Delta University Scientific Journal Vol.07 – Special Issue (2024) 228-244

Delta University Scientific Journal
Journal home page: https://dusj.journals.ekb.eg

Towards Smart Sustainable Cities: The Role of IoT and 6G Wireless Networks

Mohammed shaheen[1], Hossam El-Din Moustafa[2], Hanaa Salem Marie[3], Walid Raslan[1]

[1]Electronics and Communications Engineering Department, Faculty of Engineering, Delta University for Science and Technology, Gamasa 11152, Egypt.
[2]Electronics and Communications Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt
[3]Faculty of Artificial Intelligence, Delta University for Science and Technology, Gamasa 11152, Egypt.

Correspondence: [Mohammed Shaheen]; Tel [+20109485266]; Email : mohamed.shahen11211@gmail.com

Abstract:

The development of smart sustainable cities is crucial to addressing the growing challenges of urbanization, including resource scarcity, environmental impact, and the demand for improved public services. As cities evolve, the integration of advanced technologies such as the Internet of Things (IoT) and next-generation wireless networks like 6G becomes essential to enable real-time data collection, efficient resource management, and enhanced connectivity. However, the rapid expansion of IoT devices and sensors in urban environments also brings significant energy demands, presenting a major obstacle to achieving true sustainability. Energy harvesting, which involves capturing ambient energy from sources such as solar, wind, thermal, and kinetic energy, offers a promising solution to power these devices sustainably.

This paper surveys the role of energy harvesting in the context of IoT and 6G networks for smart city development. It examines the potential of various energy harvesting techniques to address the energy requirements of densely connected urban environments, discusses the technical, economic, and environmental challenges associated with these methods, and explores their integration within IoT and 6G infrastructures. The survey also identifies current research gaps and highlights opportunities for innovation in developing energy-efficient, smart city solutions. By providing a comprehensive analysis of energy harvesting's role in IoT and 6G-enabled smart cities, this paper aims to offer valuable insights for future research and practical implementation strategies in creating sustainable urban spaces.

Keywords: *Smart Cities, IoT, 6G, Wireless Networks, Energy harvesting, Sustainability.*

1. Introduction:

Smart sustainable cities represent the next evolution in urban development, where digital technologies are harnessed to create more efficient, livable, and environmentally friendly urban spaces. These cities integrate advanced information and communication technologies (ICT) with sustainable practices to optimize energy use, improve public services, reduce environmental impact, and enhance the quality of life for residents [1]. As global urbanization accelerates, the importance of developing smart sustainable cities has never been greater. Current trends in smart city development focus on data-driven decision-making, real-time monitoring, and automated control systems across various domains, such as transportation, healthcare, waste management, and energy. Among the key technologies driving this transformation are the Internet of Things (IoT) and the next generation of wireless networks, 6G [2].

The growing significance of IoT and 6G wireless networks in smart city development lies in their ability to provide the foundational infrastructure for connected urban ecosystems. IoT enables the seamless interconnection of billions of sensors and devices, facilitating the collection and analysis of data needed for efficient city management t[3]. At the same time, 6G networks promise to offer unprecedented levels of speed, capacity, and reliability, addressing many of the limitations of current 5G networks. Together, IoT and 6G have the potential to transform urban environments by enabling applications such as intelligent traffic systems, smart grids, remote healthcare, and real-time surveillance, all of which are critical for achieving sustainability goals [4].

This research specifically focuses on exploring the intersection of IoT, 6G wireless networks, smart city technologies, and energy harvesting solutions. As cities become smarter and more connected, they face significant challenges in meeting the rising energy demands of millions of interconnected devices and sensors. Energy harvesting, which involves capturing and converting ambient energy from sources such as solar, wind, thermal, and kinetic energy into usable electrical power, is emerging as a key strategy to address these challenges [5]. Efficient energy harvesting is crucial for maintaining the operation of IoT devices and sensors, especially in remote or hard-to-reach urban areas where traditional power sources may be impractical [6].

However, energy harvesting in the context of IoT and 6G within smart cities presents several challenges [7]. These include limited energy conversion efficiency, variability in energy availability, and the need for advanced materials and technologies that can operate under diverse environmental conditions. Additionally, managing the harvested energy to ensure continuous and reliable operation of devices in a 6G-enabled smart city infrastructure poses a significant technical hurdle [8]. As IoT networks grow and evolve with the advent of 6G, optimizing energy usage and storage becomes increasingly critical to maintaining sustainable urban ecosystems.

The motivation behind this survey is to provide a comprehensive overview of the role of IoT and 6G networks in the development of smart sustainable cities, with a particular focus on the challenges and opportunities associated with energy harvesting. The objectives of this paper are to analyze the current state of research, identify existing gaps, and propose future directions for integrating IoT, 6G, and energy harvesting technologies in urban environments. By doing so, this paper aims to offer valuable insights for researchers, urban planners, and policymakers to develop more efficient and sustainable smart city solutions.

The remainder of the paper is organized as follows: Section 2 provides a detailed overview of smart sustainable cities, including key components and technologies. Section 3 discusses the role of IoT in smart city development and its potential applications. Section 4 explores the evolution of wireless networks from 5G to 6G and their implications for urban environments. Section 5 addresses the challenges and opportunities associated with energy harvesting in the context of IoT and 6G networks. Section 6 presents the motivation and objectives of this survey, followed by a discussion of future research directions in Section 7. Finally, Section 8 concludes with a summary of findings and recommendations.

2. Overview of Smart Sustainable Cities:

Smart sustainable cities are urban environments that leverage advanced technologies and data-driven approaches to enhance the quality of life for residents while minimizing environmental impact and optimizing resource use [9]. These cities are designed to be efficient, resilient, and adaptable, using interconnected systems and digital solutions to address the challenges of urbanization, such as congestion, pollution, and resource scarcity [10]. A smart sustainable city integrates multiple aspects of urban life, including governance, infrastructure, services, and communities, to create a more livable and sustainable environment. Figure 1 represents the key components of a smart sustainable city, highlighting the integration of smart infrastructure, sustainable environment, smart governance, quality of life, and smart economy. These components work together to enhance urban living by utilizing technologies such as IoT sensors, smart grids, and intelligent transportation, promoting renewable energy and green building practices, enabling digital governance and data-driven decision-making, improving healthcare and public safety, and fostering a sustainable and innovative economy.

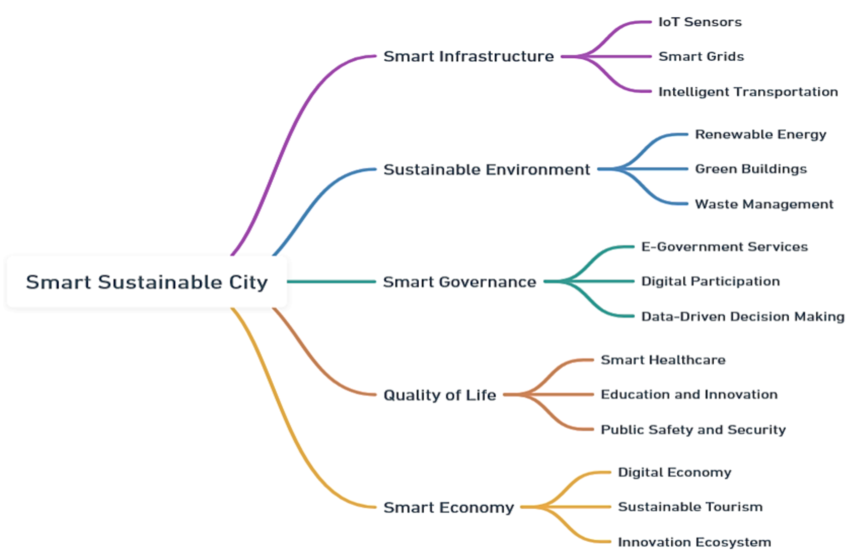

Fig. 1. Key Components of a Smart Sustainable City

The development of smart sustainable cities relies on several core components that work together to improve urban functionality and sustainability. Smart grids enable efficient energy distribution and management by utilizing real-time data to balance supply and demand, integrate renewable energy sources, and reduce overall energy consumption [11]. Transportation systems in these cities are optimized using intelligent traffic management solutions, public transport enhancements, and infrastructure for electric and autonomous vehicles to reduce congestion, lower emissions, and improve mobility [12]. Environmental monitoring is another crucial component, employing IoT sensors and networks to monitor air and water quality, waste management, and noise pollution, allowing for proactive management of environmental issues [13]. Smart buildings are designed to use energy and water efficiently, equipped with automated systems for heating, cooling, lighting, and security, contributing to overall energy savings and a reduced carbon footprint [14].

Technology plays a central role in achieving the goals of smart sustainable cities by integrating various digital tools and innovative solutions. IoT enables the deployment of a vast network of interconnected devices and sensors that collect, analyze, and share data across urban systems, facilitating efficient management and decision-making [15]. 6G wireless networks, with their promise of ultra-fast, reliable, and secure communication, provide the backbone for these interconnected systems, supporting massive IoT deployments and enabling advanced applications like real-time surveillance, smart grid management, and remote healthcare [16]. Additionally, energy-harvesting solutions are vital to power the widespread network of IoT devices sustainably [17]. By capturing and converting ambient energy from sources like solar, wind, and kinetic energy, these solutions help overcome the energy challenges associated with operating large-scale IoT networks, thus contributing to the overall sustainability of smart cities. Together, these technologies provide the foundation for building smarter, more sustainable urban environments capable of meeting the needs of present and future generations

3. Internet of Things (IoT) and Its Role in Smart Cities:

The IoT refers to a network of interconnected devices and sensors that collect, exchange, and analyze data in real-time, allowing for enhanced communication and automation across various systems [18]. The architecture of IoT typically consists of three main layers: the perception layer, which involves sensors and devices that collect data from the physical environment. The network layer, which provides the communication infrastructure to transmit this data; and the application layer, where data is processed, analyzed, and used to perform specific tasks or make informed decisions, as shown in figure 2[19].

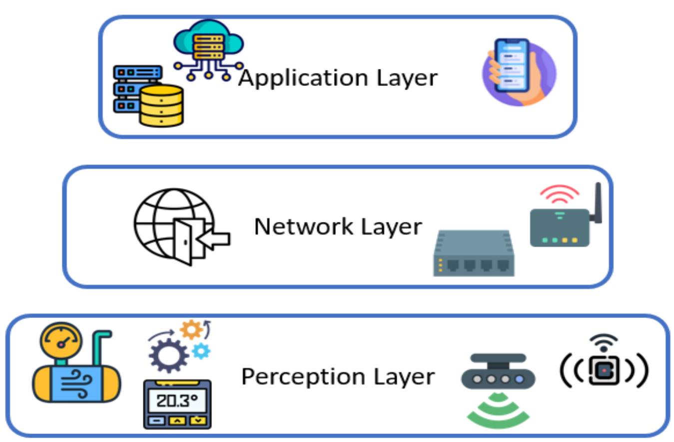

Fig. 2. IoT Architecture

Key technologies that enable IoT include wireless communication protocols (such as Wi-Fi, Bluetooth, Zigbee, and upcoming 6G networks), cloud computing for data storage and processing, and edge computing to handle data processing closer to the source, reducing latency and bandwidth use [20].

In the context of smart cities, IoT plays a crucial role in optimizing urban functions and improving the quality of life for residents, as shown in figure 3. Traffic management is one of the primary applications, where IoT sensors embedded in roads, traffic lights, and vehicles collect data on traffic flow and congestion, enabling dynamic traffic control systems to optimize signal timings and reduce delays [21]. Similarly, IoT can enhance waste management by using smart bins equipped with sensors that monitor fill levels and optimize collection routes, reducing operational costs and environmental impact. For public safety, IoT technologies like connected surveillance cameras, environmental sensors, and emergency response systems provide real-time monitoring and rapid response capabilities, enhancing security and reducing crime rates[22]. In energy management, IoT enables smart grids that monitor and balance energy supply and demand in real-time, integrate renewable energy sources more efficiently, and reduce energy consumption through automated control systems in buildings and public infrastructure[23].

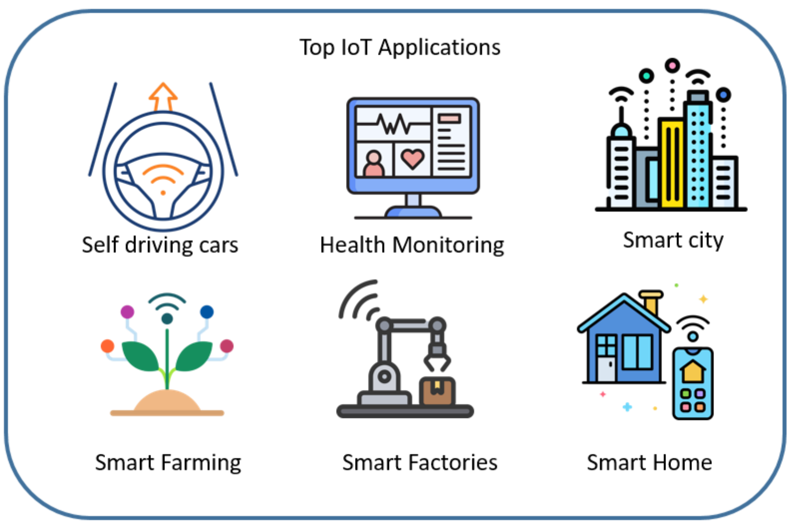

Fig. 3. IoT Applications

However, as IoT deployments in smart cities expand to large scales, they pose significant energy consumption challenges. With millions of connected devices and sensors continually collecting, transmitting, and processing data, the energy demands can become substantial. Traditional power sources may be inadequate or impractical for maintaining continuous operation in all urban settings, especially in remote or hard-to-reach areas. This challenge necessitates innovative energy solutions, such as energy harvesting technologies, which capture and convert ambient energy from sources like solar, wind, or kinetic energy to power IoT devices sustainably. Addressing these energy consumption challenges is critical to ensuring the scalability and sustainability of IoT applications in smart cities, where maintaining uninterrupted connectivity and operation is essential for the city's overall functionality and resilience.

4. 6G Wireless Networks

The evolution of wireless networks from 1G to 6G reflects a continual drive to improve connectivity, speed, capacity, and reliability to meet the ever-growing demands of digital communication, as shown in table 1. 1G networks introduced basic analog voice communication, while 2G brought digital voice services and text messaging. 3G enhanced mobile internet access, enabling data services such as web browsing and video calling. The advent of 4G revolutionized mobile communication by providing faster data rates and lower latency, supporting a wide range of applications from HD video streaming to online gaming[24]. 5G, the current generation, has further pushed the boundaries by delivering ultra-fast speeds, low latency, and the ability to connect a massive number of devices, forming the backbone for many IoT applications[25]. However, 6G is expected to go even further, offering new capabilities that are crucial for the development of next-generation smart cities[26].

Table 1: comparison between mobile generations.

Generation	Time Period	Technology	Data Speed	Key Features	Applications
1G	1980s	Analog cellular networks	Up to 2.4 Kbps	Basic voice communication	Voice calls
2G	1990s	Digital cellular networks (GSM, CDMA)	Up to 64 Kbps	Digital voice, SMS, limited data services	Voice calls, text messaging
3G	2000s	Mobile broadband (UMTS, HSPA)	Up to 2 Mbps	Mobile internet, video calling, GPS	Web browsing, video calls, multimedia
4G	2010s	LTE (Long Term Evolution), WiMAX	Up to 1 Gbps	High-speed data, HD video streaming, VoIP	Streaming, online gaming, video conferencing
5G	2020s	Millimeter waves, Massive MIMO, Beamforming	Up to 10 Gbps	Ultra-low latency, enhanced mobile broadband, massive IoT	Smart cities, autonomous vehicles, IoT
6G (Expected)	2030s	Terahertz communication, Quantum communication, AI-driven networks	Up to 1 Tbps	Ultra-low latency, massive connectivity, AI integration, high energy efficiency	Holographic communication, digital twins, advanced AI applications

6G networks will feature several advancements that make them a game-changer for smart cities. These include ultra-low latency, which is crucial for real-time applications like autonomous vehicles and remote healthcare; massive device connectivity, allowing for the seamless integration of billions of IoT devices and sensors across urban landscapes; energy efficiency, aimed at reducing the power consumption of devices and networks, which is critical given the high density of connected devices in smart cities. Enhanced security, with built-in capabilities to protect against increasingly sophisticated cyber threats[27]. These features position 6G as a foundational technology to support a wide range of smart city applications, from intelligent traffic management and smart grids to environmental monitoring and public safety systems.

The potential of 6G networks to support IoT-based smart city applications lies in their ability to handle enormous amounts of data generated by interconnected devices while providing ultra-fast, reliable, and secure communication [28]. For instance, in traffic management, 6G can enable vehicle-to-everything (V2X) communication, facilitating real-time data exchange between vehicles, infrastructure, and pedestrians to enhance safety and reduce congestion [29]. In healthcare, 6G can support remote diagnostics and telemedicine by enabling high-quality, low-latency video streaming and real-time data transmission from medical IoT devices[30]. Furthermore, 6G's ability to support massive machine-type communication (mMTC) will enable large-scale deployment of IoT sensors for monitoring air quality, noise levels, water quality, and other environmental parameters critical for maintaining a healthy urban ecosystem [31].

However, the deployment of 6G networks will also bring significant energy challenges [32]. The high data rates, vast number of connected devices, and complex network architectures required for 6G demand sustainable energy solutions to minimize the overall carbon footprint of smart cities [33]. Traditional power sources may not be sufficient to support the extensive infrastructure needed for 6G, particularly in areas where deploying conventional power grids is not feasible. Therefore, innovative energy harvesting methods, such as capturing energy from ambient sources like solar, wind, radio frequency (RF) waves, and kinetic energy, become essential to power IoT devices and network components efficiently [34]. Addressing these energy challenges is critical to ensuring that the deployment of 6G networks aligns with the broader goal of building smart sustainable cities that are both highly connected and environmentally responsible.

5. Energy Harvesting in Smart Sustainable Cities:

5.1 Introduction to Energy Harvesting:

Energy harvesting refers to the process of capturing and converting ambient energy from the environment into electrical energy to power electronic devices, systems, or sensors, as shown in Figure 4 [6]. In the context of smart sustainable cities, energy harvesting is essential for powering the vast network of IoT devices and sensors that collect and transmit data for various urban applications [35]. The importance of energy harvesting lies in its potential to provide a sustainable, reliable, and maintenance-free energy source, reducing the dependence on conventional power grids and batteries, thereby enhancing the energy efficiency of smart city infrastructure. Key technologies in energy harvesting include photovoltaic cells, piezoelectric materials, thermoelectric generators, and RF energy harvesters, all of which enable devices to draw power from diverse environmental sources, as illustrated in Table 2 [36].

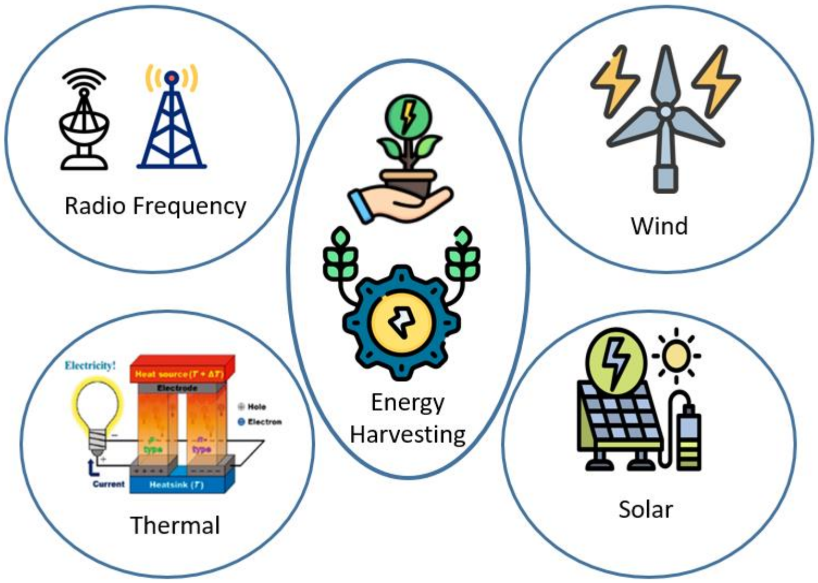

Fig. 4. Types of Energy Harvesting Methods.

Table 2: Comparative analysis between energy harvesting methods

Energy Harvesting Method	Energy Source	Technology Used	Applications	Advantages	Challenges
Solar Energy Harvesting [37, 38]	Sunlight	Photovoltaic (PV) cells convert sunlight into electricity	Smart street lighting, remote sensors, solar-powered IoT devices	Abundant, renewable, and efficient in sunny conditions	Dependent on sunlight availability; less effective in cloudy or nighttime conditions
Wind Energy Harvesting [39, 40]	Wind	Small-scale wind turbines or piezoelectric materials convert wind energy into electricity	Urban wind turbines, rooftop generators, IoT sensors in windy areas	Sustainable, effective in areas with consistent wind	Inconsistent in areas without steady wind; noise and visual impact concerns
Thermal Energy Harvesting [41, 42]	Temperature differences	Thermoelectric generators (TEGs) convert temperature differences into electrical power	Industrial waste heat recovery, smart buildings, IoT sensors in variable temperature environments	Utilizes existing temperature gradients, effective in waste heat environments	Low efficiency, requires large temperature differences; material constraints
Kinetic (Mechanical) Energy Harvesting[43]	Motion or vibrations	Piezoelectric materials or electromagnetic induction convert	Wearable devices, road sensors, smart infrastructure exposed to motion/vibration	Harvests energy from existing movements or vibrations, suitable for high-activity areas	Limited power output, dependent on frequency and

		mechanical energy into electricity			magnitude of movement
RF (Radio Frequency) Energy Harvesting [44, 45]	Electromagnetic waves	RF energy harvesters convert ambient electromagnetic waves (Wi-Fi, radio signals) into electricity	IoT sensors in urban areas, smart meters, low-power electronic devices	Leverages existing RF signals, suitable for densely populated urban areas	Limited range and low energy output; dependent on proximity to RF sources

5.2 Energy Harvesting for IoT Devices and Sensors in Urban Environments:

Energy harvesting is particularly relevant for IoT devices and sensors in smart sustainable cities, where there is a need for large-scale deployment of these devices to monitor and manage various urban systems. Conventional power sources, like batteries, may be impractical due to frequent maintenance requirements, limited lifespan, and environmental concerns. Energy harvesting provides a sustainable alternative by enabling IoT devices to operate autonomously without frequent battery replacements or reliance on grid power. This is especially important in remote or hard-to-reach locations, such as underground water pipes, high-rise buildings, or smart traffic systems, where regular maintenance is challenging.

Energy harvesting for IoT applications in smart cities has gained significant attention in recent years as a sustainable solution to meet the energy demands of extensive IoT networks. Numerous studies have explored different energy harvesting techniques, their applications, and the challenges associated with integrating these methods into smart city infrastructures. This literature review synthesizes the findings from various research studies to provide a comprehensive understanding of the current landscape and future directions in this field.

Piezoelectric energy harvesting, which converts mechanical energy from vibrations into electrical energy, has emerged as a promising approach for powering IoT sensors in smart cities. Izadgoshasb [46] highlights the potential of piezoelectric materials to create self-powered IoT sensors in urban environments where continuous motion from vehicles, pedestrians, and infrastructure can provide a reliable energy source. Similarly, Shirvanimoghaddam et al. [47] emphasize the role of piezoelectric energy harvesting in achieving a green and self-powered IoT, discussing advancements in materials and device designs that enhance energy conversion efficiencies and sustainability.

Several studies provide overviews of various energy harvesting mechanisms and their integration into smart cities. Akin-Ponnle and Carvalho [6] present a detailed review of energy harvesting methods, including solar, wind, and kinetic energy, highlighting their suitability for different urban environments. Aldin et al. [48] offer a comprehensive analysis of energy harvesting and routing strategies for IoT sensor sustainability and communication technology, stressing the need for efficient energy management techniques to extend device lifespans. Sanislav et al. [49] further discuss various energy harvesting techniques, including RF, piezoelectric, and thermoelectric, and their potential applications in IoT-enabled smart cities.

RF energy harvesting, which captures ambient electromagnetic radiation from wireless communication systems, has been explored as a viable solution for low-power IoT devices in smart cities. Zeb et al. [50] investigate the feasibility of zero-energy IoT devices using RF energy harvesting in urban areas rich in RF signals. Alzahrani and Ejaz [51] discuss resource management strategies for cognitive IoT systems powered by RF energy harvesting, emphasizing its potential in densely populated urban settings where RF signals are abundant.

Integrating green energy harvesting strategies with edge-based urban computing is a growing area of interest. Lu et al. [52] explore green energy harvesting strategies in edge-based urban computing for sustainable IoT applications, focusing on the need to reduce carbon footprints and operational costs. Liu, Guo, Liu, and Lee [53] discuss advancements in energy harvesting technologies that enable self-powered sensors and sustainable IoT systems, highlighting new applications that can benefit from these innovations. Liu, Guo, and Lee [54] also promote the use of advanced mechanical energy harvesters in IoT applications to support smart cities in the 5G era, suggesting that these technologies will pave the way for more efficient and resilient urban infrastructures.

Thermal and mechanical energy harvesting techniques have also been studied for their applicability in smart cities. Elahi et al. [34] review methods of energy harvesting for self-powered IoT devices, focusing on the use of thermoelectric and mechanical energy harvesters in urban settings. Kamruzzaman et al. [35] explore energy harvesting wireless sensors for smart city applications, discussing their potential for environmental monitoring and public safety. These studies underscore the versatility and potential of thermal and mechanical energy harvesting in diverse urban environments.

Energy harvesting wireless sensors are essential for enabling sustainable smart city applications. Ramirez-Moreno et al. [55]review various sensors used in smart cities and discuss the importance of energy harvesting to ensure their continuous operation. Weddell and Magno [56] explore the application of energy harvesting in smart city contexts, focusing on the design of sensors and devices that can operate autonomously without the need for frequent battery replacements.

Salama and Al-Turjman [57] review sustainable energy production methods, emphasizing the integration of energy harvesting technologies into smart city frameworks to align with sustainability goals. Ejaz et al. [58] discuss efficient energy management techniques for IoT networks in smart cities, proposing methods to optimize power allocation and consumption to extend the life of IoT devices.

Zeadally et al. [59]and Belli et al. [60]explore design architectures for energy harvesting in IoT ecosystems, focusing on integration challenges, scalability, and interoperability. Liu and Yang [5] discuss the convergence of communication, sensing, computing, and energy harvesting in smart cities, highlighting the importance of designing flexible and scalable IoT networks that can adapt to diverse energy sources and demands. Gambin et al. [61] propose energy cooperation models for sustainable IoT services in smart cities, emphasizing the need for collaborative energy management strategies to optimize resource utilization.

The reviewed literature demonstrates that energy harvesting is a critical enabler for IoT applications in smart cities, providing a sustainable solution to meet the growing energy demands of extensive IoT networks. Current research focuses on various energy harvesting techniques, including piezoelectric, RF, thermal, and mechanical methods, and their integration into smart city infrastructures. However, several research gaps remain, such as improving energy conversion efficiencies, developing hybrid systems, and creating new network protocols for better energy management. Future studies should address these gaps to advance the field and support the development of resilient and sustainable smart city ecosystems.

Furthermore, energy harvesting helps enhance the scalability and resilience of IoT networks by ensuring a continuous power supply, even in the event of power outages or other disruptions. By capturing and utilizing ambient energy, smart cities can reduce operational costs, lower carbon footprints, and contribute to achieving broader sustainability goals. Thus, integrating energy harvesting solutions with IoT devices is critical to building a robust, energy-efficient infrastructure that supports the dynamic needs of future urban environments.

6. Innovative Approaches to Energy Harvesting in IoT and 6G-Enabled Smart Cities

The integration of energy harvesting techniques in IoT and 6G networks offers promising solutions to meet the increasing energy demands of smart cities while enhancing sustainability. With 6G networks set to provide ultra-reliable, low-latency communications and massive IoT connectivity, leveraging innovative energy harvesting methods becomes critical to achieving energy-efficient and resilient urban environments. This literature review synthesizes recent research on various innovative approaches to energy harvesting for IoT and 6G-enabled smart cities, examining key technologies, frameworks, applications, and challenges.

Several studies have focused on using AI and machine learning (ML) to optimize energy harvesting and management in IoT and 6G networks. Gera et al. [28] propose leveraging AI-driven 6G IoT frameworks to create energy-efficient smart cities. Their research highlights the potential of AI to predict energy consumption patterns and optimize the harvesting process in real-time, thereby minimizing energy waste and maximizing sustainability. Similarly, Jabbari et al. [62] introduce a federated reinforcement learning approach to maximize energy for wireless-powered IoT devices. This method employs AI to manage power distribution effectively in non-orthogonal multiple access (NOMA) environments and utilizes solar-powered UAVs to enhance the energy efficiency of 6G networks.

Kamruzzaman [8]presents a comprehensive review of key technologies and trends in IoT and 6G for energy-efficient communication, highlighting several energy harvesting techniques, including solar, RF, and piezoelectric methods. The study suggests that integrating these multiple energy sources can achieve optimal energy efficiency in smart cities. Murroni et al. [29] provide a survey on how 6G enables new smart city applications, discussing the integration of diverse energy harvesting technologies into 6G networks to support smart city applications, such as smart grids, autonomous vehicles, and real-time monitoring systems.

Sodhro et al. [63]discuss the architecture of 6G for energy-efficient communication in IoT-enabled smart automation systems, focusing on integrating energy harvesting with advanced communication protocols to enhance network performance. Hosseinzadeh et al. [64]provide an overview of 6G-enabled IoT, emphasizing techniques like intelligent reflecting surfaces (IRS) that enhance energy efficiency by optimizing signal paths for better energy harvesting from ambient sources.

The combination of energy harvesting with edge computing is gaining traction as an innovative approach to reduce energy consumption in smart cities. Lu et al. [52] explore green energy harvesting strategies that utilize renewable energy sources like solar and wind in edge-based urban computing, enabling local data processing to minimize latency and energy use. Similarly, Mishra and Singh [7] propose a 6G-IoT framework focusing on integrating sustainable energy harvesting with edge and cloud computing to enhance the performance and sustainability of smart city applications.

Emerging technologies offer new opportunities for energy harvesting in 6G networks. Huang et al. [65] explore energy efficiency maximization in UAV-assisted intelligent transport systems, proposing the use of energy harvesting to extend UAV operational life, which serves as mobile communication nodes in 6G networks. Adhikari and Hazra [66] discuss ultra-reliable low-latency communication (URLLC) in edge networks, emphasizing the need to integrate energy harvesting to optimize energy efficiency while maintaining communication reliability.

Nguyen et al. [4] provide a comprehensive survey on 6G IoT, outlining the potential of emerging technologies like terahertz (THz) communication and AI-driven networks for improving energy harvesting and energy management in urban environments. Dabas et al. [67]discuss optimizing network protocols and frameworks to incorporate energy harvesting in intelligent IoT applications, such as smart traffic management and healthcare monitoring.

Quantum technologies are being explored to enhance energy harvesting security and efficiency in 6G networks. Prateek et al. [68] investigate quantum-secured 6G technologies, proposing applications that combine quantum communication with energy harvesting to achieve secure and efficient networks. These quantum technologies could solve the security challenges related to energy harvesting in smart cities, especially in densely populated urban environments.

The optimization of network architectures and resource management for energy harvesting is essential for developing sustainable smart cities. Taneja et al. [69] propose an energy-efficient dynamic framework for resource control in massive IoT networks, emphasizing smart algorithms to manage energy resources in 6G-enabled smart cities effectively. Al Amin et al. [70] examine innovations in 6G/B6G wireless communication for power infrastructure, such as energy beamforming and distributed energy harvesting, to optimize power consumption in urban settings.

Sharma et al. [71] discuss the role of 6G technologies in advancing smart city applications, highlighting opportunities for integrating energy harvesting methods with 6G networks. Their research identifies key challenges such as interoperability, scalability, and regulatory requirements for deploying energy harvesting solutions in real-world smart city environments.

The reviewed literature highlights various innovative approaches to energy harvesting in IoT and 6G-enabled smart cities, ranging from AI-driven energy management and green energy strategies to emerging quantum technologies and collaborative energy models. While significant progress has been made, future research should focus on addressing the challenges of integrating diverse energy harvesting methods into 6G architectures, optimizing network protocols, and developing new frameworks that balance energy efficiency, security, and scalability. These efforts will be crucial in realizing the full potential of sustainable and resilient smart cities.

7. Research Gaps and Future Directions: Summary

7.1 Current Research Gaps:

- Low Energy Conversion Efficiency: Current energy harvesting technologies (solar, thermal, RF) often have low conversion rates, especially in suboptimal conditions (e.g., low light, weak signals). More research is needed to enhance their efficiency for powering IoT devices and 6G infrastructure.
- Intermittent and Unreliable Energy Sources: Energy sources like solar and wind are variable and unpredictable, making it challenging to ensure a consistent power supply. Research is needed to develop hybrid systems combining multiple sources and improved storage solutions for reliability.
- Integration with 6G and IoT Architectures: Many current IoT and 6G devices are not designed to be powered by harvested energy and lack dynamic power management capabilities. New designs and protocols are needed for seamless integration of energy harvesting into existing and future architectures.
- Material and Scalability Constraints: Existing materials for energy harvesting devices have limitations related to cost, scalability, and environmental impact. Research into new materials that are affordable, abundant, eco-friendly, and efficient is necessary.

7.2 Future Directions:

- Advanced Materials: Development of new materials (e.g., perovskite solar cells, nanomaterials, graphene) could improve the efficiency, durability, and scalability of energy harvesting devices.
- Hybrid Energy Harvesting Systems: Creating systems that combine multiple energy sources (solar, wind, RF) can provide a more consistent power supply. Innovations in design, management algorithms, and control strategies are key.
- AI-Driven Energy Management: Applying AI and ML techniques can optimize energy use by predicting availability, dynamically allocating resources, and managing storage, reducing waste, and enhancing network reliability.

- New Network Protocols: Developing new protocols designed for energy harvesting and efficient operation (e.g., energy-aware routing, adaptive duty cycling) is essential to minimize energy consumption and extend device life.

Conclusion:

This survey highlights the critical role of energy harvesting in supporting the vast networks of IoT devices and 6G wireless infrastructure needed for smart sustainable cities. Key findings indicate that energy harvesting offers a viable solution to address the significant energy demands posed by IoT and 6G technologies, reducing reliance on conventional power sources and enhancing the sustainability of urban environments. Various energy harvesting methods, including solar, wind, thermal, kinetic, and RF energy, show promise in powering IoT devices. However, challenges such as low energy conversion efficiency, variability in energy sources, and integration with existing IoT and 6G networks need to be addressed. Opportunities for innovation lie in developing advanced materials, hybrid energy harvesting systems, AI-driven energy management techniques, and new network protocols to optimize the use of harvested energy.

The implications of these findings are substantial for researchers, urban planners, and policymakers. Researchers are encouraged to focus on improving energy conversion efficiencies, developing novel materials, and creating intelligent power management systems to enhance the effectiveness of energy harvesting solutions. Urban planners can leverage these technologies to design more sustainable cities by integrating multiple energy sources into urban infrastructure, reducing overall energy consumption, and minimizing environmental impact. Policymakers should consider establishing regulations and incentives that promote the adoption of energy harvesting technologies, fostering innovation and ensuring sustainable urban development.

Future research should explore advanced materials that offer higher efficiency and lower environmental impact, as well as hybrid energy harvesting systems that combine multiple sources to ensure a consistent and reliable power supply. Practical applications should focus on implementing AI-driven energy management solutions and new network protocols to better integrate energy harvesting into IoT and 6G networks. By addressing these challenges and opportunities, smart cities can achieve greater energy efficiency, resilience, and sustainability, contributing to a more connected and environmentally responsible urban future.

References:

1. Bibri, S.E., *Smart sustainable cities of the future*. 2018: Springer.
2. Saadane, R., A. Chehri, and M. Wahbi. *6G enabled smart environments and sustainable cities: an intelligent big data architecture*. in *2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring)*. 2022. IEEE.
3. Guo, F., et al., *Enabling massive IoT toward 6G: A comprehensive survey.* 2021. **8**(15): p. 11891-11915.
4. Nguyen, D.C., et al., *6G Internet of Things: A comprehensive survey.* 2021. **9**(1): p. 359-383.

5. Liu, Y. and K.J.I.S.C. Yang, *Communication, sensing, computing and energy harvesting in smart cities.* 2022. **4**(4): p. 265-274.
6. Akin-Ponnle, A.E. and N.B.J.S.C. Carvalho, *Energy harvesting mechanisms in a smart city—A review.* 2021. **4**(2): p. 476-498.
7. Mishra, P. and G. Singh, *6G-IoT framework for sustainable smart city: Vision and challenges*, in *Sustainable Smart Cities: Enabling Technologies, Energy Trends and Potential Applications*. 2023, Springer. p. 97-117.
8. Kamruzzaman, M.J.E., *Key technologies, applications and trends of internet of things for energy-efficient 6G wireless communication in smart cities.* 2022. **15**(15): p. 5608.
9. Bibri, S.E., J.J.S.c. Krogstie, and society, *Smart sustainable cities of the future: An extensive interdisciplinary literature review.* 2017. **31**: p. 183-212.
10. Bansal, N., V. Shrivastava, and J. Singh. *Smart urbanization–Key to sustainable cities*. in *REAL CORP 2015. PLAN TOGETHER–RIGHT NOW–OVERALL. From Vision to Reality for Vibrant Cities and Regions. Proceedings of 20th International Conference on Urban Planning, Regional Development and Information Society*. 2015. CORP–Competence Center of Urban and Regional Planning.
11. Moreno Escobar, J.J., et al., *A comprehensive review on smart grids: Challenges and opportunities.* 2021. **21**(21): p. 6978.
12. Singh, B. and A.J.J.o.t.I. Gupta, *Recent trends in intelligent transportation systems: a review.* 2015. **9**(2): p. 30-34.
13. McDonald, T.L.J.E.m. and assessment, *Review of environmental monitoring methods: survey designs.* 2003. **85**: p. 277-292.
14. Kim, D., et al., *Design and implementation of smart buildings: A review of current research trend.* 2022. **15**(12): p. 4278.
15. Mouha, R.A.R.A.J.J.o.D.A. and I. Processing, *Internet of things (IoT).* 2021. **9**(02): p. 77.
16. Zhang, Z., et al., *6G wireless networks: Vision, requirements, architecture, and key technologies.* 2019. **14**(3): p. 28-41.
17. Priya, S. and D.J. Inman, *Energy harvesting technologies*. Vol. 21. 2009: Springer.
18. Madakam, S., et al., *Internet of Things (IoT): A literature review.* 2015. **3**(5): p. 164-173.
19. Soumyalatha, S.G.H. *Study of IoT: understanding IoT architecture, applications, issues and challenges*. in *1st International Conference on Innovations in Computing & Net-working (ICICN16), CSE, RRCE. International Journal of Advanced Networking & Applications*. 2016.
20. Pan, J. and J.J.I.I.o.T.J. McElhannon, *Future edge cloud and edge computing for internet of things applications.* 2017. **5**(1): p. 439-449.
21. Udoh, I.S., G.J.I.C.P.S.T. Kotonya, and Applications, *Developing IoT applications: challenges and frameworks.* 2018. **3**(2): p. 65-72.
22. Khanna, A. and S.J.W.P.C. Kaur, *Internet of things (IoT), applications and challenges: a comprehensive review.* 2020. **114**: p. 1687-1762.
23. Ghasempour, A.J.I., *Internet of things in smart grid: Architecture, applications, services, key technologies, and challenges.* 2019. **4**(1): p. 22.
24. Agrawal, J., et al., *Evolution of mobile communication network: From 1G to 4G.* 2015. **3**(5).
25. Sharma, P.J.I.J.o.C.S. and M. Computing, *Evolution of mobile wireless communication networks-1G to 5G as well as future prospective of next generation communication network.* 2013. **2**(8): p. 47-53.
26. Gawas, A.U.J.I.j.o.r., i.t.i. computing, and communication, *An overview on evolution of mobile wireless communication networks: 1G-6G.* 2015. **3**(5): p. 3130-3133.
27. Banafaa, M., et al., *6G mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities.* 2023. **64**: p. 245-274.
28. Gera, B., et al., *Leveraging AI‐enabled 6G‐driven IoT for sustainable smart cities.* 2023. **36**(16): p. e5588.
29. Murroni, M., et al., *6G—Enabling the New Smart City: A Survey.* 2023. **23**(17): p. 7528.
30. Kaiser, M.S., et al. *6G access network for intelligent internet of healthcare things: opportunity, challenges, and research directions*. in *Proceedings of International Conference on Trends in Computational and Cognitive Engineering: Proceedings of TCCE 2020*. 2020. Springer.
31. Sharma, S.K., X.J.I.C.S. Wang, and Tutorials, *Toward massive machine type communications in ultra-dense cellular IoT networks: Current issues and machine learning-assisted solutions.* 2019. **22**(1): p. 426-471.

32. Naser, S., et al., *Zero-energy devices empowered 6G networks: Opportunities, key technologies, and challenges.* 2023. **6**(3): p. 44-50.
33. Asopa, P., et al. *Reducing carbon footprint for sustainable development of smart cities using IoT*. in *2021 Third International Conference on intelligent communication technologies and virtual mobile networks (ICICV)*. 2021. IEEE.
34. Elahi, H., et al., *Energy harvesting towards self-powered IoT devices.* 2020. **13**(21): p. 5528.
35. Kamruzzaman, S.M., X. Fernando, and M. Jaseemuddin. *Energy harvesting wireless sensors for smart cities*. in *2017 IEEE Canada International Humanitarian Technology Conference (IHTC)*. 2017. IEEE.
36. Williams, A.J., et al., *Survey of energy harvesting technologies for wireless sensor networks.* 2021. **9**: p. 77493-77510.
37. Sharma, H., et al., *Solar energy harvesting wireless sensor network nodes: A survey.* 2018. **10**(2).
38. López-Lapeña, O., M.T. Penella, and M.J.I.T.o.i.e. Gasulla, *A new MPPT method for low-power solar energy harvesting.* 2009. **57**(9): p. 3129-3138.
39. Perera, S.M., et al., *Wind energy harvesting and conversion systems: A technical review.* 2022. **15**(24): p. 9299.
40. Truitt, A., S.N.J.I.J.o.P.E. Mahmoodi, and Manufacturing, *A review on active wind energy harvesting designs.* 2013. **14**: p. 1667-1675.
41. Lu, X. and S.-H. Yang. *Thermal energy harvesting for WSNs*. in *2010 IEEE International Conference on Systems, Man and Cybernetics*. 2010. IEEE.
42. Mouis, M., et al., *Thermal energy harvesting.* 2014: p. 135-219.
43. Vocca, H. and F. Cottone, *Kinetic energy harvesting*, in *ICT-Energy-Concepts Towards Zero-Power Information and Communication Technology*. 2014, IntechOpen.
44. Ibrahim, H.H., et al., *Radio frequency energy harvesting technologies: A comprehensive review on designing, methodologies, and potential applications.* 2022. **22**(11): p. 4144.
45. Divakaran, S.K., et al., *RF energy harvesting systems: An overview and design issues.* 2019. **29**(1): p. e21633.
46. Izadgoshasb, I.J.S., *Piezoelectric energy harvesting towards self-powered internet of things (IoT) sensors in smart cities.* 2021. **21**(24): p. 8332.
47. Shirvanimoghaddam, M., et al., *Towards a green and self-powered Internet of Things using piezoelectric energy harvesting.* 2019. **7**: p. 94533-94556.
48. Aldin, H.N.S., et al., *A comprehensive review of energy harvesting and routing strategies for IoT sensors sustainability and communication technology.* 2023: p. 100258.
49. Sanislav, T., et al., *Energy harvesting techniques for internet of things (IoT).* 2021. **9**: p. 39530-39549.
50. Zeb, H., et al., *Zero energy IoT devices in smart cities using RF energy harvesting.* 2022. **12**(1): p. 148.
51. Alzahrani, B. and W.J.I.A. Ejaz, *Resource management for cognitive IoT systems with RF energy harvesting in smart cities.* 2018. **6**: p. 62717-62727.
52. Lu, M., et al., *Green energy harvesting strategies on edge-based urban computing in sustainable internet of things.* 2021. **75**: p. 103349.
53. Liu, L., et al., *Recent progress in the energy harvesting technology—from self-powered sensors to self-sustained IoT, and new applications.* 2021. **11**(11): p. 2975.
54. Liu, L., X. Guo, and C.J.N.E. Lee, *Promoting smart cities into the 5G era with multi-field Internet of Things (IoT) applications powered with advanced mechanical energy harvesters.* 2021. **88**: p. 106304.
55. Ramírez-Moreno, M.A., et al., *Sensors for sustainable smart cities: A review.* 2021. **11**(17): p. 8198.
56. Weddell, A.S. and M. Magno. *Energy harvesting for smart city applications*. in *2018 International symposium on power electronics, electrical drives, automation and motion (SPEEDAM)*. 2018. IEEE.
57. Salama, R. and F.J.S. Al-Turjman, *Sustainable energy production in smart cities.* 2023. **15**(22): p. 16052.
58. Ejaz, W., et al., *Efficient energy management for the internet of things in smart cities.* 2017. **55**(1): p. 84-91.

59. Zeadally, S., et al., *Design architectures for energy harvesting in the Internet of Things.* 2020. **128**: p. 109901.
60. Belli, L., et al., *IoT-enabled smart sustainable cities: Challenges and approaches.* 2020. **3**(3): p. 1039-1071.
61. Gambin, Á.F., et al. *Energy cooperation for sustainable IoT services within smart cities*. in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*. 2018. IEEE.
62. Jabbari, A., et al., *Energy Maximization for Wireless Powered Communication Enabled IoT Devices With NOMA Underlaying Solar Powered UAV Using Federated Reinforcement Learning for 6G Networks.* 2024.
63. Sodhro, A.H., et al., *Toward 6G architecture for energy-efficient communication in IoT-enabled smart automation systems.* 2020. **8**(7): p. 5141-5148.
64. Hosseinzadeh, M., et al., *6G-enabled internet of things: Vision, techniques, and open issues.* 2022. **133**(3).
65. Huang, J., et al., *Energy Efficiency Maximization in UAV-Assisted Intelligent Autonomous Transport System for 6G Networks With Energy Harvesting.* 2024.
66. Adhikari, M. and A.J.I.C.S.M. Hazra, *6G-enabled ultra-reliable low-latency communication in edge networks.* 2022. **6**(1): p. 67-74.
67. Dabas, D., et al., *6G for Intelligent Internet of Things*, in *Network Optimization in Intelligent Internet of Things Applications*. Chapman and Hall/CRC. p. 19-36.
68. Prateek, K., et al., *Quantum secured 6G technology-based applications in Internet of Everything.* 2023. **82**(2): p. 315-344.
69. Taneja, A., N. Saluja, and S.J.W.N. Rani, *An energy efficient dynamic framework for resource control in massive IoT network for smart cities.* 2022: p. 1-12.
70. Al Amin, A., et al., *Emerging 6G/B6G wireless communication for the power infrastructure in smart cities: Innovations, challenges, and future perspectives.* 2023. **16**(10): p. 474.
71. Sharma, S., et al., *The Role of 6G Technologies in Advancing Smart City Applications: Opportunities and Challenges.* 2024. **16**(16): p. 7039.