smart cities

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Review

A Review of IoT-Based Smart City Development and Management

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Abstract: Smart city initiatives aim to enhance urban domains such as healthcare, transportation, energy, education, environment, and logistics by leveraging advanced information and communication technologies, particularly the Internet of Things (IoT). While IoT integration offers significant benefits, it also introduces unique challenges. This paper provides a comprehensive review of IoT-based management in smart cities. It includes a discussion of a generalized architecture for IoT in smart cities, evaluates various metrics to assess the success of smart city projects, explores standards pertinent to these initiatives, and delves into the challenges encountered in implementing smart cities. Furthermore, the paper examines real-world applications of IoT in urban management, highlighting their advantages, practical impacts, and associated challenges. The research methodology involves addressing six key questions to explore IoT architecture, impacts on efficiency and sustainability, insights from global examples, critical standards, success metrics, and major deployment challenges. These findings offer valuable guidance for practitioners and policymakers in developing effective and sustainable smart city initiatives. The study significantly contributes to academia by enhancing knowledge, offering practical insights, and highlighting the importance of interdisciplinary research for urban innovation and sustainability, guiding future initiatives towards more effective smart city solutions.

Keywords: smart city architecture; smart city applications; communication technologies; smart city standards; smart city challenges

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1. Introduction

Unprecedented urbanization has created many challenges, such as increased energy usage and its environmental impacts, increased traffic congestion, security and privacy concerns, and overall difficulty in providing efficient services to a growing population. Governments are seeking solutions to address these challenges, including using the Internet of Things (IoT) to implement a smart city. Smart cities encompass a comprehensive approach to urban development and management that goes beyond the mere implementation of technology. Smart cities represent an innovative urban strategy that integrates a variety of components—technological, human, and institutional—to improve the quality of life of their residents and improve the efficiency of urban operations and services.

In a smart city, technology acts as a facilitator rather than an end in itself. It is used to collect and analyze data that are then used to inform decision making, optimize resource allocation, and improve service delivery. However, the core objective of a smart city extends to the promotion of an environment that is economically vibrant, socially inclusive, and environmentally sustainable. This involves a holistic approach where smart technology is intertwined with strategic urban planning. It includes the development of intelligent infrastructure, sustainable resource management, and the provision of efficient public services, all aimed at improving the living conditions of residents.

Smart city initiatives are being applied across all smart city domains by deploying IoT devices to efficiently observe the city's condition and manage its services. IoT-based management is crucial for smart cities as it enhances efficiency, sustainability, and quality of life. IoT enables real-time data collection and analysis, improving decision making and resource allocation. This optimizes resources, reduces costs, and improves services like traffic management, energy consumption, and public safety. IoT devices, coupled with other information and communication technology (ICT) infrastructure, provide many new possibilities that were previously difficult or impossible to achieve. Using the large amount of data now available through distributed sensor deployments, city managers can now have a more holistic and real-time view of the city's status. This newfound situational awareness is made possible through data processing and analysis techniques that are implemented across edge computing resources throughout the city, as well as in the cloud. Now, with the help of the Internet of Things, cities are becoming more efficient and more manageable, which is ultimately necessary to support the ever-growing urbanization challenges faced worldwide.

Internet of Things can be defined as a conglomeration of interconnected objects that allow remote management and access to the data they generate [1]. As more devices or things in our environment are connected to the internet, they require the ability to communicate reliably to be able to function intelligently [2]. IoT builds upon various network communication technologies and protocols to allow heterogeneous devices to communicate seamlessly with other systems. By removing interoperability limitations, modern ICT provides access to data from sensing devices to track, monitor, and manage the world around them. The plethora of new smart devices, coupled with exponential growth in the network infrastructure, has led to widespread adoption and acceptance of IoT [3,4]. In general, IoT can be considered an epicenter of IoT and data, and its successful implementation is only made possible by information and communication technologies that abstract the details of implementation. This abstraction allows users to ignore the minutiae of each device and focus on developing applications that utilize these devices.

Recent years have seen a surge of interest in the Internet of Things from academics and industries. Subsequently, the rise in popularity of the IoT has also led to an increase in its implementation in smart cities. From 2010 to 2023, the number of IEEE publications related to the Internet of Things has increased exponentially from less than 100 per year to more than 4000 per year. Similarly, publications related to smart cities have grown at a proportional rate, from less than 10 per year to more than 400 per year. We collected keywords and abstracts from all research articles with the combined expression "smart city + IoT" in their metadata and plotted them in a graph to show the trending nature of this topic. The number of publications containing the terms "Smart City" and "IoT" has significantly increased in popularity over the last twelve years, as shown in Figure 1.

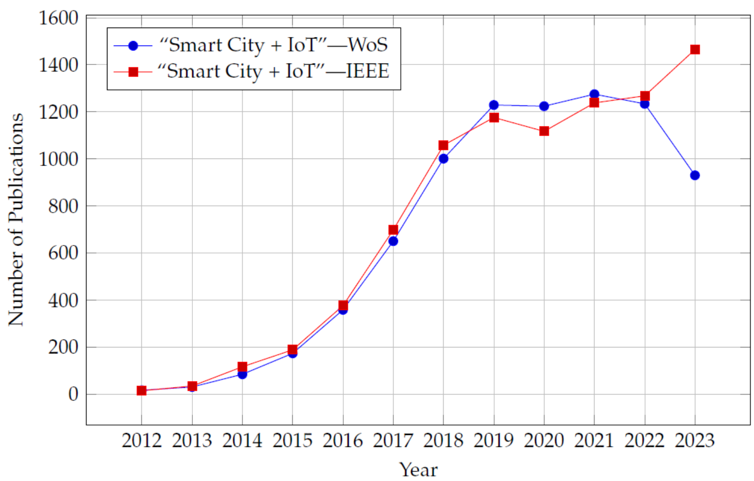

Figure 1. Trends in publications on "Smart City + IoT".

Although the rapid adoption of IoT-based smart city implementations is often used to address the challenges faced by urbanization, it also comes with its own challenges. Establishing effective communication networks can be challenging, and integrating these heterogeneous digital devices has often been difficult, especially on a scale. As the number of connected devices is predicted to reach billions, these device quantities significantly increase the size and scope of IoT, which provides both new opportunities and challenges [5]. More details about these challenges are discussed in Section 7.

Paper Structure and Contributions

This paper seeks to advance the understanding of Internet of Things (IoT) applications within smart cities by exploring several key questions that address the architecture, implementation, and impact of these technologies. Six research questions are investigated in this study:

(i) What are the key architectural elements of IoT-based smart city systems, and how do they integrate with existing urban infrastructure?
(ii) How do different IoT applications impact the efficiency and sustainability of smart cities across various sectors such as healthcare, transportation, and energy?
(iii) What are the current global examples of smart cities, and what lessons can be drawn from their experiences with IoT implementations?
(iv) Which standards are critical for the successful implementation of IoT technologies in smart cities, and how do these standards promote interoperability and security?
(v) What metrics are used to evaluate the success of IoT-based smart city initiatives, and how do these metrics address the diverse needs of urban populations?
(vi) What are the major challenges in deploying IoT-based systems in urban settings, and what solutions exist to overcome these challenges?

To address these questions, this study provides an in-depth analysis of how smart cities use IoT-based management strategies, which can be used as a guide for practitioners and policymakers interested in using IoT solutions in urban settings. The survey's analysis of the pros and cons of using Internet of Things technology within the framework of smart cities is a significant addition. It lays out the primary areas of interest, or domains, into which cities could implement IoT-based solutions and gives specific examples of these applications within each domain. Additionally, this study presents a collection of fundamental criteria that may be benchmarks for smart development in a city. Furthermore, it elucidates preexisting guidelines that municipalities may immediately use to strengthen their smart projects. This study is a significant resource for researchers, politicians, and urban planners by compiling a wealth of information in one place, encouraging new ideas, and providing a roadmap for the future of smart cities enabled by IoT.

To provide a clear understanding of the organization and focus of this study, Figure 2 details the structure of the paper, outlining the objectives, contributions, and key components of each section. As illustrated in Figure 2, the paper begins with a discussion on a generalized IoT-based smart city architecture in Section 2. This is followed by an in-depth examination of various IoT-based smart city applications in Section 3. Section 4 presents case studies of smart cities globally, illustrating practical implementations and outcomes. In Section 5, we discuss essential standards facilitating smart city initiatives, while Section 6 outlines criteria for evaluating the success of these initiatives. The paper introduces potential challenges encountered in deploying IoT-based systems in urban environments in Section 7 and discusses key solutions in Section 8. It concludes with a summary of key findings and future research directions in Section 9.

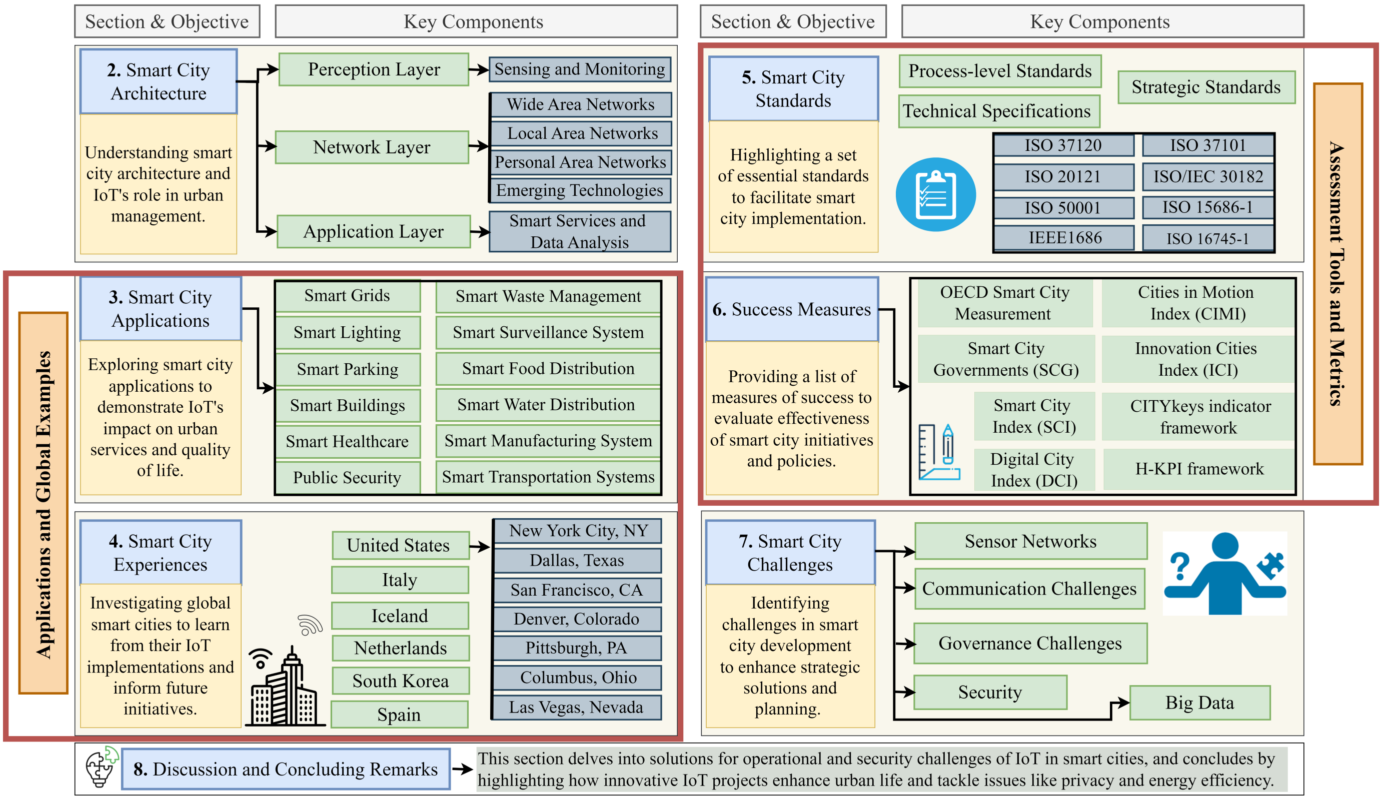

Figure 2. Overview of the paper's structure: highlighting key contributions to smart city research.

2. Smart City Architecture

The IoT-based digital architecture of a smart city includes perception, network, and application layers that work together to enable new public services and revitalize existing services. Figure 3 provides a generalized depiction of these three layers and indicates the flow of data in this paradigm: from the perception of real-world conditions encoded as digital signals to transforming data into actionable information and functional applications [6].

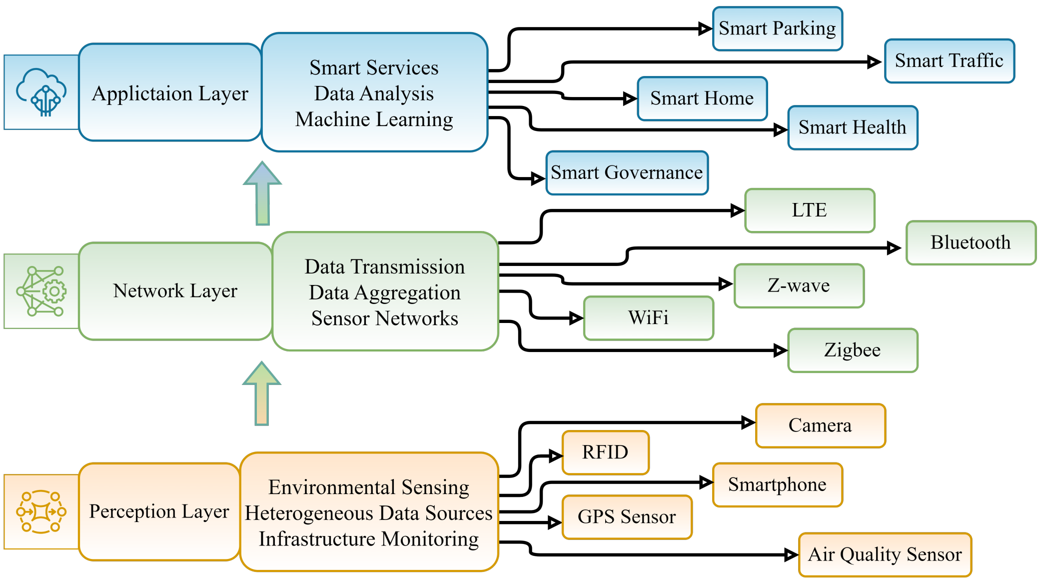

Figure 3. Architectural layers of smart cites.

The generalized architecture of IoT in smart cities, consisting of the perception, network, and application layers, is fundamental for structuring the interaction between physical and digital systems and ensuring the scalability and efficiency of urban operations. This architecture supports the holistic management of data flows and technology integration, which is crucial for optimizing resource use, enhancing service delivery, and improving the overall urban experience. By enabling these capabilities, the IoT architecture directly addresses the challenges of urban sustainability, safety, and efficiency, making it a cornerstone for future smart city developments.

2.1. Perception Layer

The perception layer of the smart city is made up of sensor hardware capable of perceiving the physical world, which then communicates these perceptions to other systems in the smart city [3]. Perception layer devices include sensors that monitor the environment such as weather conditions and asset tracking systems that monitor transportation infrastructure. Sensing plays an integral part in all intelligent systems found in a smart city. For example, with sensors to observe public infrastructure, such as bridges, highways, and facilities, it is possible to conduct maintenance more efficiently based on data obtained from those sensors. Intelligent Transportation System (ITS) energy management applications allow load forecasting by using traffic monitoring sensors, which help reduce energy consumption and decrease traffic congestion and accidents [7]. In most cases, sensors must be distributed in enormous quantities to achieve a complete view of what is being observed, which can bring about additional challenges. The data collected from these sensors are ultimately processed within the application layer, which can infer information from the data to be used for analysis and control applications.

2.2. Network Layer

The primary purpose of the network layer is to transfer data from the data producers in the perception layer to the data consumers in the application layer. There are several options available to establish a suitable network infrastructure, subject to device capabilities, application constraints, and the requirements of the networks [3]. As networking technologies improve, more advanced features such as data aggregation and enhanced interoperability are added to support the requirements of smart cities [6]. For the vast majority of smart city devices, wireless networking solutions are preferred over wired networking. Here, we will discuss four well-known technologies in detail.

2.2.1. Wide Area Networks

WAN networks are generally the largest of all network types, capable of covering large areas, including cities. 5G networking is an emerging popular technology that can be used for many smart city applications. One of the benefits of 5G is that it spans several RF bands to support many devices in a congested network. With this benefit, along with the appropriate Quality of Service (QoS) rules, 5G can help reduce the latency of the networking [8]. In addition to 5G networks, Low-Power Wide Area Network (LPWAN) technology is another good solution for smart city communication applications. As its name suggests, LPWAN is a logical choice for low-power devices, such as battery-powered sensors. Devices that require low-latency communications but do not need high data rates can leverage LPWAN [9].

2.2.2. Local Area Networks

Wireless Local Area Network (WLAN) mesh topologies are among the most suitable methods for developing smart city communication infrastructure due to their low cost and ease of deployment. Wireless mesh technologies are good candidates for Wireless Sensor Networks (WSNs) due to their flexibility, cost-effectiveness, and robustness [10]. When properly deployed, they can span much larger areas than traditional wireless networks. Some mesh technologies are included in the IEEE 802.11, 802.15, and 802.16 standards [11].

2.2.3. Personal Area Networks

PANs are usually the smallest-scoped networks implemented in smart city applications and generally provide a device communication range of less than 10 m. However, some of the latest revisions of traditional PANs, such as fifth-generation Bluetooth, enable communication ranges in the hundreds of meters. Low-rate Wireless Personal Area Networks (LWPANs), not to be confused with LPWANs, are also useful for implementation in smart cities, especially for Wireless Sensor Networks. The coverage distance of LWPANs can be as high as 15 km, making them useful for communicating with sensors distributed across a whole city. Several protocols are implemented using LWPAN, including ZigBee and 6LoWPAN [3].

2.2.4. Emerging Technologies

Edge Computing is a technology gaining popularity in smart cities. It can reduce the load on smart city network infrastructure by performing computational tasks closer to intelligent city devices, rather than in one centralized location [12]. Fog computing in smart cities is seen as a fundamental paradigm shift to create a hierarchical architecture connecting sensor networks to the services and applications that power smart cities [13]. Fog computing can be incorporated alongside existing network infrastructure such as Long-Term Evolution (LTE) and 5G base stations, which can increase network performance [14]. Fog Computing Architecture Network (FOCON) is an implementation of fog computing that can be utilized in smart cities [8]. Similar to edge computing, Software-Defined Networking (SDN) technology can address some challenges in building smart city networks. Using cognitive resource engines, SDN can modify and optimize networks to improve their performance. With the inherent heterogeneity of devices in smart cities based on IoT, SDN can also be used to meet the QoS demands required to improve the interoperability of these devices and applications [15]. A novel concept for leveraging existing city infrastructure to provide additional communication capabilities in a smart city is Visible Light Communication (VLC). VLC aims to implement high-speed data communication using existing lighting infrastructure to illuminate the city. This technology shows great potential, as VLC network links have been shown to provide throughput as high as 224 Gbps [16]. However, there are still challenges to overcome to fully realize VLC [17,18]. Visible Light Communication, also referred to as Li-Fi in some contexts, is particularly useful in smart city applications where RF interference can be problematic.

2.3. Application Layer

The application layer builds on the perception and network layers to complete the IoT-based smart city architecture. Using the physical infrastructure of the smart city, it provides a software infrastructure to process data and provide services to the community. Many of these services operate on real-time data, which must be aggregated and processed efficiently in order to be effective. Many smart cities rely on cloud-based platforms and distributed computing frameworks to achieve this goal such as Apache Hadoop [19], Apache Storm [20], Smart City Data Analytics Panel (SCDAP) [21], BASIS [22], and Big data-enabled smart healthcare system framework (BSHSF) [23]. Apache Hadoop [19] is one such framework which aims to solve scalability concerns in big data processing at the application layer. There are several projects related to Hadoop that complement this functionality and provide additional solutions to support the types of data processing applications that smart cities require. Apache Storm [20], a distributed computation system, and Apache Spark [24], an analytics engine capable of running on Hadoop, are just a couple of examples of projects used to support near-real-time data analysis applications. Complementary technologies such as Apache Storm and Apache Spark enhance Hadoop's capabilities by supporting real-time data processing and advanced analytics. In the application layer, machine learning technology can also be used to develop applications to support smart city services [25]. For instance, in the context of parking management, machine learning algorithms can analyze real-time data from sensors and cameras to predict parking availability, guiding drivers to open spots efficiently and reducing congestion. These applications not only streamline city operations but also significantly improve citizen engagement and satisfaction [26].

An adaptable, scalable IoT infrastructure is crucial for effectively handling a wide range of extensive data in smart cities, which poses significant issues related to Big Data. The integration of disparate systems is facilitated by middleware, essential for achieving interoperability among diverse devices. The platform should be capable of facilitating real-time data acquisition from several sensors while also providing scalable storage for efficient retrieval. The system should offer Web Services and APIs that allow users to access data in open, standardized forms [27]. Many smart cities rely on integrated IoT platforms that centralize data management and facilitate the interaction between hardware and application services. Platforms such as Dimmer and Flexmeter [27], Santander [28,29], Cisco's Smart + Connected Digital Platform and IBM's Watson IoT [30], PortoLivingLab [31], FIWARE [32], OpenMTC, EdgeX Foundry, PwC Smart City Platform, Nokia IMPACT IoT Platform, Invipo Integration Platform, UniSystem City4Life Platform, Cumulocity IoT [33] provide frameworks that allow cities to harness IoT data to optimize various services—from traffic management to environmental monitoring.

3. Smart City Applications

As described in Section 2, the architecture of an IoT-based smart city is branched into three layers, with the application layer providing the key services of a smart city. Over the years, several different types of smart city applications have been proven effective. Tables 1 and 2 list several essential domains in a smart city, described in the literature. As shown in these two tables, the fields in which smart city planning policies are applied can be categorized into hard or soft domains. Hard domains cover the tangible aspects of a smart city, such as building, power system, transportation, and healthcare, whereas soft domains cover aspects such as the economy and various social aspects. Hard domains are the most dynamic city environments, with sensors, wireless technology, and technological solutions to manage big data in the vision of a smarter community. This section lists some of the domain-specific IoT applications in smart cities. Figure 4 outlines some important smart city applications.

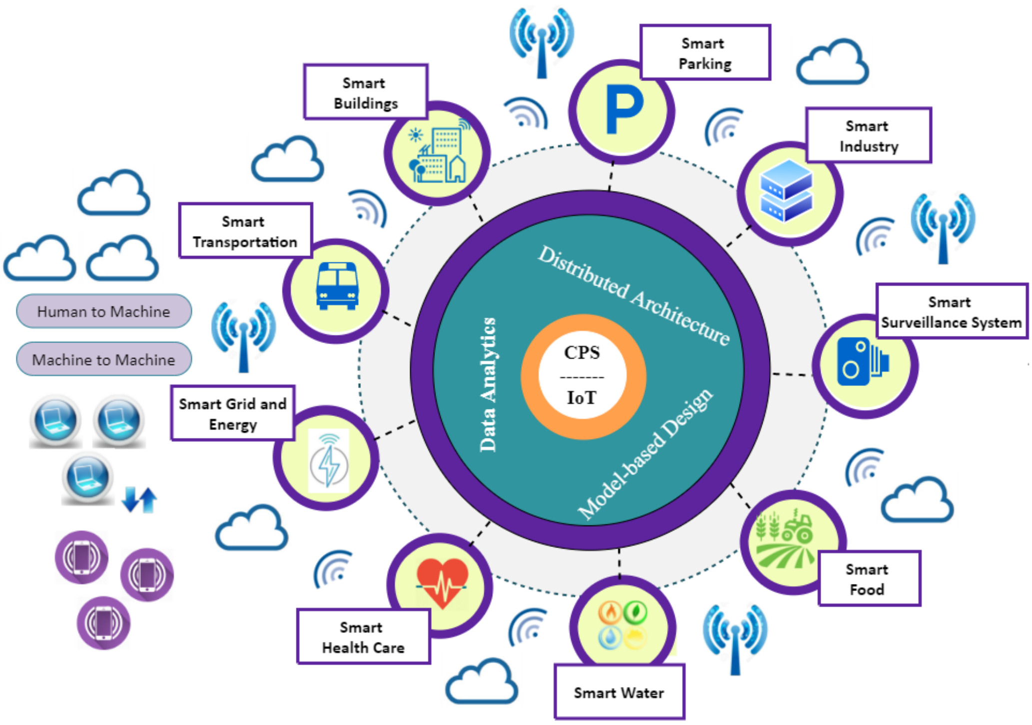

Figure 4. Smart city applications.

3.1. Smart Grids

Power distribution is one of the most critical services a city must provide, because all other city services require a reliable source of power to function properly. Even minor disruptions to the power infrastructure, or grid, can have negative consequences. Modern cities usually have robust power networks already established, but there is always room for improvement to make power generation and distribution safer, more fault-tolerant, more efficient, and more economical. Smart grids can establish two-way communications in network nodes, where newer communication protocols are being used, such as LPWANs and NB-IoT, to enable advanced energy metering capabilities. This can improve the grid's overall energy efficiency and reliability, and can decrease energy consumption with customer integration (both passive and active) [34]. Demand-side management techniques are being used more frequently to help balance the supply and demand of power, since real-time information can be sent from consumers to control nodes distributed throughout a city [35]. This study employs simulation tools and virtual hardware in OpenCyberCity, a small smart city testbed, to evaluate and make new technologies in smart grid deployment more accessible by showcasing improved capabilities and verifying a control implementation for emulated smart grid hardware [36].

Table 1. Classification of literature on the hard domains of smart cities.

References	Energy	Transportation	Water Management	Waste Management	Healthcare	Public Security	Environment	Buildings
Giffinger et al. [37]		✓						
Caragliu et al. [38]		✓					✓	
Dirks et al. [39]		✓				✓		
Toppeta et al. [40]		✓						
Atzori et al. [41]		✓					✓	
Washburn et al. [42]	✓	✓			✓	✓		✓
Berthon et al. [43]		✓	✓	✓	✓	✓	✓	✓
Webb et al. [44]		✓	✓	✓	✓			✓
Correia et al. [45]	✓	✓			✓		✓	✓
Nam et al. [46]		✓			✓	✓	✓	
Sheikh et al. [47]	✓	✓					✓	
Chourabi et al. [48]	✓							
Hughes et al. [49]		✓						
Arasteh et al. [50]	✓	✓	✓	✓	✓		✓	✓
Ahmed et al. [51]	✓	✓			✓			✓
Talari et al. [3]	✓	✓	✓	✓	✓	✓	✓	
Rajab et al. [4]	✓	✓	✓	✓		✓	✓	✓
Bhatti et al. [52]		✓						
Sharma et al. [53]				✓				
Ali et al. [54]				✓				
Abril-Jiménez et al. [55]					✓			
Malche et al. [56]							✓	
Dwivedi et al. [57]								✓
Poongodi et al. [58]					✓			

Table 1. *Cont.*

References	Energy	Transportation	Water Management	Waste Management	Healthcare	Public Security	Environment	Buildings
Kim et al. [59]	✓							
Thornbush et al. [60]	✓							
Ghazal et al. [61]					✓			
Singh et al. [62]								✓
Roccotelli et al. [63]								✓
Yarashynskaya et al. [64]	✓							
Keriwala et al. [65]			✓					
Sosunova et al. [66]					✓			
Selvaraj et al. [67]	✓							
Barroso et al. [68]			✓				✓	
Sen et al. [69]	✓							✓
Galán-Madruga et al. [70]							✓	✓
Roy et al. [71]				✓				✓
Ehsanifar et al. [72]	✓			✓				✓
Rai et al. [73]			✓				✓	

3.2. Intelligent Transportation Systems

ITSs (Intelligent Transportation Systems) integrate ICT and transportation infrastructure to build a system of roads, people, and vehicles that employ advanced technologies. ITS uses technology to accommodate drivers with enhanced information and services to reduce traffic jams and increase transportation efficiency [74]. ITS usually focuses on four primary aspects: monitoring, communication, energy efficiency, and lighting control. There are testbeds for the traffic management system that combine data analysis and model-based control to enhance performance, consisting of a network of connected vehicles, intersection controllers, data analysis services, and a variety of control services [75]. Other research focuses on vehicle routing, as travel time ambiguity affects identifying optimal routes and schedules on very congested urban roads and safe propagation using convolutional neural network [76].

3.3. Smart Lighting

Traffic light control systems are based on different control methods: fixed, actuated, and adaptive. Lighting control aims to achieve optimal traffic speed and throughput by minimizing the number of stops for vehicles, while also maintaining safety. Researchers have proposed an adaptive traffic light control algorithm that uses real-time traffic information to select the optimal sequence and length of the traffic light. Compared to the baseline approaches, the proposed approach can provide better results by increasing the cross capacity and decreasing the average waiting times for the car [77]. To implement smart lighting control systems, traffic signals and other lights require a method to communicate with centralized or distributed controllers. A proposed solution provides a remote monitoring and control system for many traffic lights in a city, capable of adjusting the schedule and altering the brightness of the lights using LoRa networks [78]. A similar system has been demonstrated that can detect light malfunctions to alert a remote management system [79]. Lighting consumes a significant amount of energy in a city [80]; therefore, SLSs (Smart Lighting Systems) are being developed to help cities become more efficient. One such system has been demonstrated that emphasizes energy efficiency, whereby street lights are activated only when people or vehicles are nearby [81].

Table 2. Classification of literature on the soft domains of smart cities.

References	Education and Culture	Public Administration	Social Aspects	Economy
Giffinger et al. [37]		✓	✓	✓
Dirks et al. [39]	✓	✓		
Caragliu et al. [38]			✓	
Toppeta et al. [40]		✓	✓	
Atzori et al. [41]		✓		
Washburn et al. [42]	✓			✓
Berthon et al. [43]	✓			
Correia et al. [45]		✓	✓	✓
Nam et al. [46]	✓			
Baltac et al. [82]			✓	
Makarova et al. [83]	✓			
Chourabi et al. [48]		✓	✓	✓
Talari et al. [3]		✓		
Beretta et al. [84]			✓	
Stübinger et al. [85]				✓
Duygan et al. [86]				✓
Wu et al. [87]			✓	
Vasilev et al. [88]		✓		
Nastjuk et al. [89]		✓		
Al Sharif et al. [90]			✓	
Molnar et al. [91]	✓			
Attaran et al. [92]	✓			
Farazmand et al. [93]		✓		
Pedro et al. [94]				✓
Alizadeh et al. [95]			✓	
Lee et al. [96]	✓			
Buhaichuk et al. [97]	✓			✓
Wirtz et al. [98]	✓	✓		

3.4. Smart Parking

Limitations with traditional parking infrastructure can exacerbate transportation problems, as vehicle traffic in cities continues to increase. Drivers often spend several minutes looking for a parking space, which generates unnecessary pollution from increased fuel consumption and increased traffic [99,100]. An IoT-based smart parking system that allows users to reserve parking spots remotely through a mobile application efficiently reduces traffic congestion [101]. One SPS architecture uses graph theory algorithms to find the best parking spot at minimal cost. The proposed framework decreases the number of vehicles that do not locate accessible parking and minimizes moving costs [99]. Other techniques involving machine learning and neural networks have also been shown to help solve urban parking problems. Another system uses survival analysis, which can predict the probability that a parking space will be available in a specific time frame [102].

3.5. Smart Water Distribution and Processing Systems

Another city service burdened by an ever-increasing population is the distribution of water, which includes the distribution of clean, potable water and the removal of waste water. To sustain increased water use, smart water management systems are being implemented in cities, with the aim of improving the efficiency and safety of water distribution systems [103]. To reduce and mitigate risks, cities are implementing smart water management systems that integrate technologies IoT to support remote monitoring and control of water systems [104]. The development of smart water management systems can be difficult to achieve due to the costs of updating existing water distribution infrastructure.

3.6. Smart Waste Management

Another major issue in modern cities is waste management, which can be improved with IoT help [105,106]. Inefficient waste management policies can cause severe environmental problems, for example, illegal waste disposal due to the increased cost and complexity of disposal procedures. To address these challenges, various solutions based on IoT technologies were proposed, ranging from the use of RFID systems to the development of smart platforms and systems [107]. These include automatic sensor-based real-time architecture design of a multicoat waste management system known as WIWSBIS (Waste Identity, Weight, and Stolen Bins Identification System). The architecture was applied and implemented, and demonstrations have shown that when using WIWSBIS, these systems can accurately track reuse and recycling [108]. Another study presents an IoT-based smart trash bin monitoring and management system [54]. The system can successfully collect garbage, detect fires in waste material, and predict future waste output using intelligent waste bins.

3.7. Smart Manufacturing System

The advancement of IoT-based technology and subsequent integration within the industry are widely considered to constitute "Industry 4.0." Smart industry uses sustainable industrial development to increase production and distribution capabilities and efficiency. There may be different goals for the implementation of Industry 4.0, but all require sensing and control components that work together to provide reliable oversight in real-time operations [109]. One of the most critical objectives is to reduce the negative environmental impacts associated with various industrial processes, which can be achieved using sensors that allow complete monitoring of industrial emissions. Digital tools for tracking environmental pollutant parameters using IoT technologies allow tracking of environmental parameter values such as pH, NO, CO, $PM_{2.5}$, PM_{10}, temperature, humidity, and O_3 gas concentrations. In this field, platforms have also been shown to improve the health and safety of industry employees by protecting against hazardous workplace conditions using remote monitoring and control [110].

3.8. Smart Healthcare

The goal of smart healthcare is to ensure quality patient care while reducing healthcare costs and logistical challenges. Stuff often performs current procedures for patient management and monitoring. However, advances in IoT technologies are propelling the evolution of smart health systems to maintain and enhance healthcare. NIGHT-Care is a suggested RFID system that relies on a platform that can analyze several sleep factors to keep tabs on the health of the disabled and elderly while they sleep [111]. In this paper, another healthcare system is proposed that uses sensors and communication networks to allow a physician to remotely monitor a patient [112]. As telemedicine has become more prevalent, smart healthcare systems are adapting to support remote medical care. ECC (Edge Cognitive Computing)-based smart healthcare systems have been proposed; it monitors and analyzes patients' physical health using an ECC architecture [15]. Deep learning has been used in various aspects of smart healthcare. A novel system, HealthFog, delivers healthcare as a fog utility that handles cardiovascular data from various IoT sensors [113].

To support IoT-based healthcare, researchers have proposed smart healthcare frameworks to address the increase in connected technologies in healthcare [114]. In this paper, the authors outline the architecture of the smart healthcare system based on big data, including data repositories, big data processing, and infrastructure and architectures based on smart services. The authors identify and discuss a wide range of intelligent health monitoring systems. Several studies targeted both the hospital environment and the home environment for the efficient operation of such devices [23].

3.9. Smart Surveillance System

Surveillance encompasses all types of methods to monitor a geospatial environment for control, positioning, or safety. The concept of smart surveillance includes remote surveillance using various electronic devices, such as cameras. Monitoring systems produce video data, and information systems can process the data using analysis tools. The authors describe anticipated security risks and network architectures and analyze research on WSNs media protection and privacy. In addition to supporting the new norm in data compression for HEVC (High-Efficiency Video Coding), the authors suggest an EAMSuS (Efficient Algorithm for Media-based Surveillance Systems) on smart city IoT network platforms. The algorithm combines two other WSN packet monitoring and protection analysis algorithms [115]. Another study describes alarm identification using the parameters and paths of moving objects based on semantic logic and ontology [116]. For supporting many cameras, another research study proposes an encoding algorithm that provides high efficiency in energy, bandwidth, and computing costs. This encoding uses simple methods to reduce the resources needed to stream color images [117]. Other solutions focus on reducing the cost of smart monitoring systems, such as one that uses a low-cost Raspberry Pi computer. With the implementation of NodeMCU, the method is economical, portable, and lightweight [118].

3.10. Smart Buildings

The smart home is now a popular application domain in the Internet of Things, where the primary concerns include convenience, efficiency, leisure, and healthcare. Smart home systems can monitor and control air conditioning, lighting, and windows and can even enable remote access to these systems. Smart home systems can adopt many network technologies, including ZigBee, Wi-Fi, cellular networks, or Ethernet to link glsiot devices to the Internet. Consumers can easily experience smart home technology without requiring additional computational resources through cloud subscription services [119]. Smart cities can boost the economy by cutting overhead expenses and increasing the quality of services for residents by building testbeds and data analytics units [120]. The authors have developed a smart city testbed to test various IoT-based technology and city management approaches. This testbed tests and validates different control algorithms, communication infrastructures, and user interfaces. The testbed actuators are optimized by the building control unit, which aggregates building characteristics through a network of dispersed sensors and communicates them to a management system [121,122]. Another use case for this testbed is to exploit the extreme susceptibility to interruption and disturbance in cyber-physical systems (CPS) during decision making. The proposed decision support system is applied to a case study on smart buildings and its use to deal with unexpected events [123].

3.11. Smart Food Distribution

The food supply chain is related to the processes of food production, packaging, storage, distribution, and disposal. Smart food systems focus on improving aspects of the supply chain and can include tracking systems that regulate foodtuff distribution, production, processing, transport, and control. Compliance with health and safety standards is also a key objective [124]. Researchers have suggested a framework for monitoring and tracking prepackaged foods based on IoT technologies [125]. Incorporating sensors into the development of food packaging can provide reliable knowledge of the quality of the items during the storage period by monitoring variables such as temperature, humidity, storage time, and even the number of pathogenic agents. It establishes an integrated computer network, which can offer a common operating picture (COP) by sharing information on the platforms by leveraging IoT concepts [126].

4. Smart City Experiences

Smart cities are emerging as a solution to modern urban challenges, with technology at the forefront of their transformation. In this section, we will provide the experiences of several cities worldwide that have already adopted various smart city initiatives. We present a list of cities that are recognized as smart cities and highlight some of their noteworthy achievements.

4.1. United States

4.1.1. New York City, New York

New York City is leading the way in the use of smart city solutions to address critical issues such as water safety, recycling, environmental preservation, and waste management. The City's Office of Technology and Development has introduced innovative technologies such as automated water measuring devices, smart waste bins, and intelligent street lighting [127]. The City24/7 platform in New York City informs, protects, and rejuvenates the city by providing information through smart screens at public locations such as bus stations, airports, shopping centers, and gyms [128]. The city carried out a two-year study using HunchLab, a technical tool for forecasting crimes using historical evidence and simulation, to improve crime monitoring. This solution can help police identify crime hotspots in this area to enhance public security [129]. The Transportation Department invests in solutions that monitor travel times and distances for traffic congestion evaluation purposes. The city is also implementing a connected vehicle technology solution to reduce crashes and traffic-related injuries, which offers vehicles with a system that reports details on real-time road conditions [130].

4.1.2. Dallas, Texas

The Dallas city government aims to use advanced technologies to address social challenges and offers citizens more technology and connectivity, including intelligent parking, intelligent drainage, automated water infrastructure, wireless mobile kiosks, and an open-access technology portal [130]. Led by the City of Dallas, the "Smart Dallas" program uses a partnership ecosystem to create and implement large-scale smart city projects. Dallas provides added value to people by increasing the efficiency and quality of city services using technology, data, and software applications [131].

4.1.3. San Francisco, California

San Francisco's government has made transportation a priority, with a goal of having more than half of all trips taken by public transport. The city also plans to increase the use of rail, car sharing, and reduce transportation emissions by 10% through electrification and demand management [130]. They invest in smart city goals for two primary reasons: (1) to enhance government fairness, efficiency, practicality, and responsiveness, and (2) to stimulate job creation by supporting smart city and IoT-based enterprises in San Francisco. The objectives and requirements of San Francisco include Vision Zero and transportation or mobility, public safety and preparation, life quality, fairness, good governance, and economic growth [132]. They plan to increase public safety infrastructure and services and resilience to climate change and catastrophes, reduce traffic and transit congestion, combat crime and fair enforcement, promote economic growth and enterprise, allowing decision making and actions based on data [133].

4.1.4. Denver, Colorado

The city of Denver has developed plans to increase the adoption of public and private electric vehicles, install pedestrian identification systems at intersections, and establish a vehicle network that allows supply chain optimization and congestion reduction for freight trucks. A company named Easy Mile aims to improve shared mobility through the implementation of an autonomous electric shuttle service, which is expected to be completed by 2026 [130]. Denver is utilizing technology to provide flexible and accessible multimodal travel solutions that are cost-effective. These smart technologies, such as wireless communications, automotive navigation, and traffic control, offer a new approach to effectively managing transportation and traffic on a large scale [134].

4.1.5. Pittsburgh, Pennsylvania

The initiatives for implementing smart technologies in Pittsburgh include the extension of Surtrac, the city's intelligent road light network that adapts to evolving traffic trends. Analysis of Surtrac shows that the system reduced the aggregate waiting time at crossings by 40%, which resulted in a 21% reduction in vehicle emissions [130]. Carnegie Mellon University (CMU) has partnered with Pittsburgh City, the County of Allegheny, and various government agencies to create diverse technology systems that improve safety, increase mobility, promote efficiency, and manage environmental degradation. CMU has installed software to allow smart signals to adapt to congestion in real time, reducing traffic congestion by 25% and substantially decreasing emissions [135].

4.1.6. Columbus, Ohio

One of Columbus's priorities is providing a network to enhance accessibility for residents and tourists, by creating an integrated tour planning and payment application. In addition, Columbus seeks to improve freight transport, thus reducing vehicle-generated pollution. The city plans to develop a truck platooning system to allow real-time communication between two or more semi-autonomous cargo trucks, saving fuel, increasing vehicle security, and improving traffic flows [130].

4.1.7. Las Vegas, Nevada

Las Vegas launched one of the first automated, electric, public shuttles and implemented machine learning technology to automate vehicle and foot traffic movement in common areas of the city [130]. Las Vegas communities across the country face enormous problems due to population booms, higher carbon emissions, tight infrastructure, crime, and the increasing economy. Their government is dedicated to combining innovative technology and new data through a smart city strategy to address these rising problems and improve urban governance. Las Vegas has taken proactive action to improve public safety by reducing crime, improving emergency response times, and increasing bicycle and pedestrian safety [136].

4.2. Busan, South Korea

Busan has a strong connectivity network that has helped the government extend the integration of cloud technology [137]. It brings together universities, businesses, and the government to promote sustainable urban growth. The Busan Mobile Application Center (BMAC) works to help integrate ICT into the city, with several focus areas that improve civil infrastructure, quality of life, and access to services for residents. This effort has led to many creative application sectors for new companies, start-ups, and developers, collaborating with the community to build intelligent public infrastructure through a standard network [3].

4.3. Seoul, South Korea

The Seoul Government has developed a cooperative model inviting businesses, experts, and people to foster a smart city project that can provide public benefit through network governance [138]. Seoul has been named Smart City of 2022 at the Smart City Expo World Congress (SCEWC) World Smart City Awards, which are given annually to recognize the best efforts and projects in the sector of urban transformation and innovation [139]. The percentage of smart green services in Seoul related to the sustainable environment of the city is under 13%. The threshold point service is one of the city's few green services, and its incentive structure has successfully enlisted the participation of stakeholders, including homes, businesses, and banks.

4.4. Amsterdam, The Netherlands

Amsterdam's tradition for innovation is long-standing, and the city is known for its freedom, ideas, entrepreneurship, science, and arts. In recent years, Amsterdam has become more prominent in the smart city movement and was named the "European Innovation Capital" for 2016 and 2017 [140]. Amsterdam was the recipient of the City Star Award in 2011 for its role in using and supporting clean energy. Smart Flow, a cloud-based IoT platform that maintains and monitors sensors around Amsterdam, helps people find their parking faster and minimizes noise, congestion, fuel consumption, and pollution. The pilot project for this intelligent parking platform reduced the average time required to locate a parking place by 43% [141]. The Energy Atlas project for Amsterdam set the goal of developing a comprehensive analysis of the production and usage of community energy, from which an interactive energy map was created [142]. In Hoekenrodeplein, a public square near the Amsterdam Arena, the pilot project "Smart Light" aims to make public areas livable and hospitable at any time of the day [142].

4.5. Padova, Italy

In Padova, a project named "Padova Smart City" has been launched as a partnership between Padova University and the local government. The city supplies essential services and budget as a financial partner, while the university executes smart city implementation projects. In one resulting project, various sensors have been placed on street lights and connected to the Internet to collect general environmental data. Although a simple pilot project, it includes several devices and communication technologies that represent the most critical problems in designing an urban IoT-based infrastructure [3,143,144].

4.6. Reykjavik, Iceland

Reykjavik satisfies nearly all its heating and power needs with renewable energy sources, primarily geothermal and hydroelectric. It leads the world in per capita utilization of geothermal power [145]. The municipal government of Reykjavik also prioritizes solar energy, environmentally friendly construction, efficient public transport, reducing emissions, and open spaces [145]. The "Better Reykjavík" portal is an electronic platform where citizens can share their opinions on the infrastructure and services of the region. This allows the public to effectively influence the technological development of the city [146].

4.7. Madrid, Spain

Madrid is actively engaged in smart city projects and is a notable tourism destination in Europe. The city council emphasizes public engagement by providing multiple avenues for participation and access to municipal data. The promotion of smart city characteristics such as economy, governance, environment, and mobility, as well as the improvement of air quality and the enhancement of public transit with environmentally friendly cars, are important areas of concentration [147]. In addition to these city-led efforts, enhancing the interoperability of urban IoT devices and conducting feasibility studies for scaling up or down are two of the primary services provided by IoTMADLab. With an emphasis on a people-centric digital transformation, IoTMADLab supports the city's objectives to improve city sustainability and quality of life. Madrid also participated in projects like UserCentriCities, aiming to provide citizen-driven digital services, and the Living-in.eu initiative, which fosters digital urban development [148].

5. Smart City Standards

As smart cities grow in popularity around the world, certain aspects of smart cities can benefit from predefined standards. As such, standards bodies have begun to develop universal standards that can be applied to many aspects of a smart city. ISO principles reflect a global consensus on best practices that improve city efficiency and achieve the UN Sustainable Development Goals to end hunger, protect the earth, and ensure global well-being. They provide overarching mechanisms that city officials and policymakers will use to identify their strategies and objectives for sustainable urban planning. Some of these standards include aspects such as energy conservation systems, road protection, smart traffic management, and responsible water use. A core set of internationally applicable ISO standards related to smart cities is specified in Figure 5. Additionally, specific standards utilized in different sectors of smart cities are detailed in Table 3. Together, these standards provide a comprehensive framework for guiding and assessing smart city initiatives across various domains.

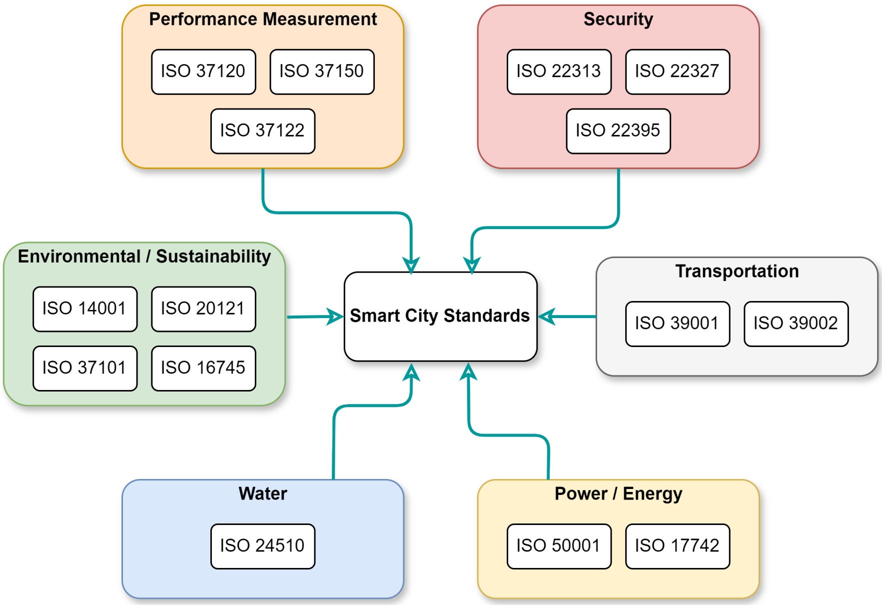

Figure 5. ISO smart city standards: ISO 37120 [149], ISO 37150 [150], ISO 37122 [151], ISO 22313 [152], ISO 22327 [153], ISO 22395 [154], ISO 39001 [155], ISO 39002 [156], ISO 24510 [157], ISO 50001 [158], ISO 17742 [159], ISO 14001 [160], ISO 20121 [161], ISO 37101 [162], ISO 16745 [163].

Table 3. Standards used in different smart city domains.

Area	Implemented Standards
Sustainable Cities	ISO 37100 [164], ISO 37120 [149], ISO 26000 [165]
Smart Grid and Energy	ISO 17742 [159], P1922.1 [166], P2814 [167], P2852 [168]
Smart Mobility and Transportation	ISO 39001 [155], ISO 39002 [156], P2406 [169], P2020 [170], P2685 [171]
Smart Water	ISO 24510 [157]
Connected Cities	ISO 30182 [172], ISO 21972 [173], ISO 27550 [174], ISO 27551 [175]
Smart Infrastructure	ISO 37151 [176], ISO 37152 [177]
Security and Resilience	ISO 22313 [152], ISO 22395 [154], ISO 22327 [153]
Smart Health	ISO 45001 [178], P3333.2.5 [179], ISOGuide 71 [180], P1752 [181]
Smart Education	P2834 [182], 1589-2020 [183], 1876 [184]
Smart Governance	P7005 [185], P7004 [186], P2863 [187]

There are three types of standards related to smart cities, strategic, process, and technical specifications, which play an important role in establishing a solid foundation for smart cities [188]. Strategic standards are most important for city leadership to develop a holistic path towards achieving smart city goals. Process-level standards are most useful for defining efficient management strategies for an established city. Technical specifications are generally applicable throughout all aspects of a smart city, and can guide leadership and management decisions towards a more connected city. More information about various standards is provided in the following subsections.

- ISO 37120 [149] specifies and sets out a methodology for several indicators for managing and measuring municipal service performance and residents' quality of life. It applies to all towns, municipalities, or local governments that are responsible for measuring performance in a verifiable way regardless of their size and location.
- ISO 50001 [158] is based on the continuous improvement management system paradigm that has previously been applied for other famous standards, such as ISO 14001 and ISO 9001. This ISO facilitates the integration of energy management by companies in their larger efforts to improve quality and environmental management.
- With ISO 20121 [161], anyone may increase an event's sustainability, regardless of its kind or scale. Resources, society, and the environment are heavily affected by events, frequently resulting in considerable waste. This international standard is designed to ease pressure on local infrastructure and services and reduce the potential for conflict in towns hosting events, in addition to promoting more responsible consumption.
- ISO 37101 [162] sets out a comprehensive strategy to ensure compliance with the community's sustainability strategy for a management system that ensures sustainable development in communities, including cities. This standard aims to enable communities to become more resilient, innovative, and sustainable by developing and demonstrating their successes by adopting strategies, programs, projects, plans, and services.
- ISO/IEC 30182 [172] provides recommendations on a SCCM (smart city concept model) that can enhance interoperability between smart city component systems by harmonizing the ontologies used in various areas. ISO/IEC 30182 targets organizations that provide data management and services, as well as decision-makers and policy makers within urban communities.
- ISO 15686-1 [189] develops and specifies broad principles for designing and implementing a life-cycle system of existing buildings and planned constructions. The life cycle includes the inception, definition of the project, design, construction, operation, maintenance, final disposal, recycling, and reuse.
- The criteria of ISO 16745-1 [163] are used to determine and report carbon metrics related to the operation of a building. It defines carbon emissions metrics derived from measured energy use during building operations, estimated energy use by users, and other greenhouse gas emissions. ISO 16745-1 focuses on the use of carbon metrics in existing residential, commercial, or building facilities.
- The IEEE1686 [190] standard describes the functions and functionalities of smart electronic devices for cybersecurity programs. The standard covers security for access, operation, setup, firmware revision, and data recovery. This also addresses some attributes such as confidentiality, integrity, and availability of external IED interfaces.

6. Success Measures

To evaluate the success of a smart city, a comprehensive collection of metrics should be established that assess the effectiveness of policies and efforts applied toward smart objectives. Cities around the world have embarked on smart city programs and projects to build a city-ready ecosystem for the future, with intelligent, efficient and fully integrated components of critical infrastructure and online services [191]. An evaluation model is crucial to achieving the desired results and sustainability in smart city initiatives. There are several standard dimensions defined for the study, assessment, and evaluation of innovative city initiatives. These dimensions include (a) management and organization, (b) technology, (c) politics, (d) governance, (e) people and communities, (f) culture, (g) developed infrastructures, and (h) the natural environment [192,193]. A primary goal of developing a set of metrics for evaluating a smart city's success is to create a set of tangible priorities for further development. Ultimately, a city's effectiveness in implementing smart city initiatives is dependent on its goals, and the priorities of one city may not be the same priorities of another city. City planners and governments can utilize different performance indicators to evaluate the effectiveness and efficiency of different IoT applications in urban management. The major performance indicators include operational efficiency measures, cost savings, environmental effect, data accuracy and reliability, interoperability, scalability, security, and social ramifications, among other factors.

Despite the technological focus, the human element is essential to the management of technology and the advancement of innovation. Numerous urban initiatives are motivated by economics, which is considered a feature of a highly successful smart city. The city's ability to increase economic development is one of the primary metrics to calculate productivity and, thereby, the success of the city [194]. Since there is no universal approach to implementing smart city initiatives, the tools and improvement methods available should be adapted for each city to achieve its unique objectives [195]. Using key performance indicators (KPIs), town planners, administrators, and policymakers can diagnose challenges and recognize areas that can be changed by improving management and incorporating new technological solutions. KPIs often help municipal governments track long-term investment results and assess their total effect or identify appropriate growth intervention initiatives. The performance of particular solutions applied in other municipalities can be used as guidelines [196]. A framework that aims to provide success measures for smart cities is the CITYkeys indicator framework [197]. The appraisal methodology and CITYkeys measurements are used to assess the progress of the smart city program and the chance of replicating successful projects in other environments. The CITYKeys indicator framework [197] is shown in Figure 6.

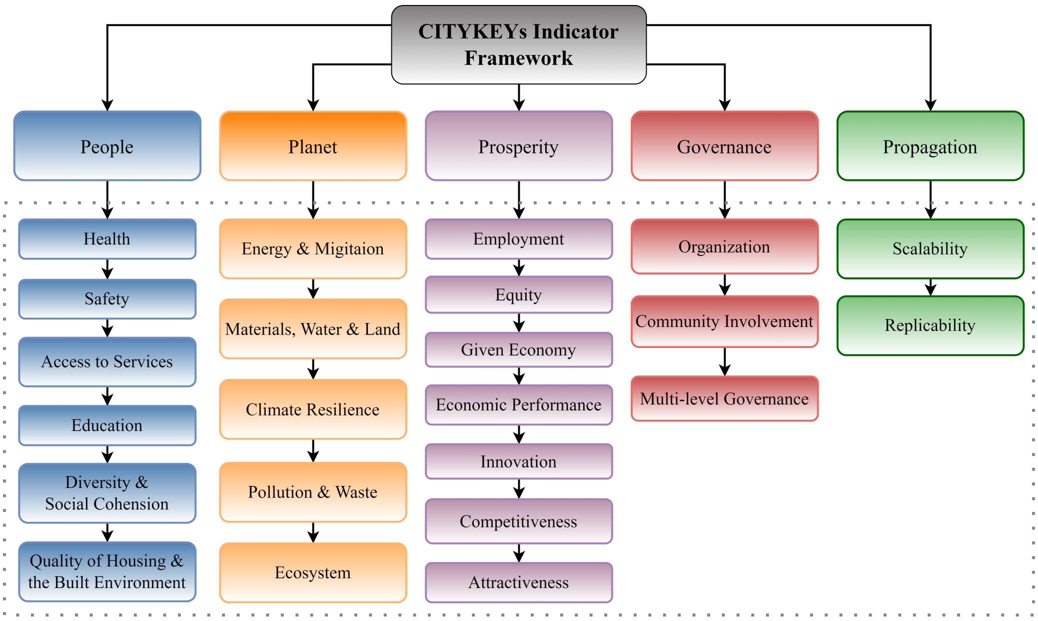

Figure 6. The CITYkeys indicator framework.

Successful smart infrastructure initiatives require accurate measurement methods for design, execution, and evaluation. Smart city efforts encourage the adoption of technology for improved quality of life, economic advantages, and growth, focusing on results rather than deployment metrics [198]. There are some other approaches to measure the success level of smart cities. The H-KPI framework, a complete measuring approach, objectively assesses smart levels in any city or community. It presents the notion of 'Elements' for varied analysis, supporting equal service access, finding implementation gaps, and maximizing smart city investments. The methodology includes five critical measures: alignment of community priorities, investment efficiency, information flow density, and quality of infrastructure services and community benefits [199,200].

The OECD Smart City Measurement Framework addresses critical considerations about what to measure and how to assess it, emphasizing inclusion and well-being. It examines digitalization, stakeholder participation, and fundamental smart city objectives—well-being, inclusivity, sustainability, and resilience—across three pillars, resulting in a holistic tool for developing inclusive, resilient, and sustainable communities [201]. The preliminary metrics for smart city success provided in Table 4 are intended to analyze the impact of programs on the well-being, inclusion, sustainability, and resilience of the residents, giving a holistic assessment of the goals of smart cities.

Table 4. Suggested indicators for smart city performance by OECD [201].

Objectives	Dimensions	Indicators
Well-being	Jobs	Employment rate (%)
	Income	People with enough money to cover their needs (%)
	Hosuing	Overcrowding conditions (rooms per inhabitant)
	Education	People 25 to 64 years old with at least tertiary education (%)
	Access to Services	Performance of public transport network (ratio between accessibility and proximity to people)
	Political Participation	Voter turnout (voters in the last national election as a % of the number of persons with voting rights)
	Health	Life expectancy at birth (years)
	Environmental Quality	Exposure to $PM_{2.5}$ in $\mu g/m^3$, population weighted (micrograms per cubic meter)
	Community	People satisfied with their city (%)
	Personal Safety	% of population that feel safe walking alone at night around the area where they live
	Life Satisfaction	Satisfaction with life as a whole (from 0 to 10)
Inclusion	Economic	Ratio between average disposable income of the top and bottom quintiles
	Migrant and Ethnic	Migrant gaps in employment rate (native-foreign, percentage points)
	Inter-generationa	Youth unemployment rate (%)
Sustainability	Energy	Energy consumption per capita (kgoe per person)
	Climate	People satisfied with efforts to preserve the environment (%)
	Material footprint	Municipal waste rate (kilos per capita)
	Biodiversity	Change in tree cover (percentage points)
Resilience	Health and Social Institutions	Active physicians rate (active physicians per 1000 people)
		Population without access to health care (%)

This research [202] includes six more smart city metrics, enabling a comprehensive and comparable assessment. These indices focus on city-level evaluations, surveying at least 100 cities around the world, and providing adequate data for in-depth research. Cities in Motion Index (CIMI) [203], Digital City Index (DCI), Global E-Government Survey (GEGS), Innovation Cities Index (ICI), Smart City Governments (SCG) [204], and Smart City Index (SCI) are concisely described, which includes definitions of smart cities, evaluation criteria, and the most recent available editions. Significantly, these indices include a variety of points of view, such as governance, digital engagement, innovation, and citizen-centric initiatives, all of which contribute to a comprehensive understanding of smart city success.

7. Smart City Challenges

The development of an IoT-based smart city comes with many challenges. Various technical and nontechnical barriers exist, from establishing the necessary ICT infrastructure, to garnering the residents' approval for such changes. ICT is fundamental for innovative city initiatives, where recent advances in cloud computing, IoT, data analytics, the semantic web, and emerging mobile technologies will help contribute to smart city growth. Such systems will deliver a wide variety of tools, including networks, software, and turnkey solutions. This section provides a list of challenges facing the development of smart city projects, from security concerns to communication infrastructure challenges.

7.1. Security

Security is crucial when smart cities provide Internet access to various devices. According to a study by HP, approximately 70% of IoT devices in a smart city are at risk of cyberattacks due to exposures such as poor authorization, inadequate software security, and inadequately encrypted communication protocols [205]. Numerous attacks such as cross-site and side-channel attacks can occur. Furthermore, significant vulnerabilities may arise in these systems due to the heterogeneity of devices linked to the identical network, where its multitenancy can guide security issues and data leakage [206]. For this reason, cities need to take action to ensure that citizen data are protected and secured. Ideally, all devices, especially critical infrastructure such as smart grids, smart healthcare, and smart transportation systems, should be protected from cyber attacks. Cities should make privacy and security their top priority for the successful implementation of IoT within their city [205]. When data are collected, distributed, and stored on a ubiquitous network, information is vulnerable to data leakage from external attackers. Sensitive information that can be vulnerable could include people's locations, medical information, bank statements, and other personal data [205]. Some privacy techniques such as encryption, anonymity, and access control measures can be applied to preserve user privacy in data fusion methods [207,208]. Since smart city data are highly granular and of various types with different data protection criteria, it is not easy to design universal privacy methods. The trade-off between efficiency and privacy needs to be addressed. Consumers are often reluctant to allow this new technology into their lives without reassurance that these systems are protected against unauthorized information sharing and maintain a high level of security [209].

7.2. Big Data

Smart city applications often need to deal with a large number of distributed devices, and the IoT framework provides an excellent forum for processing and aggregating information using various methods [210–212]. This data acquisition framework requires the proper repository and computational resources, as it is collected at high rates. A wide range of devices are used in the network to transmit, connect, and retrieve data [206]. As a result, the management of the data sources within the IoT network is critical in enabling services for consumer workflows. Data are classified into three main parameters: transmission rate, message size, and data structure. As these parameters vary from device to device, many of the big data challenges faced with these systems result from this inherent heterogeneity. To implement smart city projects based on IoT, there are multiple different challenges related to big data, based on both technological and social aspects [213]. Some of these issues are described in the following subsections.

Privacy concerns increase with increasing data generation, collection, processing, and storage, where incorrect access rights could potentially expose users' information [214]. Therefore, data must be properly managed and used to protect these data [215]. One common safeguard is data obfuscation, when the user does not have full access to their data. Due to the potential for data to be publicly exposed, either intentionally or unintentionally, sensitive information should be encrypted to protect users' privacy. These protection measures should be implemented in both software and hardware components [216]. Other big data privacy concerns include lack of viable anonymization technology, untrustworthy information, and data transmission over volatile networks. The authors in [217] address data protection problems such as lack of viable anonymization technology, data security, untrustworthy information, and data transmission over volatile networks. Suggested solutions include legal restrictions on data use, the use of data codes to secure data transfer on the Web, and the creation of background awareness structures to handle privacy issues [217].

Policies must be developed to ensure that data accessibility is equal for all users and that all parties involved in smart city applications are validated and controlled. Data intrusion from unauthorized users can lead to financial losses arising from information leaks, potentially resulting in legal troubles [218]. Ensuring data security also requires strict legal requirements at the technical, public, and business policy levels [219]. Researchers have proposed solutions to solve safety issues, such as creating functional communication groups and service protection, developing a secure mobile cloud system to solve big data storage problems, establishing the benchmark for finding various applications to track data collection, and the legal provision of services to each consumer [218].

With the emergence of the social network and connected devices, large amounts of data are continuously being generated and transmitted by smartphones, VoIP, sensors, video conferencing, and computers. People constantly create data when using different appliances, which poses problems as the data storage requirements increase exponentially [220]. While data heterogeneity improves data reliability, it also complicates big data processing, analysis, and integration processes. Researchers have proposed solutions for building cloud-based data stores that deliver secure and economical means for data storage and implement techniques that remove unnecessary data [221].

In addition to hardware and data heterogeneity, software heterogeneity creates incompatibility problems created by the convergence of data from different sources. Several potential approaches have been suggested to solve these problems, such as automated data recognition for models and the removal of outliers in data analysis applications [213,222]. These solutions turn heterogeneous, dispersed data into valuable information to acquire learning and construct data models for a detailed analysis of meaningful models.

Veracity is related to the pace of data generation and how it is processed to make decisions. The increasing rate of data generation is due to the growth of appliances connected to the Internet [222]. Data veracity concerns include latency in data collection from remote repositories and spatial limitations. Real-time analysis of extensive data might provide valuable insights for smart city management [213]. Data veracity concerns are also coupled with issues concerning the integrity of data. Veracity-related problems arise due to factors such as confusion, unregulated and untraceable data, and identification difficulties [213]. Data preprocessing methods such as data washing, integration, transformation, and deceleration can eliminate noise, fix contradictions, and help relevant information [222].

This is about the role of people in data gathering, analysis, and decision making. People evaluate data, create and experiment with theories, draw conclusions, and decide the success or failure of big data. Therefore, they should adhere to the appropriate data collection and storage policies accordingly [223]. The input of people will help improve the management of extensive data within a smart city. Significant social and institutional transitions take place during the development of smart cities, involving the human interface to support these continuous changes [224].

This measures the quality of information extraction from the data to achieve accurate analysis and conclusions. Some aspects of data collection can reduce the value of data, such as difficulties in dismantling urban data trends, wasteful data usage, data speed processed, and the cost of processing the data. However, the value of big data is crucial since the value of big data increases exponentially with new insights [225].

7.3. Sensor Networks

Previously impractical applications due to high prices and restricted availability are now possible due to the wide variety of sensors available today and the constant evolution of sensor technology. For smart cities, there are a number of different challenges relating to the integration of sensing and perception hardware. Some of these issues are explained below. The handling of a multitude of nodes scattered within a smart city can be a unique and challenging problem to solve. Although 6LoWPAN supports IPv6 on IEEE 802.15.4 [11], efficient communication routing between such large numbers of devices is a significant challenge [7].

Sensor networks can be vulnerable to cyber attacks, and some of these issues are discussed in [226,227]. Without appropriate oversight, single entities should not be trusted with data collection and storage. The cloud is considered a major data network in which cloud service providers maintain complete physical control of the data. It would be dangerous for people to trust a single company with complete control over the cloud, just as it would be dangerous to give governments too much control over personal data. Likewise, there could be concerns about trusting a single source of information from sensor networks [7]. It is better to decentralize data collection and storage and corroborate data from multiple sensing platforms to provide more reliable and trustworthy data.

Efficient use of resources is critical to managing smart city technologies. Due to the characteristics of ICT systems and the presence of latency-sensitive applications that yield decisions, optimization techniques to discover the optimal settings for these systems are computationally challenging. Managing resources that can reduce their end costs is a crucial factor driving the development and deployment of related technology [228].

7.4. Governance Challenges

Better city management is the goal of "smart governance," which involves integrating digital tools with human expertise, legal frameworks, operational procedures, public services, and cultural norms [48]. As is the case with other aspects of a smart city, smart governance poses its own set of challenges, rooted primarily in human dynamics. Since centralized control systems move toward a single, sizeable structure in which all resources are aggregated, these types of systems can lead to negative consequences, especially in a smart city context. For example, complete police control can be used for unlawful surveillance and/or violation of others' privacy [7]. The Internet of Things is a user-supplied service, where various domestic and international rules must govern the service providers' terms and conditions. Potential users of these services may need to be incentivized to participate in ethical data collection, and those organizations who wish to participate in IoT and smart city opportunities should have sufficient incentives to participate ethically [3,229].

7.5. Communication Challenges

The smart city vision is built upon connectivity, which enables interconnection among the many devices of an intelligent city [17]. The entire number of wireless appliances is estimated to have reached 50 billion by the end of 2020 [17,230]. Therefore, appropriate communications infrastructure will need to be implemented in smart cities to support various use cases, from gathering periodic environmental data to video streaming. Several current communication technologies can be incorporated into a smart city, including cellular networks (e.g., GPRS), WiMAX, LTE, SigFox, LoRa, among others [9]. Important objectives of communication and networking in smart cities include seamless connectivity, high spectral efficiency, high-rate data communication, and low power consumption [17]. Some of the communication challenges are explained in the following subsections.

7.5.1. Reliability

One main communication challenge is to provide error-free connectivity, especially since many of the existing technologies are susceptible to interference [17]. Implementing communication technologies in noisy environments such as a city without fully understanding its limitations could lead to costly infrastructure upgrades and service loss. In some test cases, the expected performance of the networking solutions was shown to not meet their specifications. For example, when a LoRa network was implemented in a smart city testbed in Italy, they found that it could not support the expected range of 5 km and only worked up to 2 km in their particular urban environment [9].

7.5.2. Heterogeneity and Interoperability

Co-existence of different communication technologies is a primary characteristic of smart cities, leading to interoperability problems between heterogeneous systems. Networks that enable communication within smart cities often become large and complex to support interoperability between data sources and consumers. As the complexity and size of networks increase with heterogeneity, other issues become more prevalent as well [231]. New features need to be handled and more thought needs to be given to improving the prevention of network security vulnerabilities introduced by bridging different networks. Such problems have been of great importance, as they include challenges with the development and deployment of heterogeneous networks in urban environments [228]. An intelligent and holistic approach to addressing these issues is necessary to connect the plethora of IoT devices in a smart city [205].

Digital Twins (DTs) can be integrated with Virtual Reality (VR) and the Internet of Things (IoT) to improve interoperability across smart city services. Incorporating these technologies can build a digital twin of urban landscapes in real time to improve urban planning, resource management, and public involvement. However, achieving effective interoperability poses significant challenges. Different city services, such as transportation, healthcare, and energy management, often use disparate systems and protocols, which can act as barriers to seamless data exchange. This lack of interoperability leads to siloed operations, where data cannot be easily shared or utilized across domains, resulting in inefficiencies and redundancies [232]. For instance, without interoperability, real-time traffic data cannot be integrated with emergency response systems to optimize routes, and energy usage data from buildings cannot be efficiently used to balance the city's power grid [233]. Addressing these interoperability issues is crucial for the cohesive operation of urban services and the overall efficiency of smart cities. Interoperability can only be enhanced by removing obstacles at both the system and field levels of silo operations, which restrict data sharing and the reuse of data gathering infrastructures for different services. To compare and classify various designs, analytical models like the SGAM [234], SCIAM [235], and GSCAM [236] provide analytical frameworks for specifying high-level criteria and interoperability for smart city platforms. To tackle these challenges, various research facilities, such as IoTMADLab, are working on actual implementations and emphasizing interoperability for effective operation and future cross-domain applications [237].

7.5.3. Communication Security

Security is another top concern of smart cities, as their network infrastructure's complexity increases to support more applications. It is noted that 50–70% of the security vulnerabilities are due to a lack of proper security controls and misconfiguration of networks [231]. Furthermore, more advanced technologies, increased interference among wireless networks, and more significant challenges were involved in establishing appropriate QoS within networks, among other issues [231]. Security must be considered, considering wireless communication vulnerabilities and new features arising from this interoperable context, which aggregate different networks. Frameworks for the accurate identification of users and the secure management of their identity are required, as many end users are likely to use and have access to intelligent city services [238].

7.5.4. Quality of Service

The high data volumes encountered by smart city networks give rise to QoS concerns. Characteristics such as differences in wireless technologies and network scalability features for specific network clients require certain provisions to ensure reliable communication. Communication networks within a smart city must accommodate any network traffic requirements and be able to determine the importance of the transmitted data. QoS rules must be set appropriately across all networks, in order not to disrupt critical communications. Many smart city services and applications are susceptible to QoS sensitivity, such as healthcare and intelligent grid applications [228].

7.5.5. Load Balancing and Scalability

Load balance in smart cities consists of efficient sharing of resources across heterogeneous wireless networks. It can optimize resource usage, increase network efficiency, and provide customers with better services [239]. The load balance depends on the architecture of the network and the use of appropriate routing algorithms. Smart cities can include hybrid network architectures that can provide new algorithms and solutions that address different requirements and provide essential features to help address interoperability and complexity concerns, such as scalability. Developing IoT-based smart cities requires wireless integration of many scattered systems and devices. Thus, scalability is paramount; the infrastructure must support new systems and future technological breakthroughs. Massive storage and processing power are also required to effectively handle enormous amounts of real-time data. Everything can fall apart if there is a hiccup in the transmission or processing of data. Therefore, it is crucial to ensure storage and operating capacity increase proportionally to the data to keep things running well [240].

7.5.6. Power Management

Power management for the many IoT-type devices and the communication infrastructure that allows smart cities is an area that still has room for improvement. Due to the sheer quantity of new IoT devices, the power consumption of these devices should be minimized [241]. Powering these devices can pose significant challenges, as improved battery life and cost minimization are needed to support many IoT devices within a smart city. This problem can be addressed by improving energy storage technologies and by advancing in the field of wireless and microelectronics communication [205]. Many smart gadgets already have low power requirements, enabling them to be battery-powered and still function for long periods of time. For example, batteries that use LWPAN for communication have a battery life of around ten years [3].

7.6. Public Awareness and Acceptance

Despite smart cities' potential benefits, privacy issues, security dangers, and unfamiliarity with the technology pose substantial obstacles to the widespread adoption of IoT-based smart cities. Establishing public trust and securing societal acceptance are essential prerequisites for the successful use of IoT technology in smart cities. The widespread data collection in IoT systems raises privacy concerns, while prominent data breaches underscore cybersecurity flaws. Lack of transparency about benefits, risks, and safeguards can lead to misinformation and fear. The success of smart city technology depends on our ability to understand and resolve public concerns. Sidewalk Toronto [242] and San Diego's street lights [243] are just two examples of how projects like these have been delayed or canceled due to growing community fear of IoT technology despite the many advantages these projects provide. These examples show how critical it is to address public concerns about data gathering and use promptly if smart city programs are to succeed. Addressing ethical concerns, such as data use and permission, is imperative to win public trust. Trust and societal approval are essential for the widespread adoption of the sensing-as-a-service paradigm. The concept's effective deployment is at risk if sensor owners do not have faith in its reliability and security. The model may collapse if the sensor owners do not trust the system [244]. Moreover, the digital gap can worsen socioeconomic disparities if access to smart city advantages is not distributed fairly. Establishing unambiguous regulatory and legal structures is essential, providing inclusive access and involving the community in planning and decision making to cultivate confidence and acceptance. To ensure the effective adoption of IoT-based smart cities, city planners should address these issues by adopting transparent procedures, implementing strong security measures, and actively involving the community [245].

7.7. Financial Affordability and Collaboration

The fundamental difficulty is to find long-term funding for smart city projects in a way that keeps services affordable [246]. Local cooperation and innovation platforms are impeded by overly tight budgets, misallocated resources, and costly initial investment costs [247,248]. It is a problem for both developed and developing economies to renovate their outdated infrastructure. Investments in innovations come with a high risk and a slow return on investment, which makes finance even more complicated. Developing new business models and integrating smart city practices into procurement are examples of market adoption initiatives that continue to face hurdles [249]. Governance difficulties, such as inflexible regulatory frameworks and institutional opposition, hinder progress [250].

The successful implementation of smart city programs also depends on having a competent workforce and strong leadership [251].

There are many obstacles to securing funding for smart city initiatives. Investors may lose faith in projects using untested technologies, known as technology risk. Valuing projects, especially those with social or economic impacts, can be difficult. Uncertain return on investment (ROI), lack of standard income pathways, and the nontraditional nature of smart city projects are additional challenges. Technology-related endeavors may struggle to attract infrastructure investors who favor long-term projects. Developing a comprehensive strategy with a robust business model and creative financing arrangements is essential to improve investment readiness and access funds. This requires a deep understanding of the project, potential cash flows, accessible financing options, and government procurement techniques to match projects with suitable financing instruments [252].

The challenges listed in Section 7 were identified through a comprehensive literature review using databases such as Google Scholar, IEEE Xplore, WoS, and MDPI. While the integration of IoT offers numerous benefits, it also poses unique challenges. We have outlined these benefits and challenges across various smart city domains in Table 5.

Table 5. Benefits and challenges in different smart city domains.

Category	Benefits	Challenges
Smart Grids	• Enhanced energy efficiency [253] • Improved reliability and resilience [253] • Integration of renewable energy [253]	• Cyber security Issues [254] • Big data, data management [255] • Interoperability [254]
Intelligent Transportation Systems (ITS)	• Enhanced traffic control management [256] • Improved safety, accident management [256] • Reducing air & noise pollution, congestion, and energy consumption [256]	• Device identification and management [257] • Data privacy and security [257] • Federated systems and authentication [257]
Smart Lighting	• Energy saving & burn hour optimization [258] • Travel time reduction [258] • High up-time & immediate fault location [258] • Load balancing and load shedding [258]	• Electronic waste, privacy violations [259] • Affordability and scalability [259] • High Initial investments [259] • Interoperability issues [260]
Smart Parking	• Fuel and time savings [261] • Reduced traffic jams [261] • Lower carbon footprint [261] • Higher safety and security [261]	• Cost, implementation challenges [262] • Maintenance and GPS accuracy ratios [262] • Interoperability issues [263] • Lack of trust [262]
Smart Building	• Enhanced tenant profitability [62] • Energy efficiency [62] • Comfort and satisfaction [264] • Operational savings [62]	• Electronic waste, privacy violations [259] • Slow connectivity, poor scalability [265] • Security issues, lack of trust [266,267] • Interoperability issues [266,268]
Smart Healthcare	• Reducing long queue time in hospital [269] • Remote patient monitoring [270] • Electronic healthcare records [270] • Cost reduction [270] • Medicine tracking [270] • Geographical independence [270]	• Security, privacy [271,272] • Wearability, low-power operation [271] • Large volume of data [272] • High-power consumption [272] • Low-latency tolerance [272] • Interoperability and scalability [272]
Smart Waste Management	• Optimized resources, reduced costs [273] • Clean & better working environments [273] • Lower carbon emissions, increased recycling rates [273]	• Electronic waste, privacy violations [259] • Security issues [271] • Data privacy and security [257] • High-power consumption [272]
Smart Manufacturing System	• Greater energy efficiency [274] • Predictive maintenance [274] • Higher product quality [274] • Reduced downtime [274] • Informed decisions [274]	• Interoperability [275,276] • Security, privacy [276,277] • Visualization services [278] • Safety in human-robot collaboration, multilingualism [276]

Table 5. *Cont.*

Category	Benefits	Challenges
Smart Water Distribution System	• Increasing efficiency & productivity [279,280] • Real-time control [281] • process optimization, service time reduction [281] • Cost saving & resource conservation [281]	• Power usage & coverage (for sensors) [282] • Security and privacy, complexity [282] • Big data, Cost of deployment [282] • Interoperability & system integration [276,282]
Smart Surveillance System	• Real-time surveillance [283] • Improved monitoring and control [283] • Enhanced security measures [283] • Streamlined operations and decision-making [283] • Increased user convenience [283] • Increased scalability [283]	• Cost & Scalability [284] • Reliability & efficiency [284] • Real-time prediction, security, & privacy [284]
Smart Food Distribution System	• Reducing waste [285] • Increasing food safety [285] • Speeding up delivery [285] • respond quickly and improve performances [286] • Proper decision making [286] • Properly monitor and control information [286]	• Capital investment [287] • Networks structure [287] • Interoperability and integration [287] • Analytical capability of big data [287] • Internet availability and reliability [287] • Operations and maintenance cost challenges [287] • Data security and trust [287]

From our analysis of the existing literature, we have identified several key challenges encountered in cities when implementing IoT-based solutions. Among these, interoperability, security, and privacy stand out as the primary challenges. The significance of interoperability as a foundational challenge is supported by its frequent mention in the literature and its important role in enabling other smart city functionalities. Security and privacy are equally critical, with security addressing vulnerabilities in IoT networks that could lead to unauthorized data access, and privacy ensuring that personal information is protected as these technologies become more pervasive. Effective management of these challenges, including interoperability, security, and privacy, is essential for overcoming other issues such as data integration and scalability, making them crucial for the successful deployment of IoT in smart cities.

8. Discussion

Smart cities' applications rely on data collection, processing, and analysis to power valuable services. Data on cars, drivers, patients, and more are crucial in the context of smart transportation and healthcare. Protecting sensitive information is a vital component of any smart city's infrastructure. It is critical to take precautions like access control, encryption, authentication, signatures, and privacy protection to keep this information safe [288]. The European Union's Agency for Network and Information Security has provided comprehensive recommendations for protecting smart cities against cyberattacks [289]. Among these methods are virtual private networks, data encryption, network intrusion detection systems, physical security measures (access control, alarms, and surveillance), the adoption of a security policy, the keeping of activity logs, the creation of frequent backups, the conducting of regular audits, and the completion of shutdown processes. Encryption, identification management, device authentication, digital signatures, certificates, and watermarking are all crucial parts of the four-layer data security architecture [290].

Due to the increasing adoption rate of the Internet of Things, sensor node design is becoming increasingly crucial in Wireless Sensor Networks. Energy-efficient sensing algorithms and approaches are essential to achieve efficiency, cost-effectiveness, and a longer network life [291]. Security management is performed through correlation and Bayesian learning. The cluster heads are chosen with the help of k-NN, PCA, and ANN. Q-learning is used to predict future energy. For energy forecasting, EH-WSN uses reinforcement learning. SVM, classification, and optimization algorithms are used in event monitoring, defect detection, and data packet routing. SVM, deep learning, and Q-learning all deal with the scheduling and QoS prediction of packets at the MAC layer. The transmission of radio waves makes use of reinforcement learning at an intense level. WSN-IoT's machine learning capabilities are a huge help in smart city healthcare [292]. Data aggregation using support vector machines and recurrent neural networks helps to reduce duplication in the context of data accumulation.

The challenge of heterogeneity in IoT applications by proposing semantic data models within the VITAL system will enable interoperability and platform-agnostic integration, facilitating the incorporation of diverse data sources into the Web, built on Linked Data principles and existing ontologies [293]. RFID, ZigBee, Bluetooth, LoRaWAN, Z-Wave, and WPANs are all examples of existing wireless technologies that enable low-power communication; nevertheless, they all have room for development regarding device compatibility, throughput, and range. Modern technologies such as Wi-Fi are insufficient for smart city communication; hence, improving smart city communication should be a top priority. The design, allocation of resources, mobility management, quality of service, and security of many wireless smart city networks are all areas of concern.

One of the main goals of current studies is to find ways to make global roaming and incorporating new wireless technologies into smart cities as smooth as possible. Due to the limited resources of the equipment used in smart cities, energy-efficient communication is paramount. WiMAX and LTEA are examples of cutting-edge technologies that offer lightning-fast data transfer rates, but at the expense of massive power consumption. Due to variable signal quality, repeated transmissions, and data power, communication technology is still relatively energy-intensive, even with better device batteries. Smart cities of the future will prioritize renewable energy management, real-time data collection, and demand-side planning [17].

9. Concluding Remarks and Future Directions

To improve the quality of life for its citizens, a "smart city" optimizes its available resources. The term "smart city" describes urban areas that use a wide range of smart technologies to improve diverse areas such as transportation, energy, healthcare, parking, building, and municipal administration. The need for smart city projects is rising exponentially due to the growing urban population and the depletion of traditional resources. However, the journey toward becoming a smart city is paved with challenges that require continuous effort to overcome.

This study explores the many features and parameters of IoT systems, highlighting their essential role in the development of smart cities. Smart cities can do so much due to the way IoT systems are integrated. We initially outline the primary motivations for this research, illuminating the complexities and challenges associated with deploying IoT technologies. The paper then explores the main applications of these technologies, showing how they improve and expand various aspects of urban life. Moreover, we highlight several innovative projects in smart city development, each of which provides significant information and could serve as a model for other towns aiming to achieve smart city status.

In the near future, IoT technologies are anticipated to become integral components across a range of smart city systems, from autonomous traffic management to utility monitoring and public safety, significantly enhancing efficiency and service quality. Ensuring the privacy rights of users and residents is essential to developing effective frameworks.

Addressing the numerous challenges smart cities face—from security and big data management to governance and communication—is crucial. Our research highlights innovative approaches that shape the future of urban environments. The integration of advanced sensor networks and big data analytics not only enhances city operations but also paves the way for proactive governance and improved public engagement. Such networks enable real-time data collection and analysis, improving security and optimizing resource use. Additionally, improvements in communication technologies such as 5G networks and IoT connections greatly facilitate the interconnectivity of devices and city systems. This improved connectivity optimizes operations and enhances the efficiency of service delivery.

By embracing these innovative solutions, cities can tackle current challenges and pave the way for a more innovative and sustainable future.

The insights provided in this paper are instrumental for academics, scientists, and policymakers, highlighting the transformative impact of IoT on smart cities. These findings support the need for enhanced cross-disciplinary collaborations and policy reforms that support sustainable urban development. Moreover, by presenting a range of global smart city initiatives, critical standards, and success metrics, and outlining key challenges, this paper serves as a valuable resource for other cities navigating the complex journey toward becoming smart cities. This contribution not only advances academic discussions but also supports practical implementations worldwide.

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Abbreviations

The following abbreviations are used in this manuscript:

ICT	Information and Communications Technology
IoT	Internet of Things
ITS	Intelligent Transportation System
QoS	Quality of Service
LPWAN	Low-Power Wide Area Network
WSN	Wireless Sensor Network
WLAN	Wireless Local Area Network
LWPAN	Low Rate Wireless Personal Area Network
VoIP	Voice over Internet Protocol
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks
DSRC	Dedicated short-range communications
GSM	Global System for Mobile Communications
ECC	Edge Cognitive Computing
QoE	Quality of Experience
SDN	Software-Defined Networking
VLC	Visible Light Communication
CPS	Cyber-Physical System
NB-IoT	Narrowband Internet of Things
SLS	Smart Lighting System
LoRa	Long Range
HSN	Hybrid Sensing Network
NFC	Near-Field Communication
SPS	Smart Parking System
WIWSBIS	Waste Identity, Weight, and Stolen Bins Identification System

RAN	Regional Area Network
WAN	Wide Area Network
MAN	Metropolitan Area Network
LAN	Local Area Network
PAN	Personal Area Network
RDS	Radio Data System
HEVC	High-Efficiency Video Coding
EAMSuS	Efficient Algorithm for Media-based Surveillance Systems
OSGP	Open Smart Grid Protocol
FOCON	Fog Computing Architecture Network
KPI	Key performance indicator
ISMS	Information Security Management System
SCCM	Smart city concept model
BIM	Building information model

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