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A comprehensive survey on an IoT-based smart public street lighting system application for smart cities

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ABSTRACT

The swift advancement and updating of urban lighting systems, along with the incorporation of smart and Internet of Things (IoT) infrastructure, have opened up numerous opportunities for technological progress across various facets of life. This paper offers a comprehensive overview on the development of smart public street lighting infrastructure tailored for IoT applications in smart cities. Initially, the focus lies on transitioning from conventional lighting to Light-Emitting Diodes (LEDs) technology in street lighting. Complementing this transition, the incorporation of the wireless networked sensors and controllers ensures dynamic brightness control in operational zones, envisioning substantial energy savings. Furthermore, the notion characterizing smart cities denotes incorporating modern digital infrastructures to develop innovative functionalities and connect various application, following the IoT paradigm. The key findings from the proposed study have enhanced knowledge regarding smart public street lighting application. This system integrates smart poles equipped with LEDs lamps technology, smart sensors, communication network and monitoring unit, leveraging current technological advancements in IoT applications. The implementation of IoT-based smart public street lighting systems presents several challenges, including integrating diverse sensors and actuators ensuring robust device communication, secure data management, and effective system scaling and maintenance. Despite these challenges, this system significantly advances smart city infrastructure by enhancing energy efficiency, safety, and sustainability. However, addressing their high initial costs, data privacy and security concerns, and ongoing maintenance are crucial in future studies to realize their full potential in smart cities.

1. Introduction

Smart cities encompass a fusion of technologies for data collection, processing, and dissemination, alongside networking, computing, and data security measures. This integration utilizes electronic tools sensors, and advanced communication methods to foster innovation across various applications, aiming to enhance the lifestyle quality for most citizens [1,2]. They strive to enhance the daily activities of its inhabitants and establishments through leveraging cutting-edge technologies to foster sustainable economic development practices [3]. This is where the Internet of Things (IoT) takes main interest. Indeed, IoT is instrumental in fostering the growth of smart cities by establishing robust connections among devices, sensors, and networks essential for their setup [4,5].

Within any IoT system, unique identifiers contribute significantly to accelerating the exchange of information across various networks [6,7]. Indeed, maintaining equilibrium in the environmental conservation and natural resource management is an essential aspect of these initiatives, reflecting a growing trend in technology-driven projects [8]. In these recent years, population progression and urbanization have seen a significant surge with more individuals seeking improved opportunities in smart cities. Indeed, smart cities leverage technology and data to enhance urban life, address environmental challenges, and boost infrastructure efficiency. By 2050, around 70 % of the global population is expected to live in urban areas, increasing the demand for smart solutions for resource management, transportation optimization, public safety, and sustainability [9–11]. Consequently, smart cities aim to create more liveable, resilient, and efficient environments by integrating IoT devices, data analytics, and automated systems. Various projects illustrate the diverse approach needed, such as a plug-and-play methodology for IoT medical devices ensuring interoperability and real-time data collection was presented in [12]. The transition from Sustainable Urban Mobility Plans (SUMP) to Mobility as a Service (MaaS) to improve urban mobility and reduce emissions was explored in [13]. Additionally,

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the importance of inclusive technology deployment for equitable benefits was highlighted in [14].

Furthermore, as fossil fuels become increasingly scarce and their prices continue to rise due to inflation [15], there is a pressing need for improved power management and monitoring strategies to achieve significant reductions in energy consumption and transition towards a low-carbon economy by 2050 [16]. In this regard, approximately 80 % of the electricity generated is dedicated to fulfilling urban needs, with about 60 % of this energy consumed by streetlamps due to their permanent operation during nighttime. Therefore, energy saving emerges as a pivotal concern within the scope of smart cities, achievable specially through smart lighting systems implementation as alternatives to conventional incandescent/fluorescent lamps [17,18]. In this way, implementing retrofit measures for lighting systems is considered a commendable approach to significantly reducing energy consumption while enhancing visual luxury and protection [19,20]. Consequently, the upgrade of conventional lighting technologies with Light-Emitting Diodes (LEDs) technology stands out as an attractive option for retrofitting older systems, primarily owing to its great luminous efficacy [21]. Indeed, LEDs technology is widely recognized as a favourable and cost-effective option, offering advantages such as low energy utilisation, extended lifespan, decreasing maintenance expenditures [22], reduced ecological effect [23], and numerous additional profits. Consequently, the potential application of light control systems holds promise for enhancing human activity, health and safety [24–26]. That's why, smart cities and municipalities find themselves in need of techno-economic analysis tools and methodologies to accurately assess the feasibility of smart lighting projects, especially public street lighting [27,28].

To this end, the widespread adoption of the Internet-of-Things (IoT) concept has introduced a novel network structure wherein a diverse array of objects and devices are equipped with software, sensors, and further technologies. These components enable devices to connect, gather data, monitor, and exchange information with other systems and devices via the internet. These advancements provide a foundation that allows numerous individuals to connect with each other. The connectivity is facilitated by communication technologies like WiFi, GSM, ZigBee, among others [29–31].

Potentially, the IoT technology encompasses numerous applications designed to enhance various sectors, particularly in smart cities. Accordingly, the integration of the IoT as an attractive paradigm into a smart city context holds significant appeal for public administrations on a wider scale. Indeed, smart cities harness these intelligent technologies to generate vast amounts of data in real-time across all public services as timely information is essential for enhancing public services and offering feedback to citizens.

By incorporating IoT devices into the information system, cities can enhance transparency in governance, involve users in political decisions and urban issues, ameliorate healthcare, promote the well-being of residents, and address various features of human life [32,33]. Consequently, the integration of IoT notions enhances smart cities and positively impacts various aspects of human life. It enables the provision of cost-effective services, improves public transportation systems, reduces traffic obstruction, and contributes to citizen safety and health. Additionally, IoT plays a crucial role at the national level, particularly which related to pollution decreasing, energy conservation, monitoring systems, lighting and essential infrastructure development. Thus, smart cities enabled IoT technology can achieve lower costs, greater efficiency, and enhanced security in operations through energy conservation measures, economic considerations, and increased reliability levels [34,35].

Recently, public smart lighting has evolved into a dynamic platform that serves as a cornerstone for the urban advancement. The transformation towards smart cities allows cities to reconsider the utility of public street lighting assets, viewing them not just as a cost factor but as opportunities to introduce new services and generate revenue streams. Indeed, smart lighting paradigms have garnered worldwide significance, prompting numerous research initiatives to demonstrate the potential and positive impacts of integrating smart technologies into streetlamp management. These technologies involve equipping smart street lighting with sensors, wireless communications capabilities and control algorithms, enabling them to operate autonomously within the IoT framework [36–38].

In this context, the progress of intelligent public street lighting, incorporating monitoring systems, is a subject of significant spotlight among several researchers. For instance, scientists in Refs. [39,40] have concentrated on providing cutting-edge advancements in smart streetlight systems. They focused on intelligent street light scheme including cameras and sensors to enhance and supervise street lighting, facilitating dynamic adjustments to lighting intensities according to traffic flow and weather circumstances. This results in an efficient and cost-effective solution for urban illumination. Researchers in Ref. [41] have reviewed the recent tendencies in smart street lighting, focusing on light lamps type choice, light intensity controlling procedures, and strategies for connecting sensors to enable remote light control, weather condition monitoring, and remote lamp failure diagnosis. They compared various intelligent street lighting structures, involving their control procedures and connectivity. Similarly, authors in Ref. [42] have introduced a technique for proposing a street lighting procedure taking into account both energy and economic considerations alongside operator choice. The project was applied initially in a test part and subsequently was expanded to cover the entirety of the campus zone. Data gathered from the test situation were examined to assess the energy advantages of such lighting techniques and compared with modelled and scheduled data from the planning stage. The subsequent implementation phase was additionally outlined, including an assessment of potential economic advantages. Others in Ref. [43] have concentrated on an optimization method designed to assist decision-makers in identifying suitable upgrade involvements for current lighting systems. They applied this technique to a definite street lighting setup located in Bari, Italy. A new systematic approach for conducting energy, illumination and economic analyses of street lighting renovation plans was investigated in Ref. [44]. This approach was implemented in the municipality of Pontedera, Italy as an illustrative example. A study in Ref. [45] discussed the feasibility and efficacy of communities organizing a network for applying public smart lighting. Another in Ref. [46] has proposed a novel, replicable method for shrewdly managing public lighting outlines, comprising three key stages: reassigning and updating outdated luminaires, incorporating daylighting approaches, and applying a dimming technique taking into consideration occupancy and real-time information. Ref. [47] introduced a streetlight regulation strategy focussed on the Artificial Bee Colony optimization procedure. This process was noted for its speed, accuracy, and reliability. In Ref. [48], a new supervisory system named the lighting level control procedure was elaborated. This process utilized sky brightness assessments to regulate lighting degrees. Unlike conventional methods relying on luminance meters, photocells, or lux meters to identify actual light and adjust lighting operation directly, this approach took a different route. Additionally in Ref. [49], an intelligent management and eco-friendly assessments of road tunnel illumination using a 3D simulation and an extended memory enhancement process was investigated. A proposed adaptive street lighting predictive scheduling solution for street lighting schemes was suggested in Ref. [50]. This method involved fulfilling traffic-conscious lighting methods and employing suitable predictive approaches, leading to notable energy savings in street lighting infrastructures. A study in Ref. [51] has explored diverse strategies, including the utilization of IoT technology, sensors, devices and wireless communication capabilities, to supervise and regulate street illumination systems. Besides, authors have drawn attention to several challenges inherent in deploying these systems, such as the requirement for reliable and secure communication protocols, as well as the substantial costs associated with installation and upkeep.

Numerous real-world applications and use cases demonstrating significant benefits are highlighted. For instance, Barcelona has implemented a comprehensive IoT-based smart street lighting system that uses sensors to adjust the brightness of streetlights based on pedestrian and vehicular traffic, reducing energy consumption by up to 30 %. San Diego has installed over 3000 smart streetlights equipped with sensors to monitor traffic and environmental conditions, aiding in urban planning and traffic management. Los Angeles has deployed an advanced street lighting system integrating Light-Emitting Diodes (LED) lamps with IoT sensors and connectivity, enabling remote monitoring and management of streetlights, which has led to a 60 % reduction in energy use and millions of dollars in annual savings. These examples illustrate how IoT-based smart street lighting systems improve energy efficiency, reduce operational costs, enhance public safety, and provide valuable data for urban management.

Thus, the aim of this work is to outline a methodology for retrofitting public street lighting within the framework of enhancing energy efficiency in smart cities. Specifically, we delve the tailored opportunities of IoT-enabled smart public lighting applications for smart cities, which play a pivotal involvement in efficient power control.

In this context, this study reveals an intelligent public street light supervisory system that integrates three key components: LEDs Street poles, communication network, and monitoring unit. The main goal is to evaluate the energy savings reachable by replacing traditional systems with LEDs technology in smart street lighting infrastructures as well as ensure the proper functioning of the smart public street lighting structure through integration with a monitoring unit. The smart public street lighting application is built upon IoT infrastructures and is equipped with a range of sensors strategically positioned on streetlight poles. These sensors are connected to the internet through a gateway, ensuring seamless communication and data transfer for effective monitoring and control within smart cities concepts. The main contributions of this study, emphasizing energy efficiency and economic growth, are summarized as follows:

➢ Highlight an overview of IoT architectures for smart cities, covering concepts, structures, and applications related to data collection, processing, and distribution.
➢ Replace traditional light sources with LEDs luminaires in public lighting infrastructure to establish a retrofitting system that not only conserves energy but also delivers superior lighting quality, demands minimal maintenance, provides adaptable light management, and mitigates environmental effect. The integration of LEDs streetlights alongside sensors and supervisory approaches demonstrates further enhancement energy effectiveness in public lighting applications.
➢ Provide an overview of the evolution of smart public street lighting infrastructure customized for IoT applications, highlighting the main architectures and their roles within the framework of smart cities.
➢ Perform a monitoring system streetlights and nodes equipped with various sensors, strategically positioned on streetlights, and connected to the internet via a gateway unit.
➢ Integrate IoT technology into smart public street lighting by deploying applications over an internet communication network. This allows real-time system supervising and monitoring through mobile devices such as smartphones.
➢ Explain the possible energy savings and cost reductions achievable through controlled LEDs smart poles, utilizing various communication networks facilitating the utilization of smart lighting.
➢ Upgrade the smart city's lighting infrastructure to ameliorate the quality of life for all humans. This involves reducing the carbon footprint, promoting sustainable growth, enhancing the efficiency of urban lighting systems, and increasing the environmental friendliness of cities.

The remaining content of the proposed paper is established as follows: Section 2 delves into the exploration of IoT, encompassing its historical evolution, developmental trajectory, architectural framework, and its applicability within smart cities for ensuring dependable data transmission. Section 3 delineates the overall structure of an intelligent public street lighting system, including its primary functions, the cost savings enabled by remotely managed LEDs smart poles, and the various communication infrastructures enhancing its smart capabilities and essential attributes. Meanwhile, Section 4 highlights the future trends in smart street lighting systems. Ultimately, Section 5 encapsulates the key takeaways and conclusions.

2. IoT services for smart cities

Recently, the concept of a smart city stands out for its integration of physical, social, and business infrastructures, along with cutting-edge technology in several domains such as energy, healthcare, communication, transportation, and governance. This holistic approach fosters collective intelligence within the city, driving increased efficiency and innovation.

The conventional city can transition to a smart city by implementing networking infrastructures and adopting emerging technologies like the IoT. This transformation prioritizes the development of efficient and sustainable infrastructures, promoting energy conservation and environmentally friendly systems aiming to mitigate pollution and support smart cities in combating climate change. Indeed, a smart city exploits IoT advancements to collect data from essential sectors and engage with governance, thereby enhancing the well-being of a nation's citizens and public functionalities. This facilitates advancements in governance, management, public security, and overall progress. By leveraging modern technologies, a smart city can empower individuals to discover optimal solutions to their challenges [52,53].

The recent implementations of a smart city, for instance smart parking utilizing IoT, smart energy management, smart water systems, smart infrastructure development, smart agriculture, smart healthcare, particularly focusing on smart public street lighting applications as outlined in this study, rely on communication devices interconnected through the IoT [54–59]. Fig. 1 summarizes the components and current applications of a smart city, highlighting their interdependence for the creation of novel solutions. These components not only interact to form innovative systems but also depend on each other to operate optimally and efficiently.

Indeed, the study in [60] explores future waste management in smart, sustainable cities, focusing on integrating advanced technologies to enhance efficiency, sustainability, and public health. It discusses challenges in applying its framework across different city contexts, highlights resource and technical demands for advanced technologies, and notes gaps in practical implementation. The investigation in [61] examines IoT devices in smart cities, noting high energy demands for data exchange. It advocates Green IoT to reduce device energy use via hybrid deep learning. Challenges include technical complexity with methods like Green energy-efficient routing (GEER), Ant Colony Optimization (ACO), and AutoEncoder (AE), and ongoing energy dependency despite reduction efforts. Authors in [62] reviews the state-of-the-art applications of deep learning in water quality management, exploring techniques for monitoring, predicting, and managing water quality to ensure safe and clean water. It predicts water quality issues for proactive intervention. However, implementing these models requires advanced technical expertise and substantial resources. Their effectiveness depends on access to high-quality datasets, and the costs involved may limit their deployment in resource-limited settings. Moreover, integrating deep learning into water management infrastructure is complex and demands significant time investment. Others in [63] address the increasing urbanization and traffic management challenges faced by cities worldwide. It proposes an IoT-based system to monitor traffic in real-time, aiming to improve city governance and urban planning. Nonetheless, implementing this architecture proves costly due to investments in infrastructure, sensors, and data management. Additionally, privacy concerns emerge from real-time data

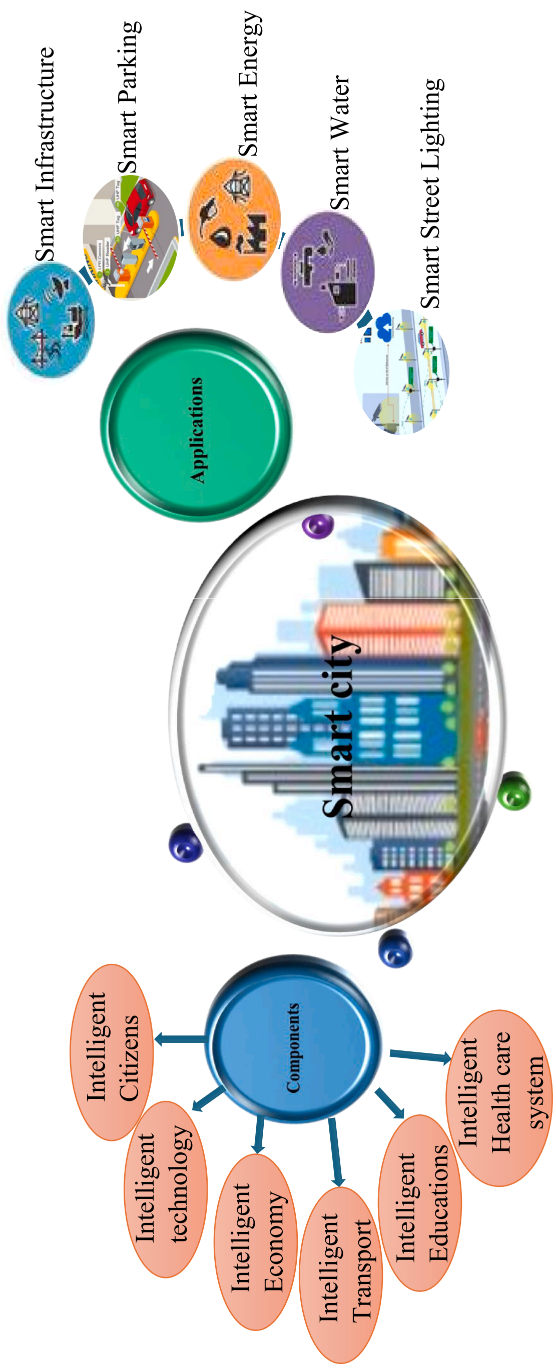

Fig. 1. Smart city components and applications.

collection on traffic, vehicles, and pedestrians, necessitating strict regulatory compliance. Addressing technical challenges includes ensuring the reliability and security of IoT devices to prevent disruptions and data breaches. Table 1 provides a summary to illustrate advancements beyond related works.

The IoT is gaining prominence as a transformative notion that harnesses the internet's capabilities to connect physical objects, mechanisms, or devices. This connectivity allows them to communicate, exchange data, and provide users invaluable services and insights. This is largely accomplished reached thanks to the cooperation of sensors and communication networks, fostering device-to-device communication. Consequently, it promotes the advancement of smarter and more efficient energy monitoring systems.

Various IoT architectures have been suggested for integration into smart cities, with the basic architecture consisting of three layers as presented in Fig. 2. Indeed, the first layer, known as the perception layer, plays a crucial role in capturing, gathering, distinguishing, and identifying information from objects in the physical world. This layer incorporates tags, sensors, laser scanners, and similar technologies. The second layer, referred to as the network layer, serves to transmit packets across a dependable communication medium. Lastly, the application layer processes the data, combines inputs from different sources, and presents it [64–67].

Here, we've explored the most crucial three layers which the main tasks are illustrated in Fig. 3:

A. Perception Layer: referred to as the device layer, encompasses a diversity of sensors (including power sensors), actuators, tags and readers (including sensor equipment (including Global Positioning Systems (GPS), cameras or Radio Frequency Identification (RFID) devices). These Internet-enabled devices are capable of perceiving, detecting objects, collecting information, and exchanging data with other devices via Internet communication networks.
B. Network Layer: termed as the connectivity layer, plays an important role for sending information from the perception layer to the application layer while considering the limitations imposed by the capabilities of devices, network constraints, and application restriction. This layer oversees the conveyance of sensor data gathered from the perception layer, facilitating its processing, management, and accessibility within the main network, and vice versa.

Table 1
Advancements beyond related works.

Research Area	Related Works	Advancements Beyond Related Works
IoT-Enabled Waste Management	Provide context and build upon the themes and findings, contributing to a broader understanding of smart city development [60].	Leveraging cutting-edge technologies and innovative strategies to address challenges in waste management within sustainable cities.
Environmental Monitoring	Provide the contributions in Green IoT, energy-efficient routing, and hybrid deep learning techniques in smart cities [61].	Enhancing the sustainability and efficiency of IoT systems within smart cities.
Smart Water Management	Contextualize the advancements and applications of deep learning in water quality management [62].	The importance of deep learning applications in water quality management lies in their enhanced prediction capabilities, improved data handling techniques, and integration of emerging technologies.
IoT-Based Traffic Management	Provide further insights into IoT applications in traffic monitoring and intelligent transportation systems [63].	Leveraging emerging technologies effectively and addressing current limitations in traffic management systems.

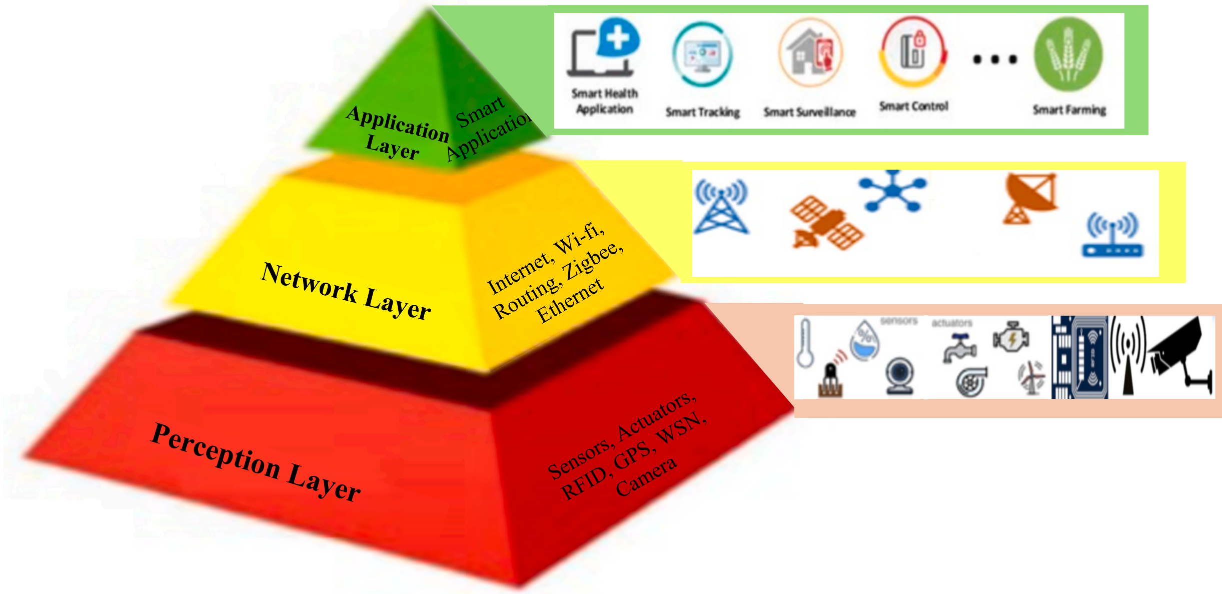

Fig. 2. IoT basic architecture.

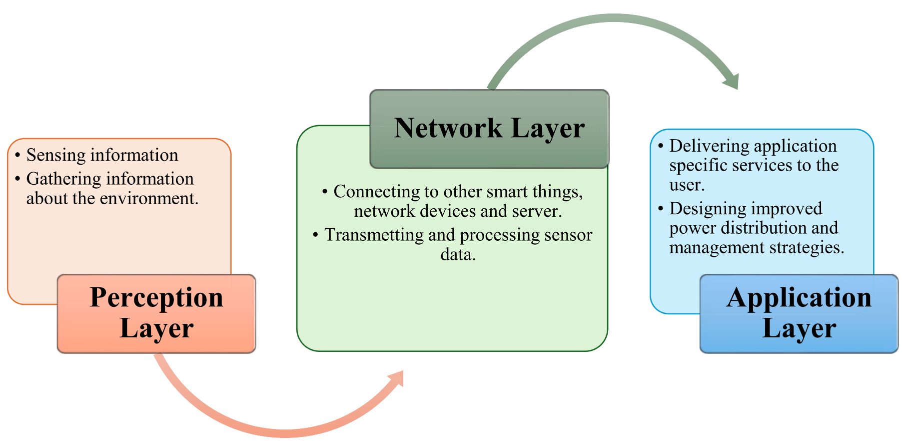

Fig. 3. IoT architecture layers key tasks.

C. IoT schemes utilize an array of short-range communication network architectures, including ZigBee and Bluetooth, with the aim of transmitting data from perception devices to a close gateway, taking into account the abilities of the communicating entities. Indeed, this layer facilitates data transfer through various networks, including Wide Area Networks (WAN) and Local Area Networks (LAN), using both wired and wireless technologies such as Cellular Networks, Wi-Fi (Wireless Fidelity), Bluetooth, Ethernet, Near Field Communications (NFC), Low-Power Wide-Area Network (LPWAN), ZigBee, 2 G, 3 G, 4 G, public switched telephone networks, cable broadband, and Power Line Communication (PLC). Additionally, this layer incorporates management and information strategies, utilizing internet technologies to transport information across extensive distances according to the application.

D. Application Layer: plays a significant role in managing data collected from the network layer in real-time to effectively control IoT devices, allowing more effective power distribution and supervision strategies. It utilizes a diversity of IoT technologies to ease a wide range of IoT services and includes the application configuration. This configuration is tasked with data processing, computing, and interfacing with resources.

Through the application layer, IoT facilitates the seamless integration of information technologies and applications, including smart buildings, smart cities, smart healthcare systems and intelligent transportation systems. These solutions feature intuitive user interfaces at the application layer, aiming to optimize power system monitoring, manage demand-side energy, coordinate distributed power storage, and integrate renewable energy sources.

3. Smart public street lighting infrastructure

Currently, energy consumption exceeds that of several decades ago, prompting calls from various sectors to conserve it. Furthermore, there is growing awareness that conserving energy is crucial not just for economic reasons but additionally for environmental sustainability. Consequently, energy efficacy has become a vital criterion for smart cities. In this context, many cities are keen to investigate the opportunities provided by smart lighting as a solution to inflexible, expensive, and ineffective method employed by traditional networks.

The intelligent public street lighting can be defined as a smart system that utilizes an innovative light source technology, serves several user-defined purposes and integrates IoT technologies. By incorporating smart features into public lighting services, smart cities strive to meet the evolving needs of their inhabitants. Therefore, this section outlines the procedure for fulfilling smart public street lighting system, one of the numerous opportunities that a smart city should prioritize. The objective is to enhance the reliability and resiliency of the smart city infrastructure while fostering energy efficiency, enhancing safety, promoting cleanliness, monitoring pollution or weather conditions, reducing electrical consumption, curbing greenhouse gas emissions, and ultimately improving overall urban liveability by creating more comfortable urban environments for residents.

Research in smart lighting systems seems to follow two main possibilities: firstly, there's a focus on enhancing the efficiency of the traditional lighting devices themselves. Secondly, many researchers concentrate on intelligent management of lighting systems to optimize their operation [68-70].

In this regard, this study addresses not only the replacement and retrofitting of traditional streetlights with LEDs technology, but also the employment of communication and information infrastructures and the potential incorporation of a wide range of procedures. These approaches involve management and monitoring systems for the entire smart city. As illustrated in Fig. 4, the proposed system is centred around defining a smart public street lighting application, highlighting its main components and ensuring:

- Remote supervision of the public street lighting infrastructure.
- Intelligent management of streetlamps to adjust illumination intensity at each lamp or group, based on daily time, nighttime, weather conditions and the presence of vehicles and/or pedestrians within the monitored region.
- Ensuring that the level of brightness meets the requirements set by regional/national/standard rules under all operating conditions.
- Establishment of an infrastructure of local communication networked technologies implemented through advanced communication protocols such as Zigbee.
- Monitoring of traffic and urgent situations, including street congestions and collisions, for fail-safe defaults.
- Evaluation of energy consumption.
- Remote management and gate to all services for organizing street lighting controls and supervising alerts via a web application.
- Establishment of remote interaction between mobile devices, smartphones as well as the web application using WiFi/3 G/4 G connections.
- Extracting all data in real-time, sharing it with the web application and warning the remote management.
- General safety, especially in the event of a connectivity or component damage, is ensured by the activation of a failsafe default condition in the smart street lighting scheme. Consequently, all intelligent features are deactivated, and the system operates like a conventional disconnected scheme.

As a result, the evolution of smart public street lighting systems over the past two decades has seen significant advancements, particularly with the shift from traditional lighting to LED technology. This transition has enhanced energy efficiency and reduced operational costs. Initially costly, LED and IoT sensor integration has become more affordable due to technological progress and economies of scale, expanding access for municipalities. Government policies and incentives have further accelerated adoption, aligning with sustainability and smart city initiatives. Additional factors, such as advances in communication networks, predictive maintenance through data analytics, and increased environmental awareness have also shaped the current landscape of smart lighting systems, highlighting their historical context and economic importance. Indeed, the standard configuration of a smart public street lighting system delineates its essential components specifically, the Smart poles, the Communication Network and the Monitoring Unit [71,72].

3.1. Smart poles

A smart pole, essentially a street light fixture, typically consists of a streetlight equipped with highly efficient LEDs lamps technology, a local light controller, smart sensors and communication devices.

Indeed, the smart poles are interconnected, capable of exchanging supervisory commands and information requests with each other and can interface with a monitoring unit via a gateway. The monitoring unit acts as the central infrastructure management hub, tasked with

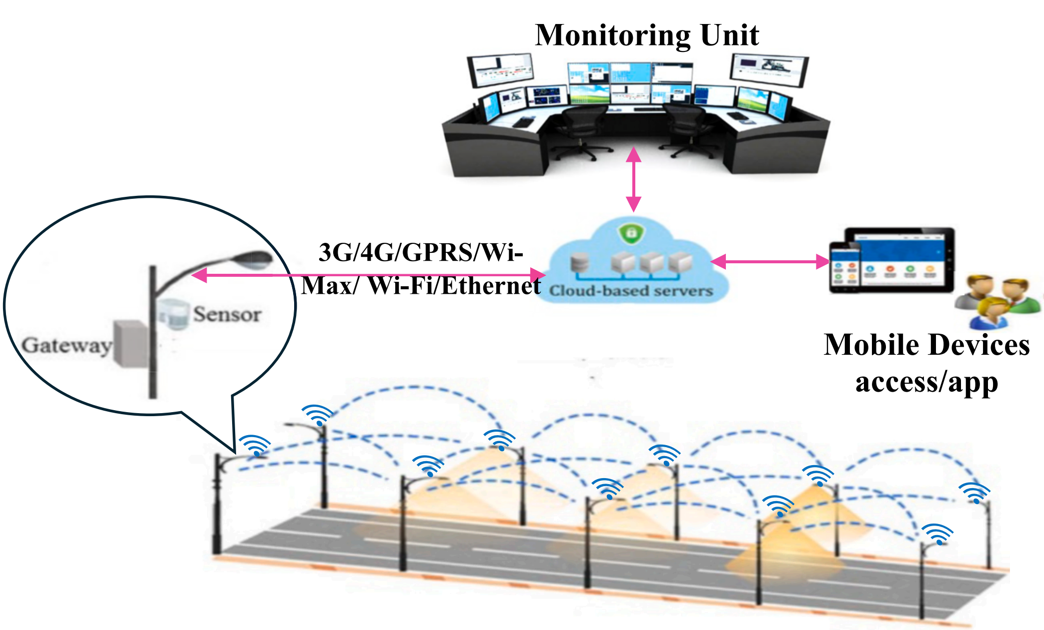

Fig. 4. Smart public street lighting infrastructure.

commanding and configuring each streetlight while also monitoring their operational status. Communication between the monitoring unit and individual streetlights is facilitated through a communication network, ensuring comprehensive coverage across the entire deployment area of street light fixtures. Local light controllers serve as the intelligent components of streetlights, integrated with IoT sensors within the framework of a smart city. They are responsible for executing commands received from the monitoring unit and providing essential feedback as needed.

3.1.1. LEDs lights

A smart public street lighting system is incomplete without LEDs Lights. The choice of lighting type is an important factor in all streets to accomplish an energy-effective smart public lighting system. Therefore, retrofitting by directly substituting conventional lampposts with LEDs technology yields substantial savings in the modernization and advancement of smart public street lighting. Indeed, a 130 W non-LEDs lamp provides a comparable level of luminosity to a 70 W LEDs lamp. Accordingly, a 46 % reduction in electricity costs is attained by merely substituting the lamppost, resulting in a 32 % annual saving per fixture compared to the original installation [25,73]. Currently, LEDs technology is widely adopted by most cities as one of the optimal alternatives for streetlight thanks to the fast response, lower power consumption, and smaller footprint. Contrary conventional lampposts, LEDs streetlights possess the following characteristics [41,74–76]:

- Extended lifespans ranging from 50,000 to 100,000 operating hours in standard conditions, with the potential for further extension through the use of intelligent control systems.
- Higher durability due to their construction without glass, being mounted on a circuit board, emitting cool light, lacking toxic materials, and allowing for fast switching.
- Higher efficiency, typically ranging from 100 to 120 lumens per watt from the light source, making them suitable for road applications.
- Lower maintenance frequency compared to traditional street light devices.
- Generate a luminous pattern that enhances user visibility while ensuring maximum comfort for the eyes, provide better visibility for pedestrians and vehicles along a route, and reduce the light pollution factor.
- Reduce energy usage by up to 50 % even as preserving equivalent illumination degrees in comparison to conventional streetlamps and emitting less heat.
- Simple to manage and upkeep, with a shorter payback period.

3.1.2. Local light controller

The local light controller must remain operational 24/7, either due to its support for additional IoT facilities or because it continually monitors for potential commands from the monitoring unit. Hence, introducing a light controller capable of real-time monitoring of lamp functionality (including lamp status and electrical parameters), adjusting lamp brightness based on daily time and traffic intensity, and establishing a communication link by transmitting collected data alongside the corresponding pole to the monitoring unit can lead to additional savings. To this end, it is responsible for minimizing power consumption while ensuring proper lighting levels are consistently maintained, regardless of weather conditions. Furthermore, it also plays a crucial role in timely inferring or predicting failure conditions, preventing malfunctions, and improving failure retrieval procedures. In this regard, hardware malfunctions and defects can be promptly identified and, in certain instances, even predicted. For example, damaged bulbs can be discovered along with their locations, facilitating the deployment of maintenance teams to be deployed based on a carefully organized timetable, which takes into consideration the most efficient route to address all malfunctions within the same region. Real-time management enables predictive repairs, to reduced expenses by preventing costly urgent maintenances that may require adjustments to vehicular traffic flow.

Local light controller can also be distinguished based on the quality and quantity of data they can obtain about the electrical network. Real-time procurement of electrical parameters transforms light controller into distributed lighting infrastructure analyzer, providing valuable insights into of the operational status of the city's electrical grid to which they are interconnected, as well as offering pertinent data for the grid manager.

3.1.3. Smart sensors

A Smart street lighting system is equipped with smart sensors that gather data, which is then transmitted to a light controller system to determine the appropriate action. These sensors are interconnected via ZigBee technology and, along with a monitoring system, oversee and regulate the streetlights. With internet access becoming increasingly ubiquitous in cities, IoT-based streetlight control systems are widely adopted recently.

Smart sensors are IoT-enabled devices capable of connecting to the internet. They detect real-time changes in various parameters such as, weather conditions, natural light availability environmental factors, lamp orientation, traffic conditions and air quality. These sensors transmit the collected data to a light controller system to determine the appropriate action, operates alongside the monitoring unit application service to analyze and visualize the data. IoT sensors come in various types, including Humidity/Moisture sensors, Temperature sensors, Ambient Light sensors, Acoustic/Sound/Vibration sensors, Motion/Velocity/Displacement Detectors, Motion sensors, LDR (Light Dependent Resistor) detector, PIR (Passive Infrared) sensors and Infrared (IR) sensors.

3.1.4. Gateway

The Gateway is a crucial component within the smart public street lighting system, primarily responsible for interconnecting several endpoints across different monitoring unit networks and ensuring continuous communication among nodes. Typically, the gateway operates at Gigabit network communication speed and adheres to industrial-grade standards. It is sometimes referred to as an IoT Gateway, as it facilitates data exchange among numerous IoT-enabled sensors within the smart street lighting system. Some key aspects of the Gateway include:

- Enhanced security provision.
- Communication bridging and Machine-to-Machine (M2M) communication facilitation.
- Device configuration and change management capabilities.
- Acting as a data cache, buffer, and streaming device.
- Supporting offline services and real-time device control.
- Aggregating, pre-processing, cleaning, and filtering data before transmission.

3.2. Communication network

To facilitate the management of streetlights, it's essential to connect the lampposts via a network infrastructure to a monitoring system. Considering the static configuration of smart street lighting setups, both wired and wireless networks are viable options. Wireless technologies like WiFi, ZigBee, and 2G/3G/4G, as well as wired options like Power Line Communication (PLC) or Ethernet cables, can be employed to link the streetlights [8,47,77]. The system architecture utilizes both remote and local communication networks. The local network facilitates information sharing between the intelligent poles, while the remote network allows communication between the intelligent poles and a remote monitoring unit. This setup enables for monitoring unit to collect data, including power consumption, traffic conditions across the street, and weather conditions.

Indeed, communication among the smart street poles relies on the

802.15.4 IEEE ZigBee wireless process, recognized as a universal and worldwide standard for wireless device connectivity. Certainly, Zigbee technologies offer seamless integration into IoT software using Zigbee gateways.

Different routing policies are employed within the network to facilitate message exchange (commands or information requests) among smart street poles. Consequently, the gateway has the capability to transmit commands or information requests to individual smart street poles, a selected group of them, or all intelligent poles linked to the communication network. Furthermore, data exchange between the gateway (the network coordinator) and the monitoring system, as well as with users' smartphones, is facilitated via a WiFi/3G/4G/ communication network.

3.2.1. Wired networks

A direct method to incorporate all smart poles into a wired networks is by leveraging current power lines to transmit data commands. This is achieved through Power Line Communication (PLC) protocol, transforming the power grid into a telecommunications network. Communication is facilitated by employing modulated signals transmitted over the electrical power distribution systems [78].

3.2.2. Wireless networks

Wireless communication components are typically installed either separately on the streetlighting poles or in close proximity to the LEDs lights themselves. These modules, as their name suggests, enable wireless connectivity with both the monitoring system and other network devices. They facilitate bidirectional communication, allowing the monitoring unit and network devices to exchange data with the LEDs lights, including sensor data and information regarding light intensity. In certain instances, these wireless communication modules are outfitted with external antennas to optimize data transmission and reception. Additionally, some modules may integrate GPS devices to provide precise location management capabilities [79].

A-Cellular Networks: are extensive, encompassing approximately 95 % of the global population and nearly all inhabited areas. With such extensive coverage, they present an optimal paradigm for easily connecting smart poles to monitoring unit. Essentially, within the scope of cellular network services, linking a lamppost to a smart public street lighting system is as straightforward as outfitting it with a cellular modem and activating it. Additionally, cellular networks offer data rates ranging from a little kbps to hundreds of Mbps, accommodating a multitude of services, from basic telemetry to more data-intensive applications. For the fundamental smart lighting service, leveraging developing cellular-based IoT protocols like long-term evolution (LTE)-Cat-M1 and narrowband-IoT (NB-IoT) is feasible. These standards are designed to implement Low-PowerWide-AreaNetworks (LPWANs), facilitating long-range communications (several kilometers) at low bit rates among connected devices.

Considering the advancements in cellular networks and LPWAN technologies, they undoubtedly offer a convenient method for equipping smart public street lighting infrastructure with the necessary connectivity.

B-Non-Cellular LPWANs: are becoming more popular for smart lighting paradigms thanks to their ability to lower the operational costs associated with lampposts networking compared to cellular networks. Among the LPWAN infrastructures commonly utilized in smart street lighting initiatives, LoRa wide area network (LoRaWAN) and Sigfox stand out as the most prominent options.

C-Mesh Networks: It's evident that streetlights are organized into clusters, facilitating hop-by-hop communication among neighbouring lights. These communications typically utilize short-range, cost-effective communication technologies, with IEEE 802.15.4 and Bluetooth being the primary options for mesh networking. In each cluster, one or more lampposts have the capability to communicate with a dedicated network node outfitted with long-range communication protocols, such as optical fiber or cellular. This specialized node functions as a gateway, facilitating the transfer of data and commands among the monitoring unit and the smart poles within the cluster, thereby enhancing connectivity and coordination.

3.3. Monitoring unit via application web and mobile app

Another vital crucial aspect of smart public street lighting application the user-friendliness in communications between system operators and the infrastructure. The monitoring unit serves as the system's host and can be installed either on the on-premises or Cloud, depending on requirements [25,72]. Therefore, the smart public street lighting system includes a web application and a mobile app to facilitate remote control and supervision. These platforms offer additional features and functionalities, particularly when leveraging advanced IoT sensors, high technology infrastructure, and robust application software:

- Selecting control operating modes and configuring operations for street poles.
- Implementing comprehensive lighting monitoring and control: This includes scheduling for lights on/off, dimming capabilities, and outage notifications.
- Detecting abnormal conditions and generating alarms.
- Utilizing predictive diagnostics to analyze unusual conditions, detect functional defects, identify malfunctioning lamps, and schedule preventative maintenance.
- Developing web and mobile app interfaces featuring user dashboards displaying power consumption, energy savings, diagnostics, monitoring data, fault data, environmental statistics, and more.
- Analyzing data and generating usage reports for energy consumption evaluation: This includes insights into current or average energy consumption, peak power usage, energy savings, traffic volume and classification, weather information, and any additional alarms.
- Interfacing with multiple endpoints of the monitoring unit throughout the smart city, encompassing streetlights, parking lights, garden lights, ground lights, and traffic lights.
- Conducting comprehensive data analytics on the stored data from monitoring unit endpoints.
- Securely encrypting and storing data from various endpoints.
- Encouraging renewable energy adoption: Promoting the adoption of green energy sources, optimizing costs, and resulting in overall cost savings.
- Managing user accounts: empowering system operators, such as managers, users, and super-administrators, to configure authorizations and accessibility settings for both the web application and mobile app.
- Verifying users based on monitoring unit policies.
- Enhancing the sense of security for residents and visitors in smart cities.

The mobile app not only encompasses all features available on the web application but also allows authorized managers to precisely adjust the brightness levels of specific streetlights. This feature enables swift response during street emergencies. Any authorized user, such as a police officer can communicate with the infrastructure to promptly take action, thus enhancing overall visibility as needed. Table 2 summarizes comprehensive details on sensors, actuators, coordinator devices, communication devices, and other relevant components utilized in previous studies of IoT-based smart public street lighting systems.

To this end, applying a smart public street lighting infrastructure involves integrating advanced technologies such as IoT devices, sensors, actuators, and centralized control software. This infrastructure aims to increase energy efficiency, improve safety, promote sustainability in urban environments and enhance quality of life. Fig. 5 summarizes the steps outlining a structured approach to implement this architecture effectively.

Table 2
Details employed in IoT-based smart public street lighting systems.

Studies	Sensors	Actuators	Coordinator Devices	Communication Devices	Relevant Components
Ref. [80]	Day/Night Sensors/Light Intensity Sensors	LED Lamps	Gateway Devices	LoRa Wireless Modules	Power Supply Units, Control Software, Monitoring and Control Systems
Ref. [81]	LDR, DHT11 Temperature-Humidity Sensor	LED Lights	Arduino Board	Wi-Fi Modules	Power Supply, Software Interface, Cloud Platform.
Ref. [82]	IR sensors, LDR sensors	LED lights	STM32 microcontroller	ESP32 Wi-Fi modules	L298N Drivers, ThingSpeak Cloud.

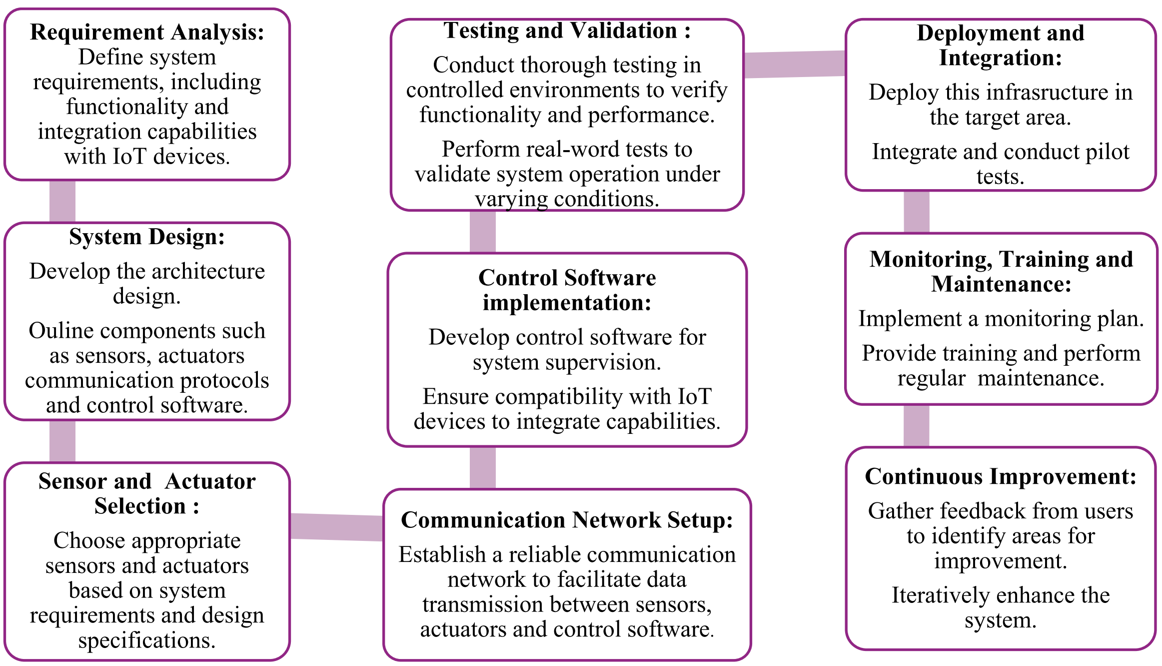

Fig. 5. Flowchart outlining a structured architecture steps implementing.

3.4. Sustainable action plan: overcoming limitations and challenges

To effectively address the limitations and challenges of our study, a sustainable time plan is essential. The plan is structured over six phases. Phase 1 begins with a comprehensive review to identify technical, economic, social, and environmental barriers. Phase 2 focuses on stakeholder consultations, gathering insights and feedback from urban planners, policymakers, IoT developers, and community representatives. Phase 3 encompasses research and development efforts aimed at enhancing system efficiency, reducing costs, and strengthening security and sustainability measures. Phase 4 involves pilot testing to validate solutions in real-world settings and refine them based on feedback. Phase 5 is dedicated to documenting outcomes and preparing reports for widespread knowledge sharing, while phase 6 ensures ongoing monitoring and evaluation to drive continuous improvement and sustainable advancements in smart city infrastructure. Key steps throughout the plan include stakeholder engagement, training, resource allocation, risk management, leveraging technology and innovation, fostering collaboration, and maintaining transparent communication.

4. Future trends

The advantages of upgrading traditional public street lighting system to a smart infrastructure extend beyond economic considerations. When the lighting paradigm is approached with a forward-thinking, a significant subsequent benefit emerges: the establishment of a pervasive wireless technology that extends globally through smart lampposts. This facilitates data gathering from close sensors and the introduction of innovative services warrant further exploration. Moving forward, these services are positioned to emerge as a notable trend in the future and may include:

- Smart parking: Utilizing real-time supervising to track parking lot occupancy status. (available/engaged).
- Waste management: Implementing sensors to detect trash levels in receptacles, optimizing rubbish gathering roads and schedules.
- Structural health: Utilizing sensors to monitor material information in residences and historic landmarks.
- Air quality: Employing supervising systems to track air pollution levels.
- Vehicular traffic: Implementing systems to detect traffic congestion and suggest other routes throughout the message signals.
- Incorporating cybersecurity measures into the architecture of the upcoming smart street lighting infrastructures.
- Utilizing artificial intelligence methods to forecast traffic flow and alleviate the burden on smart public street lighting infrastructures.
- Utilizing smart poles to offer charging stations for plug-in electric vehicles.
- Examining sensor reliability and physical device security to optimize energy consumption and reduce costs.
- Enhancing safety features: Programming smart streetlamps to control lighting levels automatically using real-time data, thereby improving street safety and reducing accident risks.
- Integrating with traffic management system: Smart streetlights can contribute to managing traffic movement and alleviating overcrowding in real-time.

– Promoting ecological sustainability: Powering smart poles with green energy sources including wind or solar power to reduce the carbon footprint of public street lighting infrastructures.

5. Conclusion

Public lighting serves as the bedrock of numerous smart city inventiveness worldwide. By upgrading traditional streetlights with LED technology, electrical grid can substantially diminish energy and operational expenses by at least 46 %. Beyond energy efficiency, equipping each smart streetlight with two-way communication flows establishes a city-wide communication infrastructure. This network enables the transmission of information, data collection, and service delivery to and from numerous IoT devices. In this context, this study provides a comprehensive overview of IoT technology, highlighting its function as a network of networks. It discusses the applications, architectural layers, and advancements specific to smart cities, along with their key tasks. Furthermore, we introduced the concept of smart public lighting infrastructure as an IoT application for smart cities. Initially, we provided a comprehensive system description, followed by an outline of the basic ideas, key features, and essential components of the smart public street lighting application. Recently, the transition to LEDs technology and the adoption of LEDs lampposts for street lighting are crucial factors for the success and implementation of a smart public lighting concept. Indeed, LEDs lamps offer enhanced efficiency, durability, environmental friendliness, and full controllability. The overall architecture of the system is scalable, allowing for increased functionality and seamless integration of smart devices into the network. Moreover, we discussed communication network technologies that can be employed. Then, we highlighted the significant services delivered by the monitoring unit, underscoring its crucial role in enriching the user experience and facilitating interaction with the infrastructure. Consequently, this study gives insights into how the upgrading of street lighting concept into a smart, sustainable asset and energy-effective can enhance the safety, modernity, efficiency, and attractiveness of a city. Surly, the application of a smart street lighting system holds the potential to achieve reduced energy consumption and substantial energy savings when compared to traditional street lighting system. Finally, we introduced future trends, including the potential for supplementary functionalities that a smart public lighting system could facilitate, as well as the advantages of incorporation with the forthcoming 5 G cellular network. These aspects warrant further attention to explore their potential impact and scope.

CRediT authorship contribution statement

Siwar Khemakhem: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lotfi Krichen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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