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Original
The Role of 5G/6G Networks in Building Sustainable and Energy-Efficient Smart Cities / Shehab, Muhammad; Khattab, Tamer; Kucukvar, Murat; Trinchero, Daniele. - ELETTRONICO. - (2022), pp. 1-7. (Intervento presentato al convegno 2022 IEEE 7th International Energy Conference (ENERGYCON) tenutosi a Riga, Latvia nel 09-12 May 2022) [10.1109/ENERGYCON53164.2022.9830364].

Availability:
This version is available at: 11583/2970715 since: 2022-10-05T09:39:01Z

Publisher:
IEEE

Published
DOI:10.1109/ENERGYCON53164.2022.9830364

(Article begins on next page)

The Role of 5G/6G Networks in Building Sustainable and Energy-Efficient Smart Cities

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***Abstract*—Future wireless networks aim to provide high-energy efficiency, high spectral efficiency, low cost, and support a massive number of connected devices in prospect the evolution of Internet of Things (IoT) and smart cities. This calls for an immediate need to inspect sustainability in future wireless networks, and how can these networks be energy-efficient and environmentally friendly. The goal of this article is to investigate the role of future communication systems in building sustainable and energy-efficient smart cities. An overview of 5G / 6G networks, their KPIs, and use cases will be presented. This is followed by discussing the use cases served by these networks, green 5G / 6G technologies, and sustainability indicators. We will discuss the recent research studies on green technologies such as energy harvesting and their sustainability measures across the economic, environmental, and social dimensions. Finally, we will identify potential solutions and research directions to optimize sustainability in future wireless communications.**

***Index Terms*—Energy Harvesting, Energy Efficiency, 5G, 6G, IRS, NOMA, Sustainable Development, Smart Cities, Internet of things.**

I. Introduction

ACHIEVING sustainability is one of the research hotspots in the future radio networks, due to the exponential growth of wireless technologies and the enormous evolution in the users' demand. With the tremendous development in the field of wireless communication systems, future networks are anticipated to support higher energy and spectral efficiencies, lower power consumption, reduced latencies, higher capacities, and an immense number of network connections, inter alia other merits. This enables future networks to serve many smart cities' applications that includes smart healthcare, smart agriculture, smart grid, smart manufacturing, smart education, and smart transportation. Based on this, 5G / 6G networks are expected to be key enablers for energy-efficient and sustainable smart cities. These networks are fueled with green technologies like green IoT, energy harvesting, renewable energy sources, intelligent reflecting surfaces (IRSs), non-orthogonal multiple access (NOMA), simultaneous wireless information and power transfer (SWIPT), mmWaves, terahertz (THz), massive MIMO, beamforming, ultra-dense networks (UDNs), and device-to-device (D2D) technology. Green 5G / 6G technologies are environment friendly, and fundamental elements in increasing the energy and spectral efficiencies, boosting capacities and data rates, minimizing the power consumption, reducing the delay and CO2 emissions, to preserving public health, safety, and security [1]–[3]. The strict requirements along with the key performance indicators (KPIs) that the 5G/6G communication systems are anticipated to meet, made sustainability a fundamental factor for the forthcoming communication schemes and a research priority in this field. To this end, understanding sustainability challenges in smart cities and future networks is substantial to minimize their effects, and find out a scheme to employ 5G/6G green technologies to foster sustainability and increase energy efficiency in smart cities.

In this article, our objective is to inspect the role of 5G and 6G networks in achieving sustainable development goals (SDGs) and building sustainable and energy-efficient smart cities. First, we present the 5G / 6G KPIs, requirements, and main services. Then, we demonstrate the use cases served by 5G / 6G networks. Further, we investigate the green enabling technologies in 5G / 6G and their role in achieving the sustainability indicators. Based on this, we will have a roadmap of the technologies that enable green future networks. Finally, we identify and examine future research work to further increase sustainability in future communication systems. The structure of this research article is demonstrated in Fig 2. Our main

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contributions in this work can be listed as follows:

- An unprecedented methodological article that examines the entire sustainability motif covering the environmental, economical, and social pillars of sustainability in 5G and 6G communication network schemes.
- The majority of the research papers in the literature studied the importance of 5G and 6G networks and their relevance of transforming cities into smart components. Nevertheless, no articles have yet highlighted the role of 5G and 6G communication systems as fundamental enablers in converting cities to smart sustainable units.
- The article exhibits a broad coverage of sustainability subindicators related to 5G/6G networks, where the majority of the studies focused on the environmental, and socio-economic sustainability indicators without covering the subindicators such as energy efficiency, power consumption, health, safety, security, etc.

II. Overview of 5G/6G Networks and Main Services

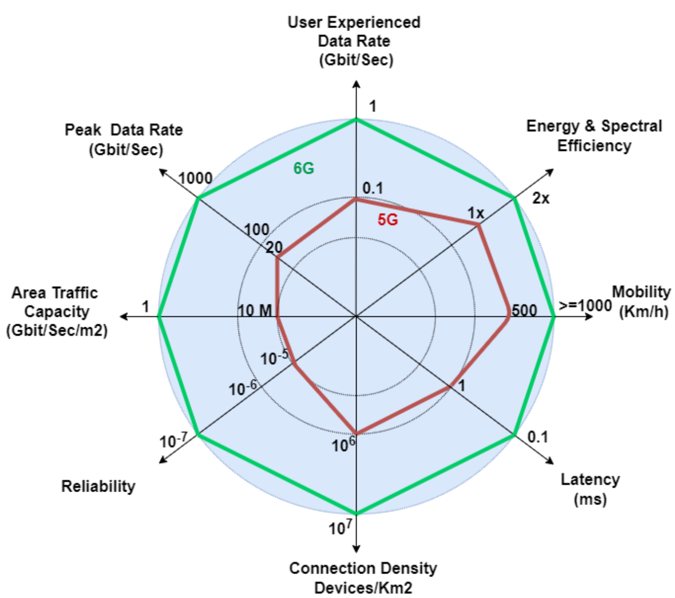

Fig. 1: 5G vs 6G key performance indicators.

Global efforts are in progress to increase the network and energy efficiency of future networks and minimize carbon emissions. The adoption of sustainable methodologies which involves energy harvesting and renewable energy sources has a tremendous positive impact on the environment, development, and growth. Future communication networks enable a new set of industry practices and green technologies that will lead to more energy-efficient and environment-friendly networks. Table I and Fig 1 reveal the key performance indicators (KPIs) for 5G networks compared to the next generation 6G as specified by the ITU. Table II shows the fundamental KPIs needed for 5G and 6G main services. Supporting all these KPIs altogether is challenging, various use cases and services will demand to meet various combinations of KPIs in 6G networks [4]. Although the 5G scenarios are different from others, and each scenario has its features, but most of the 5G applications and services can be grouped into one of the following categories:

TABLE I: Comparison between 5G and 6G KPIs

KPIs	5G Networks	6G Networks
Peak Data Rate	20 Gb/s	1 Tb/s
Maximum Bandwidth	1 GHz	100 GHz
Mobility	500 Km/h	$\geq$ 1000 Km/h
Peak Spectral Efficiency	1x (30 b/s/Hz)	2x (60 b/s/Hz)
Energy Efficiency	1x	2x (1 pJ/b)
Experienced Data Rate	0.1 Gb/s	1 Gb/s
Area Traffic Capacity	10 Mb/s/m^2	1 Gb/s/m^2
Latency	1 ms	10 to 100 µs
Jitter	Not Mentioned	1 µs
Connection Density	10^6 devices/Km^2	10^7 devices/Km^2
Reliability	10^{-5}	10^{-7}

A. Enhance Mobile Broadband (eMBB)

eMBB provides high data rates, high throughput, and large bandwidth. This enables a huge amount of traffic and data transfer, which makes this use case significant for complex visual solutions and applications like virtual reality (VR), and augmented reality (AR).

B. Massive Machine Type Communication (mMTC)

mMTC is utilized for communication among devices. This enables up to 10^5 connections per km^2, and it is important for the industrial applications and automation of production operations. A massive amount of devices, and low-power, low-cost sensors are used in this category which provides considerable end-to-end coverage.

C. Ultra-Reliable Low Latency Communication (uRLLC)

uRLLC enables autonomous, and intelligent decisions in a real-time manner. This use case provides low latency, high availability, reliable connectivity, real-time applications, robust coverage, and ensures sustainability and security. This is vital for healthcare, remote surgery, V2V, self-driving driving, high-speed trains, smart grid, intelligent transportation systems, industrial automation, factory automation, and tactile internet.

Nonetheless, the 6G usage scenarios are categorized as follows:

D. Ubiquitous Mobile Broadband (uMBB)

uMBB possesses the power to allow enormous pieces of technology to communicate. This will enable a massive array of technologies such as VR, AR, autonomous functioning, artificial intelligence (AI), machine learning (ML), and automation. It will support global ubiquitous connectivity, high-quality communication, and boosts the network capacity and data rate.

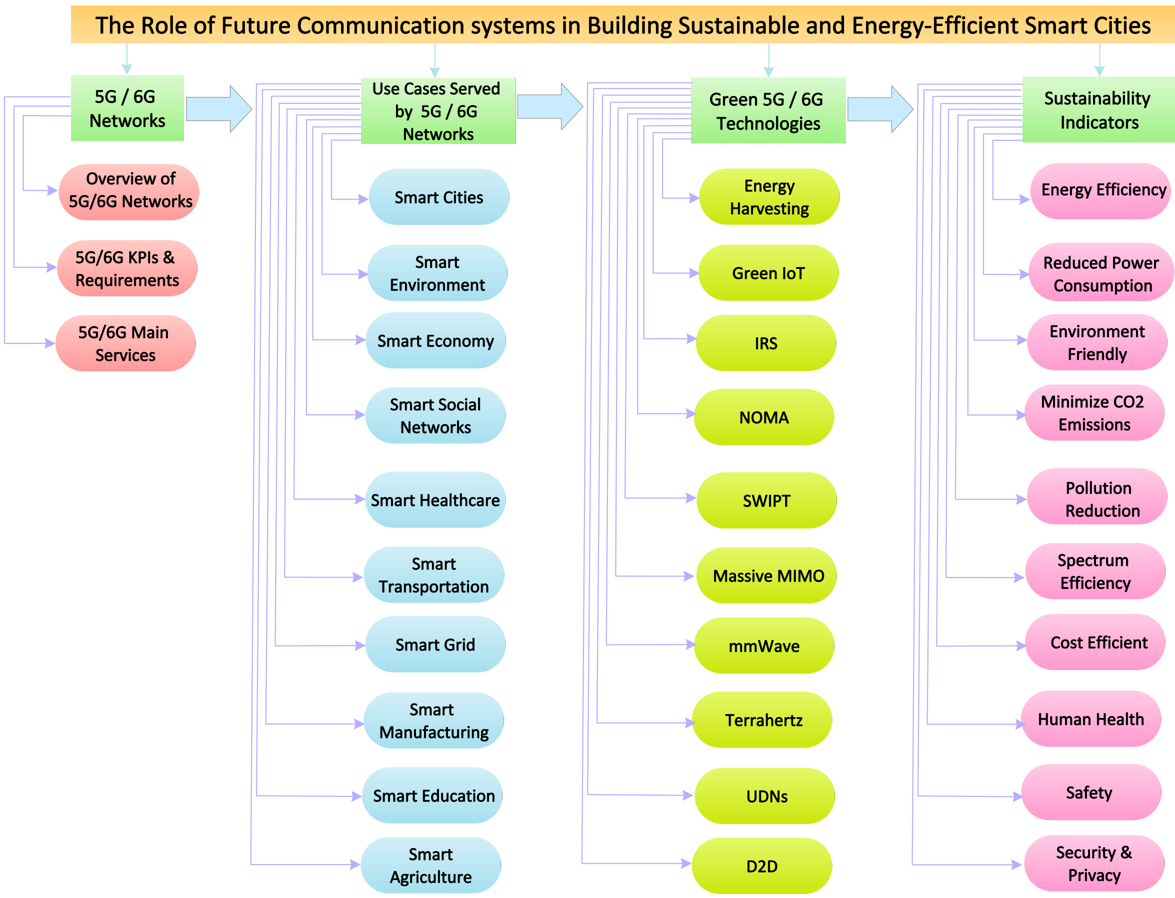

Fig. 2: The role of future communication systems in building sustainable and energy-efficient smart cities.

E. Massive Ultra-Reliable Low Latency Communication (mULC)

mULC aids applications that require both the uRLLC and the very high throughput such as Tactile Internet, immersive gaming, pervasive intelligence, and multi-sense experience.

F. Ultra-Reliable Low Latency broadband communication (ULBC)

ULBC mingles the merits of both the uRLLC and mMTC. It facilitates the installation of actuators and massive sensors in the industries [5].

III. Use Cases Served by 5G and 6G Networks

In this section, we will discuss the applications served by future communication networks such as the smart city units. This includes the smart grid, smart education, smart transportation, and smart healthcare, in addition to many other components as revealed in Fig 3. Further, we will investigate how 5G/6G networks can be key enablers for these components, especially that these networks are characterized by performance indicators that support very high bandwidth, capacity, and data rates, in addition to increased spectral and energy efficiency, and reduced latencies.

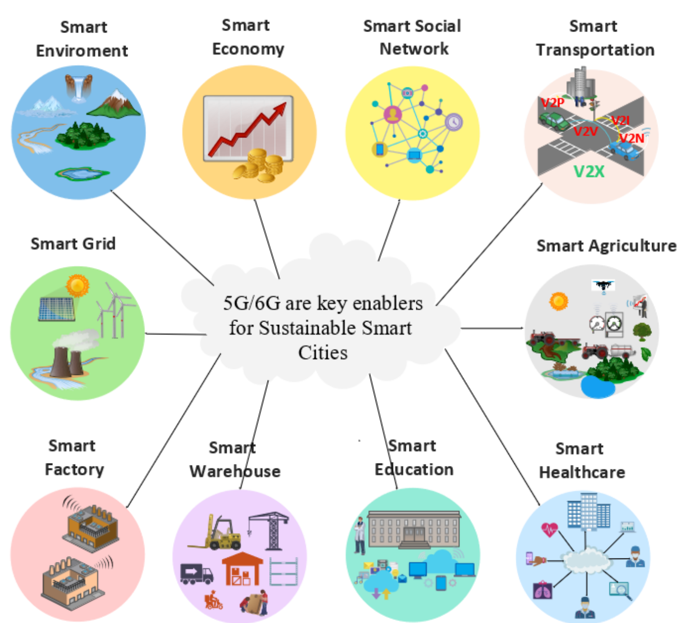

Fig. 3: 5G/6G communication systems are fundamental enablers for sustainable smart cities.

TABLE II: Fundamental KPIs for 5G/ 6G Services.

Future Communication Systems' Main Services and Use Cases						
	5G			**6G**		
Fundamental KPIs	**eMBB**	**uRLLC**	**mMTC**	**uMBB**	**mULC**	**ULBC**
Peak data Rate	✓✓			✓✓		✓✓
User Experienced Data Rate	✓✓			✓✓		✓✓
Latency	✓	✓✓		✓	✓✓	✓✓
Mobility				✓✓		✓
Connection Density	✓		✓✓		✓✓	
Energy Efficiency	✓	✓	✓✓	✓	✓✓	✓
Peak Spectral Efficiency	✓✓			✓✓		✓✓
Area Traffic Capacity	✓✓			✓✓		✓✓
Reliability		✓✓		✓	✓✓	✓✓
Signal Bandwidth	✓✓	✓		✓✓	✓	✓✓
Positioning Accuracy		✓		✓	✓	✓
Coverage	✓	✓✓	✓	✓✓	✓✓	✓✓
Security and Privacy	✓	✓✓	✓	✓	✓✓	✓✓
CAPEX and OPEX	✓✓			✓✓		
Legend: ✓✓= Significant Impact, ✓= General Impact						

A. *Smart Grid*

The smart grid is considered a next-generation energy system. It is a smart electrical network, one of the most significant applications on the IoT, incorporated with a power grid to collect and analyze information obtained from substations, transmission lines, and users. It is cost-efficient (SDG 8), power-efficient (SDG 7), sustainable (SDG 11), with low losses, and possesses high quality of supply, security, and safety (SDG 15). The smart grid is a fundamental element of smart energy and it has a substantial role in boosting social coordination, economy (SDG 8), and sustainable development (SDG 11). However, to increase the reliability and flexibility of these networks and improve the connectivity, it needs to be powered by 5G / 6G communication systems [6].

B. *Smart Education*

Distance learning already exists, but future communication networks with their super-fast connectivity are expected to fuel this service and enhance the quality of education via distance (SDG4). Further, 5G / 6G networks will enable real-time interactivity with reduced energy consumption, which will allow the learners to collaborate in real-time classes. Moreover, improving the quality of online and distance learning (SDG 4) will raise the number of competent staff, which will reflect positively in satisfying other goals such as the increase of high-skilled workforce. This in turn will improve productive employment, foster powerful institutions (SDG 16), and ensure sustainable economic growth (SDG 8) [7].

C. *Smart Transportation*

5G/6G networks are essential to improving sustainability in the transportation sector and for enabling smart transportation. The reason is that 5G and 6G are characterized by very low latencies which can reach less than 1ms in 5G and less than 0.1 ms in 6G networks. The emerging technologies in smart transportation include vehicle to vehicle (V2V), vehicle to everything (V2X), vehicle to the device (V2D), vehicle to pedestrian (V2P), vehicle to the network (V2N), vehicle to grid (V2G), vehicle to infrastructure (V2I), vehicle to cloud (V2C), new radio (NR) for V2X (NR-V2X), and cellular vehicle-to-everything (C-V2X). These enabling technologies will allow vehicles to share data about their locations and speed through 5G, 6G, Bluetooth, and Wi-Fi. Further, these technologies will help drivers to avoid collisions (SDG 3), save energy (SDG 7), improve road safety (SDG 3), and enhance the efficiency of the traffic. Thus, 5G/6G will provide a reliable connection to driverless vehicles to operate and control with reliability and safety (SDG 3) [8]–[10].

D. *Smart Healthcare*

5G/6G communication systems are fundamental tools in powering the smart healthcare sector (SDG 3), because these networks possess high data rates, high mobility, massive connection density, low latency, and can support better connections, and high quality live videos. Thus, they play a vital role in enabling applications such as the AR, VR, remote surgery, telemedicine, intra-hospital monitoring, remote patient, remote teaching for doctors, nurses and staff (SDG 4), remote consultation, large file transfers, data analysis, quick emergency response, and wireless specialist diagnosis. Nowadays, telemedicine is present, but with 5G/6G networks the connection speed will increase and new technologies such as edge computing will foster its adoption [11].

IV. Green Communication 5G and 6G Technologies

Green future networks have always been a goal for the telecom industry to mitigate energy consumption, minimize fossil fuel utilization, and reduce CO2 emissions (SDG 15). In 5G/6G networks, the size of the network infra and the number of connected devices will increase exponentially. This results in rising energy costs and CO2 emissions. It becomes a research hotspot and growing interest to investigate the green technologies in 5G/6G networks. Nonetheless, it is for sure that 6G will have diversified and rigorous requirements for flexibility, security, and Quality of Service (QoS) to improve energy efficiency (SDG 7). The Telecom industry conducted comprehensive research to reduce energy consumption, increase energy efficiency, and adopt energy harvesting in different communication models (SDG 7) [12]. In this section, we will inspect the green technologies and their impact on sustainability.

A. IRS

These are fundamental elements and key enablers for 6G networks. It aids the transmissions between the transmitter and the receiver, especially if there is no line of sight (LOS) path between the transmitter and the receiver, or if the users are far from the base station (BS). IRS controls the environment and regulates the channel to increase the spectral and energy efficiencies (SDG 7). It is cost-effective (SDG 8), and expected to be a promising solution for 6G networks [13].

B. NOMA

NOMA provides high spectrum efficiency and supports massive connectivity. It achieves more capacity and data rate than traditional orthogonal multiple access (OMA) techniques while preserving fairness among users. The reason is that it enables multiple users to transmit altogether in the same set of shared resources. This results in an interference, but NOMA uses a process denoted by successive interference cancellation (SIC) to minimize the resulting interference. Nowadays, NOMA research papers are focusing on its superior spectral efficiency performance. Nonetheless, several research studies have highlighted the energy efficiency performance of NOMA. SWIPT is an emerging green technology that can extend the duration of the battery of the wireless devices by using energy harvesting from radio waves. Integrating SWIPT with NOMA will improve the spectral and energy efficiencies (SDG 7) [14].

C. mmWave and THz

MmWaves and THz waves are characterized by narrow beams and small wavelengths which increase the transmission speed, boost the throughput, enhance spectral efficiency, and increase the capacity in 5G/6G systems, but the transmission distances of these waves are limited. This rationalizes the need for UDNs which consist of a huge number of small cells. The basic idea of these cells is to provide high capacity, data rate, and increase spectral and energy efficiencies (SDG 3, SDG 7) and reduce latency. It minimizes the distance between the BS and users, this decreases the propagation loss, reduce the interference, and result in a high-quality connection. Combining massive MIMO with small cells increases the capacity, QoS, and reduces AWGN [15]. THz communications support low latency and bandwidth-hungry applications such as AR, VR, and ultra-HD videos. It will also enable applications such as the internet of nano things, intra-body communication of nano-machines, on-chip communications, and nano-machine communication [16].

D. Massive MIMO and Beamforming

M-MIMO technology utilizes an enormous number of antennas to attain high transmission bandwidth and increased energy (SDG 7) and spectrum efficiencies without requiring more spectrum. However, M-MIMO has its disadvantages and complications. Nowadays the antennas of the mobiles broadcast signals in all directions at the same time and all these crossing signals result in serious interference, this calls the demand for the beamforming technology [17]. The beamforming technology focuses the wireless signal toward a particular receiving device, instead of spreading the signal in all directions as it normally would from a broadcast antenna. This results in a faster, reliable, and more direct connection, enabling the BSs to transmit a focused stream to a particular user, this prevents interference and increases the spectral efficiency.

V. SUSTAINABILITY INDICATORS AND POTENTIAL SOLUTIONS TO PROMOTE SUSTAINABILITY

Many indicators are considered to assess the degree of sustainability in communication networks. These are classified under environmental, economical, and social sustainability dimensions. Every sustainability indicator involves many subindicators. The environmental indicator includes power efficiency, energy efficiency, environment friendly, and CO2 emissions. The social indicator includes privacy, security, safety, quality of life, and human health. The economic indicator includes spectral efficiency and cost efficiency. Fig.4 reveals the green technologies employed by 5G/6G networks and their sustainability indicators.

To promote sustainability and drive these indicators, various approaches can be used. The use of green 5G/6G technologies, D2D communications, renewable energy sources, energy harvesting, solar power, efficient power amplifiers, efficient deployment of IoT sensors, improve energy efficiency and reduce CO2 emissions in smart city verticals. Green 5G/6G technologies will increase the energy and spectral efficiencies, such as mmWave and THz, which can be used to increase the spectrum efficiency since mmWave and THz aid wide bandwidth and large data rate. UDNs and D2D communications minimize the distance between the source and the destination, which will result in saving energy (SDG 7) and increasing the duration of the batteries for mobile equipment. Massive MIMO plays a vital role in boosting energy and spectral efficiencies (SDG 7). Energy harvesting, fuel cells, solar and wind power, minimize cost (SDG 8), environmental impacts (SDG 15), and increases energy efficiency (SDG 7). The massive deployment of IoT sensors in many sectors, such as smart transportation for traffic monitoring, smart agriculture for water conservation (SDG 6), measuring the quality of air (SDG 13), supplying farmers with specific information to aid them in taking decisions that enhances the agriculture (SDG15), smart meters for smart, clean energy design (SDG 7), and energy cost reduction (SDG8), will enhance sustainability in these sectors. These sensors need ultra-reliable, superfast, and high-quality connections, which shows the importance of 5G/6G networks in supporting IoT sensors to enhance sustainability. Thus, exploiting the advantages of 5G/6G networks to advance sustainability is vital. This also includes the spectrum availability,

Fig. 4: Sustainability indicators in 5G and 6G Networks.

security protection, community design, purchasing policies, interoperability, and harmonization of global markets to reduce complexity and cost (SDG 8). Each of these factors reinforces resource management, and sustainability in smart cities (SDG 11).

Further, the life cycle assessment (LCA) of end-user IoT devices, smartphones, and mobiles is of great importance while evaluating the effect of 5G/6G on sustainability. LCA can be used to assess the influence of the end-user devices on carbon and greenhouse gas (GHG) emissions, starting from the manufacturer to the power required to boot the device, and fundamentally the wastes resulting from the disposal of these devices (SDG 8). Being aware of the effect that the emerging technologies will have on the environment will assist in reducing the negative effects efficiently and operatively.

On top of this, the integration of 5G/6G and information and communication (ICT) technologies such as artificial intelligence (AI), machine learning (ML), big data, cloud, and IoT can enhance energy efficiency and improve sustainability in smart city sectors. The combination of these tools will improve the circular economy which reduces the waste production and resource utilization such as raw materials, water, and energy. Managing AI, ML, with big data can realize the performance problems and envision the energy consumption models. This adds up numerous social, environmental, and economical benefits.

VI. Conclusion And Future Work

Motivated by the growing attention about the sustainability in 5G/6G networks, we investigated the role of these networks in building sustainable smart cities. We first illustrated the KPIs, and main services of these networks. Then we discussed the smart city units served by these networks. Furthermore, we examined the green technologies and their impact on sustainability by demonstrating the sustainability indicators for each technology, and we identified the potential solutions that assist in driving the sustainability indicators. In the future, we will investigate the role of deep learning (DL) in future communication systems to enable the circular economy and enhance sustainability, particularly in security, safety, and privacy dimensions. Further, we will inspect the challenges for future communication systems to address a secure and sustainable smart city.

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