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Empowering the Energy Sector: IoT and Cloud Computing for Enhanced Efficiency and Inclusivity

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Abstract: This research paper delves into the potential transformation brought about by technology, specifically the Internet of Things (IoT) and Cloud Computing, in reshaping the energy sector. It explores how these contemporary technologies can provide utility customers with unprecedented control over their electricity consumption, ultimately leading to enhanced reliability and cost savings within the electric system. Alongside these overarching advantages, the study highlights the multifaceted applications of IoT and Cloud Computing, encompassing improvements in energy efficiency, the promotion of renewable energy adoption, and the mitigation of environmental impacts. Of particular significance is the examination of the relevance of these technologies for low-income communities, scrutinizing the specific challenges and opportunities that arise within this context. The paper offers a comprehensive review of the foundational technologies of IoT, incorporating the pivotal role of cloud computing and various platforms, thereby shedding light on their diverse applications within the energy sector. Furthermore, the research conducts a critical assessment of the barriers associated with the deployment of these cutting-edge technologies, with a specific focus on addressing privacy and security concerns. As the energy landscape continues its evolution, this study presents an informative overview of how technology can optimize energy systems. Moreover, it underscores the necessity of addressing issues related to accessibility for low-income communities. The paper concludes by proposing future research directions that prioritize the development of programs and policies aimed at ensuring equitable access to these transformative technologies for underserved populations.

Keywords: Internet of Things (IoT), low-income, cloud computing, energy efficiency.

1. Introduction

A Diverse Array of Cutting-Edge Technologies, including Communication Systems (e.g., 5G), Intelligent Robotics, and the Internet of Things (IoT), as Catalysts for the Fourth Industrial Revolution. IoT, in particular, serves as a linchpin by seamlessly interconnecting various devices, individuals, data streams, and processes. This interconnectedness holds the potential to imbue numerous processes with greater quantifiability and measurability through the collection and analysis of vast volumes of data. The transformative impact of IoT extends across multiple domains, promising enhancements in various facets of life, such as healthcare services, the development of smart cities, advancements in the construction industry, agricultural practices, water resource management, and energy sector operations. This is facilitated by the augmentation of real-time decision-making through increased automation and the provision of tools to optimize these decisions.

While the literature has extensively examined the application of cutting-edge technologies like IoT and Cloud Computing across different sectors and industries, much attention has also been dedicated to evaluating the challenges and opportunities associated with the deployment of specific IoT technologies, such as sensors or 5G networks. In contrast, within the realm of the energy sector, most survey studies have tended to focus on specific sub-sectors or the technical potential of particular IoT technologies, often neglecting the comprehensive exploration of these technologies' application from energy generation through transmission and distribution (T&D) to the demand side.

This paper aims to bridge this gap by providing a holistic review of the application of the latest technologies, including IoT and Cloud Computing, within the energy sector. Furthermore, it scrutinizes the specific challenges encountered when deploying these technologies for low-income households. The scope of analysis encompasses the entirety of the energy sector, from generation to T&D and demand-side considerations. To facilitate this exploration, we offer a brief introduction to IoT and Cloud Computing technologies as foundational knowledge for discussing their roles within the energy sector.

2. **Internet of Things (IoT)**

The Internet of Things (IoT) represents an emerging technology that leverages the Internet to establish connectivity among physical devices or 'things' [7]. These physical devices encompass a wide array of objects, from household appliances to industrial machinery. By incorporating appropriate sensors and communication networks, these devices can generate valuable data and facilitate the delivery of diverse services to individuals. For instance, implementing intelligent energy management systems in buildings through IoT enables the optimization of energy consumption, resulting in cost savings [8]. IoT finds applications across various sectors, including manufacturing, logistics, and the construction industry [9]. Moreover, IoT plays a pivotal role in environmental monitoring, healthcare systems and services, efficient energy management within buildings, and the provision of drone-based services [10–13].

The initial phase of designing an IoT system involves careful planning, with component selection representing the first step. These components encompass sensor devices, communication protocols, and data storage, all tailored to suit the intended application. For instance, the design of an IoT platform intended for regulating heating, cooling, and air conditioning (HVAC) in a building necessitates the inclusion of relevant environmental sensors and the use of suitable communication technologies [14]. Figure 1 provides a visual depiction of the various components comprising an IoT platform [15]. The second component, IoT devices, can take the form of sensors, actuators, IoT gateways, or any device involved in the data collection, transmission, and processing cycle. For instance, an IoT gateway device facilitates data routing within the IoT system, establishing bidirectional communication links between the device-to-gateway and gateway-to-cloud.

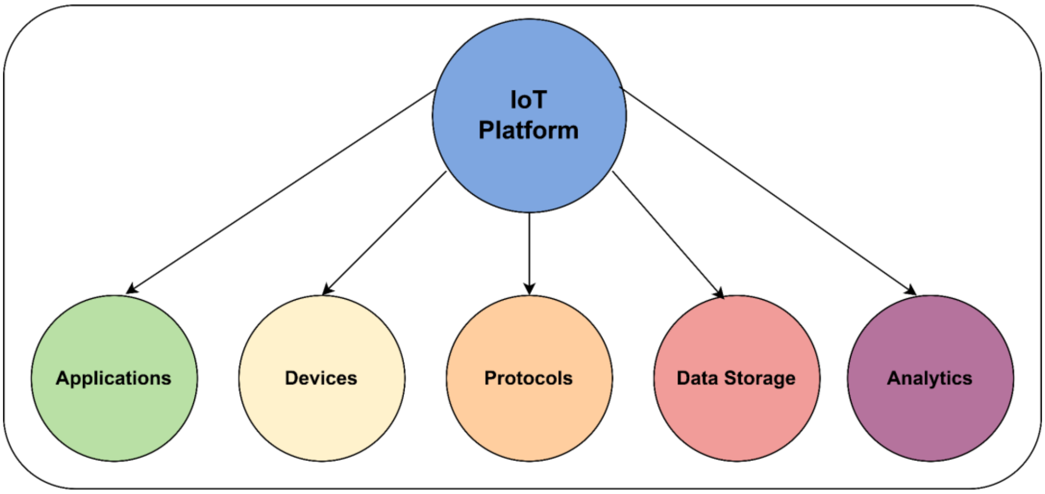

Figure 1. IoT Platform Components

Communication protocols, constituting the third component of an IoT platform, enable diverse devices to communicate and share their data with controllers or decision-making centers. IoT platforms offer the flexibility to select communication technologies, each endowed with specific features, according to the requirements of the application. Examples of such technologies include Wi-Fi, Bluetooth, ZigBee [16], and cellular technologies like

LTE-4G and 5G networks [17]. The fourth component, data storage, enables the effective management of collected data originating from the sensors.

In practice, the data generated by these devices tends to be voluminous, necessitating the development of efficient data storage solutions. This storage can be implemented either within cloud servers or at the edge of an IoT network. The stored data, which serves as a crucial resource for analytical purposes, represents the fifth integral component of IoT platforms. Data analytics can take two primary forms: offline analytics or real-time analytics. The choice between these approaches hinges on the specific requirements of the application and its operational needs. Offline analytics entails the collection of stored data, followed by its subsequent visualization on-site using dedicated visualization tools. Conversely, real-time analytics leverages cloud or edge servers to provide immediate visualization and analysis, exemplified by stream analytics [18].

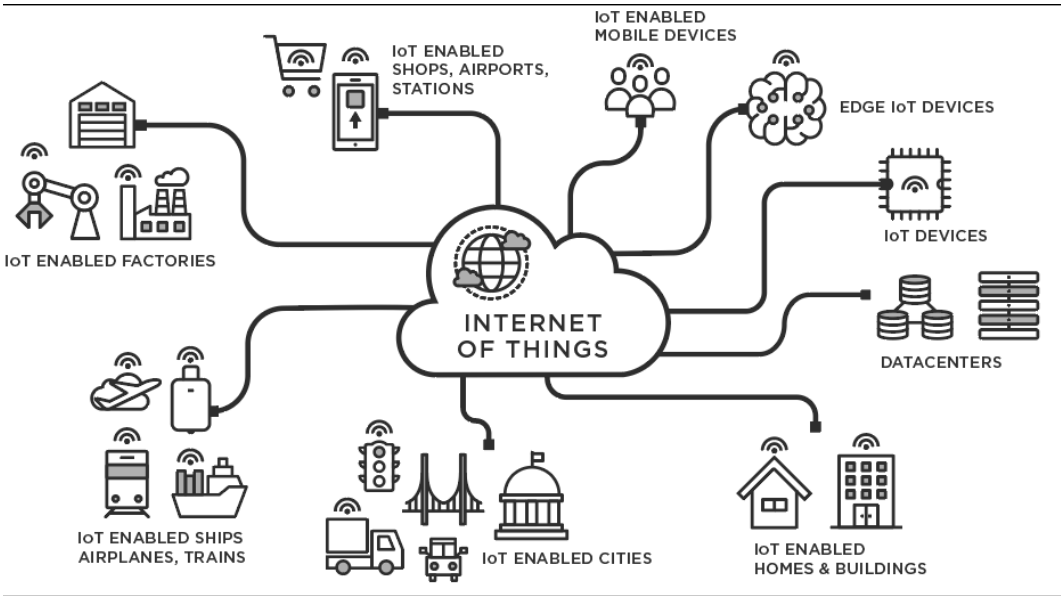

Figure 2. Internet of Things (IoT)

3. Technological Foundations for IoT

IoT represents a paradigm wherein objects and components within a system are equipped with sensors, actuators, and processors, enabling them to establish communication channels and deliver meaningful services. Within IoT systems, sensors play a pivotal role in capturing and gathering data. Subsequently, this data is channelled through gateways to reach control centers or the cloud, where it undergoes further processes such as storage, analysis, and decision-making. Following the decision-making phase, corresponding commands are transmitted to actuators integrated into the system, prompting responses in alignment with the initially sensed data. Given the diverse array of sensor and actuator devices, communication technologies, and data processing approaches available, this section offers an elucidation of the existing technologies that underpin the functionality of IoT. Subsequently, we draw from literature examples to showcase how these technologies find practical application within the energy sector.

3.1. Sensors

Sensors represent the cornerstone of IoT [19], playing a pivotal role in real-time data collection and transmission. Their utilization significantly enhances effectiveness and functionality, serving as a critical factor in the success of IoT initiatives [20]. A wide spectrum of sensor types has been developed to cater to various application needs. These applications span diverse fields such as agriculture, environmental monitoring, healthcare systems, and public safety [21]. In the energy sector, encompassing energy production, transmission and distribution, as well as consumption, sensors are extensively deployed.

Within the energy sector, sensors are harnessed to drive savings, both in terms of cost and energy consumption. They empower smart energy management systems, enabling real-time energy optimization and paving the way for innovative approaches to energy load management. Research and future trends in sensor devices within the energy sector are geared towards the development of sensor applications that enhance load shaping, raise consumer awareness, and bolster the production of renewable energies [22]. In essence, the integration of sensor devices into IoT greatly enhances diagnostics, decision-making, analytics, optimization processes, and the tracking of integrated performance metrics.

Given the extensive use of sensors in the energy sector, let us delve into a few examples of commonly employed sensor devices in energy production and consumption:

Temperature Sensors: These sensors are utilized to detect temperature fluctuations in heating and cooling systems [23]. Temperature is a fundamental environmental parameter in the energy sector, as power generation often involves the conversion of mechanical energy into electrical energy, with heat energy (thermal energy) as an intermediary. This applies to various energy sources, including thermal power plants, wind turbines, hydropower, and solar power plants. On the consumption side, temperature sensors optimize system performance by responding to temperature variations during normal operations. For instance, in residential areas, temperature sensors help identify the most opportune times for activating or deactivating ventilation and cooling systems, thereby effectively managing energy usage [19].

Humidity Sensors: These sensors quantify moisture levels and air humidity, with relative humidity being the ratio of moisture in the air to the maximum moisture capacity at a specific air temperature [24]. Humidity sensors find extensive use in wind energy production, especially in offshore wind farms where humidity levels are elevated. Placing humidity sensors in wind turbines, such as within the nacelle or at the turbine's base, enables continuous moisture monitoring. This empowers operators to take timely actions in response to changing environmental conditions, resulting in more consistent operations, optimized performance, and reduced energy costs.

Light Sensors: Light sensors gauge luminance (ambient light levels) or brightness. In terms of energy consumption, these sensors hold numerous applications in industrial and everyday settings. Lighting accounts for a significant portion of energy consumption, with buildings, in particular, consuming nearly 15% of total electricity usage [25]. Light sensors offer the means to automatically control indoor and outdoor lighting by adjusting light levels, either by turning lights on/off or dimming them in response to changes in ambient light. This leads to reduced energy consumption for indoor lighting [6].

Passive Infrared (PIR) Sensors: Also known as motion sensors, PIR sensors measure infrared light radiation emitted by objects within their surroundings. These sensors find application in energy consumption reduction within buildings. For instance, PIR sensors detect human presence within spaces, enabling intelligent lighting control. When no movement is detected, the lighting system is automatically switched off, exemplifying smart lighting control. This approach effectively reduces electricity consumption in buildings [27]. Similarly, PIR sensors can be employed to control air conditioning systems, which can account for nearly 40% of energy consumption in buildings [25].

Proximity Sensors: Proximity sensors are designed to detect the presence of nearby objects without requiring physical contact [28]. Wind energy production utilizes proximity sensors to ensure the longevity and reliable position sensing of various components in wind turbines. These sensors are applied in blade pitch control, yaw position sensing, rotor and yaw brake position monitoring, brake wear detection, and rotor speed monitoring [29].

3.2. Actuators

Actuators are devices designed to convert various forms of energy into mechanical motion. They receive electrical input from automation systems, translate this input into physical actions, and execute tasks on devices and machinery within IoT systems [30]. Actuators produce a diverse range of motion patterns, including linear, oscillatory, or rotational motions. They are categorized into different types based on their energy sources [31]:

Pneumatic Actuators: These actuators harness compressed air to generate motion. They typically consist of a piston or diaphragm to produce motive power. Pneumatic actuators are employed in processes that demand rapid and precise responses, as they excel in tasks requiring moderate motive force.

Hydraulic Actuators: Hydraulic actuators use fluids, usually liquids, to create motion. They comprise a cylinder or fluid motor that utilizes hydraulic power to drive mechanical operations. These actuators yield output in the form of linear, rotary, or oscillatory motion. They find extensive use in industrial process control, particularly in scenarios where high speed and substantial forces are essential.

Thermal Actuators: Thermal actuators utilize a heat source to generate physical action. They convert thermal energy into kinetic energy or motion. Typically, thermostatic actuators incorporate a temperature-sensing material sealed within a diaphragm. This material exerts pressure on a plug, thereby moving a piston. The temperature-sensing material can encompass various substances, such as liquids, gases, wax-like materials, or any substance that undergoes volume changes in response to temperature variations.

Electric Actuators: Electric actuators rely on external energy sources, such as batteries, to generate motion. These mechanical devices have the capacity to convert electrical energy into kinetic energy, producing either linear or rotary motion. The design of electric actuators is contingent on their intended tasks within different processes.

In the energy sector, pneumatic actuators, for instance, are traditionally used to control valves in power plants. The adoption of electric control-valve actuators has enabled enhanced energy efficiency in power plant operations. Additionally, a variety of actuators have been developed specifically for the energy industry, such as the LINAK electric actuator (https://www.linak.com/business-areas/energy/). These actuators offer solutions aimed at minimizing energy waste during operations like opening hatches, engaging brakes in wind turbines, and enabling motion in solar tracking panels.

The literature also contains numerous studies showcasing the applications of actuators within IoT systems. For example, a study in [33] proposes a wireless sensor and actuator network to create an IoT-based automatic intelligent system. By optimizing the operation of devices and machinery within IoT, this system achieves reductions in overall energy consumption during specific time intervals.

3.3. Wireless Communication

Wireless communication systems assume a pivotal role in enabling IoT functionality. These wireless systems establish connections between sensor devices and IoT gateways, facilitating end-to-end data exchanges within the IoT framework. Wireless systems are designed based on various wireless standards, and the selection of a particular standard hinges upon the specific needs of the application, including factors like communication range, bandwidth, and power consumption requirements. For instance, renewable energy sources like wind and solar power plants are frequently situated in remote and isolated areas. Consequently, ensuring dependable IoT communications in such distant locations presents a formidable challenge. Implementing IoT systems in these environments necessitates the careful selection of appropriate communication technologies capable of ensuring a consistent connection and supporting real-time data transmission in an energy-efficient manner.

3.4. Data Processing and Computing

Processing and analysing the data generated by IoT systems play a crucial role in gaining profound insights, ensuring accurate system responses, and facilitating informed decisions regarding energy consumption [34]. However, handling IoT data, often referred to as 'Big data,' presents a formidable challenge. Big data encompasses vast quantities of structured and unstructured data originating from various components within IoT systems, including sensors, software applications, smart devices, and communication networks. Due to the inherent characteristics of Big data, characterized by its sheer volume, rapid generation rate, and diverse formats [35], efficient processing and analysis are imperative [36]. Traditional methods, such as storing data on local hard drives for subsequent computation and analysis, are inadequate for managing Big data. Instead, advanced computing and analytical techniques are essential for handling this data effectively [37,38]. In the subsequent sections, we delve into two prominent approaches, namely cloud computing and fog computing, which are widely employed for processing and computing Big data.

3.5. Cloud Computing

Cloud computing represents one of the most transformative shifts in modern Information and Communication Technology (ICT) and services for enterprise applications. It has evolved into a robust architectural framework for conducting large-scale and intricate computations. In cloud computing, the term 'cloud' refers to the 'Internet,' and 'computing' pertains to the provision of computational and processing services through this approach. The advantages of cloud computing encompass virtualized resources, parallel processing capabilities, robust security features, and seamless integration with data services, all supported by scalable data storage solutions. Cloud computing not only serves to reduce the cost and complexity associated with automation and computerization for individuals and enterprises but also offers benefits like lower infrastructure maintenance expenses, efficient management, and user-friendly access [4].

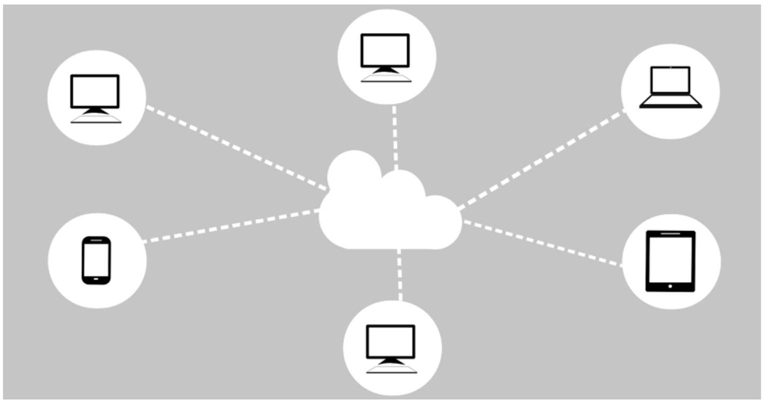

Figure 3. Cloud Computing

Consequently, numerous applications leveraging various cloud platforms have been developed, resulting in a significant escalation in the scale of data generated and consumed by such applications. Early adopters of big data in cloud computing include users who deployed Hadoop clusters in highly scalable and flexible computing environments provided by vendors like IBM, Microsoft Azure, and Amazon AWS [5]. Virtualization forms the foundation for many platform attributes necessary to access, store, analyse, and manage distributed computing components within a big data context. Furthermore, cloud computing alleviates the need for significant investments in hardware and software acquisition, as well as the computational algorithms for processing IoT data, leading to substantial reductions in electricity consumption associated with local data computation.

4. IoT's Role in the Energy Industry

Currently, the energy sector heavily relies on fossil fuels, constituting nearly 80% of the global final energy consumption. However, excessive extraction and combustion of fossil fuels have detrimental effects on the environment, health, and economy, including issues related to air pollution and climate change. In response, two primary alternatives have gained prominence to mitigate the adverse impacts of fossil fuel use: enhancing energy efficiency, which involves consuming less energy to provide the same service, and increasing the deployment of renewable energy sources [3,4].

In this section, we explore the role of IoT in the energy sector, spanning from fuel extraction, operation, and maintenance (O&M) of energy-generating assets, to transmission and distribution (T&D) and end-use energy consumption. IoT can play a pivotal role in reducing energy losses and lowering CO_2 emissions. Energy management systems based on IoT can monitor real-time energy consumption and elevate awareness about energy performance at every level of the supply chain [5,39]. This section begins by examining the application of IoT in energy generation stages. Subsequently, we delve into the concept of smart cities, encompassing various IoT-based subsystems such as smart grids, smart buildings, smart factories, and intelligent transportation. We then proceed to discuss each of these aforementioned components individually.

4.1. IoT in Energy Generation

The adoption of automation in industrial processes and the introduction of Supervisory Control and Data Acquisition (SCADA) systems gained popularity in the power sector during the 1990s [14]. These early stages of IoT contributed to the power sector by monitoring and controlling equipment and processes, reducing the risk of production losses or blackouts. Challenges faced by older power plants include issues related to reliability, efficiency, environmental impact, and maintenance. Aging equipment, coupled with inadequate maintenance, can result in significant energy losses and reduced reliability. Some assets may exceed 40 years in age, are costly to replace, and lack easy replacements. IoT can help alleviate these challenges in power plant management. By implementing IoT sensors, Internet-connected devices can detect equipment failures or abnormal decreases in energy efficiency, signalling the need for maintenance. This not only enhances system reliability and efficiency but also reduces maintenance costs [40]. According to [41], a new IoT-based power plant can save $230 million over its lifetime, while an existing plant of similar size can save $50 million if equipped with IoT capabilities.

To reduce dependence on fossil fuels and promote the use of local energy resources, many countries are endorsing Renewable Energy Sources (RESs). Weather-dependent or variable renewable energy (VRE) sources, such as wind and solar energy, introduce new challenges to the energy system, known as "the intermittency challenge." In an energy system with a high proportion of VRE, matching energy generation with demand becomes a significant challenge due to supply and demand variations on different timescales. IoT systems offer the flexibility to balance generation with demand, helping alleviate the challenges of deploying VRE sources, resulting in increased integration of clean energy and reduced greenhouse gas emissions [42]. Additionally, IoT can enable more efficient energy use by utilizing machine-learning algorithms to determine an optimal balance of different supply and demand technologies [14]. For instance, artificial intelligence algorithms can balance the power output of a thermal power plant with the contributions from in-house power generation sources, such as aggregating energy from numerous small-scale solar PV panels [43].

4.2. Smart Cities

The rapid pace of urbanization and population growth has raised several global concerns, including air and water pollution [44], energy access, and environmental issues. Addressing these challenges requires providing cities with clean, affordable, and reliable energy sources. Recent advancements in digital technologies have paved the way for the adoption of smart, IoT-based solutions to tackle urban challenges [45]. In the context of a smart city, smart factories, smart homes, power plants, and farms can be interconnected, allowing for the collection of data on energy consumption at different times of the day. For example, if residential areas are identified as consuming the most energy in the afternoon, the energy allocation to other sectors, such as factories, can be automatically reduced to achieve overall system balance at minimal cost and with a lower risk of congestion or blackouts.

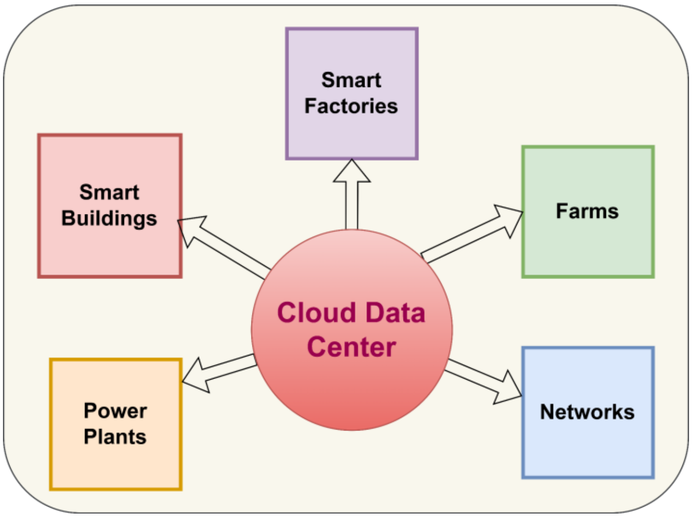

Figure 4. Centralized Data Connectivity in a Smart City

In a smart city, various processes such as information transmission, communication, intelligent identification, location determination, tracing, monitoring, pollution control, and identity management can be efficiently managed with the assistance of IoT technology [46]. IoT technologies facilitate the monitoring of virtually every object within a city, connecting buildings, urban infrastructure, transportation, energy networks, and utilities to sensors. These connections enable continuous data monitoring, promoting energy-efficient practices in a smart city. For instance, IoT-based monitoring of vehicles can enable the optimal control of street lights to minimize energy usage. Furthermore, authorities gain access to valuable information, allowing them to make informed decisions regarding transportation choices and energy demand.

4.3. Smart Grid

Smart grids represent modern grid systems that employ highly secure and reliable Information and Communication Technology (ICT) solutions to control and optimize energy generation, transmission, distribution (T&D) grids, and end-user consumption. By integrating numerous smart meters, smart grids facilitate bidirectional data flow, which can be leveraged for optimal system management and efficient energy distribution [47]. The applications of smart grids can be highlighted across various sub sectors of the energy system, including energy generation, buildings, transportation, or viewed as a comprehensive whole.

In traditional grid systems, batteries were typically recharged through electricity cables and AC/DC inverters [47]. However, in smart grids, batteries can be wirelessly charged using inductive charging technology. Additionally, smart grids enable the analysis of end-user energy demand patterns by collecting data through an IoT platform. This data can encompass the timing of activities such as mobile phone or electric vehicle charging. Subsequently, the nearest wireless battery charging station can allocate suitable time slots for device/vehicle charging, optimizing energy distribution. IoT-based solutions also lead to better monitoring and control of battery-equipped devices, enabling more precise energy distribution and reducing unnecessary energy consumption.

Moreover, IoT can find application in isolated and microgrids, especially in scenarios where uninterrupted energy supply is essential, such as data centers. In such systems, all grid-connected assets can communicate and share data on energy demand, ensuring optimal energy distribution at all times. When different city sectors collaborate within a smart city equipped with IoT-based smart grids, it fosters comprehensive energy management [47].

During collaborative communication among different sectors, smart grids can alert operators through smart appliances before critical issues arise [39,48]. For example, continuous monitoring can detect instances where energy demand surpasses grid capacity. With real-time data acquisition, authorities can implement strategies to reschedule energy consumption to times of lower expected demand. In certain regions, dynamic pricing tariffs, such as real-time pricing (RTP) tariffs, have been introduced to incentivize energy consumption during periods of lower demand [49]. By leveraging data collected from smart grid components, energy consumption and generation can be optimized through forward-looking strategies. Examples of IoT applications in this context include the reduction of transmission losses through active voltage management or the reduction of non-technical losses through a network of smart meters [14].

4.4. Smart Buildings

Energy consumption in urban areas can be categorized into different segments, including residential buildings (domestic), commercial (services), and transportation. Residential energy consumption encompasses lighting, appliances, domestic hot water, cooking, refrigeration, heating, ventilation, and air conditioning (HVAC) [50]. HVAC systems typically account for half of the energy consumed in buildings. Therefore, efficient management of HVAC systems is essential to reduce electricity consumption. IoT devices can play a crucial role in minimizing energy losses within HVAC systems. For instance, wireless thermostats equipped with IoT technology can detect unoccupied areas by assessing occupancy. Once an unoccupied zone is identified, measures can be taken to reduce energy consumption, such as scaling back HVAC system operations, resulting in significant energy savings and reduced losses.

IoT can also be applied to manage energy losses in lighting systems. IoT-based lighting systems can notify users when energy consumption exceeds predefined thresholds. By analyzing real-time data efficiently, loads during peak demand periods can be shifted to off-peak hours, contributing to optimal electrical energy usage [45,51] and a reduction in greenhouse gas emissions. IoT enhances the agility and flexibility of demand response, making monitoring and demand-side management more efficient.

4.5. Smart Energy Usage in Industry

IoT can be employed to design fully connected and flexible systems in the industrial sector to reduce energy consumption while optimizing production. Traditional factories consume significant energy during production and quality control processes. Additionally, monitoring every process usually necessitates manual intervention. However, the implementation of agile and flexible systems in smart factories allows the early detection of failures in real-time rather than discovering them at the end of the production line. This enables prompt action to prevent wasteful production and the associated energy waste.

IoT and its enabling technologies are pivotal in monitoring manufacturing processes. Various monitoring equipment, including gateway devices, IoT hub networks, web servers, and cloud platforms accessible via smart mobile devices like smartphones or personal computers, can be utilized. Wireless communication technologies like Wi-Fi, Bluetooth, ZigBee, Z-wave, or wired communications like Local Area Networks (LAN) can connect all equipment pieces [52]. To maximize IoT efficiency, sensors can be installed on each industrial component to identify those exceeding nominal energy levels. This allows for precise component management, timely fault resolution, and energy optimization, resulting in reduced energy losses within smart factories.

In a smart factory, data processing plays a central role, with data analyzed in cloud platforms serving as the "brain" of the system [78]. When monitoring and maintaining manufacturing assets, a significant challenge is the wear and tear of machines and mechanical devices. With the right IoT platform and tools, appropriate device sizes can be selected to reduce wear and tear, lowering maintenance costs. IoT-based condition monitoring ensures mechanical devices never reach their failure thresholds, prolonging their lifespan and minimizing failures. Additionally, IoT facilitates anticipatory detection and resolution of failures that result in energy losses.

Agile IoT systems can establish smart collaboration between customers, manufacturers, and companies. This allows for the direct manufacture of specific products according to customer orders. Consequently, energy consumption during the storage of spare parts and associated warehouse energy losses are substantially reduced. Only a limited variety of products in various types are manufactured and stored, enhancing energy consumption management and production efficiency [52].

4.6. Intelligent Transportation

One of the primary contributors to air pollution and energy waste in large cities is the excessive use of private vehicles over public transportation. Unlike traditional transportation systems with independent components, IoT technologies in transportation, often referred to as "smart transportation," provide a holistic management system. Real-time data processing is crucial for effective traffic management. All transportation system components can be interconnected in smart transportation, enabling data integration. Smart transportation applications include congestion control and smart parking systems utilizing online maps. Implementing smart transportation empowers passengers to select cost-effective routes with shorter distances and faster travel times, leading to significant time and energy savings [46]. Citizens can predict their arrival times and manage their schedules more efficiently [51]. Consequently, city travel times are reduced, and energy losses are significantly diminished, resulting in substantial reductions in CO_2 emissions and other air pollutants originating from transportation [45].

5. Challenges in Implementing IoT

While IoT offers numerous benefits for energy conservation, there are several challenges associated with its implementation in the energy sector. This section highlights these challenges and provides insights into existing solutions.

5.1. Energy Usage

In energy systems, the primary objective of IoT platforms is to save energy. However, the operation of IoT systems, including the transmission of massive amounts of data from IoT devices, demands a considerable amount of energy [53]. Therefore, addressing the energy consumption of IoT systems remains a significant challenge. Nevertheless, various strategies have been devised to mitigate the power consumption of IoT systems. These include optimizing sensor behaviour to enter sleep mode and activate only when necessary, designing efficient communication protocols that facilitate energy-efficient data transmission, employing radio optimization techniques like modulation optimization and cooperative communication, and implementing energy-efficient routing techniques such as cluster architectures and multi-path routing [54–56].

5.2. IoT Integration with Subsystems

One of the central challenges is integrating an IoT system into the subsystems of the energy sector. Subsystems within the energy sector often employ diverse sensor and data communication technologies, making it essential to devise solutions for managing data exchange between these subsystems [57–59]. A potential solution involves creating an integrated framework for the energy system that takes into account the IoT requirements of each subsystem. Another approach entails developing co-simulation models for energy systems, enabling seamless integration and minimizing synchronization delays between subsystems [60,61].

5.3. Privacy Concerns for Users

User privacy is a critical concern, involving the protection of individual or collective energy consumers' personal information when shared with organizations [62,63]. While IoT data can enhance decision-making related to energy production, distribution, and consumption, it poses privacy challenges. To mitigate privacy violations, energy providers can seek user permission to utilize their data, assuring users that their information will not be shared with third parties. Additionally, implementing trusted privacy management systems, granting energy consumers control over their information and privacy, is a recommended solution [65,66].

5.4. IoT Security Challenges

The utilization of IoT and the integration of communication technologies in energy systems amplify the threat of cyberattacks targeting user information and the energy systems themselves, spanning production, transmission, distribution, and consumption [67,68]. These security threats pose a significant challenge in the energy sector [69]. Solutions to address this challenge include the introduction of encryption schemes to safeguard energy information from cyberattacks and the deployment of distributed control systems that enable control at different levels of IoT systems, reducing the risk of cyberattacks and enhancing system security [70,71].

5.5. IoT Standardization

IoT relies on various technologies with differing standards to connect single devices to extensive networks of devices. The inconsistency among IoT devices using different standards presents a substantial challenge [72]. In IoT-enabled systems, there are two types of standards: those related to network and communication protocols, data aggregation standards, and regulatory standards concerning data security and privacy. Challenges related to IoT standardization include handling unstructured data, addressing security and privacy issues, and establishing regulatory standards for data markets [73]. Overcoming this challenge involves defining a system of systems with a common understanding to ensure equal access and use among all parties. Additionally, developing open information models and standard protocols through collaboration can result in freely accessible and publicly available standards [74].

5.6. Architectural Design in IoT

IoT-enabled systems comprise a wide array of technologies and an increasing number of interconnected smart devices and sensors. IoT is expected to enable communications at any time and anywhere, often in an autonomic and ad hoc manner. This implies that IoT systems, designed to fulfill various application purposes, exhibit complex, decentralized, and mobile characteristics [74]. Given the diversity of IoT applications and their unique requirements, a one-size-fits-all reference architecture is not feasible. Therefore, IoT systems demand heterogeneous reference architectures that are open and conform to standards. These architectures should also provide flexibility and not constrain users to fixed, end-to-end IoT communications [74,75].

6. Challenges for Low-Income Households

Low-income and disadvantaged communities face distinct barriers due to systemic inequalities, a history of limited access to capital and financing, higher energy burdens, and lower rates of property ownership or business ownership. Rural areas and Native American tribes also require special consideration when implementing decarbonization solutions.

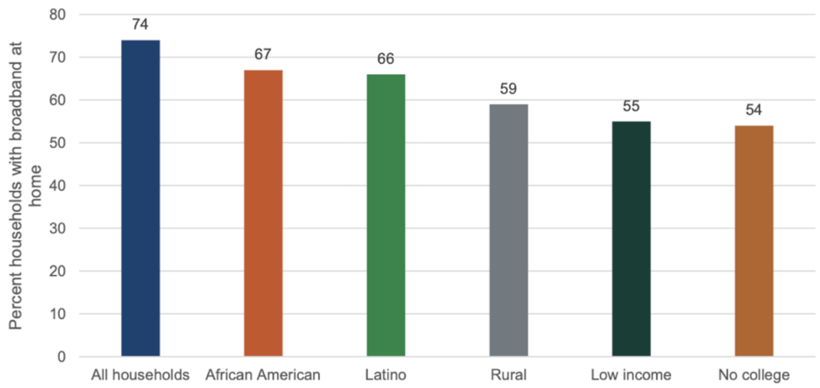

Figure 5. California Household Access to Broadband Internet

(Source: American Community Survey, 2017)

6.1. Older Residences

Older residences are more likely to contain hazardous construction materials and outdated equipment. Individuals with low incomes residing in older, unhealthy homes face an elevated risk of chronic illnesses like asthma, heart disease, stroke, and hypertension. Structural deficiencies can also render households ineligible for participation in energy programs, further marginalizing them from the benefits of clean energy. These challenges increase the expenses associated with upgrades, whether undertaken incrementally or comprehensively, and can impede the involvement of middle- and lower-income residents.

6.2. Demand Flexibility

Demand flexibility is an emerging strategy that leverages modern communication and Internet of Things technologies to enable end-use devices to automatically respond to signals from electric system operators related to greenhouse gas emissions, pricing, or grid capacity shortages. This automated responsiveness aligns building electricity demand with the available supply, reducing decarbonization costs, providing economic incentives to participants, enhancing the reliability of the electric system, and contributing to its cost-effective development.

However, concerns exist regarding the expenses associated with purchasing and installing demand-flexibility technologies, as well as the accessibility of appliances and financing for low- and moderate-income households. Most demand-responsive and demand-flexible controls require access to broadband internet, in addition to controllable appliances like heat pump water heaters, electric vehicles, swimming pools, and battery systems—items that are not typically found in low-income households. As depicted in Figure 5, broadband access is available to 74 percent of households in California, but this percentage drops to 59 percent in rural areas and 54 percent among low-income communities [77]. Moreover, demand flexibility achieved through customer response to time-of-use or dynamic rates necessitates interval meters or smart meters, which collect and store energy consumption data at least hourly for utility billing purposes. A significant challenge is that many utilities have only a limited number of smart meters in place.

6.3. Income Disparities

Low-income households contend with constrained disposable income and suffer disproportionately from environmental pollutants. These communities and households are primarily composed of Hispanic, Black, Native American, and other people of color. Within these communities and households, systemic discrimination, environmental hazards, and cycles of poverty intersect. Initiatives must be established to begin addressing these cycles through collaborative efforts with local communities and direct investments. These programs must surmount challenges such as the upfront costs associated with upgrades, the aging of existing structures, potential impacts of energy improvements on tenant rents, instability in project cash flows, ongoing and future maintenance expenses, the availability of experienced local contractors, the renter status of occupants, and proximity to and accessibility of resources. These issues are exacerbated by the ongoing global pandemic.

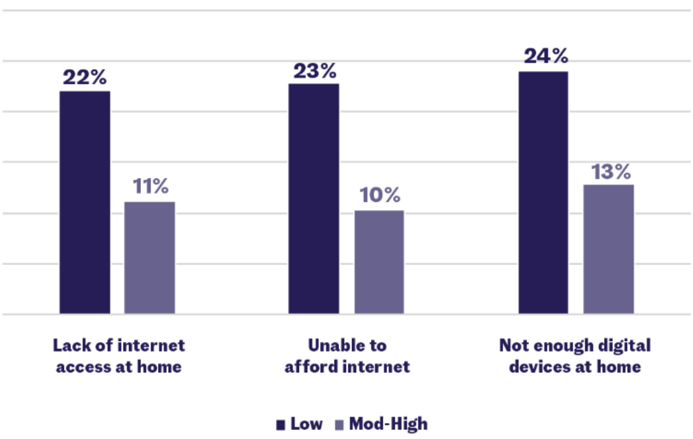

Figure 6. Percentage of low-income households that encountered Internet accessibility difficulties in the previous year.

According to the 2021 Unheard Third survey, more than one in five low-income New Yorkers (22 percent) indicated that their households lacked home internet access in the past year, which is twice the proportion of those with moderate to higher incomes (refer to Figure 6) [76]. Additionally, low-income households were also twice as likely as their moderate to higher-income counterparts to encounter difficulties in affording internet connectivity (23 percent of low-income households versus 10 percent of moderate to higher-income households). Another facet of digital equity pertains to the availability of internet-capable devices at home, such as desktop computers, laptops, or tablets. Low-income households were approximately twice as likely as higher-income households to report insufficient access to computers or other digital devices for internet use at home (24 percent compared to 13 percent).

7. Conclusions

Modern technologies like IoT and Cloud Computing have the potential to revolutionize the energy sector, transitioning it from a centralized, hierarchical supply chain to a decentralized, intelligent, and optimized system. This paper has provided an overview of the role of IoT and Cloud Computing in the broader energy sector and has examined their relevance in the context of low-income households. We have explored the benefits of IoT-based energy management systems, emphasizing their capacity to enhance energy efficiency and facilitate the integration of renewable energy sources. Additionally, we have delved into various components of IoT systems, including communication and sensor technologies, highlighting their applications in the energy sector, such as temperature, humidity, light, speed, passive infrared, and proximity sensors. Access to affordable internet services emerged as a significant barrier to delivering technological solutions to low-income households. Notably, many demand-responsive and demand-flexible controls necessitate broadband internet access, as well as the presence of controllable appliances like heat pump water heaters, electric vehicles, pools, spas, and battery systems—items that are not commonly found in low-income homes. Furthermore, we have examined the deployment of IoT across different levels of the energy supply chain, encompassing smart cities, smart grids, smart buildings, and intelligent transportation. While highlighting the numerous advantages and potentials of IoT in these domains, we have also acknowledged the associated challenges. Looking forward, future research directions may involve investigating programs and policies aimed at making these technologies more accessible to low-income populations, thereby addressing equity issues and promoting the widespread adoption of IoT and Cloud Computing in the energy sector.

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