provides fast and reliable connectivity. According to a proposed architecture in [127], smart grid data, such as user energy profiles, equipment status, etc. are transmitted to the operators through a broadband access network, i.e. EPON. In the EPON architecture, each distribution fiber connects an ONU to the OLT where an ONU is either serving to a Fiber To The Home/Building/Curb (FTTX) user or a group of residential premises which are monitored by WSNs. Thus, the Fiber-WSN network provides a combined solution for SG-HAN broadband access as well as WSN-based smart grid monitoring in the SG-NAN. Fig. 3 presents a typical Fiber-WSN network deployment in the smart grid. In [128], [129], the authors propose a gateway design for the Fiber-WSN network that allows data prioritization under urgent and non-urgent smart grid data. Energy efficiency of the integrated Fi-Wi architecture is challenging because synchronization among sleeping ONUs and PSM mode of wireless devices require careful design. In addition, energy-efficiency techniques are closely coupled with QoS of data. If undesired service degradation is anticipated or a traffic class with higher priority arrives, then energy-efficiency techniques may be opted out, however in an integrated network it is a significant problem to choose which of the networks will opt out, i.e. fiber, wireless or both.

In [132], the authors consider synchronization of energy-efficiency procedures and propose a smart Access Point (AP)-ONU synchronization strategy where the ONU sleeps between two AP beacons. In the smart grid environment, AP beacon intervals need to comply with smart grid traffic, thus ONU sleep mode. Dynamically tuning beacon intervals will require novel signaling schemes. Energy-efficiency of optical networks have been covered in a wider scope in [133], [134] which analyzes and models the energy consumption of transport and network equipment, and in [17] which provides a comprehensive survey on the studies in energy-efficient optical communications.

IV. GREEN DATA CENTERS AND THE SMART GRID

Information infrastructure along with communication infrastructure is a significant consumer of electricity globally [1].

In proportion to growing user demands, emerging video and data-intensive applications, as well as the increasing popularity of cloud computing, power consumption of data centers is increasing at remarkable rates. According to recent reports [135], on average, annual energy cost of a 400 W server is around \$800 and a data center houses thousands of those servers while these numbers are expected to escalate with the growing popularity of applications that utilize cloud data centers [136].

Energy-efficient or green data centers[2] become essential for reducing the energy expenses of the data center service providers as well as for reducing the environmental impact of the data centers. Earlier this year, cap-and-trade rules became in effect in the state of California which allow large electric power plants and large industrial plants sell and buy carbon allowances [137]. The carbon market is expected to grow in the upcoming years and data center operators will be eventually faced with the extra costs of carbon emissions. In addition, data centers put stress on the power grid and the utility that they are being served by. Therefore, green design of a data center is also important from the power grid perspective.

Research on green data centers make use of smart grid concepts such as the option to choose a greener supply, workload migration towards greener data centers, electricity price-based and emission-aware workload migration and so on. In this section, we first introduce the fundamental terminology in energy-efficient data centers and then survey the techniques that use smart grid concepts to help greening the data centers.

A. Energy-Efficiency Metrics for Data Centers

Data center energy efficiency is generally measured by Power Usage Efficiency (PUE) that is given by:

$$PUE = \frac{\text{IT Equipment energy} + \text{Facility Overhead Energy}}{\text{IT Equipment energy}} \tag{1}$$

The ideal PUE is 1.0 which corresponds to zero facility overhead [139]. Facility overhead is related to cooling, lighting and so on. As an example, Google claims that their data centers incur around 85% less facility energy consumption and around 15% less IT equipment energy consumption than a typical data center. This implies that there is still room for more energy-efficient IT operations. On the other hand, PUE metric is not enough to represent the energy-efficiency of IT equipment. Power consumption of IT equipment can be measured by the data collected from server inlets, power consumption levels for rack servers, blade servers, and power distribution units (PDUs), as well as the uninterrupted power supplies (UPSs). Recently, WSNs have been used for data center monitoring in the Microsoft Genome Project [140]. Measurements from sensors are used to plot a thermal map of the data center. In [141], the authors collect sensor data to perform thermal and energy aware resource provisioning.

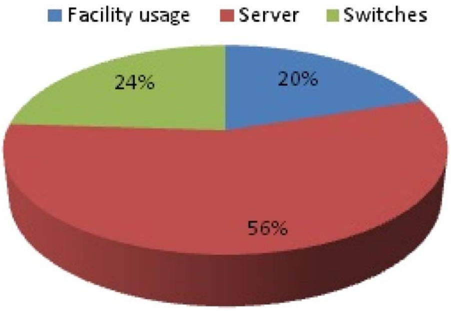

Fig. 4. Energy consumption of a data center.

Recently, standardization efforts around sustainable data centers are focusing on defining key performance indicators (KPI) for data centers. ISO 30134 standard which is expected to be released by the end of this year, will define the KPIs for data centers. Along with PUE, IT Equipment Utilization (ITEU), IT Equipment Energy Efficiency (ITEE) and Green Energy Coefficient (GEC) are among the considered metrics to measure the energy-efficiency of a data center [142].

ITEE refers to the use of IT equipment with higher energy-efficiency and is defined as:

$$ITEE = \frac{\sum \text{IT equipment rated work capacity}}{\sum \text{Rated Energy Consumption of IT equipment}} \tag{2}$$

ITEU refers to the efficient use of IT equipment through consolidation and virtualization and is given by:

$$ITEU = \frac{\sum \text{Measured energy consumption of IT equipment}}{\sum \text{Rated Energy Consumption of IT equipment}} \tag{3}$$

GEC corresponds to the utilization of renewable energy resources which are generated on-site by the data center operators rather than the green energy supplied by the grid. GEC is defined as:

$$GEC = \frac{\sum \text{Energy input from renewable resources}}{\sum \text{Energy consumption of data center}} \tag{4}$$

These metrics can be combined into Data center Performance Per Energy (DPPE) metric which is computed as:

$$DPPE = \frac{\text{IT equipment work rate x IT equipment work capacity}}{\sum \text{Energy consumption of data center} - \text{Green energy}} \tag{5}$$

In the context of smart grid, ITEU, GEC and DPPE seem to be the relevant metrics since price- or emission-aware workload consolidation and renewable energy usage impact only those. Approximate energy consumption of a data center is presented in Fig. 4 for illustrative purposes. The data is derived from [143] and [144]. As it is seen from the figure, servers in a data center incur the lion's share in power consumption.

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[2] In this paper, we use the term Green Data Centers (GDC) to refer to data centers that adopt energy-efficiency techniques or those that make use of renewable energy. However, energy-efficiency may not always mean green or low-emission data center. For instance, an energy-efficient data center powered from the Texas power grid (which is dominated by coal and natural gas) may have more emissions than a non-energy-efficient data center in Denmark that is powered by wind energy. To give an idea on the amount of emissions, according to [138], migrating services of a 48-core multiprocessor server system from Alberta's fossil dominant power grid to a greener region may save 28.5 tons of GHG emissions annually.

In addition to the abovementioned metrics, eBay has developed a metric to quantify its buy/sell transactions. According to a white paper from eBay that is published in March 2013, Digital Service Efficiency (DSE) metric computes power consumption per transaction [145]. DSE can be seen as the equivalent of the "bits-per-joule" metric used in energy-efficient communications. This metric can be extended to Green Digital Service Efficiency (GDSE) to compute the amount of renewable power per transaction once total renewable energy input to a data center is known.

B. Smart Grid-Aware Energy-efficiency Techniques in Data Centers

Data centers benefit from ToU prices, distributed renewable energy generation and similar smart grid related concepts to reduce their energy intake, expenses and emissions. In this section, for the sake of presentation clarity, we group the energy-efficiency efforts in data centers under three titles and later discuss their interaction with the smart grid:

- **Energy-efficient facility management**: The actual facility that houses the servers, UPS, cooling equipment, operations room and so on, is known as the data center facility. Most of the power consumed by a data center facility is spent for cooling the servers and the UPS. The rule of thumb for facility management is to organize hot isles and cold isles appropriately. Cold air intake of two rows of servers, i.e. rack fronts, faces each other forming a cold isle while hot air exhaust of two rows of servers face each other forming hot isles. Those isles are isolated by containments such as plastic covers. Raising floors, running cooling equipment at higher temperatures have been among the other techniques that provide energy savings. In addition, placing UPS in a separate containment has been also implemented at Google's data centers [139]. To analyze the effectiveness of the implemented techniques Computational Fluid Dynamics (CFD) is used to model the airflow and the heat transfer in data centers. In general, energy-efficiency of a data center facility is considered independent of smart grid concepts. Only recently, several ideas have emerged from the industry advocating to use eco-modes of UPSs during high electricity prices or to recharge UPSs during overnight hours similar to electric vehicle charging [146], [147].
- **Energy-efficiency techniques for IT equipment**: Energy-efficiency of IT equipment is implemented through energy-efficient server hardware as well as virtualization and dynamic workload consolidation [19]. Although data centers contain switches for intra data center networking, the total power consumption of core, aggregation and access switches is less than half of server power consumption approximately as seen in Fig. 4. Therefore most of the efforts in the literature focus on energy-efficiency of servers. One of the primary energy-efficiency techniques for server hardware is the Dynamic Frequency and Voltage Scaling (DFVS). DFVS dynamically adjusts the frequency of the CPU of a server to save power [148]. Virtualization is a concept that helps running multiple user demands on a single physical host by placing more than one virtual machine on a server. With the combination of virtualization and dynamic workload consolidation, some servers may be left idle and put to sleep. This technique is known as Dynamic Power Management (DPM). To this end, smart grid-driven DFVS or DPM still remain as open problems. Since energy efficiency of facility management and IT equipment has not been investigated from the perspective of smart grid, we do not include those works and refer the interested readers to [20] for a comprehensive survey on energy-efficient facility management, IT equipment and intra-data center network.
- **Energy-efficiency techniques for multiple data centers**: Those techniques are designed for geographically-diverse, large-scale Internet data centers such as the ones owned and operated by Google, Yahoo, Microsoft, Amazon, eBay, etc. The general idea is to route user demands towards one or more data centers either considering heating and cooling constraints or to minimize cost or to minimize emissions. In this survey, we are primarily focusing on the energy-efficiency of such large-scale Internet data centers since smart grid-driven techniques have been tailored for those in most of the cases. Energy-efficiency techniques for multiple data centers can be further grouped under three categories: 1) Minimizing electricity bills of data centers; 2) Minimizing energy consumption of inter data center network and 3) Data centers powered by renewable energy.

In the following sections, we will focus on energy-efficiency techniques for multiple data centers and their corresponding transport networks. Furthermore, we will look into the adoption of data centers for hosting smart grid services to give a complete picture of the interactions between the smart grid and data centers.

1) Minimizing Electricity Bills of Data Centers: Qureshi *et al.* have exploited the temporal and the geographic diversity of electricity prices in the smart grid to reduce the OPEX of data center operators [149]. When user demand is below the peak, the authors have proposed to migrate workloads towards data centers that can take advantage of less expensive electricity according to local ToU tariffs. During workload mitigation, user demands may suffer from increased delay, especially if the assigned data center is geographically distant and overloaded due to forwarded demands from other data centers. This issue has been addressed in [150]–[152]. In [150] and [151], load balancing of Internet data centers has been considered. For this purpose, workload constraints, a multi-electricity market model and QoS constraints have been formulated in an optimization problem. In [152], the authors augment [150] with additional cost savings resulting from server level design. Furthermore, in [153] a holistic cost minimization approach has been proposed, considering DPM, DFVS, workload migration as well as the cooling systems. The authors claim that 20% of energy expenses could be cut down even under peak workloads by using their proposed scheme.

In [154], the authors take an interesting approach and consider minimizing operation costs under uncertainty in demand

and electricity price. According to [154], data center operators buy electricity beforehand (when the price for electricity is low) to compensate for the fluctuations in workload and electricity prices. The authors propose a two-level optimization model which first determines the amount of electricity to buy via forward contract for each data center and then solves a mixed integer nonlinear programming problem with the objective of minimizing the unit electricity cost at each data center as well as balancing load among data centers. Furthermore, in [155], the interaction between electricity prices in deregulated markets and data center energy demand has been explored. The authors have assumed that the price is a piecewise linear function of the demand where the price of electricity rises steeply after a certain demand threshold. Considering this price model, the authors have aimed to identify an optimum operating regime for data centers. Workload migration is performed in order to minimize electricity bills under the assumed smart grid pricing scheme. All of the above summarized works, use smart grid pricing concepts to reduce bills, therefore they are ideal examples of studies that reveal mutual interactions between the smart grid and green data centers.

Although pricing related workload migration has been extensively studied, workload migration and its impact on the local grid is not well understood. In [156], the authors propose a two stage optimization that first balances the load on the power grid with data center load and then data center operators migrate workloads in order to reduce their energy costs. The interesting approach of this paper is power balancing decisions of utilities play a role in workload migration in addition to cost minimization decisions of data center operators. Power grid interaction with data centers have also led to the use of data centers as controllable loads in [157]. Data centers commit to curtail their loads as a response to utility requests. Load curtailment occurs in the form of migrating workloads to other data centers that do not need to curtail their loads. When responding to utility requests workloads need to be migrated in a timely manner since power grid operates in real-time. Thus the load on the transport network is taken into account in order to curtail load within delay bounds. In [157], the authors have formulated an optimization problem considering the power grid requirements and network load conditions.

2) Minimizing Energy Consumption of Inter Data Center Network: With the growing popularity of cloud computing, computational complexity is shifting from end users towards the data centers which is reducing the power consumption of end users but at the same time increasing the power consumption of the data centers as well as the transport network [158]. In this section, we focus on the works that aim to minimize the energy consumption of the data centers as well as inter data center networks. The latter is handled by the works in the previous section.

In [159], the authors study the impact of ToU-awareness on the OPEX and energy-efficiency of the cloud transport network infrastructure. The TOU tariff in different locations and traffic profile of users are exploited in order to minimize the network and the data center power consumption. The proposed Mixed Integer Linear Programming (MILP) model helps to migrate user demands over network nodes that incur less OPEX. In [160], the authors extend this work to include inter-data center workload sharing where each data center is allowed to migrate a certain amount of its workload to several destination data centers. Delay has been identified as a fundamental tradeoff in power minimizing or cost minimizing schemes.

In [161]–[163], the authors aim to minimize power consumption as well as make the best use out of renewable energy when transporting data between data centers. First, the authors determine the optimal locations of data centers in an IP-over-WDM network that minimizes the network's power consumption. Then, they investigate further savings when renewable energy is utilized either by generating on-site or transporting through the smart grid. The authors have reported 73% savings when multi-hop bypass routing with renewable energy is used together with a popularity-based replication scheme. Note that, the studies surveyed in this section, consider using renewable energy at the network equipment. In the next section, we summarize the works that use renewable energy at the data centers.

3) Data Centers Powered by Renewable Energy: Islanding data centers from the utility grid and powering them from renewable resources whenever sun penetration or wind power is adequate, offer reduced emissions and OPEX. The GreenStar Network (GSN) testbed of Canada is a network of renewable-powered data centers [164]. The GSN testbed aims to explore the feasibility of powering a network of data centers with solar and wind power. When there is a shortfall of renewable energy at one data center virtual machines are migrated towards another data center if that data center is capable of working on renewable power and QoS requirements of users can be met. The virtual machines are transported using the high-speed Canarie network to tackle latency tradeoff.

Mahdi *et al.* [165] optimize workload distribution based on the availability of renewable energy, QoS constraints and electricity price. They propose the "behind-the-meter" notion to refer to renewable resources operated at the data center facilities. The main purpose of those generators is to supply electricity to the data center, however if surplus power is generated it can be sold to the grid as well. In [166], the authors extend their work to take service rates into consideration and they propose an optimization for profit maximization. When investing for on-site renewable energy generation is costly, data center operators can also sign up with a local renewable energy generator. In [167], the authors have exploited the concept of futures contracts to allow data centers exchange workloads. With futures contracts a customer commits to purchase an amount of renewable power ahead of time. When there is excessive user demand and the data center utilizes all the futures contract limit, its workload is migrated to a data center that has under used renewable energy capacity.

Besides energy-efficiency, emission awareness has been another dimension of the smart grid-driven research in green data centers. In [168], the authors device a request distribution policy by taking Service Level Agreements (SLAs) and "brown energy"[3] consumption of the data centers into consideration. The authors incorporate carbon market dynamics in their

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[3] The term brown energy is used to refer to a mix of green and fossil-fuel based energy.

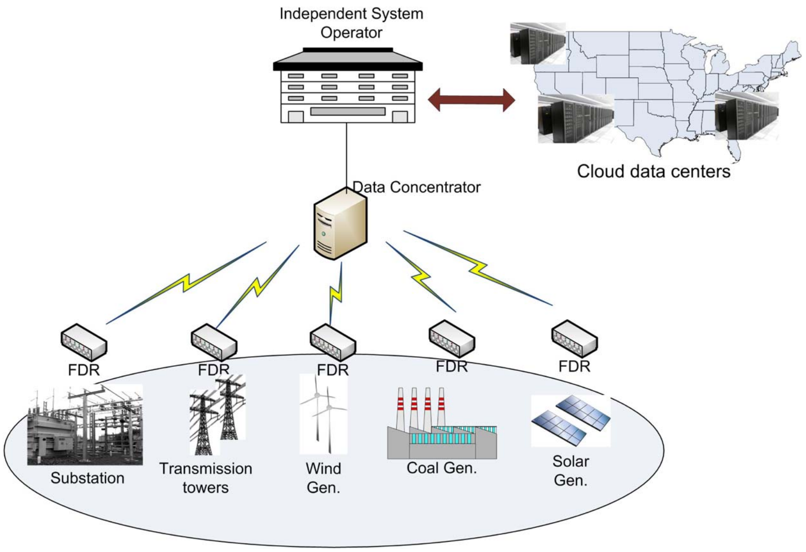

Fig. 5. FNET Architecture.

optimization model and minimize the overall cost per service. In [169], the authors have considered various ways of including renewable energy in data center operations such as renewable energy certificates and power purchase agreements in addition to the widely used on-site generation. The authors have concluded that on-site generation can provide carbon reduction to some extend however off-site generation and power purchase through agreements is more cost-efficient.

In addition to price, emission or renewable energy aware workload migration, grid status awareness has been considered in [170]. The authors have looked into the interaction of the smart grid and cloud computing from a different perspective and proposed grid-aware cloud computing that considers workload migration in the event of power grid failure risk. For this purpose, the authors have formulated an optimization problem to solve demand routing jointly with power flow analysis.

C. *Data Centers for Hosting Smart Grid Services*

Besides smart grid-driven energy-efficiency techniques for greening the data centers, the interaction of smart grid and data centers include the use of data centers at the service of the power grid. As the amount of data generated by smart grid applications is increasing rapidly, storage and processing of those data are shifting from utility servers to the cloud or Internet data centers. A typical example of a smart grid application with high volume of data is the power system frequency monitoring network (FNET). FNET collects timestamped measurements from the grid using Frequency Disturbance Recorder (FDR) and provide functionalities such as real-time event alerts, accurate event location estimation, animated event visualization, and post event analysis [5], [60]. FDR is a type of PMU that allows single phase measurements. Measurement data from the FNET are managed in the data center as seen in Fig. 5. Energy-efficiency techniques employed at the data centers may impact the access patterns of utilities, yet these interactions have not been explored yet.

V. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

This survey takes a closer look at the smart grid-driven research in green information and communication systems, in particular communication networks and data centers. In this section, we summarize the lessons learned and point out the open research issues in those fields.

A. *Lessons Learned*

There is an increasing interest from the academia and the industry to reduce the OPEX, energy consumption and emissions of ICTs. With the development of smart grid these efforts gained another dimension as to include smart grid concepts to improve the overall energy-efficiency and cleanness of communication and information infrastructures. Most of the ideas have evolved around distributed renewable energy generation, price dependent and emission aware operation. In the communication infrastructure putting high energy consuming network equipment to sleep has been one of the fundamental approaches while in information infrastructures, more specifically in data centers, putting less busy servers to sleep has been considered. Putting an equipment to sleep either during low user load or high electricity price has brought forward QoS challenges. It is natural to expect performance degradation when some nodes on the network or servers in the data center are sleeping. Most of the approaches have focused on researching operational limits of latency and packet loss and energy-efficiency. Another fundamental approach has been using renewable energy to power either network equipment or data centers. Those works have mostly considered using on-site generated energy, usually by the behind-the-meter generators. Only recently grid integrated generators or off-site generation has been considered. In the former data centers are able sell surplus energy and in the latter case they do not generate energy themselves but they purchase it from a generator. The latter has been found more economically feasible in [169]. Another less explored direction has been responsiveness of ICTs to grid events such as failures, voltage drops and interaction with other heavy loads like EVs.

In general, researchers' perspective for smart grid's interaction with green ICTs has been inclined towards utilizing smart grid related concepts for the benefit of ICTs. However, another less explored direction is the impacts of greening ICTs on smart grid communications and applications. Smart grid is a vast Machine-to-Machine (M2M) network and it involves intense communications with devices on utility assets as well as homes. Energy-efficiency of smart grid communications and its impact on reliability and latency is one of the open problems.

B. Open Issues in Smart Grid-Driven Research on Green Communications

In green wireless communications, relaying, cooperative communications and small cells are recent techniques that are developed for extending the cell coverage and providing high data rates for the users within a cell. On the other hand, they are considered to be energy efficient since they can serve the users who are far from the macro cell BS, incurring energy savings for the macro BS. Although they are promising techniques for the AMI and WAN communications of the smart grid, their deployment in the smart grid environment is not well explored. Furthermore, femtocells and picocells are energy efficient alternatives to macrocells, however when they are densely deployed, they may reduce the efficiency of the macrocell as the primary BS will operate under low traffic [16]. A relevant question is; what is the optimum network design for cellular smart grid communications? Since smart grid traffic is machine-generated and previous research on optimal network design is based on human-generated traffic, those results may not be blindly applicable to smart grid domain. Moreover, depending on the price of electricity utilization of macro cell BS can vary and alternative techniques may used to provide coverage to the cell users, as such in [87]. Yet, there are only a few works that investigate price-awareness in BS operation and corresponding coverage issues. Therefore, the mutual impact of sleeping BSs on the QoS requirements of smart grid data needs to be further investigated. Meanwhile, mean and variance of the traffic load and the density of BSs is know to impact energy savings under sleep mode [171]. Thus, how does the traffic generated by smart grid applications impact the energy efficiency of communication systems? Smart grid traffic is heterogenous since it is fed by a variety of devices. For instance, smart meter data is collected every 10–15 minutes while sensor data is collected in the order of seconds. Particularly, transformer or capacitor bank monitoring requires near-real-time data delivery. Under these traffic types what is an ideal sleep schedule for a BS is another open problem.

MIMO is an efficient technique to increase throughput, however it incurs high energy consumption. To overcome this challenge previous studies have proposed to use SISO during low traffic intensity. Adaptively changing the number of active antennas in the smart grid environment is another interesting research direction. To this end, the implications of adaptively configuring MIMO in a smart grid environment have not been explored yet.

In a wireless network, spectral efficiency, cost, coverage and QoS are generally conflicting requirements with energy-efficiency. QoS guidelines for smart grid communications and their tradeoffs with energy-efficiency techniques need to be explored. Particularly, SG-NAN carries various types of data with a large spectrum of QoS requirements as we have mentioned before. Future research needs to explore the impacts of energy-efficiency techniques on the QoS of different types of smart grid data, as well as the bounds for energy-efficiency under various QoS classes of smart grid data.

In the optical domain, the impact of sleeping ONUs on the QoS requirements of smart grid data is an interesting research problem. In addition, in the integrated Fi-Wi architecture developing efficient mechanisms for sleeping ONUs and APs so that smart grid data requirements is not violated is an open problem. Although coordination of ONUs and APs according to beacon intervals have been considered in [132], scheduling of intervals in the smart grid environment remains as an open problem. Furthermore, when there is QoS degradation concern determining which of the integrated networks, i.e. optical or wireless, will opt out sleeping is a further research issue.

Finally, in PLC energy-efficient resource allocation schemes consider ideal channel conditions, however PLC channel is impacted by the disturbances in the low voltage circuit. Thus, energy efficient physical and medium access under power disturbances needs to be studied.

C. Open Issues in Smart Grid Motivated Research on Green Data Centers

In green data centers, workload migration is usually done based on either price or emission or renewable energy awareness. Emission aware workload migration is relatively recent and has seen less attention because carbon market is newly shaping with the new carbon cap-and-trade regulations. In addition, emission awareness has been considered only for data centers and not for the transport network that carry data center traffic. Workload migration for jointly minimizing emissions of data centers and their transport network is still an open problem. Furthermore, the impact of power grid events such as failures, disturbances, voltage drips has been less explored. Thus, inter-data center load distribution based on power grid events is an open issue.

Smart grid and data centers are large-scale cyber-physical systems. As electric vehicles are becoming a conventional demand for the grid, their heavy loads may cause service degradation. In that case, load-following data center operations may be necessary in order to avoid putting too much stress on the distribution transformers. Those interactions have not been addressed in the literature, therefore future research needs to explore green data center operation under local distribution system loading. In Table I, we provide a taxonomy of all the surveyed smart grid-driven approaches in this paper. We decidedly left out the energy-efficiency approaches that are not related to smart grid. Thus, all of the approaches included in the table are load or price or emission or supply-aware where some have additional links to smart grid. Price-awareness and utilization of renewable energy has often found its way to energy-efficient ICTs frequently. On the other hand, emission and grid-awareness have been less explored. Meanwhile, QoS has been addressed in a considerable amount of works.

TABLE I
A Taxonomy of Research That Uses Smart Grid Concepts in Energy Efficient ICTs

Proposed Scheme	**Network/Data Center**	**Traffic Load**	**Price**	**Emission**	**Renewable**	**Electric Load**	**QoS**	**Grid Events**
Bu et al. [87]–[89]	Wireless SG-WAN	✓	✓	×	×	×	✓	×
Niyato et al. [91]	Wireless SG-WAN	✓	✓	×	✓	×	×	×
Dong et al. [120]	Optical SG-WAN	✓	✓	×	✓	×	✓	×
Despins et al [121]	Optical SG-WAN	✓	✓	×	✓	×	×	×
Cavdar et al. [122]	Optical SG-WAN	✓	✓	×	×	×	×	×
Qureshi et al. [149]	Data center	✓	✓	×	×	×	×	×
Rao et al. [150]–[152]	Data center	✓	✓	×	×	×	✓	×
Li et al. [153]	Data center	✓	✓	×	×	×	✓	×
Rao et al. [154]	Data center	✓	✓	×	×	✓	✓	×
Wang et al. [155]	Data center	✓	✓	×	×	✓	✓	×
Wang et al. [156]	Data center	✓	×	×	×	✓	✓	✓
Wang et al. [157]	Data center	✓	×	×	×	✓	✓	✓
Kantarci and Mouftah [159], [160]	Network & Data center	✓	✓	×	×	×	✓	×
Dong et al. [161]–[163]	Network & Data center	✓	×	×	✓	×	✓	×
Nguyen et al. [164]	Network & Data center	✓	×	×	✓	×	×	×
Ghamkhari and Mohsenian-Rad [165], [166]	Data center	✓	✓	×	✓	×	✓	×
Erol-Kantarci and Mouftah [167]	Data center	✓	×	×	✓	✓	×	×
Le et al. [168]	Data center	✓	×	✓	✓	×	✓	×
Ren et al. [169]	Data center	✓	×	✓	✓	×	×	×
Mohsenian-Rad and Leon-Garcia [170]	Data center	✓	✓	×	×	✓	✓	✓

VI. Conclusion

Information and Communication Infrastructures (ICTs) are among the major power consumers and GreenHouse Gas (GHG) emitters. In particular, the power consumption of communication networks and data centers in total is comparable to consumption of large countries. Consequently, the Operational Expenditures (OPEX) of communication networks and data centers are growing with increasing electricity prices and emerging carbon caps and taxes. For this reason, recently vast amount of efforts have been put into enhancing the energy-efficiency of ICTs. In addition to traditional approaches, smart grid-driven techniques have found their way to provide OPEX reductions. Dynamic pricing schemes, distributed generation, demand management, fine-tuned monitoring of faults and disturbances are new concepts brought by the smart grid and they can be effectively utilized to reduce the bills, consumption and emissions of ICTs.

In this survey paper, we have focused on the studies that investigate the challenges and opportunities arising from the interaction of the smart grid with green ICTs. We have provided a comprehensive survey of the smart grid-driven works in energy-efficient communication networks and data centers. We have first given a brief introduction to the smart grid and introduced the fundamental concepts that have emerged with the smart grid. Next, we have elaborated on the use of energy-efficient wireless, wireline and optical communications in different domains of the smart grid such as Home Area Networks (HAN), Neighborhood Area Networks (NAN) and Wide Area Networks (WAN). Then, we have surveyed the studies that take smart grid factors into consideration while managing data center's power consumption, emissions and electricity bills. Finally, we have outlined the lessons learned and the open research issues regarding smart-grid awareness in energy-efficient ICTs. In addition, we have pointed out new research directions.

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