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Review

A Review of Using IoT for Energy Efficient Buildings and Cities: A Built Environment Perspective

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Abstract: Applications of the Internet of Things (IoT) are rapidly utilized in smart buildings and smart cities to reduce energy consumption. This advancement has caused a knowledge gap in applying IoT effectively by experts in the built environment to achieve energy efficiency. The study aims to provide an extensive review of IoT applications for energy savings in buildings and cities. This study contributes to the field of IoT by guiding and supporting built environment experts to utilize IoT technologies. This paper performed a thorough study using a systematic review that covered an overview of IoT concepts, models, applications, trends and challenges that can be encountered in the built environment. The findings indicated limitations in developing IoT strategies in buildings and cities by professionals in this field due to insufficient comprehension of technologies and their applied methods. Additionally, the study found an indefinite implementation and constraints on using IoT when integrated into the built environment. Finally, the study provides critical arguments and the next steps to effectively utilize IoT in terms of energy efficiency.

Keywords: Internet of Things; smart buildings; smart cities; built environment; energy efficiency

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1. Introduction

Massive challenges caused by rapid digitalization have greatly increased the demand for energy [1]. Energy consumption around the world is estimated to increase by 56% in 2040 [2]. Internationally, there are efforts to reduce energy consumption in buildings and cities such as the EU's 2050 roadmap which aims to lessen energy and gas emissions by approximately 40% [3]. The new era of digitalization opens new possibilities to improve human health and productivity and enhance energy efficiency in the built environment. The Internet of Things (IoT) represents one of these opportunities to decrease energy demands and meet sustainable development goals. In general, the concept of IoT was introduced as interconnected objects using radio-frequency identification (RFID) for the first time in 1999 by British technology pioneer Kevin Ashton. The two words "internet" and "things" as combined, convey an innovation with regard to information and communication technology (ICT). The notion of interconnected objects enables everyday physical objects to integrate electronics seamlessly into any global physical infrastructure [4]. Even though the term is established within these two words, the definition of IoT still depends on the research perspective [5,6].

IoT provides tremendous potential in offering smooth interaction in intelligent environments among devices/appliances with or without human interference [7]. For instance, the term "smart thing" can be presented in a human with a monitoring sensor, a car equipped with a safety sensor or a bird with a GPS sensor, etc. [8]. Currently, there are more than 31 billion devices connected over the internet as IoT that are distributed in different sectors from individual buildings to city blocks or even entire cities and are estimated to rise to 170 billion by 2050 [9]. This surge relates to the capability of devices connected via IoT to perform a key role in sensing, measuring and processing data that open immense opportunities to be used for monitoring, controlling and boosting the efficiency of energy use in any system [10]. Generally, various studies in IoT applications discussed and investigated energy efficiency at different levels and scales [11,12].

From the perspective of the built environment, IoT is applied in smart buildings and smart cities. In smart cities, energy resources are managed, utilized and stored in an efficient way [13]. The term "smart" in buildings and cities refers to the use of numerous types of electronic systems and sensors that are interconnected or interlinked to gather particular data. The adoption of smart technologies based on IoT can provide network connectivity through which information and services related to physical devices can be exchanged. This may further underline the potential of IoT for preserving energy within the contexts of both buildings and cities. Mostly, IoT in the built environment is employed to work with data via collection, transmission, storage and analysis [14].

Recent studies indicated that profiling energy consumption in buildings has attracted many researchers to examine IoT and energy efficiency strategies [15]. In addition, the movement of integrating smart buildings with up-to-date detecting techniques has started to lay the groundwork to consider IoT as an essential element of smart cities. Lately, studies have shown an increased interest in IoT applications in smart buildings to improve energy efficiency and reduce environmental impacts [8]. Further studies stated that if buildings consider good communication between their systems for operation, a considerable amount of energy use could be lowered [16,17]. Therefore, the advancement in networking, computing and sensing technologies set IoT to be an important component in the design and the operation of any smart object in the built environment [14,18].

On the other hand, there is a gap between conventional and advanced methods to develop and incorporate integrated building design to shape a smart built environment and, furthermore, a gap between building design and automation solutions [19]. Ryu et al. [20] and Shinde and Jaind [21] indicated that the integrated energy-efficient building design process (IEBDP) is still conventional and limited between the planning and the operational phase. For instance, Pan et al. [22] recorded the energy usage of a LEED-gold-certificated green office building for one year. The analysis of energy usage showed that the building may not be energy efficient when its real energy consumption was considered. Xu et al. [15] indicated that energy consumption in buildings is assessed by the pattern of energy-appliances usage and power rating, however, building systems operate through dynamic behaviors that depend on the interaction between the building space, system and users. Thus, estimating the energy load for maintaining human comfort inside any space makes it challenging to provide efficient solutions. Moreover, it has been observed that there are limitations in understanding IoT from the perspective of built environment professionals. Overall, these issues consider critical when we equip cities and buildings with IoT technologies with the aim to achieve a net zero future.

Therefore, the study aims to review the applications of IoT to explore energy efficient solutions in buildings and cities. Specific objectives are set to understand IoT in the built environment through (1) reviewing and examining IoT applications and their trends, (2) exploring IoT directions toward net zero buildings and cities and (3) identifying challenges in using IoT in the built environment. The novelty of the study is demonstrated by providing an extensive review of IoT that focuses on energy efficiency and establishing a conceptual guide for built environment experts to perceive IoT technologies.

2. Materials and Methods

The research used a systematic literature review by surveying only IoT studies that were performed in smart buildings and smart cities. The review applied a comprehensive search that covered an overview of IoT concepts, models, applications, trends and challenges that can be challenged in the built environment. The study applied a search strategy by targeting journals in Web of Science (WoS), SCOPUS, official documents and selected books in this review. However, some supportive information was identified from certain conferences and nonprofit organizations' websites. The study used a combination of keywords related to IoT in buildings and cities with a focus on energy consumption and energy efficiency to obtain published materials. The review identified and listed recent studies between 2020 and 2022 in specific tables in targeted sections to demonstrate up-to-date research for experts in the built environment. The search only considered papers published in journals with an impact factor to maintain the quality of the content obtained. The study followed four steps in the form of identification, screening, eligibility and inclusion. Finally, the study developed the review based on two main directions. First, introduce the architecture of IoT systems to non-experts in this field. Second, demonstrate IoT applications for experts in the built environment via (1) IoT in Smart Buildings (2) IoT in Building Monitoring and Data Visualization and (3) IoT in Smart Cities.

3. Architecture of IoT Systems

This section presents fundamentals and essential knowledge of IoT architecture systems to provide an overview for non-experts to understand IoT technologies. This section consists of four parts that describe, explain, identify and discuss the main aspects of IoT: (1) Layers of Common IoT Architecture, (2) IoT Communication Models, (3) IoT Sensor Boards, (4) IoT Wireless Communication Technologies and (5) IoT Challenges; this part demonstrates the main challenges that should be considered to facilitate IoT limitations for experts in the built environment.

3.1. Layers of Common IoT Architecture

IoT architecture incorporates sensor data, operation to or from devices, sending or receiving info, sensed data, storage, processing, analysis, services, applications and end exploitation using fog, cloud and edge computing [23]. IoT frameworks implement various technologies. However, it is widely acknowledged that there is no single solution for the architecture of an IoT system [24]. In the literature, the common IoT architecture contains three or five layers [25–28]. Figure 1 shows IoT architecture with three and five layers [23,24].

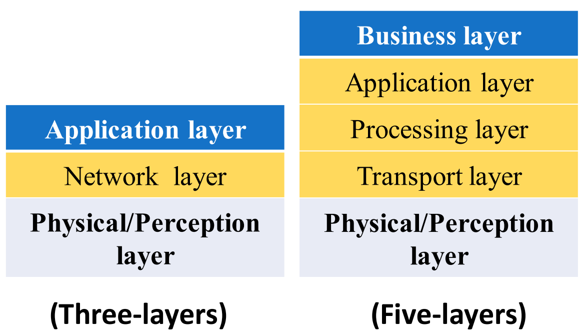

Figure 1. IoT architecture with three and five layers.

IoT architecture with three layers consists of: (i) **Application Layer**: this layer has the function of delivering numerous facilities required by the user. This layer houses a variety of applications that are employed in smart buildings and smart cities [29,30]. Despite this, event-driven apps have grown in popularity due to the growth of IoT devices and systems. The previous cohort of smart systems in buildings and cities mostly focused on straight up applications that employ data management processes such as Extract, Transform and Load (named ETL) or Extract, Load and Transform (named ELT) procedures and languages that are only supported by pull protocols. (ii) **Network Layer:** this layer is responsible for forming connections with other intelligent tools, servers and network devices. This layer functions by performing data transmission and distribution. More information about IoT wireless communication technologies is provided in the next section. (iii) **Physical Layer**: this layer has the functionality of sensing/perception which contains sensors that detect and collect info from nearby surroundings. Additionally, it establishes additional smart nodes and detects physical properties in the environment.

IoT architecture with five layers consists of (i) **Application Layer** and (ii) **Physical Layer** as mentioned above and (iii) **Transport Layer:** this layer has the capability to utilize different communication techniques such as Wi-Fi/ZigBee or Long Range (LoRa) to send detected data from the physical/perception layer to the processing layer wirelessly. (iv) **Processing Layer:** this layer performs analysis, storage and handling of the received data from the transport layer. It is responsible for the upkeep of the lower layers and provides services to them. It utilizes a wide range of tools, such as databases, big data and cloud processing modules, among others. IoT processing solutions can generally provide the following functions [31]: (a) abstraction of the device, management detection and regulations which take account of interoperability between heterogeneous connected objectives by means of diverse standards; (b) distribution and management of information by providing different data pre-processing functions, for instance, passing through a filter, deduplication and combination. (v) **Business Layer:** this layer manages the full structure of IoT, together with apps, user privacy profit and business models. IoT data is only useful for business planning and strategy. Each company has its own set of objectives that could be achieved by using collected data. Business owners and others use historical and current data to create an effective action plan. Figure 2 depicts the most prevalent protocols depending on the levels of IoT architecture [32].

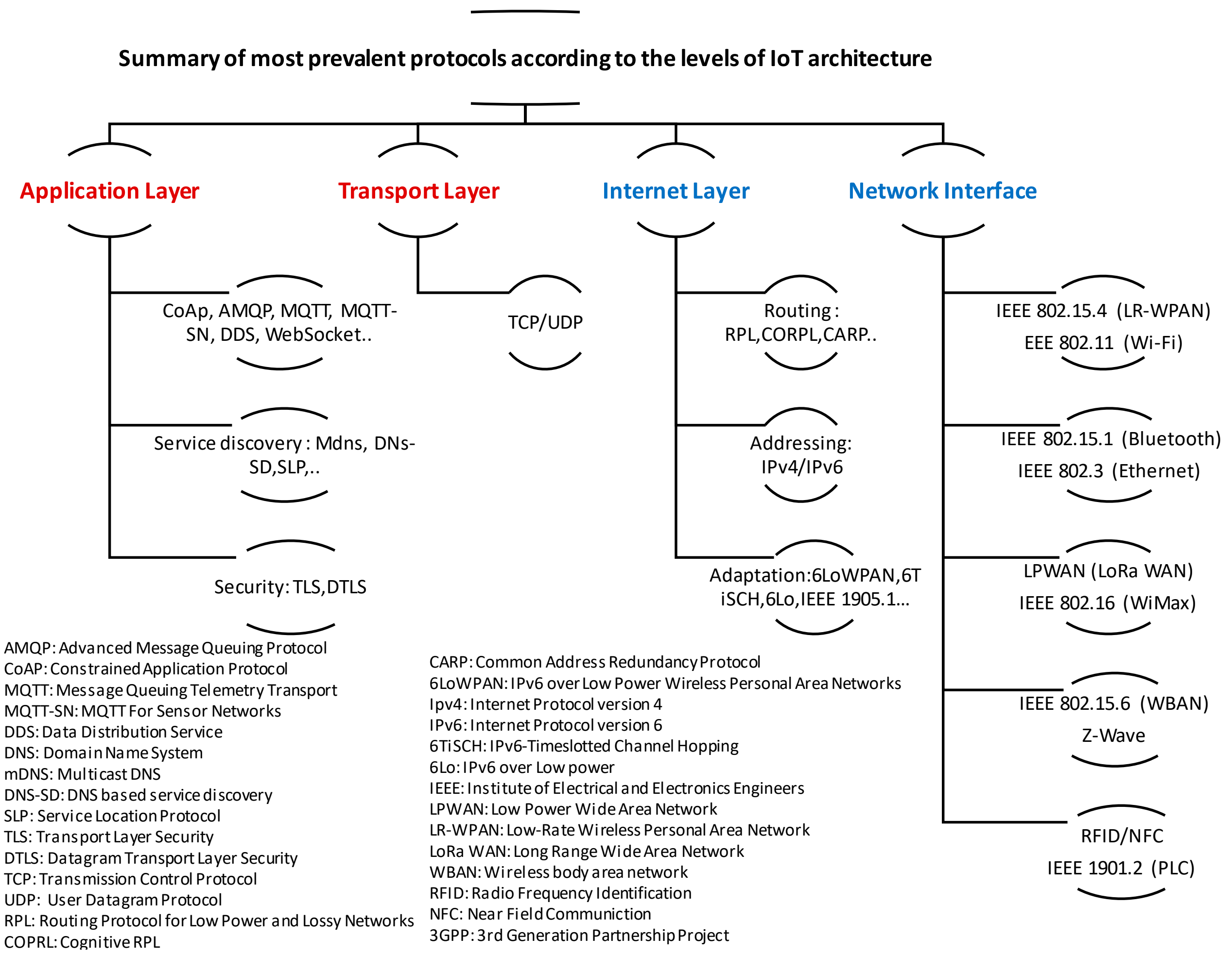

Figure 2. Summary of most prevalent protocols according to the levels of IoT architecture.

3.2. IoT Communication Models

In IoT applications, various realistic communication models are employed, each with its unique set of properties. Figure 3 illustrates three public communication models [33]: (i) IoT node to device, (ii) IoT node to cloud, and (iii) IoT node to base station. These models emphasize the versatility with which IoT devices can connect and deliver value to users. Furthermore, the selection of a communication model in IoT for certain applications depends on the ability of the devices to implement full protocol stacks, such as Internet protocols IPv4, IPv6, Hypertext Transfer Protocol (HTTP), etc., as follows:

i. Devices that are unable to implement full protocol stack without external support such as Arduino Uno (R3) with 32 kB of flash memory, 16 MHz single core processor and 2 kB of static ram that are battery powered. These devices consume a few milliwatts (mW) while operating.
ii. Devices that are able to implement a full protocol stack yet are still limited by their resources such as ESP8266 and ESP32 chips that are battery powered. These devices consume hundreds of milliwatts while operating.
iii. Devices that offer various and advanced network services are capable of implementing protocol stack with ease, yet not servers, routers or gateways, i.e., Raspberry Pi and its clones. They are usually DC powered and consume far above 1–2 W, usually up to between 10 and 15 W.
iv. Dedicated solutions for gateways and routers with embedded and hardware-based implementations of the switching logic consume between 10 and 50 W.

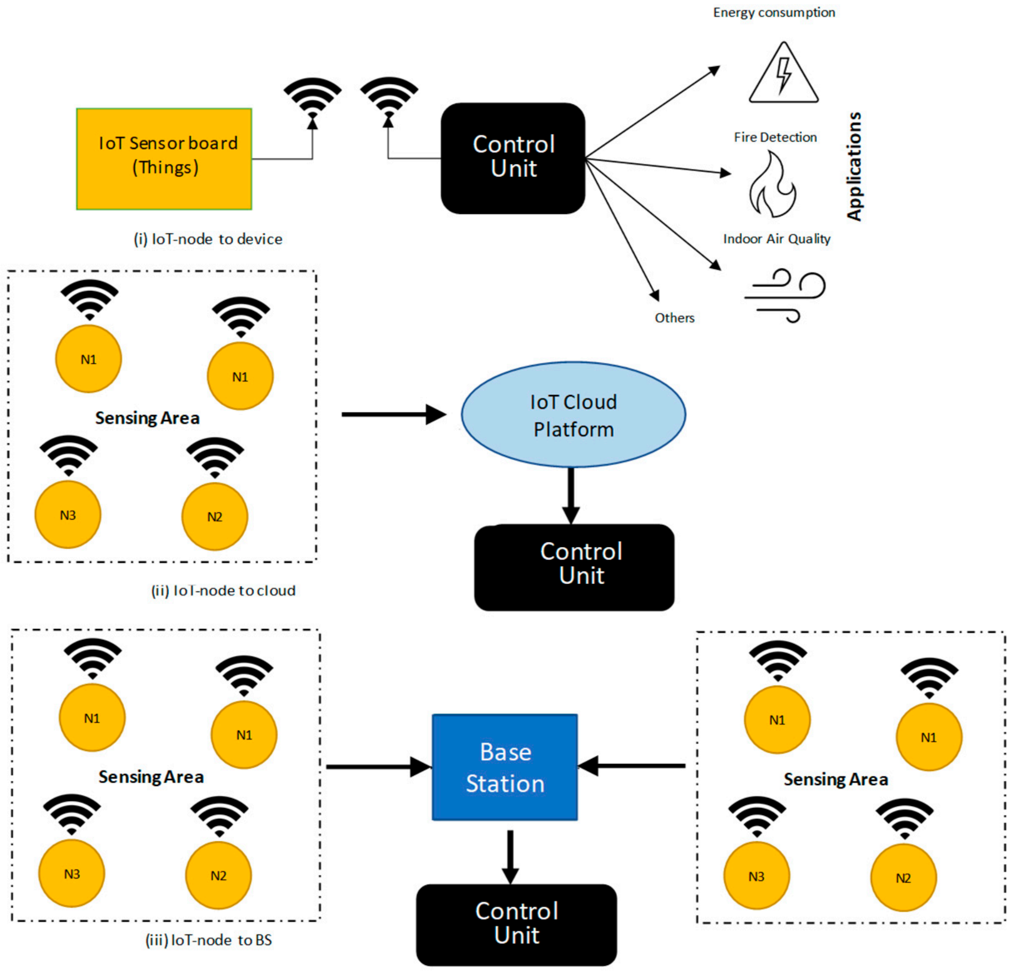

Figure 3. Structures of IoT communication models.

3.3. IoT Sensor Boards

The sensor board is a device that contains various sensors used to sense and respond to some inputs from the physical environment. Most IoT devices contain multiple sensors, a microcontroller (MCU), Bluetooth or Wi-Fi radio and power management. In addition, central processing units (CPUs) include wireless chips, as well as other components that can be purchased in pre-built kits and are ready to be programmed [34,35].

Sensor boards for IoT are becoming increasingly significant as IoT-based applications proliferate across a wide range of industries. For instance, many indoor and outdoor IoT applications now rely on IoT as a data collection platform for a variety of physical phenomena to avoid manual techniques for tracking measures that are not only less precise but also more difficult to administer and maintain [36]. IoT has been used in industrial sectors as a platform for gathering and monitoring key parameters to ensure quality. Furthermore, IoT is also used for energy management and consumption control in green and smart building applications; in these circumstances, IoT sensor boards are used to detect and record environmental factors such as humidity, temperature and light. Thus, in this section, the differences between some of the most prevalent IoT boards are summarized in Table 1.

Table 1. Summary of the differences between some of the most common IoT boards.

IoT Board	Speed of CPU	Memory-Used	Connectivity-Used	Program-Language
Giant Board	Microchip SAMA5D2-500 MHz	128 MB DDR2 (RAM)	"1 × I^2C, 1 × SPI, 1 × UART, more with Flexcom"	CircuitPython supports Linux.
Particle Photon	STM32F205 120-MHz	128 KB (RAM)	802.11 b/g/n Wi-Fi	C
Arduino Nano 33 IoT	64-MHz	256 KB (RAM)	Bluetooth and Wi-Fi	Arduino C
Pycom Fipy	266–550 MHz	4 MB (RAM)	"Wi-Fi/Bluetooth/and global LPWAN networks"	Micropython
Arduino Uno	16-MHz	2 KB (SRAM)	Bluetooth/Wi-Fi/GSM	C and C++
MICAz	8-MHz	4 KB (SRAM)	802.15.4 and Tiny OS	nesC
OpenMote	32-MHz	32 KB RAM	6LoWPAN/ZigBee/802.15.4	C/Python
Intel Galileo	400-MHz	256 MB (RAM)	10 and 100 Ethernet	GCC and ICC
IoT Waspmote	14-MHz	8 KB (SRAM)	LoRa/802.15.4/3GGPRS ZigBee/WI-FI/Bluetooth	API
Raspberry Pi-4	1.5-GHz	1–8 GB (RAM)	"Bluetooth 4.1/802.11n WLAN 10/100 Ethernet" "ARCH/Debian/Fedora/NetBSD and etc."	C++/Scratch/Java Python /Ruby, any for ARMv6

3.4. IoT Wireless Communication Technologies

Different techniques of IoT to communicate wirelessly are explained below.

- ZigBee (developed by Connectivity Standards Alliance) is a specification for high-level communication protocols based on IEEE 802.15.4. It is utilized in the construction of personal area networks through the employment of low-power digital radios. ZigBee was developed by Connectivity Standards Alliance (https://csa-iot.org/ (accessed on 15 February 2022)).
- Sigfox aims to launch the world's first global IoT network, which will listen to billions of object broadcasts. There is no signaling overhead in this wireless approach, as well as compact and optimized protocols and non-networkable objects. Sigfox is a cloud-based network and computational complexity management solution that reduces energy consumption as well as device costs [37] (http://www.sigfox.com/ (accessed on 15 February 2022)).
- LoRa is a wireless modulation developed by Semtech [38] for long-distance low-power and data rate uses. It was developed to lessen the impact of interference. LoRa

employs a Frequency Hopping Spread Spectrum (FHSS) which provides access to all channels. It has been demonstrated that communication ranges of 15 km or more are possible in urban settings [36,39].

- Bluetooth was developed based on the IEEE 802.15.1 WPA communication standard [40], which enables low-speed and short distance ad-hoc communication among devices working in the 2.4 GHz-ISM bands [41]. Bluetooth Low Energy (BLE), also known as "Intelligent Bluetooth Low Energy" and "Bluetooth 4.0," was developed to save power.
- Wi-Fi: This technology aims to deliver high throughput connections, and it is specifically intended for high bandwidth communication among devices positioned in close proximity [36]. The IEEE 802.11 standard series utilizes this technology [42] and refers to it as a wireless LAN (WLAN). Finally, Figure 4 illustrates Wi-Fi properties and summarizes different techniques for IoT to communicate wirelessly.

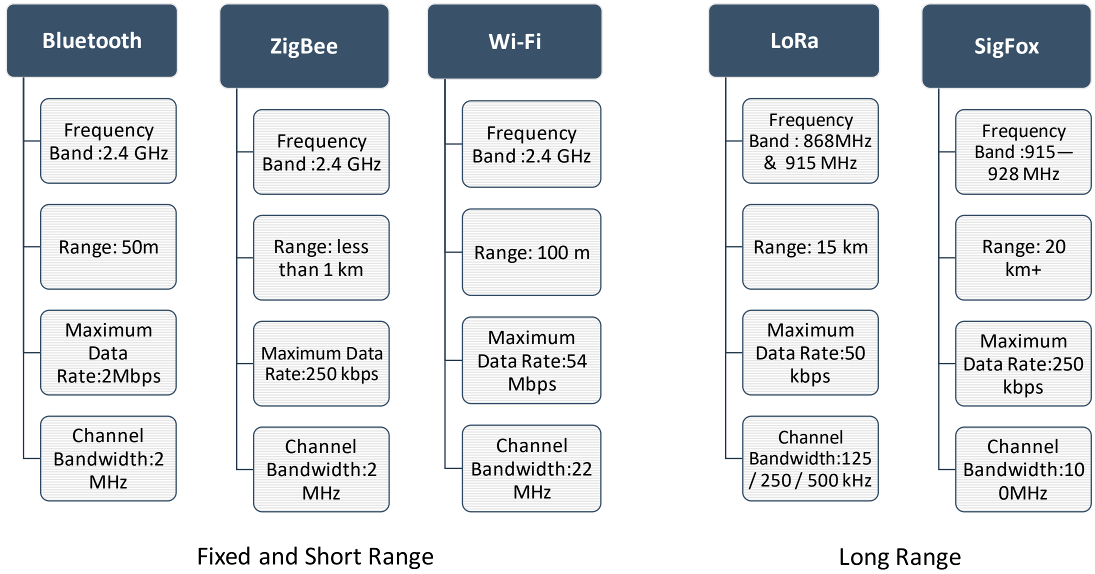

Figure 4. Summary of IoT wireless communication technologies.

3.5. IoT Challenges

This part presents most of the IoT challenges highlighted by researchers [43–51] that should be considered by experts in the built environment.

- **Architecture:** IoT includes many technologies such as cameras, biometric, physical, and chemical sensors that are intelligent, interconnected, non-invasive, transparent and invisible. Combining data from different environments is difficult due to the impact of services which are mobile and complex. As a result, providing structured models will enable systems to combine large amounts of data from different sources which determine and interpret key data and help the user to make decisions. Therefore, it is advised to not use the same reference architecture for all applications.
- **Technical:** An alternative technology, complexity, market constraints and competition may cause challenges. Unnecessary schemes and communication methods may prevent IoT systems from being migrated to cost-effective and proficient platforms. These issues limit IoT from being connected to as many "Things" as possible.
- **Hardware:** Intelligent systems are developed by smart devices that promote interaction. Because it is independent, the deployment and implementation of IoT applications and services can advance rapidly. Currently, studies on developing hardware devices demonstrate some directions toward creating wireless identification systems that are portable, low in cost and practical. On the other hand, low active power is an issue in this field. Typically, low-cost hardware indicates either poor performance or an additional delay in the procedure. Longer processing times result in higher overall energy use.

- **Security and privacy:** Since most IoT devices are used as a part of massive hardware, system or device, they are designed to be small and energy-saving.
    i. Most algorithms that implement enhanced security require a lot of resources which cannot be supported by IoT devices. For IoT devices to manage data authentication and data gathering, general trust is needed between different entities involved in the IoT system, as trust is needed for dissipation phases in strong cryptographic techniques or digital signatures.
    ii. A major challenge in IoT presents in providing secured access control in IoT systems and devices which is achieved by providing various strategies to restrict access. However, due to the permission that is provided for different users and processes to access data, the process is considered difficult and complicated to offer secured access.
    iii. Another important aspect of the security challenges within IoT systems is identity management. It considers critical to detect and convey specific data to particular users, after using the same system to identify and validate the correct user's credentials and information. However, similar to secured access control, identity management is complex and cannot be properly executed in current IoT systems.
    iv. Although IoT devices are interconnected to offer efficiency and convenience, privacy vulnerabilities are possible via exploiting user information that is accessed and spread by third parties with malicious intents. Thus, there is a lot more that needs to be carried out to protect privacy.
- **Electromagnetic (EM) radiation:** As stated in this study, IoT is an enabling technology that transmits data through various wireless communication techniques. The development of smart buildings that leverage 5G and IoT is one potential next step toward an efficient built environment. However, IoT devices have the potential to emit electromagnetic radiation, especially when they use 5G or 6G technology. Therefore, EM researchers are investigating innovative materials that can be used as anti-EM radiation in smart and green buildings.
- **Electronic waste (E-waste):** E-waste is a rapidly expanding environmental issue, especially in most technologically advanced countries. Cities are becoming smarter as IoT plays a critical role in transforming urban areas into smart environments. However, studies estimated that 50 billion devices will be connected by the end of 2030. Generally, IoT devices have a limited lifetime, which clearly indicates the possibility of facing issues with E-waste. Therefore, this problem should be considered by experts in the built environment when integrating IoT technologies during the early design stage.
- **Data centers challenge:** IoT-based smart buildings and city systems use a data center, which is a physical structure that stores data from various cloud storage sources, including data from IoT devices. However, data centers use enormous amounts of natural resources and will continue to do so soon as they grow in demand, size and space when they become more integrated into urban areas. In fact, these centers will constantly demand more energy.
- **Standards:** Standards have a significant role in shaping IoT. It promotes equal rights to actors regarding access and use. If standards and proposals are produced and coordinated, infrastructures of IoT, services and plans will evolve rapidly. In general, information models and protocols contained in collaborative multiparty standards must be open. The standard improvement method is essential to be entirely open to all parties, and the resulting standards must be freely and publicly accessible. In today's networked world, global norms are frequently more significant than local agreements.
- **Business:** An established application has a well-defined business model and scenario that is easy to translate into technological specifications. As a result, business-related components do not necessitate a significant amount of work from engineers. However, there are far too many unknowns and potential consequences in the development of IoT business models and application scenarios. As a result, in terms of business-technology alignment, it is useless, and a single solution cannot handle all

potential concerns. IoT poses a challenge to traditional business structures. Small-scale applications have proven to be successful in some businesses, but they are unsustainable when applied to other industries. To reduce the likelihood of failure, business concerns should be addressed before the design of IoT.

4. IoT in Smart Buildings

Nowadays, smart devices with the capacity for computation and communication are ubiquitous, ranging from simple sensors to household appliances and smartphones. The integration of such smart elements helps to develop heterogeneous networks, leading to the consolidation of an IoT basis [52]. The integration of IoT technologies in smart buildings demonstrates effective solutions to lower energy consumption, reduce environmental impacts, assist in utilizing renewable energy resources and offer flexibility to users that all help in establishing smart and sustainable cities [53]. The advancement in networking infrastructure, wireless technologies and smart algorithms open new opportunities for intelligent buildings to achieve efficient communication and proper control between multiple systems and spatial spaces to reach optimal integration [54]. Lê et al. [55] described smart buildings via five essential features: Interactivity, Adaptability, Multi-functionality, Automation and Efficiency. Al Dakheel et al. [56] conducted a review on smart buildings to identify features and indicators, the study provided key aspects in designing smart buildings using four aspects: grid response, climate response, monitoring and supervision and user response. In Europe, the Energy Performance of Buildings Directive (EPBD) [57] stated that smart buildings are defined as nearly Zero Energy Buildings (nZEB) that are equipped with sensing systems for smart monitoring, automated control, diagnostics, fault detection and supervision that respond to external conditions and user needs.

Generally, the utilization of IoT by building experts is limited and requires further studies to understand its application. Therefore, this section aims to clarify these limitations by demonstrating the gaps for specialists in building design. This section focuses on two research directions: (1) studies of IoT in computer science and engineering that are mostly presented for demonstration and explanation, and (2) studies of IoT by experts in the built environment to highlight the gaps from this perspective.

Experts from computer science and engineering characterize smart buildings as premises that are equipped with appliances/devices that are handled by IoT. For instance, in smart homes, smart systems consist of home gadgets, interface tools, switch modules, records collectors, RF transmitter-receiver and processors to communicate with the network and internet [58]. Martín-Lopo et al. [59] indicated that the physical layer of IoT in buildings provides a platform to understand energy consumption between users and energy markets. The study stated several services such as (1) home automation services that operate devices in the form of lightbulbs, blinds or presence sensors, (2) thermal services that regulate thermal demand to control radiators, heat pumps, furnaces and air conditioning systems, (3) electric services to monitor power consumption by using sensors installed between the plug and the socket or in the distribution board and (4) storage services that use energy systems such as integrated batteries or photovoltaic panels.

Imran et al. [58] presented a study to demonstrate IoT task management to reduce energy consumption in smart buildings. Figure 5 demonstrates a diagram of data flow with an optimization approach that was applied to control energy consumption from only IoT technologies [58]. The method pointed out that regardless of spatial requirements and building design. The approach operates in four phases. First, it collects data from the indoor environment via sensors such as carbon dioxide (CO_2), air temperature (AT) and relative humidity (RH). Second, it employs a prediction module to prepossess and control the noisy sensing data. Third, it utilizes a mathematical optimization module to compute the appliance's usage in a specific situation when it increases and decreases. Finally, the outputs from modules optimize the usage and reduce the cost of energy consumption.

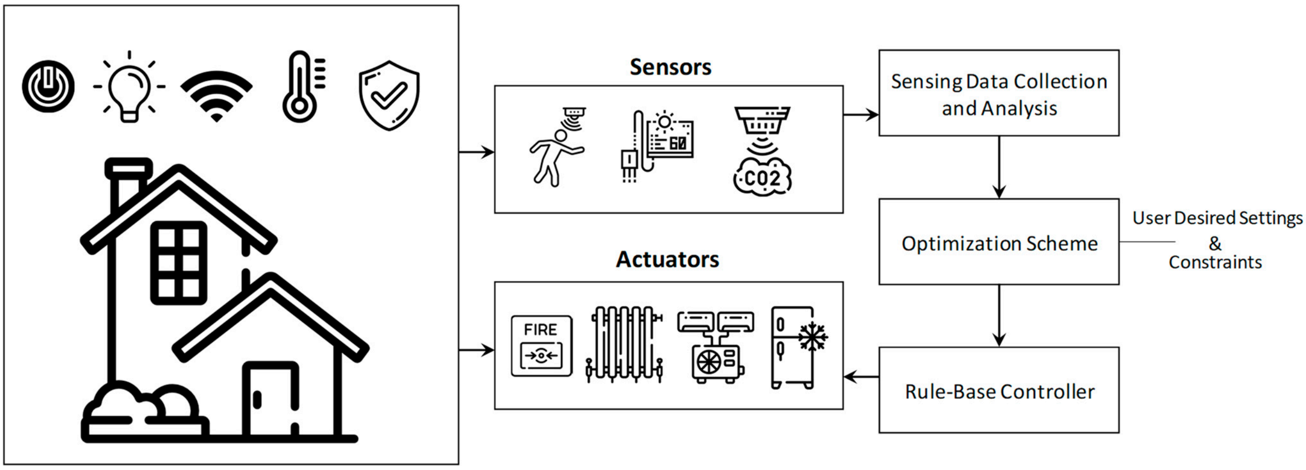

Figure 5. Model of optimization mechanism to achieve energy efficiency in a smart building [58].

At a different level, Li et al. [60] used IoT with a solar water heating (SWH) system to improve energy efficiency in a building. The study was conducted in a hospital in Singapore to demonstrate IoT efficiency by monitoring solar levels, operational schedule, water flow and electricity consumption. The study was performed by a thorough energy audit. The IoT sensors are demonstrated in Figure 6. Several sensors were used for this study, including a solar irradiance sensor, flow meter, temperature sensor, status sensor and electricity meter. The study found that the SWH with simultaneous control has the capability to save electricity by up to 32.9%.

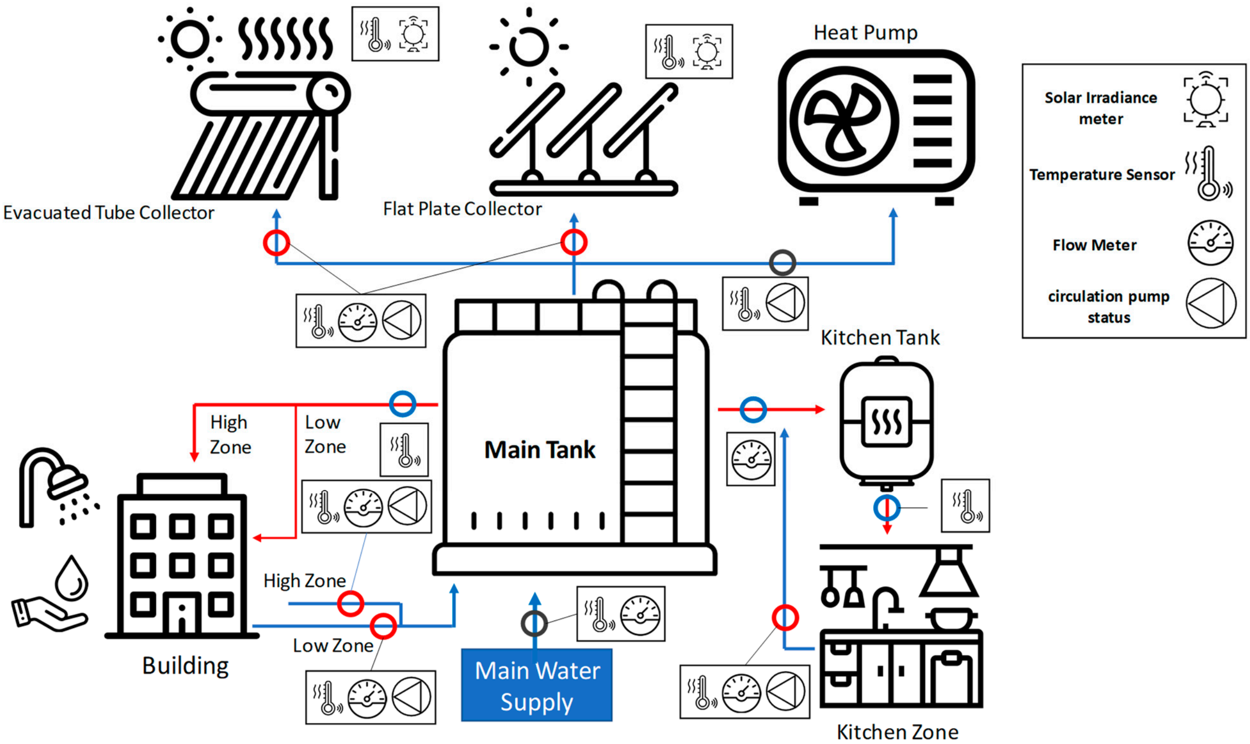

Figure 6. IoT of solar water heating systems in Singapore [60].

Beyond building components and the physical layer of IoT technologies, building occupants, or in other words, users, play an important role to determine energy consumption in any building. Users represent the main entity that utilizes energy to attain comfort, safety and satisfaction. Generally, IoT offers a wide range of options that benefit occupancy detection and activity recognition [61]. Many studies indicated the importance of occupant energy behavior in reducing electricity consumption [62,63]. Zhang et al. [64] stated that 30% of energy use in commercial buildings could be saved by adopting energy-aware behaviors among building users. Rafsanjani et al. [65] studied user energy behavior using IoT. The study demonstrated useful results by employing data in the form of static and dynamic factors in a building as shown in Figure 7.

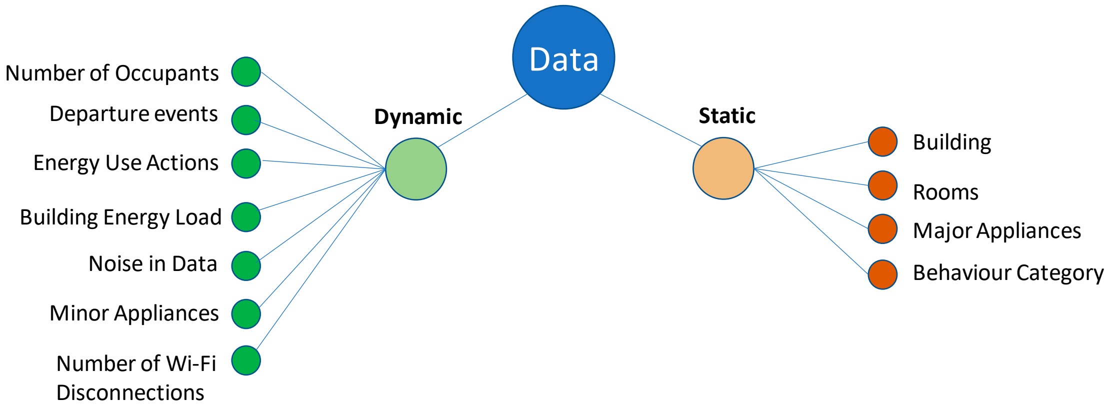

Figure 7. Diagram of data types in a building [65].

IoT experts employ different analysis methods based on various statistical procedures from historical data, analyzing current data, data mining and optimization algorithms for predictions of unknown events [66]. Several studies over the past few years were conducted by introducing IoT models in buildings that managed to improve energy efficiency. Ahn and Cho [67] provided a model that integrates energy control and thermal comfort, the model managed to reduce energy consumption by 17.4% in office buildings. Gobakis and Kolokotsa [68] proposed a method to assess the effect of outdoor conditions on building energy consumption and indoor environmental quality (IEQ) by connecting Building Energy Simulation (BES) and microclimatic conditions. Papatsimpa and Linnartz [69] presented a solution to save energy by up to 30% via a probabilistic framework for occupancy-based control in intelligent buildings. Ain et al. [70] presented a system to provide comfort by maintaining the thermostat set points by using humidity via a Fuzzy Inference System (FIS); this approach helped to achieve a 28% reduction in energy consumption. Png et al. [71] presented an IoT prototype developed based on the implementation of a smart and scalable control system to support the minimization of energy use of Heating, Ventilation and Air Conditioning (HVAC) systems in a commercial building. The results showed energy savings of up to 20%. Chang et al. [72] presented an IoT model via a system named the "Sensible Energy System" (SENS) that connects solar energy simulation with device consumption data to support the interaction between occupant behavior and energy consumption. In a recent study, Ramadan et al. [73] presented an IoT based criterion using non-intrusive load monitoring (NILM) to promote energy efficiency in smart buildings. NILM is an energy management technique that allows users to accurately manage energy consumption in buildings. To this end, they utilized the Factorial Hidden Markov Model, a NILM technique to amalgamate energy usage of all household appliances, including air-conditioning, fan, lighting, heater and microwave, into individual appliance load consumption.

Berry et al. [74] stated that studies on IoT in buildings demonstrated random possibilities and limitations. Furthermore, it is found that IoT requires utilizing multiple factors and exploring new research directions. Generally, the approach of IoT in a building cannot be measured by a single indicator, for instance, achieving thermal comfort does not necessarily mean providing good air quality [75]. Broday and da Silva [76] indicated that studies in smart buildings lack investigations of different IEQ parameters such as light, noise and air conditions that play an important role for energy saving purposes. Rafsanjani et al. [65]

found that even though their study managed to modify energy-use behaviors during the experiment, feedback could hardly be continued over time by users. The study found that users returned to their original behaviors after the experiment. Imran et al. [58] conducted a study from the perspective of network and data science to provide a solution for IoT task management by implementing thermal comfort monitoring, fire detection and notification, safety systems and elderly patient health monitoring. The approach only used the building in the form of individual spaces for environmental assessment regardless of its design characteristics. In general, the missing link in these studies is that IoT solutions and their platforms should not only be limited to the users and energy markets but integrating the physical layer of IoT with building design and components should be considered to achieve efficient solutions. As a result, this section presents a summary of recent studies in this field as shown in Table 2.

From the perspective of experts in building design, the European Union developed a legislative framework for the Energy Performance of Buildings Directive (EPBD) to support smart buildings [57]. The directive indicated that buildings with IoT technologies are going to play an important role in the near future. As a result, the document of Directive (EU) 2018/844 presents an indicator known as the Smart Readiness Indicator (SRI) that assesses the smart readiness of buildings [57]. This indicator introduced a methodology that is based on the capability of buildings to maintain their performance by optimizing energy efficiency and adapting their operation to the needs of the users to reduce carbon emissions and facilitate the integration of renewable energy sources. The main aim of using SRI is to promote the upgrade of the building stock. The method to calculate SRI is based on assessing the functionality level of smart-ready services that are scored in a building unit or a building. This assessment could be conducted at the design stage or at present in any form, such as available building information models or digital twins. However, SRI only covers general assessments of technological services and their functionalities. Following EPBD goals, Heritage energy Living Lab onsite (HeLLo) is a project in the EU to explore refurbishment strategies and to spread the awareness of some retrofit solutions in the case of intervention on historic buildings. The project aims to increase awareness by demonstrating the strengths and weaknesses of the most common energy retrofit technical solutions. Andreotti et al. [82] investigated some refurbishment strategies via hygrothermal models by using a developed metering hot box to measure and monitor heat flux, surface temperature, air temperature and relative humidity. The study managed to assess specific technology under HeLLo, however, further exploration to utilize IoT in this context is required.

It is evident that IoT technologies in the near future are going to be integrated into many buildings to monitor, optimize and utilize different devices to collect data about everyday operations and to support building energy management systems. However, in building design, there is an indefinite implementation of IoT in the design process. For instance, in office buildings, how IoT could help to optimize the number of users in space, number and location of desks, lighting conditions, blind types and performance, types of HVAC systems, efficient electricity output and so on [19]. Positioning of IoT sensors inside a building requires a critical examination based on climatic conditions. Studies showed that there are different factors affecting this position such as comfort zones, seating and furniture, lighting, HVAC, ventilation, air quality, air temperature and solar access which are different based on climate type. Nagarathinam et al. [83] indicated the risk of positioning IoT sensors in buildings based on theoretical models as many unknown factors exist in real life. Thangamani et al. [77] stated that there are issues concerning IoT positioning in design documents and in handover. The study also mentioned that there are concerns between the design and operation phase, for instance, actuators placement, HVAC lines routing and embedded sensors that have a certain lifetime.

Table 2. Summary of recent studies on IoT towards energy efficiency in smart buildings.

	Studies	Scope	Research Methods	Building Type	Sensor Type	Applications Towards Energy Efficiency	Country
1	Thangamani et al. [77]	Issues of IoT application in intelligent buildings	Interview and Delphi method	Intelligent buildings	Lighting and HVAC	Key performance indicators and the business model	India
2	Metwally et al. [78]	Evaluating IoT solutions in buildings	Review and Qualitative method	Non-specific	Occupant, structure, appliances, HVAC system and energy control, lighting, space optimization and building utilities	Framework to assess IoT implementation level in buildings.	Egypt
3	Imran et al. [58]	Consumer behavior smart residential buildings	Mathematical and AI based approaches and Case Study	Residential	Microwave, dishwasher, fridge, air conditioner, heater, AT, RH, pressure, windspeed and dewpoint	IoT task management mechanism for energy consumption minimization	South Korea
4	Kumar et al. [8]	Integration of IoT-based sensing systems into smart buildings	Energy-based methodological approach using Simulation	Residential	CO_2, AT, RH and electricity consumption data	Minimizing energy consumption	USA
5	Ramallo-González et al. [79]	Occupant behavior and energy consumption	Case Study and EnergyPlus Software	Educational	AT, CO_2, lighting and RH	Energy reduction use in buildings by behavioral changes	Spain
6	Yasuoka et al. [80]	Energy management of air-conditioning system	Case study and Qualitative description	Educational	AT, RH, air quality, light and ultrasonic distance	Monitor thermal comfort of occupants.	Brazil
7	Berawi et al. [19]	Building design and IoT systems	Empirical measurements, Case Study and Interview	Office	Network, movement, light, HVAC	Framework of Smart Integrated Workspace Design (SIWD) with IoT	Indonesia
8	Li et al. [60]	Energy efficiency of a solar water heating system (SWH)	Empirical measurements and Energy Audit	Hospital	Water flow, heat and water pump, operational schedule, solar and electricity consumption	Develop control strategies for efficient operation	Singapore
9	Rafsanjani and Ghahramani [81]	Personalized energy-use information of workstation	Empirical measurements and Case Study	Office	TED Pro—energy-load data (kW), voltage (V), and cost	Energy behavior index	USA
10	Rafsanjani et al. [65]	Energy-use efficiency index and human behaviors	Empirical measurements and Simulation	Commercial	Energy and Occupancy	Energy assistant tool	USA
11	Xu et al. [15]	Forecasting in smart buildings	Empirical measurements, Simulation and Learning methodology	Residential	AT, CO_2, RH, lighting and solar irradiance	Model for predicting the indoor temperature	China

From the built environment perspective, architectural programming could provide a solution to integrate IoT at the early design stage [19]. Cherry and Petronis [84] described architectural programming as a decision-making process that influences the design, construction and operation of any building. Pena and Parshall [85] identified six stages in architectural programming, namely: describing project type, setting goals and objectives, gathering related data, specifying work strategies, defining the requirements at each stage of the building life cycle and producing a program summary to be validated by all stakeholders. Generally, architectural programming reinforces project efficiency to avoid redesign [86], cutting costs [83] and raising the opportunity of meeting environmental goals.

Furthermore, to understand IoT applications at the early design stage, IoT technologies could be assessed based on several factors to effectively integrate them into any building [87]. The factors could cover outdoor parameters, boundaries of site context, building functions, building structure, spaces, desired indoor parameters and human comfort parameters, building shape and form, building services, height, orientation and envelope type. Metwally et al. [78] proposed a framework method that consists of three main areas: input that covers fixed parameters, throughput that represents controlled variables and outcome in the form of impact. In addition, the study presented IoT in buildings within four levels: (1) occupant level that covers modes of users' preferences and activities in each space, (2) zone type level that assesses tasks and space parameters, (3) building control level which covers the control strategies using IoT technologies and (4) operation level in a building includes system maintenance, data and facility management and the relations between the building and the city. Figure 8 demonstrates IoT framework domains and indicators as introduced by Metwally et al. [78].

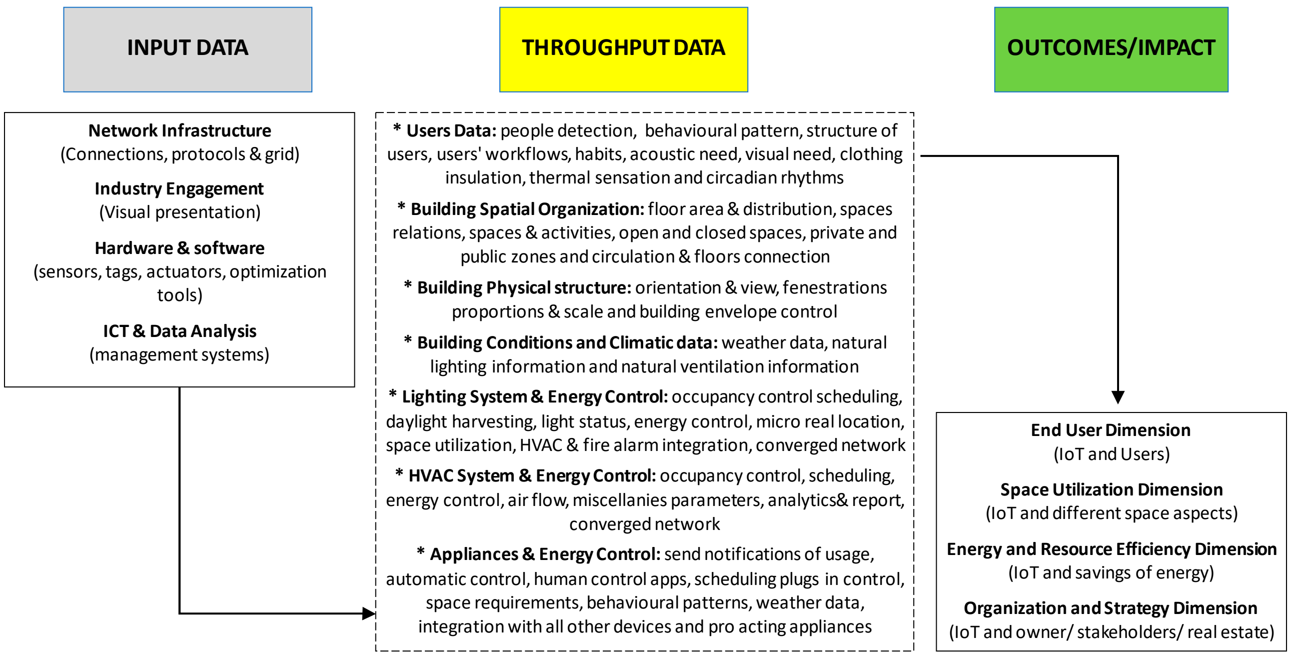

Figure 8. IoT framework domains and indicators.

These domains, levels and components play an important role to set the number of building users, indoor spatial relations, thermal insulation, types of services, indoor environmental conditions and expected occupants' behavior that all have an impact on energy consumption. Achieving energy efficiency in a smart building with the IoT approach requires a set of clear design actions that could achieve by enhancing the interoperability between systems and building components. Thus, providing flexible architectural and planning programming, running constant environmental measurements and ensuring an optimum configuration to control the installed devices could help to attain efficiency and integration [21]. Therefore, IoT technologies should be integrated within architectural programming at the early design stage to identify their role, function, impact and cost to achieve energy efficiency and to guide built environment experts to integrate IoT in the design, construction, operation and refurbishment stage.

5. IoT in Building Monitoring and Data Visualization

This section focuses on reviewing the application of IoT in building monitoring and data visualization and its contribution to the energy efficiency of the built environment sector. Firstly, it provides a general overview of data monitoring and visualization. Secondly, it reviewed recent and original studies using IoT sensors. The elaborations on the review include research location, in-use building types, applied IoT sensors, monitoring and visualization of thermal comfort, occupancy, environmental performance and energy consumption with their impacts on humans and energy efficiency. Lastly, the section concludes with personal critical reflections on the topic.

Energy monitoring of a building plays a vital role in energy efficiency. As referred by Ambati [88], energy cannot be managed if it cannot be measured. While considering building monitoring, data types can be occupancy comfort information, lighting, plug load (power consumptions), water use and any environmental or energy data measured by reliable equipment [89]. IoT sensors enable monitoring buildings remotely and, hence, this low-cost technology is widely used in the building industry [90,91]. In the context of this, data visualization can be defined as the presentation and representation of data to enable understanding in three phases—perception, interpretation and comprehension [92]. The IoT-based data visualization method has already been found as an effective technique for continuously monitoring performance data of in-use buildings remotely in real-time [93]. Figure 9 shows an example of IoT sensors and data visualization of real-time indoor environmental monitoring.

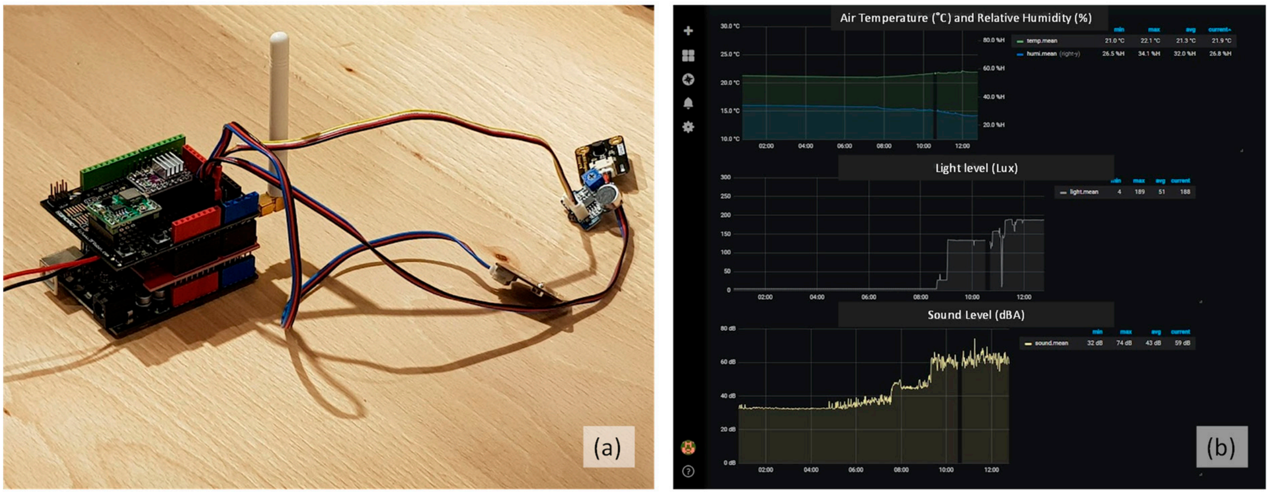

Figure 9. Example of (**a**) IoT sensors and (**b**) real-time data visualization of an indoor environment.

Table 3 lists the relevant studies published during the years between 2020 and 2022 and conducted in various countries across the world. The next parts elaborate on certain aspects and limitations of IoT applications, and how they are being utilized in building monitoring and data visualization for energy efficiency.

Table 3. Summary of recent studies on IoT-based building monitoring and IoT-based data visualization techniques.

	Studies	Scope	Research Methods	Building Type	Sensor Type	Application Towards Energy Efficiency	Country
1	Brik et al. [94]	Thermal comfort	Field Surveys	Office	AT, RH, power consumption	Prediction and control AT, energy saving through comfort optimizing	USA
2	Burunkaya and Duraklar [95]	IEQ	Mathematical algorithm	Educational	AT, RH, sound level (dB), light (lux) and $PM_{2.5}$	Energy saving through data visualization for managing the efficient use of energy resources	Turkey
3	Calvo et al. [96]	IEQ	Field surveys	Educational	AT, RH, equivalent carbon dioxide (eCO_2), TVOC	Energy saving through IEQ monitoring and energy efficient IoT sensors	Spain
4	Chiesa et al. [97]	Thermal comfort	Field surveys	Residential	AT, RH, globe temperature (GT), air velocity	Low-cost comfort monitoring and real-time comfort data visualization for an energy efficient control system	Italy
5	Mitro et al. [98]	Thermal performance	Field Surveys	Cultural heritage	AT, RH, dew point, power efficiency of sensors	Energy efficiency of IoT sensors for building monitoring, energy saving through visualizing real-time environmental conditions	Greece, Italy, Norway, Spain
6	Mendez-Monroy et al. [99]	IEQ, Power Consumption	Experimental	Residential	Energy Consumption, AT, RH	Energy saving through energy efficient IoT sensors, energy efficiency through effective visualization and management of building performance	Mexico
7	Floris et al. [100]	Occupancy	Field Surveys	Residential	AT, RH, Light (lux), TVOC, eCO_2, Infrared (IR) Obstacle	Energy saving through occupancy predictions and energy efficient IoT sensors	Italy
8	Hoang et al. [101]	Thermal comfort and human alertness	Experimental	Residential	Indoor AT, RH, body temperature (BT)	Indoor environment monitoring and making alertness to users to improve energy efficiency	Italy
9	Liang et al. [102]	Façade performance	Experimental	Educational	AT, pressure, water flow, wind speed, solar radiation intensity	Energy generation through efficient monitoring of façade performance	China
10	Luna-Navarro et al. [103]	Façade performance and human awareness	Field surveys	Office	Light (lux), ST, sound level (dBA)	Energy efficiency through monitoring façade and indoor environment, and human perception with visualizing façade performance	UK
11	Mataloto et al. [104]	Thermal and energy data and human perception	Field surveys	Educational	AT, RH, energy consumptions	Energy saving through 3D data visualization and optimizing perception of users and facility managers on thermal environment	Portugal

Table 3. *Cont.*

	Studies	Scope	Research Methods	Building Type	Sensor Type	Application Towards Energy Efficiency	Country
12	Tagliabue et al. [105]	Indoor air quality (IAQ)	Case studies	Educational	AT, RH, CO_2	Energy efficiency through monitoring the indoor environment	Italy
13	Valinejadshoubi et al. [106]	Thermal comfort and human perception	Field surveys	Office	AT, RH	Energy saving through thermal comfort monitoring, data visualization, improved perception and spontaneous actions from users or facility managers	Canada
14	Barot et al. [107]	IAQ	Technical mathematical algorithm	Residential	$PM_{2.5}$, PM_{10}, carbon monoxide (CO), AT, RH	Energy consumption optimization by deploying IoT prototype of IAQ monitoring	India
15	Gilman et al. [108]	IEQ, interactive data	Field survey	Educational	AT, RH, CO_2, light (lux), activity level	Smart IoT sensors for realizing indoor environment and interactive measures from users for energy efficiency	Finland
16	Hossain et al. [109]	Environmental data and human awareness	Field survey	Educational	AT, RH, light (lux) level, sound level (dB)	IoT platform and data visualization to improve awareness of energy efficiency and sustainability	UK
17	Jo et al. [110]	IAQ	Experimental	Educational	Concentration of aerosol, VOC, CO, CO_2, AT, RH	Energy saving through the deployment of IoT platform with meaningful and real-time IAQ data monitoring	Korea
18	Oh [111]	Power consumption	Empirical study	Residential	Electricity consumption	Energy saving through real-time power consumption monitoring	Korea
19	Mudaliar and Sivakumar [112]	Power consumption	Technical computing	Industrial	Electricity consumption	Energy saving through monitoring and visualizing real-time power consumption	India

While focusing on thermal comfort and occupancy of buildings, Brik et al. [94] proposed an IoT-based comfort monitoring system and showed that deployment of this system in an office space of 24 occupants could accurately predict and control the indoor thermal comfort parameters and, thus, help to control the indoor environment real-time saving energy. Another study also utilized low-cost IoT sensors to collect comfort data in prototype residential buildings and interpreted those data into Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) indexes and Operative temperatures with an easy and real-time data visualization interface guiding seasonal strategies and energy efficient HVAC control systems [97]. Similarly, other studies adopted BIM-based, COZyBIM (combined IoT-based platform and computer-simulated BIM) and IoT integrated thermal comfort monitoring systems for the energy efficient control of HVAC systems in office and educational buildings [106,113]. Hoang et al. [101] focused on how IoT can be implemented to monitor the indoor environment and simultaneous human body temperature levels during quarantine in a home environment. Floris et al. [100] explored two occupancy prediction models by collecting 10 days of data using low-cost IoT sensors in a prototype residential building and showed how this can help to predict occupancy and save energy. Another study also proposed a mathematical method through experimenting with IoT sensors which can accurately predict the laboratory's occupancy pattern and help save energy.

For monitoring, environmental data, IEQ and Indoor Air Quality (IAQ), the majority of reviewed studies commonly utilized specific IoT sensors, such as AT, RH, Total Volatile Organic Compound (TVOC or VOC), CO_2 and Particulate Matter (PM), for deploying and testing innovative prototypes. However, as shown in Table 3, they were not always consistent in terms of combining these sensors to represent IAQ. For instance, Barot et al. [107] introduced a Quality of Service (QoS)-enabled IoT prototype that can be used for air quality monitoring (both indoor and outdoor) using PM2.5, PM10, CO, AT and RH sensors, while other studies utilized CO_2, living gas, fine dust and PM only [105,110,114,115].

Recent studies in Table 3 show that using energy efficient IoT sensors and low-powered systems to monitor power consumption, e.g., LoRa System called 'EnerMon', Smart Tags, could significantly help optimize energy consumption and even help generate additional energy in both residential and non-residential buildings [96,98,99,102,112,116]. Complementing the real-time visualization of the power consumption data could also help users and facility managers to be aware of consumed energy and control usage as needed [117]. Figure 10 illustrates the overall summary of the review focusing on the relevant topics.

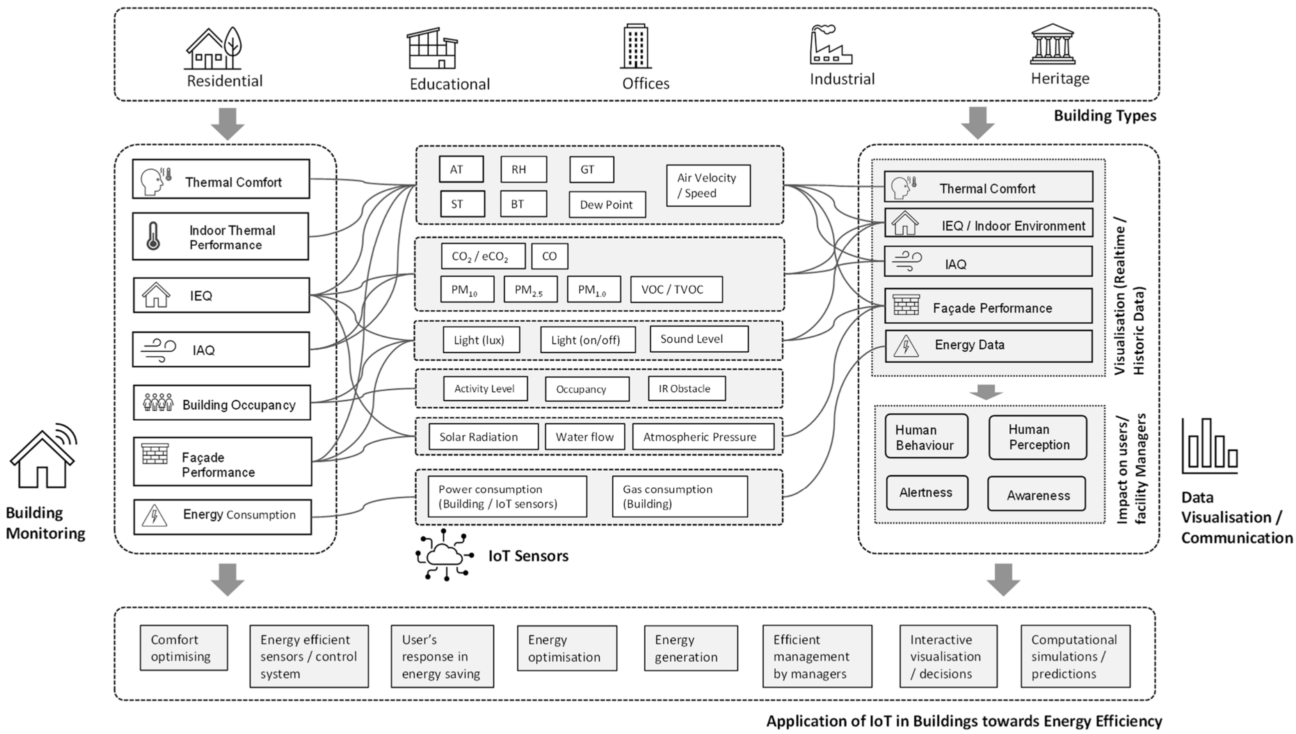

Figure 10. Application of IoT sensors in building monitoring and data visualization for energy efficiency.

As presented in Table 3, recent studies showed that data visualization was a complementary method to improve user and manager perceptions, alertness, awareness and adaptive behavior on thermal comfort, activities and energy consumption. The study conducted by Burunkaya and Duraklar [95] introduced the Smart Classroom Incubator (SCI) algorithm to visualize indoor environmental data to manage energy resources efficiently and save energy as a result. Luna-Navarro et al. [103] showed a 9-month-long deployment of an IoT-based 'Building Impulse Toolkit' (BIT) attached to a facade of an office building to monitor the IEQ and how humans respond to the data for improving their IEQ and save energy. In addition, the 3D real-time interface of the thermal environment along with energy consumption helps users and facility managers to improve their perception of the optimum thermal performance of the spaces at ISCTE-IUL university campus and save energy [104]. Similarly, a real-time data visualization platform can improve awareness among users, including students and staff members, on energy efficiency and sustainability [109]. While considering residential buildings, one study implemented energy monitoring for 15 months in the residential building using IoT-based smart plugs while other research communicated energy consumption, associated costs and $KgCO_2$ emissions to improve user awareness and help energy saving [111,118,119].

Both advantages and limitations were highlighted in the reviewed articles with some indications for future scope for improvement. The research conducted by Mitro et al. [98] identified that the IoT is not only reliable in real-time monitoring and visualizing the environmental conditions affecting the cultural heritage buildings in Europe, but also energy efficient with low power consumption and long operational life. Gilman et al. [108] highlighted the advantage of interactive data visualization in a longitudinal IoT deployment within a university campus, and lessons learnt and challenges were shared, e.g., infrastructure and reliability of data were highlighted. While the research conducted by Martín-Garín et al. [120] highlighted the scalability of this IoT platform for the future application of retrofitting, Chen et al. [121] showed lack of temporal information can be a constraint for future applications.

As a built environment expert and the first author of the article produced by Hossain et al. [109], our reflection focuses on the application and challenge of implementing IoT in built environments. Recent studies deployed IoT sensors or IoT-based prototype systems for both building monitoring and visualizing associated data contributing toward energy efficiency and users or facility managers' adaptive responses to save energy. The context of the studies includes the USA, Europe, UK, India, Korea, China, Mexico, Canada, Turkey and Taiwan with certain types of climates. Considering the advancement and usefulness of IoT technology, the review indicates the lack of adequate studies on applications of IoT for monitoring and visualizing the performance of building in the rest of the world. A range of IoT sensors was utilized for both building monitoring and data visualizations. However, no research has fully utilized those sensors and Figure 10 shows how sensors are partially used for various levels of monitoring and visualization. While these studies were mostly conducted in residential and educational buildings with a few offices, and industrial and heritage buildings, there might still be opportunities for applying IoT in other types of non-domestic buildings, such as retail shops, warehouses, government buildings and agricultural buildings.

6. IoT in Smart Cities

The section introduces the concept of a smart city and IoT technologies on a large scale. It discusses specific IoT applications for energy efficiency and extends the understanding of using IoT at the city level. The aim of this section is to inform experts in the built environment about the latest trends and challenges in this area of research.

The term "smart city" refers to an urban environment that uses smart technologies and data analysis to optimize city functions [122]. Smart and green living is a top priority for governments around the world as they seek to enhance physical infrastructure, protect the environment, strengthen the economy, achieve energy efficiency and increase the quality of life for citizens [123]. The digital city and information city are concepts that have all benefited from the initial integration of ICT into city operations. Recently, IoT led to the creation of "smart cities" that support city operations with minimal human intervention [124]. Smart sensors and contextual systems can assist in the development of future smart cities, however, there are a wide range of challenges, including the need to improve the energy efficiency of various city components.

The main components of a smart city, as depicted in Figure 11, are a few of many that shape a smart urban environment. These key components include smart energy grids, smart communities, smart healthcare and smart transportation. Nevertheless, the composition of smart cities differs from one city to another, varying based on the areas of interest. For instance, a city may consider incorporating a disaster management system into its smart community, whereas another intends to implement smart grid systems. In general, the concept of a smart city has emerged as a solution to the problems caused by exponential urbanization and population growth. However, due to technological, economic and governmental barriers, the concept is still evolving and has not yet reached mainstream status worldwide. As a result of the widespread interest in the IoT concept, several applications are extended in smart cities to improve the current technologies of smart grids, smart homes, smart health and smart transportation [122]. Furthermore, the application of IoT in each smart city differs based on several factors such as the city's needs and priorities, ICT Infrastructure, and the economic and maturity level of experts and citizens.

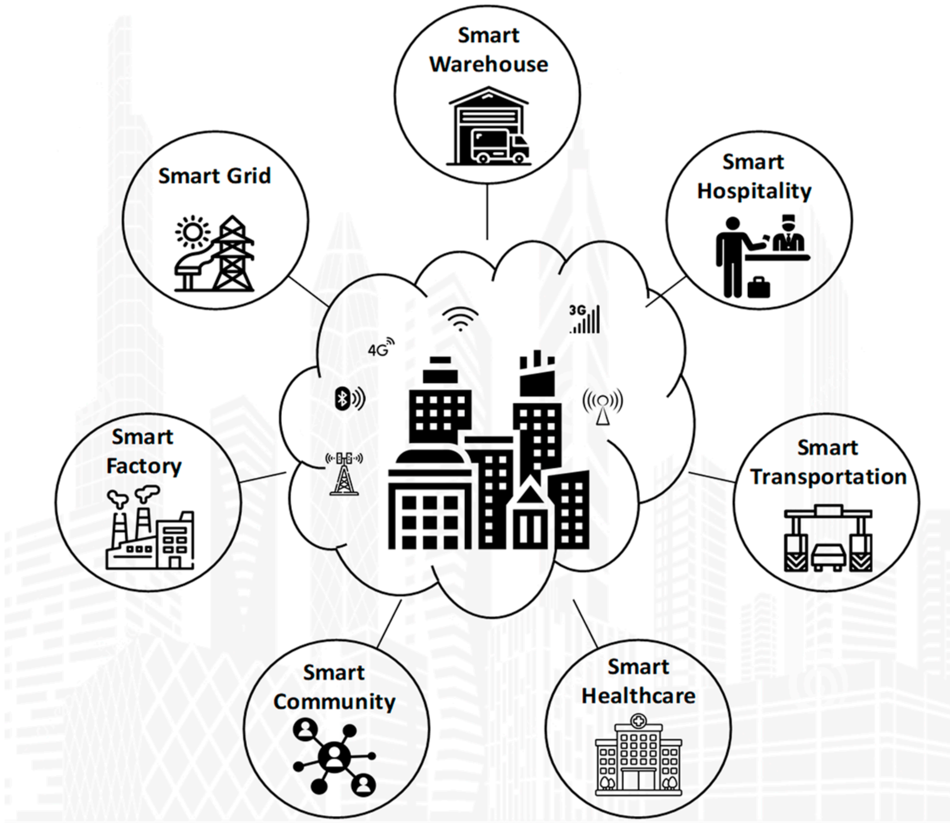

Figure 11. Generic composition of smart city architecture.

Therefore, in considering IoT, experts in the built environment need to take into account a wide variety of possible scenarios and conditions. For the output to be as effective as possible, it is critical to select the appropriate sensors and determine the best way to process the data from IoT systems. Additionally, the solutions should be efficient in order to achieve sustainability [125–127]. Integrated smart cities that make use of IoT ought to be efficient in terms of energy management, cost, protection and security. In addition, IoT systems should operate autonomously, without interfering with the operation of other networks and with sufficient quality to improve system operation. Therefore, the operation of IoT systems as well as their lifespan and energy efficiency, are the primary obstacles to future smart city innovations [128].

IoT Applications in Smart Cities

This part discusses the current utilization of IoT technology towards energy efficiency at a smart city level. Figure 12 depicts the directions of IoT applications to reduce energy consumption. Understanding the ability of IoT at the level of a smart city help to guide several parties, designers and decision-makers to achieve efficiency in energy use.

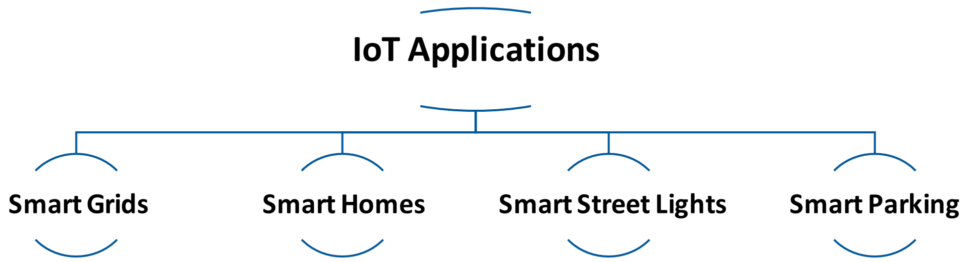

Figure 12. IoT applications for energy efficiency in smart cities.

On the basis of IoT, a number of studies have been conducted in order to promote energy efficiency in smart cities. However, the impact of IoT on energy efficiency varies from sector to sector. Smart grid management and smart lighting systems, for example, are regarded as key players in energy optimization in smart cities [129,130]. In a recent study, Liu et al. [131] provided a comprehensive review of the energy harvesting-assisted IoT applications with the possibility of being used in smart environmental monitoring, smart transportation, smart homes and smart healthcare (e.g., wearable/portable devices and implantable devices). The findings highlighted the potential of IoT-powered cities for transitioning urban environments towards carbon neutrality. It was also mentioned that the development of "self-powered sensor nodes", "self-sustainable wireless sensor nodes" and "self-charging energy storage units" may contribute to the reinforcement of the IoT concept by increasing 5G endpoints and accelerating digitalization in smart cities. As a result, examples of IoT utilization for energy efficiency in smart cities are as follows:

- **Smart Grids:** According to the definition by the American Electric Power Research Institute, a smart grid is a power network that permits a two-way flow of information and electricity [132]. A smart grid provides a two-way flow of electricity between power grids and electricity customers, in opposition to conventional electric power grids, which only allow for a flow of electricity in one direction. Furthermore, incorporating ICT into power grids results in a two-way information flow, allowing grids to self-heal and electricity users to take an active role in the system's operation. The conceptual model of the smart grid is depicted in Figure 13. There are seven areas in which energy and information are exchanged. Researchers have broadened their focus to include the management of smart grids as a means of increasing energy efficiency. For example, Abbas et al. [124] provided a brief overview of challenges in smart cities using energy management in power plants prior to introducing a framework for energy sustainability in IoT-based smart cities. Furthermore, IoT utilization in business applications and smart energy systems was examined by Ahmad and Zhang [133]. To further boost the energy market's efficiency in smart cities, He et al. [134] studied the optimal decentralized purchasing and selling decisions of energy storage under market uncertainty. Liu et al. [130] combined the cyber-physical system with the Power Internet of Things (PIoT), which resulted in the creation of a cyber-physical power system (CPPS) for the next generation of smart grids. Sanduleac et al. [135] introduced an unbundled smart meter (USM) to make it possible for both the customer and the energy provider to have simple and safe access to data in both their local and remote environments. Zhang et al. [136] proposed IoT-based Smart Green Energy (IoT-SGE) to assess the formation of smart power systems using a variety of on-site and off-site resources. The aim is to provide smart cities with the ability to become more energy efficient. Generally, the most intelligent and interconnected grids ensure a constant and secure power supply for the consumers through the smart grid [129]. However, integrating home energy management with smart grids maximizes energy utilization; there are limited studies that have connected smart grids with the different smart city components to enhance energy optimization at the city level.

- **Smart Homes:** Since it has such a significant bearing on the overall amount of energy that is consumed in smart cities, numerous energy management systems have been proposed for use in the home environment. Mahapatra et al. [123] proposed a method, called Home Energy Management as a Service (HEMaaS) for optimizing the energy usage of buildings in smart cities based on a neural network-based Q-learning algorithm. The developed model catered to enhance occupants' convenience and robustness of the system. The analysis showed that the method was capable of formulating viable strategies for decreasing the demand and conserving energy during peak periods. The adopted method was further shown to be effective for city blocks congested with various residential buildings in minimizing the total energy consumption through mitigating and shifting their energy demand during peak periods. Ejaz et al. [128] provided an illustration of the significance of energy efficiency in smart homes through the presentation of two case studies. The first case study describes an optimization strategy for appliance scheduling within the context of smart home networks, with the goal of lowering the cost of electricity usage. The second case study examines how to schedule dedicated energy sources for IoT devices in smart cities in an efficient manner. Alhasnawi and Jasim [137] proposed a real-time electricity scheduling (RTES) system for smart home energy management towards energy efficiency in smart cities. Moreover, Jackson et al. [138] proposed a multi-agent system (MAS) in smart homes for peak demand reduction and smart energy management based on IoT in smart cities. Furthermore, adaptive and automated home energy control systems based on IoT systems in smart cities were proposed by Tipantuña and Hesselbach [139]. In this regard, managing energy consumption at the foundational level appears promising for enhancing the sustainability of energy management at the city level.
- **Smart Street Lighting:** This application places an emphasis not only on the reduction in energy consumption but also on convenience. During the night, an automatic and smart lighting control system is activated in response to the movement of both people and automobiles. It is also possible for it to be activated or deactivated automatically according to the amount of sunlight present. The adoption of an IoT-based intelligent automation strategy can help conserve energy in street lighting. The energy costs associated with the street lighting system are extremely high. Using IoT on smart streets, the average cost of smart lighting systems could be reduced between 50 and 70% [129]. In this regard, numerous researchers have developed smart street lighting systems to reduce energy consumption in smart cities. For example, Chen et al. [129] proposed a smart street lighting system that is both energy efficient and environmentally friendly. The system utilizes renewable energy sources, IoT sensors and an effective decision-making module and dimming system. Moreover, to optimize the energy efficiency of smart city street lighting systems, Humayun et al. [140] suggested a model based on IoT, 5G and cloud computing. Additionally, Prasad [141] presented a case study of a smart lighting system in Nagpur smart city, where the ultimate purpose was to lower the amount of energy being consumed.
- **Smart Parking:** One of the key infrastructure concepts for IoT in smart cities is smart parking. Finding a free parking lot can help reduce the amount of energy consumed, as well as the amount of gas and emissions that are produced. Considering that drivers spend 7.8 min on average finding a parking space, developing smart parking systems to locate free spaces would reduce traffic congestion and increase energy efficiency in smart cities [142]. Geng et al. [143] stated that 30% of daily traffic congestion is caused by drivers searching for a free and available parking space, which not only adds to the frustration of drivers attempting to complete daily tasks but also dramatically increases fuel and energy consumption in smart cities. Several solutions have been proposed in recent years to address the issue of finding free parking spaces with the goal of establishing a green built environment and energy efficiency in smart cities [144,145]. These solutions mostly consist of mobile applications that inform customers about nearby parking lots (Figure 14). Solutions such as Parking Guidance and Information

(PGI) to Parking Reservations Systems (PRS) are available to drivers via the internet and provide them with information on the availability of parking spaces [146].

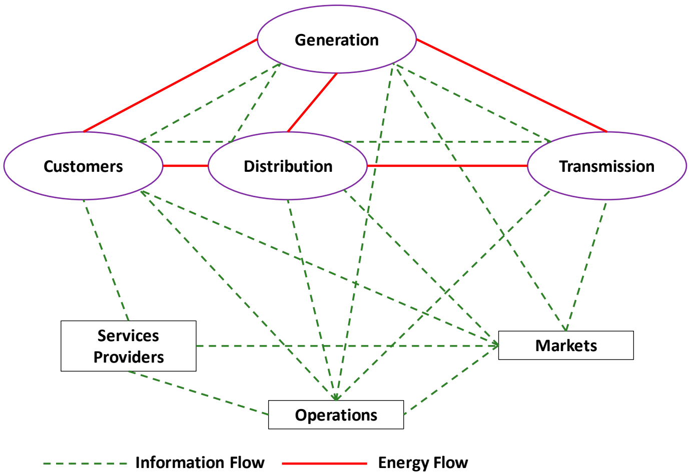

Figure 13. Conceptual model of a smart grid [130].

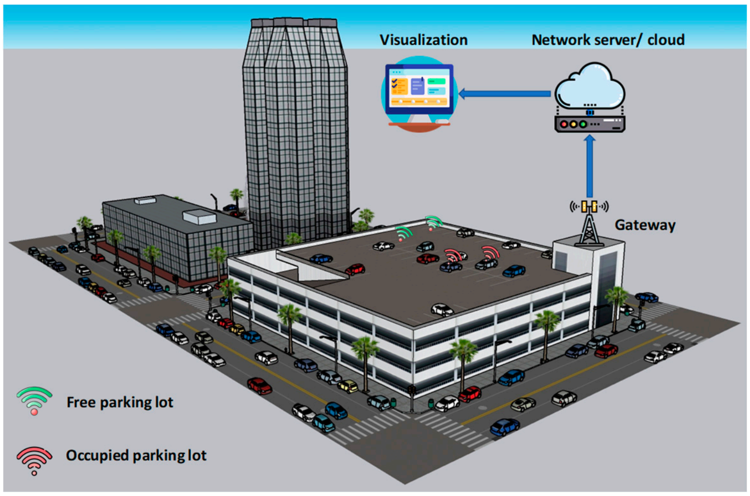

Figure 14. IoT-based Smart Parking System.

A plethora of research has spotlighted the potential of IoT in smart cities, e.g., modern built environments, which are intelligently functionalized to facilitate the realization of sustainability [147,148]. In this regard, IoT-based data management in tandem with cloud computing technologies has been proven effective in developing information systems in cities to encompass different sensory layer data and structures supporting network systems [147,148]. This, in turn, has led to the development of many studies aiming to employ the capacity of IoT in cities for a variety of purposes. For instance, Nahrstedt et al. [149] attempted to discuss the benefits and challenges of physical infrastructures in smart cities in connection with human stakeholders. Studies also proposed novel architectures for integrating IoT-based data with social networks in smart cities or improving the resilience of infrastructures in IoT [150]. However, there is a dearth of research investigating the potential of IoT in saving energy in the context of cities.

Efficiency in smart cities is essential to meet the rising demand for energy in the next few decades, according to a forecast of future consumption. Energy conservation can be achieved by using energy-efficient systems such as optimal operational management, smart meters and smart industrial equipment, and the use of sustainable energy resources in all spatial options [129]. Optimizing the use of energy improves both the comfort and health of the living. There are several ways to improve energy efficiency, including real-time monitoring, production planning systems and automation.

According to the preceding discussion, efficient use of energy is the main challenge in smart cities. Although there are studies that address the problem of energy efficiency in smart cities, the solutions that are provided focus on a particular aspect of a smart city, such as the smart grid, power plants or household appliances. Therefore, there is a need for an all-encompassing energy optimization solution that is capable of handling energy savings across the board. In addition, involving built environment experts such as planners, architects and designers in the revolution of IoT and its applications would facilitate the integration and enhance the energy efficiency of smart cities. In this regard, Table 4 summarizes the recent studies that used IoT to achieve energy efficiency in several components of smart cities.

Table 4. Summary of recent studies on IoT towards energy efficiency in smart cities.

	Studies	Scope	Research Methods	Applications Towards Energy Efficiency	Technology Used	Output
1	Humayun et al. [140]	Energy optimization	Modeling	SL, smart parking, billboards and household appliances	Integration of IoT, 5G and cloud computing	Reduce energy of the street and building billboards, street lighting, smart parking and smart homes appliances
2	Chen et al. [129]	Energy optimization	IoT framework and Simulation	SLS	Sensors, actuators, renewable energy and efficient decision-making module and dimming system.	Energy saving during peak and off-peak hours on highways and pedestrian areas in the suburbs
3	Xin et al. [151]	Energy management	Simulation	Residential and business	Deep learning architecture of power management (DLA-PM)	Predicting and reducing energy use (reduced by 8% for both business and residential data sources)
4	Alhasnawi and Jasim [137]	Energy optimization	Programming and Experimental measurements	Smart home	Comprising software (Wi-Fi network programming along with the system protocol) and hardware (base Station Unit and many Terminal Units)	Reducing the emissions, energy costs, and peak-to-average ratio of smart microgrids.
5	Ashwin et al. [152]	Energy optimization	Experimental measurements	Smart bins in shopping malls, colleges/university campuses, railway stations, tourist areas, parks, etc.	Sensors, servo motor and controllers with 80% solar energy	Intelligent waste management, reduced waste routes and energy saving
6	Zhang et al. [136]	Energy management	Simulation	Smart power systems	IoT and deep reinforcement learning	Energy consumption, energy demand forecasting, and cost-cutting
7	Liu et al. [130]	Energy management	Conceptual framework and Case Study	Smart grids, intelligent home	Integrating power IoT with cyber-physical systems	Intelligent decision-making and real-time agile control in a smarter power grid

Table 4. *Cont.*

	Studies	Scope	Research Methods	Applications Towards Energy Efficiency	Technology Used	Output
8	Abbas et al. [124]	Energy management	Simulation	Power plant electrical energy	Deep extreme learning machine	Energy prediction and management of electric power plant energy output in smart cities
9	Jackson et al. [138]	Energy management	Simulation	Smart homes	IoT and deep learning	Energy demand reduction
10	Prasad [141]	Energy efficiency and controlling	Case Study	SLS	Sensors and controllers	Energy and cost reduction of street light system
11	Sanduleac et al. [135]	Energy management	Case Study	Smart grids, smart homes	Unbundled smart meter	Energy demand reduction and developing energy efficiency strategies.
12	Golpîra and Bahramara, [153]	Energy management framework	Simulation	Smart city	Optimal IoT-based energy management	Cost-effective energy balance
13	He et al. [134]	Energy storage management	Modeling	Smart city	IoT and information systems design	Energy market efficiency

7. Conclusions

The findings from the review have clearly demonstrated that the integration of IoT in the contexts of buildings and cities has constructive implications for saving energy. Nevertheless, the widespread use of IoT-based technologies has revealed shortcomings and limitations that are still hampered by several challenges when integrated into the built environment. As a result, the study summarizes the main constraints in this field and possible directions to guide experts in the built environment.

Several challenges were identified: (1) The review found that most IoT applications are used as a strategy to mitigate existing issues in buildings and cities. Generally, there are limitations to integrating IoT technologies at the early design stage due to a lack of clear approaches by the experts in the built environment. (2) IoT studies in the field of computer science and engineering are well established and defined, however, studies of IoT by experts in the built environment are limited due to insufficient comprehension of technologies and their applied methods. (3) It was noticed that studies of IoT and energy efficiency mostly target devices, users and energy markets without considering the aspects of building design. (4) There are concerns about utilizing IoT between the design and operation phase as there are several factors: Physical characteristics such as coverage (boundary), selected systems and infrastructures. Environmental parameters that control comfort and safety. And economical aspects such as maintenance, cost efficiency and durability. (5) There are no clear guidelines to demonstrate the positioning of IoT sensors in buildings according to different climatic conditions. (6) The method of the Smart Readiness Indicator (SRI) is only used for raising awareness amongst building owners and occupants and checking IoT services and functionalities. (7) Studies of IoT in smart buildings lack investigations of IEQ and consistencies in IEQ parameters that play an important role in energy-saving purposes. (8) Recent studies have investigated the usefulness and scalability of IoT prototypes in residential and educational buildings, however, more investigations are required in all types of buildings at a macro level. (9) In smart buildings, the relationship between users and energy-use behaviors is shown to be diminished when there is a lack of continuous or frequent feedback. (10) In smart cities, IoT solutions are limited and could be restricted to a particular aspect of the smart environment. (11) A large amount of energy is required to provide communications that occur by each object or entity in IoT. (12) There are concerns in regard to the storage capacity needed for data generated via IoT devices, data often comes in different formats and structures, making data storage challenging and complex. (13) Interoperability of the data received from various IoT devices in buildings and cities can be challenging when the ultimate aim is to establish a uniform network within an environment that connects physical objects. (14) Issues related to cyber security can also be daunting as IoT is increasingly becoming popular in smart buildings and cities. Since the data transmission largely depends on wireless networks, IoT becomes inherently vulnerable to cyber-attacks that require further solutions that might demand more energy. (15) IoT faces many challenges and obstacles that remain critical and fundamental, for instance, IoT sensor boards rely on batteries with a limited lifespan to function. Finally, (16) the review found that the use of IoT improves the efficiency of smart built environment applications but that IoT itself has constraints that should be considered.

Therefore, the review identified some guided steps to support experts in the built environment to utilize IoT effectively: (1) IoT should be studied as a part of building services and could be considered as part of a building. (2) Further models and frameworks should be developed to integrate IoT at the early design stage. (3) IoT in smart buildings should be integrated with an energy-efficient building design process that uses four tiers: The first tier is to use IoT to minimize energy loss with design strategies, the second tier is to integrate IoT with systems for harvesting renewable energy, the third tier is to monitor the indoor environment and response to user needs and the fourth tier is to facilitate IoT with building management systems to control and assess the performance of active systems. (4) IoT applications in buildings should be reviewed by building experts to identify their functionality, efficiency, adaptability, user connectivity and energy demand. (5) The IoT approach requires a set of clear design actions to enhance the interoperability between systems and building components. Therefore, the review recommends studying IoT in two directions. First, by considering the integrated design process from Pre-design, Schematic Design; Design Development; Construction Documentation; Bidding, Construction, Commissioning; Building Operation (start-up); Post Occupancy (long-term operation). Second, by developing IoT in buildings according to levels: occupant, zone type, building control and operation. (6) Future efforts should be dedicated to developing algorithmic solutions which enable local data processing. This approach would help to use local computation that can be more cost-effective when dealing with energy consumption. The promotion of such an approach would potentially contribute to minimizing data volumes and transmitting only metadata instead of sharing raw data of massive sizes. (7) The traditional solutions, such as SQL-queried relational database management systems (RDBMSs), have been proven ineffective, thus, highlighting the need for developing more advanced techniques. This issue is further compounded when considering challenges relating to data integrity in terms of security and privacy. IoT clouds could be a viable solution for challenges attributed to the storage, as they can provide a suitable environment for data analytics as well as data storage. Finally, (8) latency issues and saturation of wireless channels can also be realized by minimizing transmissions occurring amongst IoT devices. Therefore, techniques supporting the decrease in communication overhead should be utilized, such as "data compression", "data prediction" and "in-network processing". The edge computing technique can also be employed to minimize data processing in the IoT domain to save more energy.

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