5G Networks Towards Smart and Sustainable Cities: A Review of Recent Developments, Applications and Future Perspectives

Received December 10, 2021, accepted December 25, 2021, date of publication December 30, 2021,
date of current version January 10, 2022.

Digital Object Identifier 10.1109/ACCESS.2021.3139436

5G Networks Towards Smart and Sustainable Cities: A Review of Recent Developments, Applications and Future Perspectives

MUHAMMAD J. SHEHAB [1], (Member, IEEE), IHAB KASSEM [2], ADEEB A. KUTTY [3], MURAT KUCUKVAR [3], NURI ONAT [4], AND TAMER KHATTAB [1], (Senior Member, IEEE)

[1] Electrical Engineering Department, Qatar University, Doha, Qatar
[2] Computer Science and Engineering Department, Qatar University, Doha, Qatar
[3] Industrial and Systems Engineering Department, Qatar University, Doha, Qatar
[4] Qatar Transportation and Traffic Safety Centre, Qatar University, Doha, Qatar

Corresponding author: Murat Kucukvar (mkucukvar@qu.edu.qa)

The work of Muhammad J. Shehab and Tamer Khattab was supported by the Qatar National Research Fund (QNRF) (a member of the Qatar Foundation, QF) under Grant AICC03-0530-200033. The work of Adeeb A. Kutty and Murat Kucukvar was supported in part by Qatar University through the Graduate Research Support Program under Grant QUST-2-CENG-2021-218.

ABSTRACT 5G wireless communication systems provide massive system capacity with high data rates, very short low-latency, and ultra-high reliability, in addition to high connection density with a positive experience on smart cities and the Internet of Things (IoT). Future networks are anticipated to revolutionize typical applications such as the enhanced mobile broadband services (EMBB), ultra-reliable low latency communication (uRLLC), and massive machine-type communications (mMTC) anywhere and everywhere. This rationalizes the need to investigate the sustainable elements of 5G networks in smart cities to understand how 5G networks can be more environmentally- friendly and energy-efficient. This paper aims to investigate how 5G networks can act as key enablers in achieving sustainability in smart cities, using a macroscopic review. An overview of 5G communication networks and several 5G technologies used in smart city applications to enhance sustainability is presented. This is followed by investigating the indicators that measure sustainability in 5G networks across the environmental, social, and economic dimensions; and sub-dimensions such as energy efficiency, power consumption, carbon footprint, pollution, cost, health, safety, and security. The results show that the majority of research papers focus on the environmental dimensions of sustainability (42%) when attempting to address sustainability in 5G systems and smart cities. The findings also showed a huge interest in the economic (37%) and social (21%) dimensions as well. Further, when examining the sub-dimensions, it was found that most of the studies focused on energy efficiency (20%), power consumption (17%), and cost (15%).

INDEX TERMS 5G wireless communication system, energy efficiency, Internet of Things, smart cities, sustainability.

I. INTRODUCTION

Technological advancements in the area of network services and telecommunication, accompanied by the emergence of smart cities and the Internet of Things (IoT) have boosted the necessity of sustainable practices in 5G networks and smart cities. As identified in the Brundtland report [1], sustainable development satisfies the demands of the present without compromising the capability of future descents by judiciously utilizing the existing resources. Such development strategies are vital when technologies lead societal development in the current smart era [2].

A. STATE OF THE ART CONTRIBUTION AND NOVELTY

The rigorous demands of the 5G networks and the key performance indicators (KPIs) that 5G is promising to provide have made sustainability in mobile communications a key element for the design of the forthcoming 5G wireless networks and one of the research priorities in this area. Understanding

The associate editor coordinating the review of this manuscript and approving it for publication was Francisco Perez-Pinal.

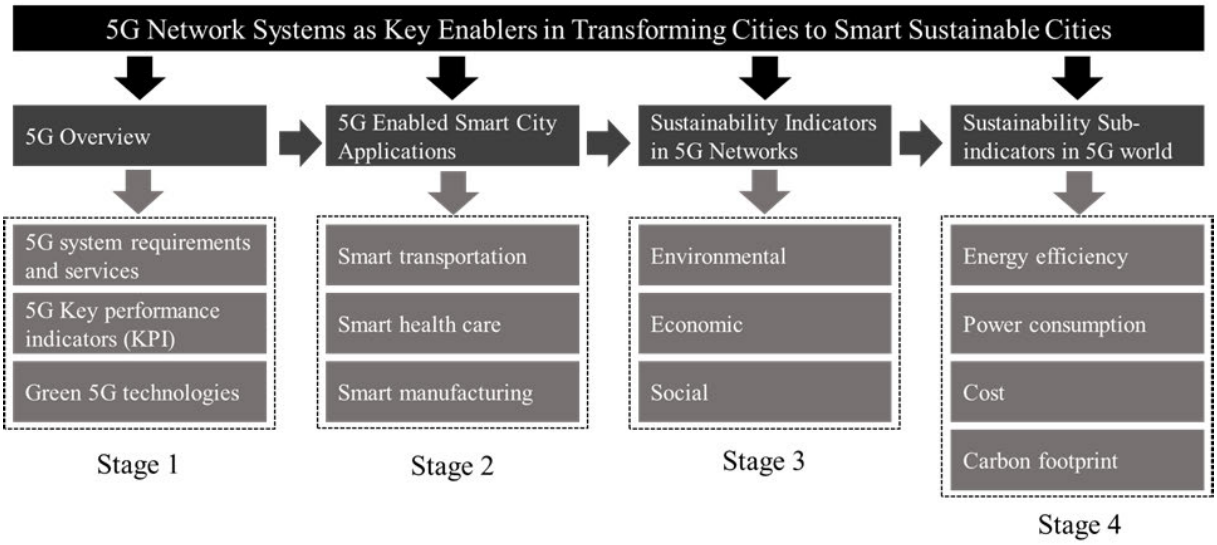


FIGURE 1. Description of the review paper stages.

the sustainability challenges in the 5G networks and smart cities is essential to reduce the influence of these challenges and determine a way to utilize the enabling technologies to enhance sustainability in smart cities. As mentioned in [2], 5G entails multi-radio connectivity to smart devices and relies on virtual networks. New services will emerge due to the utilization of the new spectrum. Network technologies such as software-defined networking (SDN) and network function virtualization (NFV) will allow the new services to be programmable among various network components. Mobile Edge Computing (MEC) will assist in minimizing the latency in the network since the traffic will not be going back to the core, and network slicing will enable numerous virtual networks in the air interface. To this end, 5G networks and smart cities will feature a massive number of sensors, smart management via developed networks, and advanced learning via real-time data analytics. Accordingly, these networks will enhance environmental sustainability and assist in securing and protecting public health [2].

A macroscopic review is conducted to investigate how 5G networks can act as key enablers in enhancing sustainability in smart cities. The research framework is presented in Fig 1. Initially, an overview of 5G networks is discussed covering the enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communication (uRLLC). Next, the Key performance indicators (KPIs) in 5G networks are, identified and discussed, which include the energy efficiency (EE), spectrum efficiency (SE), area traffic capacity (ATC), latency, mobility, peak data rate (PDR), and user experience data rate (UEDR). Further, the green technologies in the 5G network are presented, such as the millimeter wave (mmWave), massive multiple-input multiple-output (MIMO), and ultra-dense networks (UDNs).

In addition, this paper identifies 5G/6G communication networks as key enablers for smart city applications and explains the technologies that assist in enabling sustainability through the use of digital innovation. The applications that constitute the architecture of smart cities, such as the IoT, smart transportation, smart health care, smart manufacturing, and smart grid, are explained. This is followed by examining the modern technologies used in these applications, such as vehicle-to-vehicle (V2V), autonomous and electric vehicles (EVs), wireless power transfer (WPT), and energy harvesting (EH). The capabilities of the multidimensional 5G/6G communications to enable a sustainable smart city is demonstrated. The strength of integrating terrestrial communication networks with non-terrestrial networks in enabling sustainability for IoT applications is exploited. To this end, sustainability is investigated based on the five layers of communication network, space, air, ground, underground, and underwater.

The conducted review investigates the sustainability indicators focusing on energy efficiency, power consumption, spectrum efficiency, carbon footprint, pollution, cost, human health, safety, and security. These indicators are categorized based on their impact on social, economic, and environmental indicators. The review targets studies' focus on sustainability indicators and demonstrates the most inspected indicators while assessing sustainability in 5G systems. We concentrate on references from Scopus and IEEE databases on "5G + Sustainability" and "5G + Green communication" in either title, abstract, or keywords for the period between 2010 and 2021, accessed on December 2021. The structure examines the percentage of papers focusing on environmental, economic, and social indicators. Thus the main contributions that add novelty to this study can be listed as follows:

- A first of its kind systematic review that considers the holistic sustainability concept including socio-economic and environmental pillars of sustainability under the 5G network paradigm.
- Most of the reviews in the literature to date have focused on the relevance of 5G networks and the significance of converting cities into smarter living units. However, no studies have yet attempted to bring a possible link for 5G networks to act as key enablers in transforming cities into smart sustainable cities.
- The review presents an extended coverage over the sub-indicators of sustainability concerning 5G networks, where most of the review articles to date have broken down sustainability dimensions to only indicators with no coverage of sub-indicators.
- The review investigates the capabilities of the multi-dimensional 5G/6G communications in enabling sustainable smart cities, a unique approach in integrating terrestrial with non-terrestrial networks.

II. OVERVIEW OF 5G NETWORKS

With the increasing development in wireless communication and the fruition of smart cities and IoT. 5G mobile networks are anticipated to provide users with applications such as virtual and augmented reality, smart transportation including autonomous vehicles, smart healthcare including telediagnosis, telerehabilitation, telesurgery, smart hospitality, smart community, smart grid, smart factory, and smart warehouse. 5G networks can be considered as an enabling technology for IoT, and smart cities are applications on IoT. Therefore, 5G and smart cities are inherently related [3].

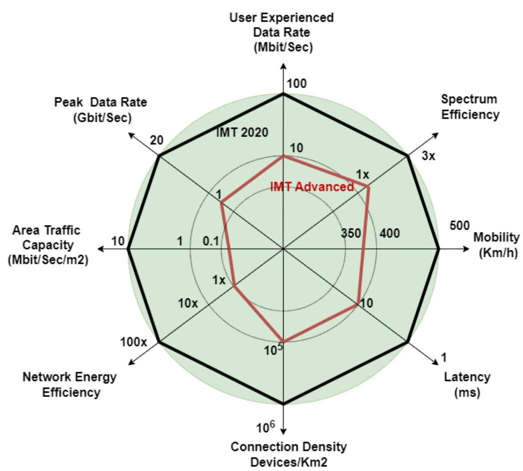


FIGURE 2. 5G system requirements.

A. 5G SYSTEM REQUIREMENTS AND MAIN SERVICES

The 5G system requirements are shown in Fig 2 as identified by the International Telecommunication Union (ITU). In addition to the requirements, there are three main services for 5G systems, which are the eMBB, mMTC, and uRLLC.

1) ENHANCED MOBILE BROADBAND

The eMBB is one of the primary use cases for the 5G new radio. To enable applications over a wide coverage area with high data rate requirements as shown in Fig 3, we need to enhance the eMBB service that focuses on increasing the system capacity and end-user data rates. The fundamental factors for enabling the eMBB are the PDR and the UEDR [4].

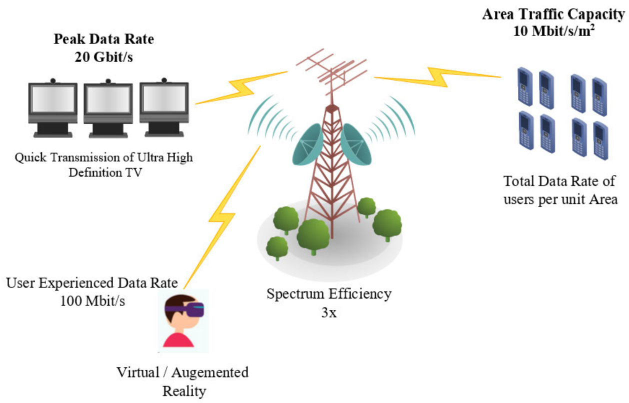


FIGURE 3. Applications on eMBB.

2) MASSIVE MACHINE TYPE COMMUNICATION

The mMTC is another use case for the 5G new radio. It involves an enormous number of devices connected to a base station (BS) as shown in Fig 4. There are several applications to mMTC such as IoT, smart meters, smart environment, smart grid, intelligent transportation, industrial control and automation, e-health, security, public safety, and drone delivery [4], [5]. The main technical challenge of mMTC is to support a massive number of devices in mobile networks. Other challenges include the congestion of the radio access network (RAN), Quality of Service (QoS) provisioning, huge signaling overhead, and handling highly mobile and intermittent

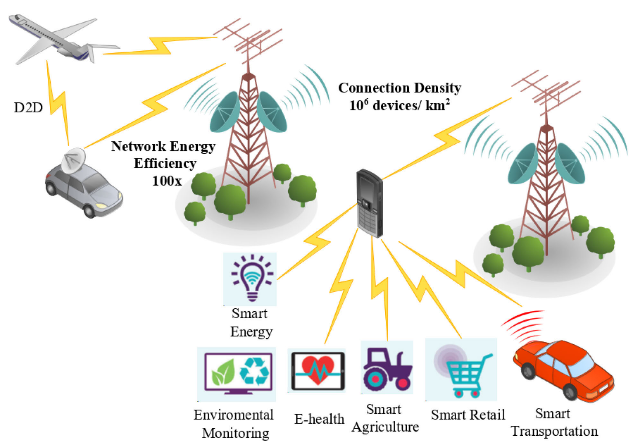


FIGURE 4. Applications on mMTCs.

MTC traffic. The two key requirements for enabling mMTC are the connection density and network energy efficiency [6].

3) ULTRA-RELIABLE LOW LATENCY COMMUNICATION

The third use case for the 5G new radio is the uRLLC, it is anticipated to aid novel levels of highly reliable and low latency communications as shown in Fig 5. There are several potential applications to uRLLC which operate either in licensed or unlicensed bands, such as smart grid, intelligent transportation system, high-speed train, self-driving car, factory automation, industrial automation, remote surgery, V2V, and tactile internet which is the next evolution of the IoT that includes machine-to-machine and human-to-machine interaction. The two important requirements for enabling uRLLC are latency and mobility [6].

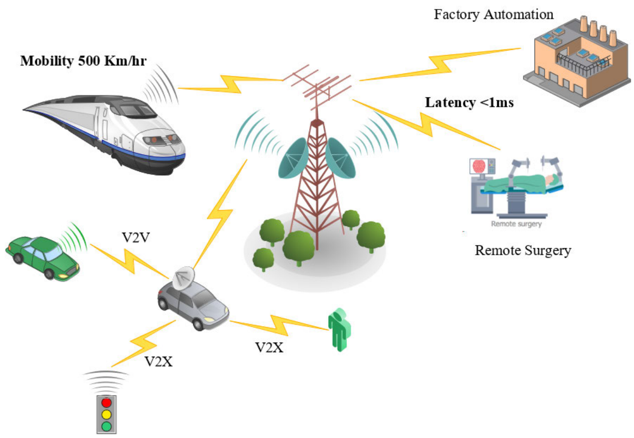


FIGURE 5. Applications on uRLLC.

B. GREEN 5G COMMUNICATIONS AND KPIS

To achieve green communication networks as shown in Fig 6 and Table 1, we need to focus on several aspects such as EE, SE, cost-efficiency, power consumption, and increased security. The KPIs for the 5G networks shown in Fig 7 are specified by the ITU. These include fiber-like-access data rate up to 20 Gbps, a latency that is mere milliseconds, UEDRs up to 100 Mbps, and ATC up to 10 $Mbit/s/m^2$. The spectral efficiencies are expected to reach 15 bit/s/Hz for uplink and 30 bit/s/Hz for downlink, while mobility is expected to reach up to 500 km/hr, and connection density up to 10^6 devices/km^2 [7]. The network EE factor is anticipated to increase from 1x on 4G LTE to 100x on 5G IMT-2020, which is an important factor to enable sustainable and green 5G networks [8]. EE is considered as a significant 5G KPI, and it is defined as the ability of the radio access technology (RAT) to minimize the energy consumption of the RAN relative to the traffic capacity supplied. Green requirements for reducing energy consumption and achieving optimal networks need to be considered from the beginning, unlike previous mobile networks [9].

To empower green 5G communication networks, several new technologies are suggested to increase the EE, which is the most widely embraced green design factor and is required to be 100x compared to 4G LTE communication networks. This can be achieved by minimizing energy consumption while preserving the QoS. In this context, EH technologies can be utilized to enable the BSs, wireless devices, and communication transceivers to harvest energy from ambient radio frequency and different renewable sources such as kinetic sources, thermal, solar, vibration, and wind [8]. EH can be used in 5G networks to prolong the battery duration of the devices and communication networks and to safeguard the environment. This enables us to achieve sustainable development goals (SDG 3 – good health, SDG 7 – renewable energy, SDG 9- innovation and infrastructure, SDG 13 – climate action, SDG 15 – life on land) [3]. Integrating renewable energy resources into future mobile networks is a fundamental factor leading to a sustainable smart city (SDG 11 – sustainable cities and communities).

C. ENSURING GREEN 5G TECHNOLOGIES

1) MILLIMETER WAVE

The relationship between the frequency, f, wavelength, λ, and the speed of light in free space, c, is $\lambda = \frac{c}{f}, = v/f$. mmWave communication is a vital technology used to scale up the capacity in 5G networks due to its considerable frequency range 30 – 300 GHz [10]. It is more affiliated with small cells and its wavelength size ranges between 1mm and 10mm. The shorter mmWave wavelengths can produce narrower beams, which enables the mmWave to transmit data more securely at a high speed with better resolution and low latency. Its range of the spectrum lies between the microwave spectrum band and the infrared spectrum band, which enables mmWaves to be used for high-speed communication since this band is considered as extremely high frequency (EHF). Due to obstacles and harsh path loss, mmWaves face problems with long distances, which brings the need for small cells that aids short-range communications in high dense areas [11], [12]. mmWave is considered a green 5G technology to enlarge the spectrum availability. It increases the throughput as it expands the available spectrum and it enhances the SE [8].

2) MASSIVE MULTIPLE-INPUT MULTIPLE-OUTPUT

The MIMO technology allows the transmission and reception of multiple simultaneous data signals over a single radio channel, it uses two to four antennas on the transmitter and the receiver, whereas massive MIMO (M-MIMO) uses a huge number of antennas from tens to hundreds since mmWaves are in the high band spectrum, which allows the wireless devices to deploy more small size antennas. The advantage of this technology is that it achieves high data rates, high-energy efficiency, high transmission bandwidth, high transfer capacity, and increased spectral efficiency of the network without demanding more spectrum. In addition, it improves energy efficiency since it focuses the energy into ever-smaller areas

FIGURE 6. Green 5G technologies and sustainability indicators.

of space, which makes it a promising technology for sustainable 5G networks [12]–[14]. In [15] the authors discussed the scenarios of boosting the energy efficiency gains provided by the M-MIMO system, such as reducing the power loss of the amplifiers, lowering the RF chain requirements, executing low complexity operations at the BS, and scaling the number of antennas at the BS. Thus, it enables the operators to lower the operating expenditure (SDG 8 – economic growth).

3) ULTRA-DENSE MOBILE NETWORKS AND SMALL CELLS

The presence of small wavelengths and narrow beams in 5G networks increases the communication speed and restricts the transmission distance of mmWaves to 100 meters, which brings the need for a large number of small cells, and this is called ultra-dense networks [12].

Small cells are small size base stations that demand minimal power to operate and can be located every 250 meters. To prohibit signals from being dropped, thousands of these stations could be installed in a city. This would compose a dense network that performs like a relay team, handing off signals and routing data to users at any place. The concept of the small cells is to increase the achievable data rate, lower the energy consumption (SDG 3 - good health, SDG 7- renewable energy) for the circuit power, and reduce the latency. It can support a huge number of user equipment in the small cell since the small distance between the transmitter and the user can reduce the loss of the propagation and avert the interference. M-MIMO wireless communication system and small cells emerging technologies are one of the key elements in 5G networks. M-MIMO can be utilized jointly with small cells to increase the QoS, the capacity of the system, and eliminate the additive white gaussian noise (AWGN) [13], [14].

In UDNs there exist a large number of small cells. This enhances the network efficiency and results in high energy and spectral efficiency (SDG 7 - renewable energy) [16]. UDN is considered a green 5G technology since it reduces the distance between the transmitter and the receiver. This increases the spectrum efficiency, provides links with high quality, and increases the spatial reuse element, which is considered high compared to 4G wireless networks [8].

The authors in [15] inspected the energy efficiency for 5G networks and the challenge of the green backhauling.

TABLE 1. Green 5G/B5G technologies.

5G Technologies	Sustainability Metrics	Features	Challenges
mmWave	Cost-efficient	High data rate	High transmission power is needed, high path loss
Massive MIMO	Spectral efficient, Energy efficient	High data rate, high throughput	High cost, complex channel model, management of interference
Beamforming	Spectral efficient, reduce signal interference between devices	Improves system coverage, high-quality signal, better SNR, boosts capacity, boosts cell range, faster information transfer	Hardware complexity, large power consumption, requires advanced processing DSP chip, high battery drain
Ultra-dense Networks	Network Efficiency, reduced power emission	Higher network capacity, higher flexibility, high real-time performance, high suitability to achieve load-balancing, high compatibility	Security and Privacy, severe interference, degraded quality-of-service, high signaling overhead
Green IoT	Energy efficient, minimize human effort, low CO2 emissions, reduce pollution	Reduce energy, reduce hazardous emissions, reduce resources consumption	Security and privacy, compatibility, complexity, device recognition
D2D	Spectral efficiency, energy efficiency, low transmission power, low circuit power	Improve throughput, reduce delay, reduce fairness	Prone to attacks, interference management, mobility management
Energy Harvesting	Energy Efficient, environmentally-friendly, offers an alternative power supply	Lower maintenance, easier installation, higher uptime, wireless power supply	Availability of energy harvesting sources, less mature technology, the upfront cost can be high
IRS	Cost-efficient, energy-efficient, spectrally efficient	Improves performance of wireless transmission	IRS Practical deployment, IRS positioning, hardware impairments, difficult to acquiring accurate channel information
NOMA	Spectral efficiency	Massive connectivity, high throughput, lower latency	High receiver complexity, high energy consumption

Their objective was to minimize the power consumption of the backhaul traffic between the small cells and the core network by deploying both passive optical fiber networks and mmWave technologies. Their idea was based on the reality that optical networks are more energy-efficient for heavy load situations while small cells provide more energy efficiency for low load situations. Due to this, they proposed a solution based on estimating the traffic load per hour and obtaining the best energy-efficient design for the backhaul for different hours of the day. Their proposed solution showed a huge reduction in energy consumption. Optical fiber communication provides sustainable and faster connectivity (SDG 9 – innovation and infrastructure). It is considered a green solution for the networks since it reduces waste (SDG 15 – life on land), energy consumption (SDG 7- renewable energy) and it is environment friendly (SDG 13 – climate action) [12].

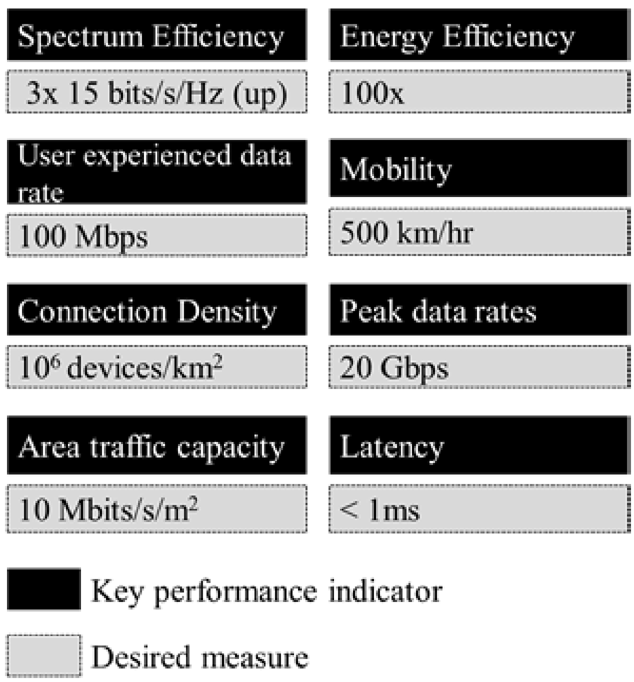


FIGURE 7. 5G KPIs.

III. 5G NETWORK ENABLING SMART CITIES APPLICATIONS

In this section, we discuss some of the various smart city components presented in Fig 8, such as the smart grid; smart transportation, smart healthcare, and smart manufacturing. However, the components of a smart city differ among the cities depending on the interest areas [17], [18].

A. 5G NETWORK ENABLING SMART GRID

The smart grid refers to the smart electrical network, which involves a set of energy operations and measures such as smart appliances, smart meters, energy-efficient resources, and renewable energy resources. It is a digitized and intelligent electricity network that supplies electricity from the source generator to the customers.

To optimize the connectivity in smart electrical grids there is a demand for flexible and reliable network connectivity to meet the requirements of various grid services. 5G network slicing is a promising technology to enhance the performance of smart electrical networks [18]. The reason is that it simplifies the network infrastructure into a single and shared network to implement multiple services. These services can be deployed using two automation technologies such as NFV and SDN to combine various layers of access, transport, and core network domains to produce custom slices for every use case. Therefore, a smart grid is one of the areas that can be revolutionized using 5G network slicing [19].

There are several technologies used in smart grids which heavily depends on the 5G technologies such as the drone/UAV based grid maintenance and inspection, smart environment monitoring of substations, vehicle to grid (V2G) communication, distribution automation (DA), advanced metering infrastructure (AMI), demand response (DR), virtual power plants (VPPs) and distributed energy resources (DERs) [19]. 5G networks increase the energy efficiency and improve the connectivity in crowded areas and inside buildings because it supports high connection density and reliability (SDG 9 – innovation and infrastructure) [12]. Hence, 5G networks can control and manage multiple sections of energy grids in a consolidated manner. This makes the smart energy grids more cost-effective (SDG 8 – economic growth) for energy consumers and utilities. The smart grid is the foundation of smart energy, and it is significant in boosting social and economic harmony. This enhances sustainable development (SDG 11 – sustainable cities). It enables a cleaner environment (SDG 13 – climate action), better life (SDG 15 – life on land), and more consistent society (SDG 3 – good health). This assists in refining energy management and allows the transformation to electrical energy and clean energy (SDG 7 – renewable energy) [18].

Furthermore, renewable energy sources are anticipated to enable the future generation of EVs, which contribute toward the green environment (SDG 15 – life on land) and diminished CO2 emissions (SDG 13 – climate action) [20]. EVs can enable a sustainable transportation sector since it contributes to fewer noise emissions and pollution (SDG 13 – climate action, SDG 15 – life on land). It solves the negative effects related to the problem of the internal combustion engine [21].

B. 5G NETWORK ENABLING SMART TRANSPORTATION

5G communication networks are key enablers for sustainable transport systems, because of the low latency feature which is less than 1 ms. 5G networks provide connectivity to autonomous vehicles that operate with safety (SDG 3 – good health) and reliability. Fig 9 and Fig 10 show the 5G use cases and benefits in smart transportation respectively. Moreover, the ways of interaction for the vehicle to everything (V2X), V2V, vehicle to infrastructure (V2I), vehicle to the network (V2N), vehicle to pedestrian (V2P), vehicle to cloud (V2C), vehicle to grid (V2G) and vehicle to the device (V2D) enables equipped vehicles to share data and information related to vehicle's speed and locations via 4G, 5G, Wi-Fi, and Bluetooth. These technologies assist the drivers in avoiding collisions (SDG 3 – good health), enhance the required safety of

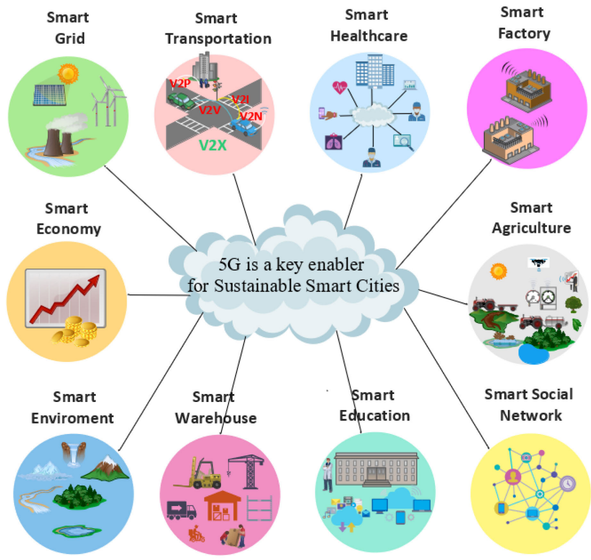


FIGURE 8. 5G to empower smart cities.

the road (SDG 3 – good health), increase the traffic efficiency and save energy (SDG 7 – renewable energy) [22], [23].

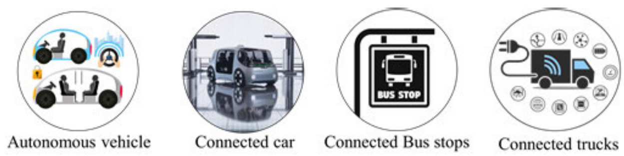


FIGURE 9. Some possible applications of 5G systems in smart transportation.

Green Internet of vehicles (IoV) was introduced in [23] and the authors focused on minimizing the energy consumption (SDG 7 – renewable energy) and maximizing resource utilization taking into consideration the existing environment. The technologies used for 5G enabled green IoV were highlighted, such as the device-to-device (D2D), machine-to-machine (M2M), NFV, SDN, self-organizing networks (SON) and non-orthogonal multiple access (NOMA) [23]. In D2D, H2H, and M2M technologies, communication is established between the devices/machines directly without being forwarded through the base station (BS). This improves the spectrum and energy efficiency, minimizes the load on the BS, saves transmission resources, increases the mobile system throughput, and reduces the latency [23], [24].

In 5G mobile systems, SDN is used for the network to be programmed, and NFV is used for network virtualization. Applying both technologies provide more options, improves vehicle connectivity, and facilitates network management. Further, SON enabled features such as self-configuration, self-planning in network deployment, self-healing, and self-optimization in network maintenance, minimize the human resources and reduce the operation cost for complex 5G networks. NOMA enables several users to reuse spectrum resources, which increases spectrum efficiency [23]. NOMA combines efficient computing and spectrum reuse to minimize network stress. Thus, it improves the traffic load efficiency, and it increases the transmission speed [23], [25].

FIGURE 10. **Possible benefits of 5G systems in smart transportation.**

C. 5G NETWORK ENABLING THE SMART HEALTHCARE

5G networks play a vital role in powering the smart healthcare (SDG 3 – good health), since 5G will enable telemedicine, remote surgery and teaching, remote patient and intra-hospital monitoring, augmented (AR) and virtual reality (VR), data analysis, large file transfers, remote consultation, wireless specialist diagnosis, and quick emergency response in addition to decentralizing the health care model (SDG 3 – good health). The reason is that these applications demand a network that can support better connections, live video with high quality, and increased data transfer capacity. Telemedicine is present today but 5G will assist in increasing its connection's speed and edge computing in 5G will encourage its adoption. Distance patient monitoring will administer and modify medication based on analyzing and collecting live data. By utilizing IoT endpoints, the health care providers can track medications, monitor vitals, and transfer data to assist staff makes faster decisions remotely. AR and VR can assist in training clinicians and taking care of patients remotely. Thus, AR/VR powered by 5G will enable staff, interns, nurses, and doctors to optimize their education (SDG 4 – quality education).

5G networks will allow the exchange of highly secure data needed for achieving an enhanced analysis. In healthcare, data is an important factor to reduce operational costs and enhance efficiencies. 5G is anticipated to support low latencies of less than 1ms, which allows edge computing to rapidly process data at the network edge. 5G can enable the medical industry to provide patients with medical care outside the hospital and close to the patients through setting up, walk-in clinics, care centers, home healthcare settings, and outpatient surgery centers (SDG 3 – good health). Moreover, it can also assist in enhancing the ability of hospitals to transfer huge image files. When a network is high on bandwidth, the transmission will take short time to send or receive data with high network performance [26], [27].

D. 5G NETWORK ENABLING SMART MANUFACTURING

5G networks with SDN and NFV will assist in enabling smart manufacturing since 5G networks will be utilized to connect machine parks, production machines, and factory sites to allow for new possibilities in respect of automation, flexibility, and novel applications [28]. Smart manufacturing is a technology that uses internet-connected machinery to supervise the process of production. The objective of smart manufacturing is to find out opportunities to automate operations and use data analytics to optimize manufacturing performance (SDG 9 – innovation and infrastructure, SDG 11 – sustainable cities). Smart manufacturing is recognized as a particular application of industrial IoT (IIoT). Implementations include installing sensors in machines to gather information and data on their performance and operational status. Before, the data was kept in databases, which is local on individual devices and utilized only to evaluate the reason for equipment failures after it occurs. Currently, by analyzing the information streamed off a whole factory's machines, engineers can check the signs for failure in specific parts. This allows preventive maintenance to avert unplanned downtime on equipment. Also, engineers can analyze the trends in the information to find out in their processes where the production is insufficient or slows down in their use of materials. Additionally, data scientists and engineers can utilize the information to run simulations of various operations to obtain the best effective and dynamic approach of doing things [28]–[30].

The authors in [31] inspected smart manufacturing and IIoT as one of the fundamental factors to realize the cyber-physical manufacturing systems (CPMS) since it generates a large amount of data in the manufacturing process. To attain real-time transmission and processing of an enormous amount of information in the manufacturing operation (SDG 9 – innovation and infrastructure), the authors mentioned the communication technology requirements for CPMS, which are the high transmission rate, high reliability, low latency, high security, high coverage and a huge number of connections. 5G communication systems have magnificent power to enable IIoT based CPMS manufacturing since 3G and 4G technologies cannot satisfy the requirements of the CPMs. Moreover, the authors investigated the manufacturing scenarios under the three 5G use cases, which are the eMBB, mMTC, and uRLLC.

Smart manufacturing is becoming more popular with the emergence of IoT where machines become connected to the internet. This enables machines to communicate with each other's and support a high automation level (SDG 9 – innovation and infrastructure).

E. A MULTIDIMENSIONAL 5G/6G COMMUNICATIONS FOR ENABLING SUSTAINABLE SMART CITIES

5G/6G communication systems are key enablers for a wide range of various IoT applications in diverse areas to attain sustainable development. The power of the existing mobile

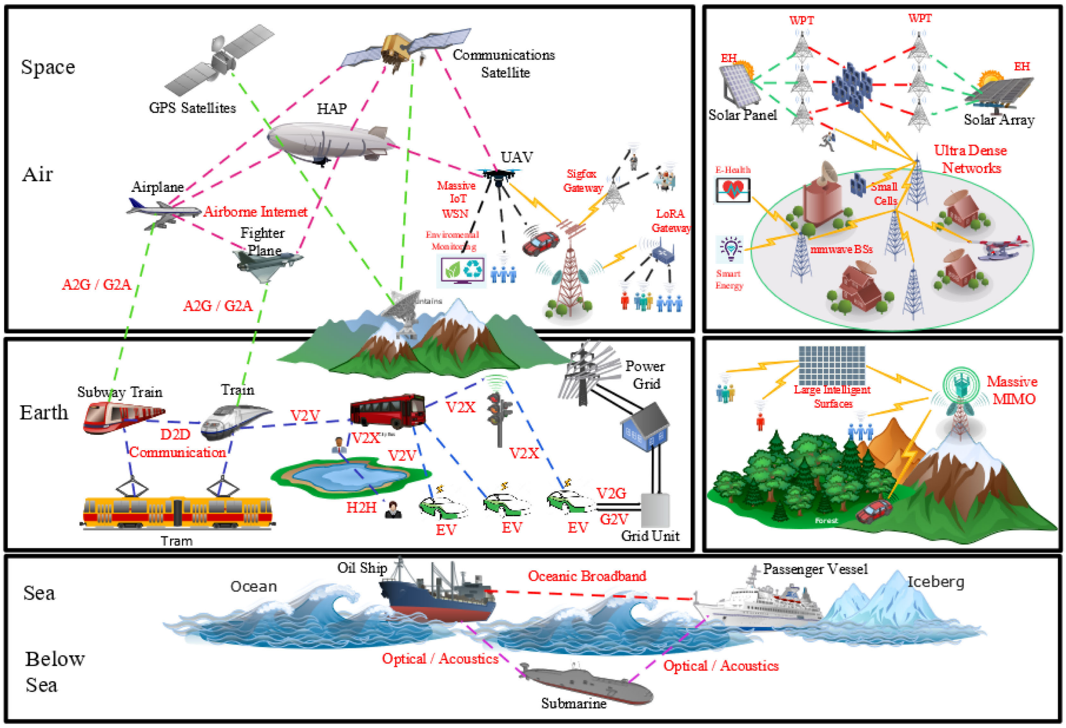


FIGURE 11. Sustainable smart city.

networks is not sufficient to provide ubiquitous connectivity and coverage needs of a sustainable city in energy, ocean, water, and climate regions. Thus, to enable sustainable IoT applications, a multidimensional communication network is required with the ability to consolidate terrestrial and non-terrestrial communication networks. A five layers communication network can support this consolidation and includes space, air, ground, underground and underwater [32] as shown in Fig 11. In the following, we discuss the five layers of communication networks, which include the terrestrial communication network, space communication network, aerial communication network, underwater communication network, and underground communication network [33].

1) TERRESTRIAL COMMUNICATION NETWORKS

The terrestrial communication networks are the base for supporting wireless communication connectivity for many sustainable IoT applications mentioned in this paper. The terrestrial communications are capable of operating at low frequencies, mmWave, microwave, and THz spectrum bands. To aid high-speed communications and high data rates, as in sustainable climate and water measurements, we can use the THz band. mmWave technology based on the M-MIMO hybrid beamforming method can provide high data rate and real-time communication requirements (SDG 9 – innovation and infrastructure) [33]. These communication networks will be densely deployed because the mmWaves do not travel long due to high attenuation and path loss, which calls the demand for small cells to assist short-range communications in dense areas. Moreover, to address the demand for a sustainable and green future for mobile networks, researchers started focusing on large and reconfigurable intelligent surfaces, which are considered beyond M-MIMO. These intelligent surfaces have a significant role in promoting energy (SDG 7 – renewable energy) and spectral efficiencies, enhancing the communication system performance (SDG 9 – innovation and infrastructure), and controlling the propagation environment [34].

Further, many considerable emerging technologies assist in achieving sustainability in smart cities and enable smart applications such as the D2D, V2V, V2X, V2G, V2I, V2P, and EV. These technologies enable smart transportation and can be implemented in vehicles to achieve future mobility (SDG 9 – innovation and infrastructure) in cities and aid in enhancing sustainability (SDG 11 – sustainable cities). Other technologies such as EH, renewable energy sources, WPT, and UDNs assist in achieving energy efficiency (SDG 7 – renewable energy) in 5G networks [23]. WPT is an important and attractive technology in 5G wireless networks since it is capable of supplying power to IoT endpoints, especially where the cost of maintenance is high, or the replacement of the battery is intractable (SDG 8 – economic growth) [35]. The authors in [36] suggested a scheme by applying the concept of effective energy efficiency, effective capacity, and simultaneous wireless power and information transfer (SWIPT) to achieve low latency and high-energy efficiency (SDG 7 - renewable energy). In [37], radiofrequency energy harvesting (RF-EH), WPT and SWIPT were addressed to satisfy the growing needs in the energy consumption, lower the operational costs (SDG 8 – economic growth), and achieve sustainability in the wireless networks. RF-EH utilizes the RF signals to recharge the batteries of the wireless nodes rather than using traditional energy sources and power grids. In this regard, RF energy can be harvested from the surrounding electromagnetic sources or the sources that transmit RF energy directionally.

Many other terrestrial communication technologies, such as the optical fiber, contribute to sustainable and green communication systems (SDG 11 – sustainable cities), since it reduces energy consumption (SDG 7 – renewable energy), reduces wastes (SDG 15 – life on land), optimizes the connectivity, enhances the infrastructure design (SDG 9 – innovation and infrastructure), provides scalability, and reduces construction materials. The optical fiber is considered a backbone for a lot of terrestrial networks. Plenty other terrestrial communication technologies play a significant role in boosting sustainability such as the mmWave communication [38], Terahertz communications, M-MIMO, full-duplex, cognitive radios, narrowBand low power wide area network (NB-LPWAN), interference cancellation, wireless sensor network (WSN), cyber threat defense, green mobile networks, smart grid, SDN, mobile edge networking, cloud-fog platforms, and the conventional software-defined radio (SDR). SDR along with the mmWave technology can be utilized to enable significant solutions by mixing the beam agility for high-speed directional communication with ultra-low power features. Designing hybrid and low loss electronically scanned arrays with the ability of beamforming at mmWave frequencies for the next generation of high-speed communications will be prime for realizing sustainable IoT [33].

Low power wide area network (LPWAN) technologies are also promising technologies in sustainable smart cities. These include sigfox, long-range (LoRa), and LoRaWAN protocols. The traditional mobile networks cannot be used for deploying IoT devices because it's very expensive and energy inefficient for driver-less vehicles that use batteries for several years. LPWAN technologies are non-cellular wireless protocols and promising technologies in smart cities where there exists a massive number of wireless sensors and IoT devices. LoRA is considered one of the best communication protocols for smart cities, it is the radio physical layer or wireless modulation technology that enables long-range wireless communication, and LoRaWAN is the mac layer that functions as a gateway for the IoT endpoints. Sigfox is an ultra-narrowband technology that uses radio transmission modulation technique binary phase shift key (BPSK), it picks extremely tight chunks of the spectrum and modifies the phase of the carrier wave to encode data. It enables the receiver to listen only to a very small chunk of the spectrum, which lessens the influence of the noise. Both sigfox and LoRa technologies possess several features, such as long-range communication, low power consumption, energy-efficient communication protocols, high scalability, and low cost, but they have some different characteristics between them [39]–[42].

2) SPACE COMMUNICATION NETWORKS

To achieve sustainability, the wireless coverage demand for IoT applications can be aided by space communications by utilizing the satellites [39], [43]. In future, the space communications can use the geostationary, medium, and low earth orbit satellites to furnish uncovered areas with wireless connectivity, such as supporting IoT sensors for agricultural sustainability (SDG 15 – life on land).

For example, in agriculture, automated technologies have broadly superseded the use of manual and hand-held moisture technologies due to the difficulties affiliated with taking the readings of hand-held soil moisture in the production domain in distant areas. Recently, the advancements in the technology of wireless information harvesting provided users and managers with instantaneous access to the data and readings of soil moisture. These technologies will result in more efficient decision-making for water management. However, the technology advancements for wireless measurements in soil moisture still face some practical challenges such as the shortage of robust and consistent wireless services in rural areas, which prohibit instant access to soil moisture information and measurements. Another challenge is installing sensors at the beginning of the crop season and dismantling them end-of-season. Nowadays, users are driving long distances to deploy or dismantle sensors in various areas over the crop season. This causes problems in implementing innovative technologies in the field of crop production.

Thus, the wireless sensors for the soil moisture embedded in the soil connected with continuous, reliable, and robust wireless network services via satellites in rural agricultural areas will effectively lead to the adoption of sustainable practices and technologies in the production fields. To attain a high data rate and long-range satellite connections in agricultural sustainability (SDG 15 – life on land), the mmWave communications with satellites can be implemented [33].

3) AERIAL COMMUNICATION NETWORKS

The modern advancements in digital technology facilitated the deployment of aerial communications in the low frequency, mmWave, and microwave spectrum bands by utilizing aerial base stations (ABSs) on the drones or UAVs consummated by space communications.

Aerial communications can allow for IoT applications in severe areas that are not covered by terrestrial communications (SDG 9 – innovation and infrastructure) [44]. One use case of aerial communications is in IoT application for sustainable water where the monitoring of pollution level and measuring of the mineral nutrients are utilized in water bodies to evaluate the quality of water to aid regulators for generating a policy for the pollution (SDG 14 – life below water). Nowadays, UAV/drone use cases in sustainable IoT applications is restricted to whether it can navigate spaces properly and in a cost-efficient way. The existing approaches for supporting localization are usually obstructed by cost (e.x GPS-RTK), overcrowded and congested environments (e.x. GPS), or service gaps (cell towers) [33].

4) UNDERWATER COMMUNICATION NETWORKS

This type of communication will be a key enabler for sustainability in IoT applications such as monitoring in wetlands, lakes, canals, rivers, streams, and oceans [45]–[48]. Because of the various characteristics of wave propagation in the water medium from over the air, the laser and acoustics propagation can be used to achieve high data rates and high-speed communications for underwater networking and communication. There are applications in monitoring undersea earthquakes (SDG 14 – life below water), in tsunami (SDG 14 – life below water), and in IoT sustainable climate (SDG 13 – climate action) [33].

5) UNDERGROUND COMMUNICATION NETWORKS

This is an active research area of wireless communication [49], [50] where radios are entombed under the ground and the communication is partially performed via the earth. The solutions and applications for underground communication (UC) are still in their beginning and rely on radios, which are not intended for the medium. As an example, we cannot establish multi-hop underground communications since the underground-to-underground communication lines are restricted to only a few meters. Further, the underground radios can communicate with the above-ground radio devices to a distance of over 200 meters. However, this distance is still restricted to some applications, and the data rates achieved by this solution are limited to tens of kilobits per second. This prevents applications, which need a lot of data, including the real-time navigation and control components [33]. To optimize the ranges of underground communications, a significant approach for underground beamforming utilizing adaptive array antenna to enhance the underground wireless communication has been studied in [51]. An algorithm called soil moisture adaptive beamforming was designed and simulation results reveal that with various optimization methods the range can effectively be enhanced.

Underground communication networks support sustainability for many IoT applications such as wastewater (SDG 6 – clean water and sanitation) and stormwater (SDG 14 – life below water) monitoring in addition to agricultural IoT (SDG 15 – life on land). Moreover, the current solutions for wireless communications over the air face many difficulties in satisfying the demands of agricultural IoT applications. Thus, IoT applications for sustainability can utilize various groups of underground networks. The incorporation of underground communication networks with agricultural IoT will aid in conserving water resources and enhance crop yields (SDG 15 – life on land) [52]–[54]. Advancements in the agricultural IoT will improve the landslide monitoring (SDG 15 – life on land) and underground infrastructure (SDG 9), pipeline evaluation, border patrol (SDG 3 – good health), and underground mining (SDG 1 - no poverty) [50], [55]–[60].

IV. SUSTAINABILITY INDICATORS IN 5G NETWORKS AND SMART CITIES

Several indicators are used to measure the degree of sustainability in 5G network systems and smart cities. These indicators are categorized under the environmental, social, and economic dimensions of sustainability. Each indicator branch into numerous sub-indicators, for example, the environmental indicator involves energy efficiency, power consumption, carbon dioxide emissions (CO2), and pollution. The social indicator includes human health, safety, and security, whereas the economic indicator involves the cost and the spectrum efficiency. Table 2 shows the key references along with the sustainability indicators and sub-indicators discussed in each reference.

In the general review that was conducted to reveal the percentage of articles focusing on environmental, economic, and social dimensions, the keywords (''5G and Sustainability'', ''5G and Green Communication'', ''Smart Cities and Sustainability'') were searched either in title, abstract, or keywords for the period between 2010 and 2021, accessed on December 2021. Scopus and IEEE databases were used to conduct the structured macroscopic review under the selected keyword combination. According to this research, we noticed that there is a growing interest in environmental indicators (42%) to achieve green and sustainable 5G networks. Nonetheless, a high number of studies are focusing on economical (37%), and social (21%) indicators as shown in Fig 12.

Revealing the percentage of articles that focus on several sustainability indicators, the review was narrowed down to reveal the percentage of the sub-indicators searched in each paper. As shown in Fig 12 the majority of the assessed studies related to sustainability in 5G networks and smart cities concentrated on the energy efficiency (20%), followed by the power consumption (17%), cost (15%), spectrum efficiency (11%), human health (9%), carbon footprint (9%), security (7%), pollution (6%), and safety (6%). Thus, 5G networks act as a key enabler in fostering sustainability in smart cities. [7].

While considering the effect of different sustainability indicators, studies have focused on defining sustainability from an intergenerational perspective that combines a set of socio-economic and environmental performance with no true essence on describing how variations in smart initiatives and technological advancements can alter sustainable development over time. Few studies to date have developed indicator systems that consider sustainable development with an eye for several stakeholder perspectives. Negligible studies exist in bringing out indicator systems that understand changes in the use of network technologies like 5G/6G on key aspects of safety and security, climate change, health, and quality of life. In addition, the contribution of business practice indicators in the proposed areas of the 5G network and smart cities to manage projects that promise sustainable outcomes to meet the smart sustainable targets is skeptical. The business practice indicators can bring in sound investment decisions from a fiscal sustainability point of view, an indicator system with prospects to describe performance in communication

TABLE 2. Some of the indicators used to measure sustainability in 5G networks and smart cities.

Paper Reference and Year		Environmental				Economic		Social		
Key Ref.	Year	Energy Efficiency	Power Consumption	CO2 Emissions	Pollution / Wastes	Cost	Spectrum Efficiency	Human Health	Safety	Security
[2]	2016	✓	✓	✓	✓	✓	✓	✓	✓	✓
[3]	2019	✓	✓	✓			✓			
[5]	2019	✓	✓			✓	✓	✓	✓	✓
[7]	2017	✓	✓			✓				
[8]	2017	✓	✓			✓	✓			
[9]	2019	✓	✓	✓	✓	✓				
[15]	2017	✓	✓	✓			✓			
[16]	2017	✓	✓				✓			
[17]	2018	✓	✓	✓	✓	✓	✓	✓	✓	✓
[20]	2019	✓	✓	✓				✓		
[23]	2019	✓	✓			✓	✓		✓	✓
[24]	2017	✓	✓	✓		✓				
[25]	2019	✓	✓				✓			
[31]	2018	✓				✓	✓	✓	✓	✓
[33]	2020	✓	✓	✓	✓	✓	✓	✓	✓	✓
[34]	2019	✓	✓			✓				
[37]	2018	✓	✓		✓	✓	✓	✓	✓	✓
[42]	2018	✓	✓		✓	✓	✓	✓	✓	✓
[61]	2018	✓	✓				✓			
[62]	2016					✓		✓	✓	✓
[63]	2016	✓	✓	✓		✓				
[64]	2019	✓	✓			✓	✓	✓		✓
[65]	2019	✓	✓	✓	✓	✓	✓		✓	
[66]	2018	✓	✓							
[67]	2017	✓	✓			✓	✓	✓	✓	✓
[68]	2018	✓	✓							
[69]	2018		✓		✓	✓	✓	✓	✓	✓
[70]	2016	✓			✓		✓			
[71]	2018	✓	✓	✓	✓	✓	✓	✓	✓	✓
[72]	2017	✓				✓				
[73]	2019	✓	✓	✓		✓				
[74]	2018	✓			✓	✓		✓	✓	✓
[75]	2011	✓	✓	✓	✓	✓	✓			
[76]	2018	✓	✓		✓	✓		✓	✓	✓
[77]	2019	✓	✓				✓			
[78]	2018	✓		✓	✓	✓		✓	✓	
[79]	2014	✓	✓				✓			
[80]	2019	✓	✓	✓		✓	✓		✓	✓
[81]	2016	✓	✓				✓			
[82]	2018	✓	✓	✓	✓	✓	✓	✓	✓	✓
[83]	2014	✓	✓			✓				
[84]	2018	✓	✓			✓		✓		
[85]	2016	✓	✓			✓	✓	✓	✓	✓
[86]	2016	✓	✓			✓	✓			
[87]	2010	✓	✓	✓	✓	✓				
[88]	2013	✓	✓	✓	✓	✓		✓		
[89]	2019	✓			✓			✓	✓	✓
[90]	2019	✓	✓	✓	✓	✓				✓
[91]	2019	✓		✓	✓					
[92]	2019	✓	✓					✓		
[93]	2020	✓	✓	✓		✓	✓			
[94]	2020	✓		✓	✓	✓				
[95]	2020	✓		✓				✓	✓	
[96]	2020	✓		✓		✓		✓		✓
[97]	2020	✓	✓	✓		✓	✓			
[98]	2020	✓	✓							
[99]	2018	✓	✓		✓			✓		✓
[100]	2020	✓	✓			✓				
[101]	2020	✓	✓			✓				
[102]	2020					✓				
[103]	2021	✓	✓	✓		✓	✓	✓		
[104]	2020					✓		✓		✓
[105]	2017	✓	✓	✓		✓	✓	✓		✓
[106]	2020	✓	✓							
[107]	2020			✓		✓	✓			
[108]	2021	✓	✓							
[109]	2020	✓	✓			✓				
[110]	2020	✓	✓	✓		✓	✓	✓	✓	✓
[111]	2021	✓	✓					✓		
[112]	2020		✓		✓	✓		✓		

TABLE 2. ***(Continued.)*** **Some of the indicators used to measure sustainability in 5G networks and smart cities.**

Paper Reference and Year		Environmental				Economic		Social		
Key Ref.	Year	Energy Efficiency	Power Consumption	CO2 Emissions	Pollution / Wastes	Cost	Spectrum Efficiency	Human Health	Safety	Security
[113]	2020	✓	✓			✓	✓			
[114]	2021	✓				✓	✓	✓		
[115]	2020	✓	✓	✓		✓				
[116]	2021	✓	✓			✓	✓	✓		
[117]	2021	✓	✓	✓		✓		✓		✓
[118]	2021	✓	✓				✓			
[119]	2020	✓	✓					✓		
[120]	2021	✓	✓			✓				
[121]	2021	✓	✓	✓		✓	✓			
[122]	2021	✓	✓				✓	✓		✓
[123]	2021	✓	✓			✓		✓	✓	✓

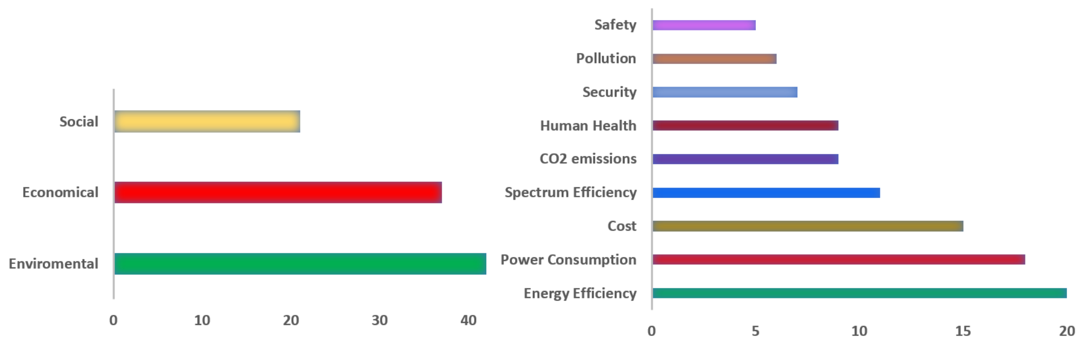


FIGURE 12. **Percentage of journal and conference papers discussing on a) sustainability indicators and b) sub-indicators.**

networks and smart cities. The authors possibly argue on the existing approaches considered in the literature to develop indicators tailored to achieve sustainability in 5G networks. Indicators in the existing studies focus on addressing stakeholder concerns and directives of corporate strategies in smart-based technologies to manage concerns of sustainable development that most likely focus on business directives. These indicators are more likely prioritize in reporting ''off the shelf'' outcomes. The effect of the latter can appraise the former, were to harmonize and manage sustainable development issues, different indicators are combined using ''top-down'' – ''expert derived'' and ''bottom-up'' – ''stakeholder scoped'' approaches.

V. DISCUSSIONS AND CONCLUSION

With the increasing innovations in wireless communications, the global market needs to consider the influence that 5G will have on the environment, social and economy before deploying it widely. This is significant so that the risks and dangers are addressed and understood. The technology used to power 5G communication networks will certainly modify how mobile equipment is utilized as well as its capabilities. Further, the advancements in technology will also modify how the technology interacts with the environment. The paradigm shifts from utilizing the radio waves to employing the mmWaves and the new role of small cells will enable a massive number of devices to be manufactured and utilized. Therefore, 5G developers need to carry out the sustainability assessment, which includes the social, environmental, and economic impact evaluation.

Various methods are utilized to achieve the sustainability indicators mentioned in this paper, such as energy harvesting, alternative energy sources, green 5G technologies, massive IoT sensors, smart meters, and life cycle assessment (LCA). One of the most important methods that assist in achieving sustainability in 5G networks is the deployment of IoT sensors. The authors in [2] discussed the sustainability in 5G networks from the environmental, economic, and social perspectives. They highlighted the usage of IoT sensors in many applications such as in urban areas for water conservation (SDG 6 – clean water and sanitation), building design, traffic management, and measuring air quality (SDG 13 – climate action). More applications on IoT sensors such as its usage in agriculture to provide farmers with certain information that assists in decision-making (SDG 15 – life on land). The authors in [2] also examined the usage of smart meters to optimize energy efficiency, which is also an important indicator used to access sustainability in 5G network systems. Smart meters can be deployed to measure energy utilization to enhance the usage, and reduce the energy cost (SDG 8 – economic growth), thus improving the energy efficiency factor. On top of this, to ensure that the communications of the IoT sensor networks are efficient and stable, and to overcome the challenges that the IoT networks face when operating in a highly variable and complex environment, the authors in [124] worked on analyzing and predicting the outage probability for these networks. This increases the adaptability of IoT networks to the environment.

Many other factors can enhance sustainability such as boosting the spectrum efficiency, harmonization, and the agreement of the global markets which results in a common factor in the technical specifications and regulatory requirements. This will assist in minimizing the complexity and the cost of deploying 5G worldwide (SDG 8 – economic growth). Further, the interoperability among IoT devices, the enhancement of the procurement policy (SDG 8 – economic growth), and the promotion of building the smart cities, community, and building design, are all key elements in reinforcing sustainability in smart cities (SDG 11 – sustainable cities). However, massive IoT devices in smart cities need a high quality, fast, and reliable connection, which reveals the significant role of 5G in supporting these IoT devices that aid in achieving sustainability [2].

Promoting sustainability in the 5G communication networks was discussed in [8], where different approaches and methodologies were investigated such as utilizing the green 5G technologies to enlarge the spectrum, this included the mmWave technology and the LTE in the unlicensed band. These green technologies will assist in increasing the spectrum and energy efficiency by taking advantage of the extra spectrum. More, the authors listed the green 5G technologies, which reduce the distance between the transmitter and the receiver such as the UDNs and D2D communications [8]. UDNs include small cells [16], which together with D2D communication will facilitate energy saving, specifically for prolonging the duration of the battery of the mobile devices. Further, M-MIMO was inspected in [8] as a green 5G technology to improve the spatial degree of freedom. This technology has an important role in increasing the energy and spectrum efficiency [8], [11]–[15] since it improves the array and multiplexing gain. Another important method to increase the energy efficiency (SDG 7 – clean energy) is by adopting energy harvesting and alternative energy sources such as solar power, fuel cells, and wind power which improves sustainability by reducing the environmental impact, minimizing costs, and assisting in making mobile networks more affordable for the clients [3], [8], [87].

Furthermore, the approach of the life cycle assessment (LCA) of mobiles and smartphones is considerably significant for assessing the influence of 5G on the environment. LCA can be utilized to evaluate the effect that mobile and IoT devices will have on the carbon emissions, from the device manufacture to the energy needed to power on the device and substantially the waste produced when throwing the device into the garbage [88]. Being cognizant of the influence of the emerging technologies on the environment will aid in combating the negative impacts in an effective way [125].

In general, smart cities which are considered applications on the IoT can involve many applications that enhance sustainability, such as e-health, environmental monitoring, smart industry, supply chain management, energy, and water management. Thus, it has the potential to address plenty of the environmental, health, and economical needs of humans. Therefore, it contributes to achieving the objectives of the sustainable development goals (SDGs). The reason is that smart cities can involve a secure, efficient, and effective ecosystem of connected devices to manage the major challenges faced by future generations. We can make use of the IoT technologies to achieve and enhance sustainable development (SDG 11 – sustainable cities) and build a brighter future.

Moreover, the 5G communication network is considered a powerful key enabler for achieving sustainability in smart cities and IoT applications. For example, investing in deploying 5G networks and seizing all the opportunities to build these networks makes it possible to enhance the quality of education as well. A vital approach is to make use of 5G networks to provide an enhanced distance learning opportunity. This will eliminate the necessity for building educational institutions and procuring large land while keeping the procurement limited process to the investment in the 5G technology itself. Remote Education already exists in several countries, but with 5G the quality of education will improve because of the ultra-fast connectivity it offers. This will enable instant interactivity without consuming much energy, which will allow students to participate in live class sessions. Further, utilizing 5G to enhance the quality of distance education will increase the number of qualified teachers available to teach the students. Increasing the quality of education (SDG 4 – quality education), assist in fulfilling other objectives, since increasing the quality of education will increase the number of high-skilled workforces. These highly skilled people will be well prepared to ensure productive employment. This will enhance the economic growth (SDG 8 – economic growth), and make up powerful institutions (SDG 16- strong institutions). Achieving the SDGs is challenging, but with 5G we have a powerful tool, and thus it can be utilized to overcome this challenge. Furthermore, deploying 5G can facilitate the usage of 3D imaging and virtual reality, in addition to enabling surgeons to assist in remote operations (SDG 3 – good health). With 5G connectivity, we can enable remote surgery, remote patient monitoring in addition to training aspiring doctors. Currently, 5G communication networks are anticipated to be significant drivers for IoT and sustainable communities such as smart health, smart transportation, smart manufacturing, and smart grid. The reason is that 5G systems are superior to 4G systems in terms of data rate, latency, mobility, energy efficiency, spectrum efficiency, area traffic capacity, and connection density. However, 5G performance suffers from some drawbacks such as the issues of the small packet size [126], which is considered as a limiting element for increased data rates. Further, the aid for sensing things and communications is confined in 5G networks and additional enhancements are required in this domain [127]. These issues can be solved with 6G network architecture. 6G communications will be able to operate at frequencies in the terahertz and visible spectrum bands, it will support quite a large and wide spectrum. More, 6G networks will be highly energy-efficient, characterized by ultra-low latency

TABLE 3. List of abbreviations.

3D	Three-dimensional	ML	Machine Learning
3G	Third Generation	M-MIMO	Massive Multiple Input Multiple Output
4G	Fourth Generation	mMTC	Massive Machine Type Communication
5G	Fifth Generation	mmWave	Millimeter wave
6G	Sixth Generation	MS	Mobile Station
ABS	Aerial base Station	NB-LPWAN	NarrowBand Low Power Wide Area Network
AMI	Advanced Metering Infrastructure	NFV	Network Function Virtualization
AI	Artificial Intelligence	NOMA	Non-Orthogonal Multiple Access
AR	Augmented Reality	PDR	Peak Data Rate
ATC	Area traffic Capacity	QoS	Quality of Service
AWGN	Additive White Gaussian Noise	RAN	Radio Access Network
BPSK	Binary Phase Shift Keying	RAT	Radio Access Technology
BS	Base Station	RF	Radio Frequency
CO2	Carbon Dioxide	RF-EH	Radio Frequency Energy harvesting
CPMS	Cyberphysical Manufacturing Systems	RTK	Real-Time kinematic
D2D	Device to Device	SDGs	Sustainable Development Goals
DA	Distribution Automation	SDN	Software Defined Network
DER	Distributed Energy Resources	SDR	Software Defined Radio
DL	Deep Learning	SE	Spectrum Efficiency
DR	Demand Response	SWIPT	Simultaneous Wireless Power and Information Transfer
EE	Energy Efficiency	THz	Terahertz
EH	Energy Harvesting	UAV	Unmanned Aerial Vehicle
EHF	Extremely High Frequency	UC	Underground Communication
eMMB	Enhanced Mobile Broadband	UDN	Ultra-Dense Networks
EV	Electric Vehicle	UEDR	User Experienced Data Rate
G2V	Grid to Vehicle	URLLC	Ultra-Reliable Low Latency Communication
GPS	Global Positioning System	V2C	Vehicle-to-Cloud
H2H	Human to Human	V2D	Vehicle-to-Device
IIoT	Industrial IoT	V2G	Vehicle-to-Grid
IoT	Internet of Things	V2I	Vehicle-to-Infrastructure
IoV	Internet of Vehicles	V2P	Vehicle-to-Pedestrian
ITU	International Telecommunication Union	V2V	Vehicle-to-Vehicle
KPIs	Key Performance Indicators	V2X	Vehicle-to-Everything
LCA	Life Cycle Assessment	VPPs	Virtual Power Plants
LoRA	Long Range	VR	Virtual Reality
LoRaWAN	Long Range Low Power Wide Area Network	WAN	Wide Area Network
LPWAN	Low Power Wide Area Network	WiFi	Wireless Fidelity
LTE	Long-Term Evolution	WSN	Wireless Sensor Network
M2M	Machine-To-Machine	WPT	Wireless Power Transfer
MEC	Mobile Edge Computing	MIMO	Multiple Input Multiple Output

which is expected to be a few microseconds, in addition to having global coverage and connectivity due to convergence of ground and space-based wireless communications [128]. Thus, the key drivers for 6G in sustainable IoT systems are the support of considerably high data rates, which is anticipated to attain Tbps, intelligence and automation in wireless communications, which relies on ML and AI, and the more dynamic and robust network architect. All these innovations will aid in meeting the SDGs, and improve the development of novel applications.

Furthermore, the integration of tools such as machine learning (ML), artificial intelligence (AI), and big data will enable the circular economy and enhance the traceability of materials. A circular economy represents an economical model and regenerative system, whose purpose is to lessen the use of resources such as energy, water, and raw materials as well as the production of waste. Thus it sustainably produces services and goods. The exponential growth in digital transformation and wireless communications along with the circular economy adds many environmental, economical, and social benefits. With big data and AI, the efficiency will be improved since smart sensors can tag assets and properties to detect the possible issues, which increases lifecycles. In several domains, such as logistics and manufacturing the geospatial data enables the business to track the pathway and flow of materials. Thus, managing big data with AI can predict the power consumption models and recognize the performance problems.

On top of that, the authors in [123] inspected the role of ML and deep learning (DL) in securing 5G networks and IoT applications, where privacy, security, safety (SDG 15 – life on land), healthcare (SDG 3 – life on land), energy efficiency (SDG 7 – clean energy), and power consumption are important sustainability indicators inspected in this study. IoT connects a massive number of devices where smart living units will operate with minimum human interference. Also, the integration of IoT with other emerging technologies such as block-chain and 5G networks will affect the security and privacy of humans. To cope with this, there is a need to implement security by focusing on communication security, authentication, authorization, encryption, and access control. This calls the need for the use of ML and DL tools that assist in realizing and coping with intelligent security systems. DL algorithms assist in overcoming many challenges in IoT security and pave the way for the amalgamation of IoT with emerging technologies such as edge computing, block-chain, and 5G. Further, the use of ML and AI tools will enable new functionalities and features in 5G that speeds up the implementation. Nowadays, legacy networks are using energy-saving features, which enable a significant reduction in energy consumption (SDG 7 – clean energy) throughout the least traffic hours. In this period, the transmitting power can be reduced, or the equipment can be put into sleep mode. However, there is always a deep pretesting procedure to determine that users do not suffer or experience any outage which is time-consuming. The use of accurate ML algorithms will allow for new features that enable faster deployment. Modern ML and AI technologies such as the RAN Intelligent Controller will allow for new use cases that automatically adjust 5G network configuration parameters to contribute to better QoS, network management, and reduction in energy consumption (SDG 7 – clean energy) [129].

In the future, investigations will be conducted in detail to understand the role of ML and DL in 5G to achieve sustainability, and challenges for B5G and 6G networks to address a sustainable and secure smart city will be inspected as well. Further, explanations on how future communication systems are anticipated to accelerate productivity and economic growth (SDG 8 – decent work and economic growth) will be investigated.

ACKNOWLEDGMENT

The statements herein are the sole responsibility of the authors.

REFERENCES

[1] G. Brundtland, *Report of the World Commission on Environment and Development: Our Common Future*, document A/42/427, United Nations General Assembly, 1987.

[2] D. M. West. (Dec. 2016). *Achieving Sustainability in a 5G World*. [Online]. Available: https://www.brookings.edu/wp-content/uploads/2016/11/gs_20161201_smartcities_paper.pdf

[3] M. Imran, L. U. Khan, I. Yaqoob, E. Ahmed, M. A. Qureshi, and A. Ahmed, ''Energy harvesting in 5G networks: Taxonomy, requirements, challenges, and future directions,'' 2019, *arXiv:1910.00785*.

[4] M. E. Morocho-Cayamcela, H. Lee, and W. Lim, ''Machine learning for 5G/B5G mobile and wireless communications: Potential, limitations, and future directions,'' *IEEE Access*, vol. 7, pp. 137184–137206, 2019, doi: 10.1109/ACCESS.2019.2942390.

[5] K. Sharma and X. Wang, ''Toward massive machine type communications in ultra-dense cellular IoT networks: Current issues and machine learning-assisted solutions,'' *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 426–471, 1st Quart., 2020, doi: 10.1109/COMST.2019.2916177.

[6] G. J. Sutton, J. Zeng, R. P. Liu, W. Ni, D. N. Nguyen, B. A. Jayawickrama, X. Huang, M. Abolhasan, Z. Zhang, E. Dutkiewicz, and T. Lv, ''Enabling technologies for ultra-reliable and low latency communications: From PHY and MAC layer perspectives,'' *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2488–2524, 3rd Quart., 2019, doi: 10.1109/COMST.2019.2897800.

[7] S. Zhang, N. Zhang, S. Zhou, J. Gong, Z. Niu, and X. Shen, ''Energy-sustainable traffic steering for 5G mobile networks,'' *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 54–60, Nov. 2017, doi: 10.1109/MCOM.2017.1700022.

[8] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, ''An overview of sustainable green 5G networks,'' *IEEE Wireless Commun.*, vol. 24, no. 4, pp. 72–80, Aug. 2017, doi: 10.1109/MWC.2017.1600343.

[9] A. Gati, F. E. Salem, A. M. G. Serrano, D. Marquet, S. L. Masson, T. Rivera, D.-T. Phan-Huy, Z. Altman, J.-B. Landre, O. Simon, E. L. Rouzic, F. Bourgart, S. Gosselin, M. Vautier, E. Gourdin, T. En-Najjary, M. El-Tabach, R.-M. Indre, G. Gerard, and G. Delsart, ''Key technologies to accelerate the ICT green evolution—An operator's point of view,'' 2019, *arXiv:1903.09627*.

[10] C. Liu, M. Li, S. V. Hanly, P. Whiting, and I. B. Collings, ''Millimeter-wave small cells: Base station discovery, beam alignment, and system design challenges,'' *IEEE Wireless Commun.*, vol. 25, no. 4, pp. 40–46, Aug. 2018, doi: 10.1109/MWC.2018.1700392.

[11] L. Zhang, H. Zhao, S. Hou, Z. Zhao, H. Xu, X. Wu, Q. Wu, and R. Zhang, ''A survey on 5G millimeter wave communications for UAV-assisted wireless networks,'' *IEEE Access*, vol. 7, pp. 117460–117504, 2019, doi: 10.1109/ACCESS.2019.2929241.

[12] H. Hui, Y. Ding, Q. Shi, F. Li, Y. Song, and J. Yan, ''5G network-based Internet of Things for demand response in smart grid: A survey on application potential,'' *Appl. Energy*, vol. 257, Jan. 2020, Art. no. 113972, doi: 10.1016/j.apenergy.2019.113972.

[13] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, ''An overview of massive MIMO: Benefits and challenges,'' *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 742–758, Oct. 2014, doi: 10.1109/JSTSP.2014.2317671.

[14] A. Salh, L. Audah, N. S. M. Shah, and S. A. Hamzah, ''Improve data rate to mitigate pilot contamination in small-cell massive MIMO systems,'' in *Proc. IEEE Int. RF Microw. Conf. (RFM)*, Dec. 2018, pp. 291–294, doi: 10.1109/RFM.2018.8846533.

[15] K. N. R. S. V. Prasad, E. Hossain, and V. K. Bhargava, ''Energy efficiency in massive MIMO-based 5G networks: Opportunities and challenges,'' *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 86–94, Jun. 2017, doi: 10.1109/MWC.2016.1500374WC.

[16] J. An, K. Yang, J. Wu, N. Ye, S. Guo, and Z. Liao, ''Achieving sustainable ultra-dense heterogeneous networks for 5G,'' *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 84–90, Dec. 2017, doi: 10.1109/MCOM.2017.1700410.

[17] B. N. Silva, M. Khan, and K. Han, ''Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities,'' *Sustain. Soc.*, vol. 38, pp. 697–713, Apr. 2018, doi: 10.1016/j.scs.2018.01.053.

[18] X. Xia, L. Zhang, C. Mei, J. Li, X. Zhu, Y. Liang, and J. Song, ''A survey on 5G network slicing enabling the smart grid,'' in *Proc. IEEE 25th Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2019, pp. 911–916, doi: 10.1109/ICPADS47876.2019.00134.

[19] IHS Markit Technology. (Jun. 2019). *5G Network Slicing Enabling Smart Grid: Commercial Feasibility Analysis*. [Online]. Available: https://pmo32e887-pic2.ysjianzhan.cn/upload/5g-networkslicing-smartgrid-commercial-feasibility-analysis-report-en.pdf

[20] I. Sami, Z. Ullah, K. Salman, I. Hussain, S. M. Ali, B. Khan, C. A. Mehmood, and U. Farid, ''A bidirectional interactive electric vehicles operation modes: Vehicle-to-grid (V2G) and grid-to-vehicle (G2V) variations within smart grid,'' in *Proc. Int. Conf. Eng. Emerg. Technol. (ICEET)*, Feb. 2019, pp. 1–6, doi: 10.1109/CEET1.2019.8711822.

[21] A. Tintelecan, A. C. Dobra, and C. Martis, ''LCA indicators in electric vehicles environmental impact assessment,'' in *Proc. Electr. Vehicles Int. Conf. (EV)*, Oct. 2019, pp. 1–5, doi: 10.1109/EV.2019.8892893.

[22] F. Yang, S. Wang, J. Li, Z. Liu, and Q. Sun, ''An overview of internet of vehicles,'' *China Commun.*, vol. 11, no. 10, pp. 1–15, Oct. 2014, doi: 10.1109/CC.2014.6969789.

[23] H. Chen, T. Zhao, C. Li, and Y. Guo, ''Green internet of vehicles: Architecture, enabling technologies, and applications,'' *IEEE Access*, vol. 7, pp. 179185–179198, 2019, doi: 10.1109/ACCESS.2019.2958175.

[24] M. P. Kumar and K. P. K. Yadav, ''Data security in mobile devices by GEO locking,'' *Int. J. Netw. Secur. Appl.*, vol. 1, no. 3, pp. 52–61, Oct. 2009.

[25] K. Yang, N. Yang, N. Ye, M. Jia, Z. Gao, and R. Fan, ''Non-orthogonal multiple access: Achieving sustainable future radio access,'' *IEEE Commun. Mag.*, vol. 57, no. 2, pp. 116–121, Feb. 2019, doi: 10.1109/MCOM.2018.1800179.

[26] M. S. Hossain and G. Muhammad, ''Emotion-aware connected healthcare big data towards 5G,'' *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2399–2406, Aug. 2018, doi: 10.1109/JIOT.2017.2772959.

[27] J. Lloret, L. Parra, M. Taha, and J. Tomás, "An architecture and protocol for smart continuous eHealth monitoring using 5G," *Comput. Netw.*, vol. 129, pp. 340–351, Dec. 2017, doi: 10.1016/j.comnet.2017.05.018.

[28] M. Peuster, S. Schneider, D. Behnke, M. Müller, P.-B. Bok, and H. Karl, "Prototyping and demonstrating 5G verticals: The smart manufacturing case," in *Proc. IEEE Conf. Netw. Softw. (NetSoft)*, Jun. 2019, pp. 236–238, doi: 10.1109/NETSOFT.2019.8806685.

[29] J. Kim, G. Jo, and J. Jeong, "A novel CPPS architecture integrated with centralized OPC UA server for 5G-based smart manufacturing," *Proc. Comput. Sci.*, vol. 155, pp. 113–120, Jan. 2019, doi: 10.1016/j.procs.2019.08.019.

[30] M. Müller, D. Behnke, P.-B. Bok, M. Peuster, S. Schneider, and H. Karl, "5G as key technology for networked factories: Application of vertical-specific network services for enabling flexible smart manufacturing," in *Proc. IEEE 17th Int. Conf. Ind. Informat. (INDIN)*, Jul. 2019, pp. 1495–1500, doi: 10.1109/INDIN41052.2019.8972305.

[31] J. Cheng, W. Chen, F. Tao, and C.-L. Lin, "Industrial IoT in 5G environment towards smart manufacturing," *J. Ind. Inf. Integr.*, vol. 10, pp. 10–19, Jun. 2018, doi: 10.1016/j.jii.2018.04.001.

[32] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019, doi: 10.1109/MVT.2019.2921208.

[33] A. Salam. (Jan. 2020). *Internet of Things for Sustainable Community Development: Introduction and Overview*. [Online]. Available: https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1025&context=cit_articles

[34] Q.-U.-U. Nadeem, A. Kammoun, A. Chaaban, M. Debbah, and M.-S. Alouini, "Asymptotic max-min SINR analysis of reconfigurable intelligent surface assisted MISO systems," 2019, *arXiv:1903.08127*.

[35] Y.-H. Lee, A.-S. Wang, Y.-D. Liao, T.-W. Lin, Y.-J. Chi, C.-C. Wong, N. Shinohara, Q. Yuan, and Q. Chen, "Wireless power IoT system using polarization switch antenna as polling protocol for 5G mobile network," in *Proc. IEEE Wireless Power Transf. Conf. (WPTC)*, vol. 5, May 2017, pp. 1–3, doi: 10.1109/WPT.2017.7953817.

[36] M. Sinaie, P.-H. Lin, A. Zappone, P. Azmi, and E. A. Jorswieck, "Delay-aware resource allocation for 5G wireless networks with wireless power transfer," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 5841–5855, Jul. 2018, doi: 10.1109/TVT.2018.2800646.

[37] T. D. P. Perera, D. N. K. Jayakody, S. Chatzinotas, and J. Li, "Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 264–302, 1st Quart., 2018, doi: 10.1109/COMST.2017.2783901.

[38] T. K. Vu, M. Bennis, M. Debbah, M. Latva-aho, and C. S. Hong, "Ultra-reliable communication in 5G mmWave networks: A risk-sensitive approach," *IEEE Commun. Lett.*, vol. 22, no. 4, pp. 708–711, Apr. 2018, doi: 10.1109/LCOMM.2018.2802902.

[39] L. Fernandez, J. A. Ruiz-De-Azua, A. Calveras, and A. Camps, "Assessing LoRa for satellite-to-earth communications considering the impact of ionospheric scintillation," *IEEE Access*, vol. 8, pp. 165570–165582, 2020, doi: 10.1109/ACCESS.2020.3022433.

[40] M. Usmonov and F. Gregoretti, "Design and implementation of a LoRa based wireless control for drip irrigation systems," in *Proc. 2nd Int. Conf. Robot. Autom. Eng. (ICRAE)*, Dec. 2017, pp. 248–253, doi: 10.1109/ICRAE.2017.8291389.

[41] F. C. de Oliveira, J. J. P. C. Rodrigues, R. A. L. Rabelo, and S. Mumtaz, "Performance delay comparison in random access procedure for NB-IoT, LoRa, and SigFox IoT protocols," in *Proc. IEEE 1st Sustain. Cities Latin Amer. Conf. (SCLA)*, Aug. 2019, doi: 10.1109/SCLA.2019.8905443.

[42] P. Cousin, F. L. Gall, C. Pham, N. Malaguti, P. Y. Danet, and S. Ziegler, "IoT standards for Africa and sustainable development goals (SDGs)," in *Proc. IST-Africa Week Conf. (IST-Africa)*, 2018, p. 8. [Online]. Available: https://www.egm.io/wp-content/uploads/2020/08/2018-05-IoT-Standards-for-Africa-and-Sustainable-Development-Goals-SDGs.pdf

[43] M. Bacco, L. Boero, P. Cassara, M. Colucci, A. Gotta, M. Marchese, and F. Patrone, "IoT applications and services in space information networks," *IEEE Wireless Commun.*, vol. 26, no. 2, pp. 31–37, Apr. 2019, doi: 10.1109/MWC.2019.1800297.

[44] S. Chandrasekharan, K. Gomez, A. Al-Hourani, S. Kandeepan, T. Rasheed, L. Goratti, L. Reynaud, D. Grace, I. Bucaille, T. Wirth, and S. Allsopp, "Designing and implementing future aerial communication networks," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 26–34, May 2016, doi: 10.1109/MCOM.2016.7470932.

[45] S. Basagni, V. Di Valerio, P. Gjanci, and C. Petrioli, "Finding MARLIN: Exploiting multi-modal communications for reliable and low-latency underwater networking," in *Proc. IEEE INFOCOM*, May 2017, pp. 1–9, doi: 10.1109/INFOCOM.2017.8057132.

[46] E. Demirors, B. G. Shankar, G. E. Santagati, and T. Melodia, "SEANet: A software-defined acoustic networking framework for reconfigurable underwater networking," in *Proc. 10th Int. Conf. Underwater Netw. Syst. (WUWNET)*,. Nov. 2015, pp. 1–8, doi: 10.1145/2831296.2831316.

[47] W. Song, Y. Wang, D. Huang, A. Liotta, and C. Perra, "Enhancement of underwater images with statistical model of background light and optimization of transmission map," *IEEE Trans. Broadcast.*, vol. 66, no. 1, pp. 153–169, Mar. 2020, doi: 10.1109/TBC.2019.2960942.

[48] Y. Wang, W. Song, G. Fortino, L.-Z. Qi, W. Zhang, and A. Liotta, "An experimental-based review of image enhancement and image restoration methods for underwater imaging," *IEEE Access*, vol. 7, pp. 140233–140251, 2019, doi: 10.1109/ACCESS.2019.2932130.

[49] I. F. Akyildiz and E. P. Stuntebeck, "Wireless underground sensor networks: Research challenges," *Ad Hoc Netw.*, vol. 4, no. 6, pp. 669–686, Nov. 2006, doi: 10.1016/j.adhoc.2006.04.003.

[50] M. C. Vuran and I. F. Akyildiz, "Channel model and analysis for wireless underground sensor networks in soil medium," *Phys. Commun.*, vol. 3, no. 4, pp. 245–254, Jul. 2010, doi: 10.1016/j.phycom.2010.07.001.

[51] A. Salam and M. C. Vuran, "Smart underground antenna arrays: A soil moisture adaptive beamforming approach," in *Proc. IEEE INFOCOM*, May 2017, pp. 1–9, doi: 10.1109/INFOCOM.2017.8056990.

[52] R. Gravina, C. Palau, M. Manso, A. Liotta, and G. Fortino, *Integration, Interconnection, and Interoperability of IoT Systems*. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-61300-0.

[53] M. A. Akkaş and R. Sokullu, "Wireless underground sensor networks: Channel modeling and operation analysis in the terahertz band," *Int. J. Antennas Propag.*, vol. 2015, pp. 1–12, Jan. 2015, doi: 10.1155/2015/780235.

[54] M. J. Tiusanen, "Soil scouts: Description and performance of single hop wireless underground sensor nodes," *Ad Hoc Netw.*, vol. 11, no. 5, pp. 1610–1618, Jul. 2013, doi: 10.1016/j.adhoc.2013.02.002.

[55] I. F. Akyildiz, Z. Sun, and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," *Phys. Commun. J.*, vol. 2, no. 3, pp. 167–183, Sep. 2009, doi: 10.1016/j.phycom.2009.03.004.

[56] X. Dong, M. C. Vuran, and S. Irmak, "Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems," *Ad Hoc Netw.*, vol. 11, no. 7, pp. 1975–1987, Sep. 2013, doi: 10.1016/j.adhoc.2012.06.012.

[57] A. Salam and M. C. Vuran, "Impacts of soil type and moisture on the capacity of multi-carrier modulation in internet of underground things," in *Proc. 25th Int. Conf. Comput. Commun. Netw. (ICCCN)*, Aug. 2016, pp. 1–9, doi: 10.1109/ICCCN.2016.7568532.

[58] A. Salam, M. C. Vuran, and S. Irmak, "Towards internet of underground things in smart lighting: A statistical model of wireless underground channel," in *Proc. IEEE 14th Int. Conf. Netw., Sens. Control (ICNSC)*, May 2017, pp. 574–579, doi: 10.1109/ICNSC.2017.8000155.

[59] A. Salam and M. C. Vuran, "Wireless underground channel diversity reception with multiple antennas for internet of underground things," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–7, doi: 10.1109/ICC.2017.7996893.

[60] A. Salam, M. C. Vuran, and S. Irmak, "Pulses in the sand: Impulse response analysis of wireless underground channel," in *Proc. IEEE INFOCOM*, Apr. 2016, pp. 1–9, doi: 10.1109/INFOCOM.2016.7524457.

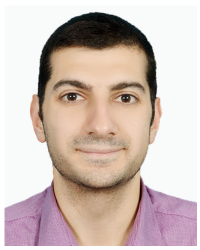
[61] S. Zhang, X. Cai, W. Zhou, and Y. Wang, "Green 5G enabling technologies: An overview," *IET Commun.*, vol. 13, no. 2, pp. 135–143, Jan. 2019, doi: 10.1049/iet-com.2018.5448.

[62] J. A. Lazaro, S. Spadaro, J. Perello, J. Gene, J. A. Altabas, A. Pages, D. Careglio, P. Barlet-Ros, A. Cabellos, and J. Sole-Pareta, "SUNSET: Sustainable network infrastructure enabling the future digital society," in *Proc. 18th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2016, pp. 1–6, doi: 10.1109/ICTON.2016.7550420.

[63] S. Buzzi, I. Chih-Lin, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A survey of energy-efficient techniques for 5G networks and challenges ahead," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 697–709, Apr. 2016, doi: 10.1109/JSAC.2016.2550338.

[64] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang, and D. Zhang, "A survey on green 6G network: Architecture and technologies," *IEEE Access*, vol. 7, pp. 175758–175768, 2019, doi: 10.1109/ACCESS.2019.2957648.
[65] J. Lorincz, A. Capone, and J. Wu, "Greener, energy-efficient and sustainable networks: State-of-the-art and new trends," *Sensors*, vol. 19, no. 22, p. 4864, Nov. 2019, doi: 10.3390/s19224864.
[66] L. D. Nguyen, "Resource allocation for energy efficiency in 5G wireless networks," *EAI Endorsed Trans. Ind. Netw. Intell. Syst.*, vol. 5, no. 14, Jun. 2018, Art. no. 154832, doi: 10.4108/eai.27-6-2018.154832.
[67] H. Yu, H. Lee, and H. Jeon, "What is 5G? Emerging 5G mobile services and network requirements," *Sustainability*, vol. 9, no. 10, pp. 1–22, Oct. 2017, doi: 10.3390/su9101848.
[68] X. Liu, X. Zhang, M. Jia, L. Fan, W. Lu, and X. Zhai, "5G-based green broadband communication system design with simultaneous wireless information and power transfer," *Phys. Commun.*, vol. 28, pp. 130–137, Jun. 2018, doi: 10.1016/j.phycom.2018.03.015.
[69] C. L. Russell, "5G wireless telecommunications expansion: Public health and environmental implications," *Environ. Res.*, vol. 165, pp. 484–495, Aug. 2018, doi: 10.1016/j.envres.2018.01.016.
[70] S. K. Routray and K. P. Sharmila, "Green initiatives in 5G," in *Proc. 2nd Int. Conf. Adv. Electr., Electron., Inf., Commun. Bio-Informat. (AEEICB)*, Feb. 2016, pp. 617–621, doi: 10.1109/AEEICB.2016.7538363.
[71] S. Beloe. (Jan. 28, 2019). *WHEB Asset Management Quarterly Report*. [Online]. Available: http://www.whebgroup.com/5g-and-sustainability/
[72] X. Huang, R. Yu, J. Kang, Y. Gao, S. Maharjan, S. Gjessing, and Y. Zhang, "Software defined energy harvesting networking for 5G green communications," *IEEE Wireless Commun.*, vol. 24, no. 4, pp. 38–45, Aug. 2017, doi: 10.1109/MWC.2017.1600360.
[73] M. M. Mowla, I. Ahmad, D. Habibi, and Q. V. Phung, "Energy efficient backhauling for 5G small cell networks," *IEEE Trans. Sustain. Comput.*, vol. 4, no. 3, pp. 279–292, Jul./Sep. 2019, doi: 10.1109/TSUSC.2018.2838116.
[74] C. Garau and V. Pavan, "Evaluating urban quality: Indicators and assessment tools for smart sustainable cities," *Sustainability*, vol. 10, no. 3, p. 575, Feb. 2018, doi: 10.3390/su10030575.
[75] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30–37, Jun. 2011, doi: 10.1109/MCOM.2011.5783982.
[76] S. K. Rao and R. Prasad, "Impact of 5G technologies on smart city implementation," *Wireless Pers. Commun.*, vol. 100, no. 1, pp. 161–176, May 2018, doi: 10.1007/s11277-018-5618-4.
[77] N. Nkordeh, A. Ayoola, O. Bankole, O. Oludotun, E. Nwabueze, and O. P. Chidi, "Green computing: Towards sustainable 5G network deployment," in *Proc. World Congr. Eng. Comput. Sci. (WCECS)*, San Francisco, CA, USA, Oct. 2019, pp. 1–4, [Online]. Available: http://www.iaeng.org/publication/WCECS2019/WCECS2019_pp140-143.pdf
[78] D. Petrova-Antonova and S. Ilieva, "Smart cities evaluation—A survey of performance and sustainability indicators," in *Proc. 44th Euromicro Conf. Softw. Eng. Adv. Appl. (SEAA)*, Aug. 2018, pp. 486–493, doi: 10.1109/SEAA.2018.00084.
[79] C. Rowell, S. Han, Z. Xu, and I. Chih Lin, "Green RF technologies for 5G networks," in *Proc. IEEE Int. Wireless Symp. (IWS)*, Mar. 2014, pp. 1–4, doi: 10.1109/IEEE-IWS.2014.6864188.
[80] M. Masoudi *et al.*, "Green mobile networks for 5G and beyond," *IEEE Access*, vol. 7, pp. 107270–107299, 2019, doi: 10.1109/ACCESS.2019.2932777.
[81] R. N. Mitra and D. P. Agrawal, "5G mobile technology: A survey," *ICT Exp.*, vol. 1, no. 3, pp. 132–137, 2015, doi: 10.1016/j.icte.2016.01.003.
[82] N. Piovesan, A. F. Gambin, M. Miozzo, M. Rossi, and P. Dini, "Energy sustainable paradigms and methods for future mobile networks: A survey," *Comput. Commun.*, vol. 119, pp. 101–117, Apr. 2018, doi: 10.1016/j.comcom.2018.01.005.
[83] Z. Zheng, X. Zhang, L. Cai, R. Zhang, and X. Shen, "Sustainable communication and networking in two-tier green cellular networks," *IEEE Wireless Commun.*, vol. 21, no. 4, pp. 47–53, Aug. 2014, doi: 10.1109/MWC.2014.6882295.
[84] S. Din, A. Ahmad, A. Paul, and S. Rho, "MGR: Multi-parameter green reliable communication for Internet of Things in 5G network," *J. Parallel Distrib. Comput.*, vol. 118, pp. 34–45, Aug. 2018, doi: 10.1016/j.jpdc.2017.12.012.
[85] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016, doi: 10.1109/COMST.2016.2532458.
[86] A. Georgakopoulos, A. Margaris, K. Tsagkaris, and P. Demestichas, "Resource sharing in 5G contexts: Achieving sustainability with energy and resource efficiency," *IEEE Veh. Technol. Mag.*, vol. 11, no. 1, pp. 40–49, Mar. 2016, doi: 10.1109/MVT.2015.2508319.
[87] A. Kumar, T. Singh, and S. G. Singh, "Sustainability in wireless mobile communication networks through alternative energy resources," *Int. J. Comput. Sci. Technol.*, vol. 1, no. 2, pp. 196–201, Dec. 2010. [Online]. Available: http://nebula.wsimg.com/237387d4d8b10649bda67045177838ce?AccessKeyId=E9CCDB3A313FC4FEB6A2&disposition=0&alloworigin=1
[88] E. M. Ercan, "Global warming potential of a smartphone: Using life cycle assessment methodology," Ph.D. dissertation, 2013.
[89] Z. Allam and Z. A. Dhunny, "On big data, artificial intelligence and smart cities," *Cities*, vol. 89, pp. 80–91, Jun. 2019, doi: 10.1016/j.cities.2019.01.032.
[90] E. O'Dwyer, I. Pan, S. Acha, and N. Shah, "Smart energy systems for sustainable smart cities: Current developments, trends and future directions," *Appl. Energy*, vol. 237, no. 1, pp. 581–597, Mar. 2019, doi: 10.1016/j.apenergy.2019.01.024.
[91] Y. Wang, H. Ren, L. Dong, H.-S. Park, Y. Zhang, and Y. Xu, "Smart solutions shape for sustainable low-carbon future: A review on smart cities and industrial parks in China," *Technol. Forecasting Social Change*, vol. 144, pp. 103–117, Jul. 2019, doi: 10.1016/j.techfore.2019.04.014.
[92] A. H. Sodhro, S. Pirbhulal, Z. Luo, and V. H. C. de Albuquerque, "Towards an optimal resource management for IoT based green and sustainable smart cities," *J. Cleaner Prod.*, vol. 220, pp. 1167–1179, May 2019, doi: 10.1016/j.jclepro.2019.01.188.
[93] S. Jamil, F. Khan, M. S. Abbas, M. Umair, and Y. Hussain, "A review of techniques and challenges in green communication," in *Proc. Int. Conf. Inf. Sci. Commun. Technol. (ICISCT)*, Feb. 2020, pp. 7–12, doi: 10.1109/ICISCT49550.2020.9080018.
[94] R. Ruggieri, M. Ruggeri, and G. Vinci, "Efficient energy and electric transport in a smart city: Evaluation of sustainability and competitivness," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I CPS Europe)*, Jun. 2020, pp. 31–34, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160676.
[95] E. Chang, S. Bahramirad, and D. Kushner, "Electric utilities' role in promoting and advancing smart city solutions," in *Proc. IEEE Conf. Technol. Sustainability (SusTech)*, Apr. 2020, pp. 1–5, doi: 10.1109/SusTech47890.2020.9150484.
[96] M. A. Ahad, S. Paiva, G. Tripathi, and N. Feroz, "Enabling technologies and sustainable smart cities," *Sustain. Cities Soc.*, vol. 61, Oct. 2020, Art. no. 102301, doi: 10.1016/j.scs.2020.102301.
[97] M. A. Inamdar and H. V. Kumaraswamy, "Energy efficient 5G networks: Techniques and challenges," in *Proc. Int. Conf. Smart Electron. Commun. (ICOSEC)*, Sep. 2020, pp. 1317–1322, doi: 10.1109/ICOSEC49089.2020.9215362.
[98] P. Jain and A. Gupta, "Energy-efficient adaptive sectorization for 5G green wireless communication systems," *IEEE Syst. J.*, vol. 14, no. 2, pp. 2382–2391, Jun. 2020, doi: 10.1109/JSYST.2019.2927718.
[99] J. Wu, S. Guo, H. Huang, W. Liu, and Y. Xiang, "Information and communications technologies for sustainable development goals: State-of-the-art, needs and perspectives," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2389–2406, 3rd Quart., 2018, doi: 10.1109/COMST.2018.2812301.
[100] Y.-N.-R. Li, M. Chen, J. Xu, L. Tian, and K. Huang, "Power saving techniques for 5G and beyond," *IEEE Access*, vol. 8, pp. 108675–108690, 2020, doi: 10.1109/ACCESS.2020.3001180.
[101] A. H. Sodhro, S. Pirbhulal, G. H. Sodhro, M. Muzammal, L. Zongwei, A. Gurtov, A. R. L. de Macedo, L. Wang, N. M. Garcia, and V. H. C. de Albuquerque, "Towards 5G-enabled self adaptive green and reliable communication in intelligent transportation system," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 8, pp. 5223–5231, Aug. 2021, doi: 10.1109/TITS.2020.3019227.
[102] A. Akande, P. Cabral, and S. Casteleyn, "Understanding the sharing economy and its implication on sustainability in smart cities," *J. Cleaner Prod.*, vol. 277, Dec. 2020, Art. no. 124077, doi: 10.1016/j.jclepro.2020.124077.
[103] S. Popli, R. K. Jha, and S. Jain, "A comprehensive survey on green ICT with 5G-NB-IoT: Towards sustainable planet," *Comput. Netw.*, vol. 199, Nov. 2021, Art. no. 108433, doi: 10.1016/j.comnet.2021.108433.

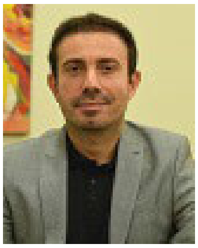
[104] E.-C. Liou and S.-C. Cheng, ''A QoS benchmark system for telemedicine communication over 5G uRLLC and mMTC scenarios,'' in *Proc. IEEE 2nd Eurasia Conf. Biomed. Eng., Healthcare Sustainability (ECBIOS)*, May 2020, pp. 24–26, doi: 10.1109/ECBIOS50299.2020.9203639.
[105] P. Gandotra and R. K. Jha, ''A survey on green communication and security challenges in 5G wireless communication networks,'' *J. Netw. Comput. Appl.*, vol. 96, pp. 39–61, Oct. 2017, doi: 10.1016/j.jnca.2017.07.002.
[106] Y. Guan, Y. Wu, and M. M. Tentzeris, ''A bidirectional absorptive common-mode filter based on interdigitated microstrip coupled lines for 5G 'green' communications,'' *IEEE Access*, vol. 8, pp. 20759–20769, 2020, doi: 10.1109/ACCESS.2020.2968931.
[107] S. Jamil, F. Khan, M. S. Abbas, M. Umair, and Y. Hussain, ''A review of techniques and challenges in green communication,'' in *Proc. Int. Conf. Inf. Sci. Commun. Technol. (ICISCT)*, Feb. 2020, pp. 1–6, doi: 10.1109/ICISCT49550.2020.9080018.
[108] D. Sharma, S. Singhal, A. Rai, and A. Singh, ''Analysis of power consumption in standalone 5G network and enhancement in energy efficiency using a novel routing protocol,'' *Sustain. Energy, Grids Netw.*, vol. 26, Jun. 2021, Art. no. 100427, doi: 10.1016/j.segan.2020.100427.
[109] R. Bolla, R. Bruschi, F. Davoli, C. Lombardo, and J. F. Pajo, ''Debunking the 'green' NFV myth: An assessment of the virtualization sustainability in radio access networks,'' in *Proc. 6th IEEE Conf. Netw. Softw. (NetSoft)*, Jun. 2020, pp. 180–184, doi: 10.1109/NetSoft48620.2020.9165481.
[110] A. Srivastava, M. S. Gupta, and G. Kaur, ''Energy efficient transmission trends towards future green cognitive radio networks (5G): Progress, taxonomy and open challenges,'' *J. Netw. Comput. Appl.*, vol. 168, Oct. 2020, Art. no. 102760, doi: 10.1016/j.jnca.2020.102760.
[111] H. Heidari, O. Onireti, R. Das, and M. Imran, ''Energy harvesting and power management for IoT devices in the 5G era,'' *IEEE Commun. Mag.*, vol. 59, no. 9, pp. 91–97, Sep. 2021, doi: 10.1109/MCOM.101.2100487.
[112] P. Gandotra and B. Lall, ''Evolving air pollution monitoring systems for green 5G: From cloud to edge,'' in *Proc. 8th Int. Conf. Rel., Infocom Technol. Optim., Trends Future Directions (ICRITO)*, Jun. 2020, pp. 1231–1235, doi: 10.1109/ICRITO48877.2020.9197950.
[113] S. Zhang, S. Xu, G. Y. Li, and E. Ayanoglu, ''First 20 years of green radios,'' *IEEE Trans. Green Commun. Netw.*, vol. 4, no. 1, pp. 1–15, Mar. 2020, doi: 10.1109/TGCN.2019.2934531.
[114] Z. Allam and D. S. Jones, ''Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies,'' *Land Use Policy*, vol. 101, Feb. 2021, Art. no. 105201, doi: 10.1016/j.landusepol.2020.105201.
[115] M. Wang and Q. Yang, ''WITHDRAWN: Green building design based on 5G network and Internet of Things system,'' *Microprocessors Microsystems*, Nov. 2020, Art. no. 103386, doi: 10.1016/j.micpro.2020.103386.
[116] Y. I. A. Al-Yasir, A. M. Abdulkhaleq, N. O. Parchin, I. T. Elfergani, J. Rodriguez, J. M. Noras, R. A. Abd-Alhameed, A. Rayit, and R. Qahwaji, ''Green and highly efficient MIMO transceiver system for 5G heterogenous networks,'' *IEEE Trans. Green Commun. Netw.*, early access, Jul. 27, 2021, doi: 10.1109/TGCN.2021.3100399.
[117] M. A. Albreem, A. M. Sheikh, M. H. Alsharif, M. Jusoh, and M. N. M. Yasin, ''Green Internet of Things (GIoT): Applications, practices, awareness, and challenges,'' *IEEE Access*, vol. 9, pp. 38833–38858, 2021, doi: 10.1109/ACCESS.2021.3061697.
[118] S. Han, T. Xie, and I. Chih-Lin, ''Greener physical layer technologies for 6G mobile communications,'' *IEEE Commun. Mag.*, vol. 59, no. 4, pp. 68–74, Apr. 2021, doi: 10.1109/MCOM.001.2000484.
[119] H. Kour and R. K. Jha, ''Half-duplex radio: Toward green 5G NR,'' *IEEE Consum. Electron. Mag.*, vol. 9, no. 6, pp. 34–40, Nov. 2020, doi: 10.1109/MCE.2020.2993105.
[120] M. Wang and Y. Hao, ''Key technologies of green communication for 5G mobile network,'' in *Proc. IEEE Int. Conf. Electron. Technol., Commun. Inf. (ICETCI)*, Aug. 2021, pp. 101–104, doi: 10.1109/ICETCI53161.2021.9563409.
[121] A. Israr, Q. Yang, W. Li, and A. Y. Zomaya, ''Renewable energy powered sustainable 5G network infrastructure: Opportunities, challenges and perspectives,'' *J. Netw. Comput. Appl.*, vol. 175, Feb. 2021, Art. no. 102910, doi: 10.1016/j.jnca.2020.102910.
[122] D. Pradhan, P. K. Sahu, A. Dash, and H. M. Tun, ''Sustainability of 5G green network toward D2D communication with RF-energy techniques,'' in *Proc. Int. Conf. Intell. Technol. (CONIT)*, Jun. 2021, pp. 1–10, doi: 10.1109/CONIT51480.2021.9498298.
[123] P. Sharma, S. Jain, S. Gupta, and V. Chamola, ''Role of machine learning and deep learning in securing 5G-driven industrial IoT applications,'' *Ad Hoc Netw.*, vol. 123, Dec. 2021, Art. no. 102685.
[124] L. Xu, X. Yu, and T. A. Gulliver, ''Intelligent outage probability prediction for mobile IoT networks based on an IGWO-Elman neural network,'' *IEEE Trans. Veh. Technol.*, vol. 70, no. 2, pp. 1365–1375, Feb. 2021, doi: 10.1109/TVT.2021.3051966.
[125] S. E. Bibri, ''A novel model for data-driven smart sustainable cities of the future: The institutional transformations required for balancing and advancing the three goals of sustainability,'' *Energy Informat.*, vol. 4, no. 1, pp. 1–37, Dec. 2021, doi: 10.1186/s42162-021-00138-8.
[126] S. E. Bibri, ''Data-driven smart sustainable cities of the future: Urban computing and intelligence for strategic, short-term, and joined-up planning,'' *Comput. Urban Sci.*, vol. 1, no. 1, pp. 1–29, Dec. 2021. [Online]. Available: https://link.springer.com/article/10.1007/s43762-021-00008-9.
[127] S. E. Bibri, ''The core academic and scientific disciplines underlying data-driven smart sustainable urbanism: An interdisciplinary and transdisciplinary framework,'' *Comput. Urban Sci.*, vol. 1, no. 1, pp. 1–32, Dec. 2021. [Online]. Available: https://link.springer.com/article/10.1007/s43762-021-00001-2
[128] S. E. Bibri. (2021). *A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Planning Process of Transformative Change towards Sustainability*. [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2763017
[129] Telefónica. (Nov. 29, 2021). *How to Deploy an Environmentally Sustainable 5G?* Accessed: Dec. 3, 2021. [Online]. Available: https://www.telefonica.com/en/communication-room/blog/how-to-deploy-an-environmentally-sustainable-5g/



MUHAMMAD J. SHEHAB (Member, IEEE) was born in Ra's-Beirut, Beirut, Lebanon, in April 1985. He received the Bachelor of Engineering (B.E.) and the Master of Electrical/Communication and Electronics Engineering (M.E.) degrees from Beirut Arab University (BAU), Beirut, in 2007 and 2011, respectively, and the Doctor of Philosophy (Ph.D.) degree in wireless communication from the Department of Electronics and Telecommunications, Politecnico di Torino (POLITO). In 2013, he joined the Department of Information Technology, Community College of Qatar (CCQ), as a Network Engineer and a Lecturer till date. Then, he joined the Faculty of Electrical Engineering, Qatar University (QU), Qatar, in 2018. His research interests include 5G, 6G networks, non-orthogonal multiple access (NOMA), intelligent reflecting surface (IRS), mmWave, THz, massive MIMO, beamforming, machine learning (ML), deep reinforcement learning (DRL), long range (LoRA), satellite, and sustainability in 5G networks and smart cities. He has actively collaborated with researchers inside Italy, Qatar, and abroad.

IHAB KASSEM is currently pursuing the Ph.D. degree in computer science with Qatar University. He is working on machine learning, the Internet of Things, and information security. He is also working as a E-Channel Application Specialist in banking sector, also managing a lot of e-banking projects, and he is supporting many different financial systems. In a recently published article, he was discussing elapsed time in ECG devices using the different Internet of Things application protocols and he is working on another review article to predict credit card fraud using a hybrid machine learning approach.

ADEEB A. KUTTY received the B.E. degree in electrical and electronics engineering from the University of Calicut, India, and the M.S. degree in technology and engineering management (MTEM) from the Universitat Rovira I Virgili, Tarragona, Spain, in 2018. He is currently pursuing the Ph.D. degree in engineering management with a focus on smart and sustainable cities with Qatar University, Doha, Qatar. Before joining Qatar University as a Sustainability Researcher, he was working as a Junior Scientist in the area of sustainable industrial systems and green supply chain optimization at the SUSCAPE Research Institute, Tarragona, till 2018. His research interests include smart cities, e-mobility, circular economy, sharing economy, food security, and sustainability. His recent paper in 2020 ''An Empirical Assessment on the Transportation Sustainability Indicators and Their Impact on Economic Productivity'' received the Best Paper Award under sustainability track in the North American International Conference on Industrial Engineering (IEOM), USA.



MURAT KUCUKVAR is currently with the Faculty of Industrial and Systems Engineering, Qatar University, and working on quantitative sustainability assessment, particularly social, economic, and environmental sustainability assessment. In the past, he also established the Sustainable Systems and Solutions Laboratory, City University of Istanbul, and many of his graduate students worked on the regional and global sustainability assessment of energy, manufacturing, and transportation sectors. In a recent review article, he was also ranked among the world's ranked scientists for the research related to carbon footprint analysis and global climate change impacts of energy and manufacturing supply chains. He published in several interdisciplinary journals, such as *Energy*, *Applied Energy*, *Energy Conversion and Management*, *Renewable and Sustainable Energy Reviews*, and *Journal of Industrial Ecology*, which is among the highly cited journals in the field of energy, environment, and sustainability. He is also managing over 2 $M value of projects related to e-mobility and sustainability assessment, obtained from the QNRF and industry partners. He is recently listed among the top 1% scientists in the world in the fields of energy, environmental and earth sciences, and sustainability, according to the global ranking published by Stanford University, USA.

NURI ONAT currently works as an Assistant Professor with the Qatar Transportation and Traffic Safety Center, Qatar University. He previously worked as an Assistant Professor and a Graduate Program Co-ordinator with the Department of Industrial Engineering. He is also the Co-Founder and the Co-Director of the Sustainable Systems and Solutions Laboratory (S3-Laboratory) (https://sustainabilitylab.herokuapp.com/index.html), Istanbul Sehir University, Turkey. He is also a Senior Sustainability Fellow at the Global Institute of Sustainability, Arizona State University, USA. His active research efforts are awarded by several global competitive fellowship programs, such as Walton Sustainability Fellowship with Arizona State University, Australian Endeavour Research Fellowship with the University of Queensland, Achievement Award from the University of Florida, and Fulbright. He has over 60 publications (journal plus conference) in various topics: sustainability assessment, sustainable mobility, system dynamics, and electric vehicles. He has been actively involved in many international research and industry-related projects encompassing contemporary issues related to sustainability assessment.

TAMER KHATTAB (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees in electronics and communications engineering from Cairo University, Giza, Egypt, and the Ph.D. degree in electrical and computer engineering from The University of British Columbia (UBC), Vancouver, BC, Canada, in 2007. From 1994 to 1999, he was with IBM WTC, Giza, as a Development Team Member, then a Development Team Lead. From 2000 to 2003, he was with Nokia (formerly Alcatel Canada Inc.), Burnaby, BC, as a Senior Member of the Technical Staff. From 2006 to 2007, he was a Postdoctoral Fellow with The University of British Columbia, where he was involved in prototyping advanced Gbits/sec wireless LAN baseband transceivers. He joined Qatar University (QU), in 2007, where he is currently a Professor of electrical engineering. He is also a Senior Member of the Technical Staff with the Qatar Mobility Innovation Center (QMIC). In addition to more than 150 high-profile academic journal and conference publications, he has several published and pending patents. His research interests include physical layer security techniques, information-theoretic aspects of communication systems, radar, and RF sensing techniques and optical communication. He serves as an Editor for the IEEE Communications Letters and an Editor for the IEEE Open Journal of the Communications Society.