EVERYTHING YOU WANTED TO KNOW ABOUT CONSUMER LIGHT MANAGEMENT IN SMART ENERGY

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ABSTRACT

Consumer lighting plays a significant role in the development of smart cities and smart villages. With the advancement of (IoT) technology, smart lighting solutions have become more prevalent in residential areas as well. These solutions provide consumers with increased energy efficiency, added convenience, and improved security. On the other hand, the growing number of IoT devices has become a global concern due to the carbon footprint and carbon emissions associated with these devices. The overuse of batteries increases maintenance and cost to IoT devices and simultaneously possesses adverse environmental effects, ultimately exacerbating the pace of climate change. Therefore, in tandem with the principles of Industry 4.0, it has become crucial for manufacturing and research industries to prioritize sustainable measures adhering to smart energy as a prevention to the negative impacts. Consequently, it has undoubtedly garnered global interest from scientists, researchers, and industrialists to integrate state-of-the-art technologies in order to solve the current issues in consumer light management systems making it a complete sustainable, and smart solution for consumer lighting application. This manuscript provides a thorough investigation of various methods as well as techniques to design a state-of-the-art IoT-enabled consumer light management system. It critically reviews the existing works done in consumer light management systems, emphasizing the significant limitations and the need for sustainability. The top-down approach of developing sustainable computing frameworks for IoT-enabled consumer light management has been reviewed based on the multidisciplinary technologies involved and state-of-the-art works in the respective domains. Lastly, this article concludes by highlighting possible avenues for future research.

Keywords Smart Energy · Smart Consumer Light Management · Smart Cities · Energy Cyber-Physical Systems (E-CPS) · Smart Home · Internet of Things (IoT)

1 Introduction

Smart city and Smart energy are interrelated concepts designed to enhance the efficiency and sustainability of urban areas. The idea of smart city represents the extensive integration of Information and Communication Technologies (ICT) in the daily lives of human beings in urban areas [1]. Implementing these technologies aims to elevate the living standards of residents by optimizing the effectiveness of services and infrastructure associated with cities. Smart

city also refers to a city that integrates the physical infrastructure, information technology infrastructure, social infrastructure, and business infrastructure through Internet of Things (IoT) to harness the collective intelligence of its community [2]. On the other hand, smart energy encompasses a much broader scope than conventional energy. It can be perceived as a model akin to the "Internet of Energy" that deals with smart power generation, smart energy management, smart energy storage, and smart energy consumption. Energy refers to the characteristics of an object or system that determine its capacity to perform work. It exists in multiple forms, including potential energy, kinetic energy, chemical energy, and thermal energy. It is worth highlighting that the wide range of energy sources includes solar, fossil fuels, electricity, vibration, biomass etc. The significance of smart energy in smart cities is fundamentally rooted in the rapid growth of smart cities and the subsequent exponential increase in energy supply demand. Smart cities are reported to improve energy efficiency, minimize electronic waste, and decrease carbon emissions through the use of smart energy. Moreover, all forms of traditional energy, clean energy, green energy, sustainable energy, and renewable energy, integrated with ICT technology, constitute smart energy. Consequently, the integration of smart energy concept in various physical processess forms Energy Cyber-Physical System (E-CPS) in smart cities. E-CPS employs advanced sensors, communication networks, and control systems to enhance energy efficiency and minimize environmental effects. These systems can adeptly manage energy resources, forecast demand trends, and modify energy output appropriately by integrating real-time data and Artificial Intelligence (AI) algorithms.

Consumer lighting constitutes a crucial application in smart city and smart home frameworks. On the other hand, it is considered as one of the most energy consuming applications, which accounts for 30% to 40% of the total energy demand of smart cities [1]. The global smart consumer lighting market is valued at roughly 16.25 billion USD, and it is anticipated to expand at a Compound Annual Growth Rate (CAGR) of 20%, potentially reaching over USD 83.81 billion by 2032 [3]. Undoubtedly, this rapid expansion is primarily driven by the rising need for energy efficient lighting solutions and the escalating trend towards smart homes and smart cities. Smart consumer light management systems serve an instrumental role in converting traditional consumer lighting systems to smart lighting systems. The integration of IoT, smart sensors, and robust control strategies for energy saving makes it a widely adopted solution. The number of features in smart consumer lighting continues to grow with the advancement in ICT technology. Subsequently, energy consumption also increases with the number of features, leading to most state-of-the-art smart consumer light management systems being energy hungry, demanding average power in terms of hundreds of milli-watts [4]. Conversely, sustainability is an essential aspect that must be integrated on a larger scale to comply with Industry 5.0 [5]. Thus, it demands a focus on optimizing power consumption in order to feature smart consumer light management systems with energy autonomy using harvesters with small form-factor.

Consumer light management system helps in reducing energy consumption and increases total lighting efficiency via sensors and data analytics techniques. It can automatically adjust lighting configurations according to various factors such as occupancy, ambient light, and weather conditions, aiding cities in minimizing their carbon impact and reducing energy expenses. It augments the safety and security of residents by ensuring adequately illuminated streets, public areas, and indoor environments. Moreover, the application has extensively improved both energy efficiency and quality of life in smart cities. The evolution of consumer lighting application over the past decades has been presented in Fig. 1.

Conventional High-pressure Sodium Lights   LED Lights   Smart LED Lights

Fig. 1: Evolution of Consumer Lighting Technology

The remainder of this survey is structured into nine Sections. Section 2 discusses the related prior work and contributions made in this manuscript. Section 3 elucidates smart consumer light management, its significance, and

its attributes. Section 4 presents the need for sustainability and various elements of smart consumer light. Section 5 illustrates power management strategies in consumer lighting management systems. Section 6 delineates energy harvesting, power conditioning, and storage techniques. Section 7 presents the sustainable computing architectures for smart consumer light management systems. Task scheduling and energy optimization techniques of these systems have been detailed in Section 8. The open research directions have been highlighted in Section 9. The manuscript has been concluded in Section 10. An appendix containing a list of acronyms used in the article is provided at the conclusion of the document.

2 Contributions of the Current Paper

The contribution made in the manuscript can be understood by reviewing the relevant literature and potential limitations existing in related works.

2.1 Related Prior Work

Numerous studies delve into different facets of smart lighting management strategies for consumer applications. An in-depth analysis is conducted on the significance of street lighting in smart cities, and the overall architectural design of smart street lights is thoroughly examined [6]. In addition, a comprehensive examination is conducted on different control strategies for street lights, as discussed in detail [7]. This survey examines the essential hardware components for designing smart street lights, including various lamps and sensors in state-of-the-art smart street lighting systems. The control algorithms that are discussed in the paper focus on advanced techniques, including video processing, AI, fuzzy logic, and web-based techniques. A thorough review of these algorithms is provided. An extensive investigation of the framework used in the design of an IoT-enabled smart public lighting system has been conducted [8]. The technology involved in each layer of the framework has been discussed in details. The technology involved in each layer of the framework has been thoroughly discussed. A detailed comparison study of existing IoT-enabled street lighting systems is presented [9]. The comparison is based on three types of street lights such as centralized, decentralized and hybrid. Subsequently, a broad overview of smart street lights and its implementation explicitly in industrial environment along with consumer applications such as smart office lighting, smart street lighting, smart home lighting have been explored in details [10]. Additionally, the implementation and impacts of street lights on order picking in warehouses have been explored. Further, the role of smart street lights in smart cities has been explained through a communication review, and security aspects are presented in addition to various control strategies [11]. Subsequently, the required drivers, protocols, technologies, communication networks, and applications for implementing smart Light Emitting Diode (LED) lighting systems in smart buildings have been reviewed [12]. In addition, the control methodologies for operating LED lighting in buildings have been systematically overviewed. The design methodologies for highway lighting have been explored, in which the advantages, disadvantages, practical research challenges involved in the design process have been highlighted [13]. Further, state-of-the-art smart lighting platforms designed for indoor uses in residential and office environments are comprehensively reviewed [14]. It examines various aspects, including autonomous control algorithms, connectivity, applications, and the associated benefits and barriers. Table 1 summarises the comparison of the proposed survey with previously published survey articles.

TABLE 1: Comparision of Previous Survey Articles on Smart Consumer Lighting Management Systems

Research Works	IoT Framework	Energy Saving Control Strategies	Power Management	Sustainability	Task Scheduling
Chew et al., 2017 [14]	✓✓	✓✓	×	×	×
Mukta et al., 2020 [13]	✓✓	✓	✓	×	×
Chinchero et al., 2020 [12]	✓✓	✓	×	×	×
Mahoor et al., 2020 [11]	✓✓	✓✓	×	×	×
Füchtenhans et al., 2021 [10]	✓	✓	×	×	×
Omar et al., 2022 [9]	✓✓	×	×	×	×
Manyake et al., 2022 [8]	✓✓	✓	×	×	×
Agramelal et al., 2023 [7]	×	✓✓	×	×	×
Khemakhem et al., 2024 [6]	✓✓	×	×	×	×
This Paper	✓	✓	✓✓	✓✓	✓✓

'✓✓' represents indepth analysis, '✓' refers general analysis and '×' indicates no analysis.

The limitations and unaddressed issues in previous published survey articles are outlined below.

- In accordance with Industry 4.0, energy-autonomous and battery-less devices are prioritized over traditional IoT devices. This shift is driven by primary concerns surrounding power consumption, carbon footprints, and environmental impacts associated with IoT devices. Most of the state-of-the-art smart consumer light management systems lack to address the issue of sustainability. The strategies for achieving sustainability in consumer light management systems have not been discussed in any previously published survey articles.
- The management system is the IoT device that features the light with IoT compatibility. Power consumption is a vital parameter in the performance metrics of any IoT device. The methodologies and techniques to optimize power consumption in management systems have not been discussed in previously published related review articles.

2.2   Contributions and Novelty of Current Paper

The contributions of the manuscript have been outlined below.

- Most survey articles typically focus on reviewing the IoT framework of smart light management systems, which comprises communication protocols, sensor technologies, cloud integration, and various control strategies adopted in it. In contrast the proposed survey briefly overviews its IoT framework particularly in the context of its application in indoor as well as outdoor environment. It emphasizes on detail reviewing of the sustainable aspect of smart consumer light management systems.
- Unlike previous surveys, the manuscript highlights the importance as well as necessity of sustainability in consumer light management system. The current issues in the existing power management of smart consumer light management systems have been critically investigated and solution is proposed.
- The primary distinction of the manuscript lies in an extensive review of the multidisciplinary technologies involved in design of a smart consumer light management framework using concepts of smart energy such as IoT, energy harvesting, power management, sustainable computation techniques, power consumption optimization and task scheduling. To the best of authors' knowledge, this is the first survey article which reviews the entire framework involved in design process of sustainable consumer light management system.
- The manuscript encompasses the comprehensive review of energy harvesting enabled IoT devices developed for a wide range of applications. Further, it presents five advanced state-of-the-art sustainable architectures with its technical advantages and limitations which can be adopted for designing smart consumer light management system with energy autonomous capability.
- Majority of the state-of-the-art sustainable IoT devices suffers through the potential threat of power failure during unavailability of energy. In this survey, the aforementioned issue has been addressed; subsequently, the importance of optimization in power consumption in consumer light management systems without affecting the real-time operation and Quality of Service (QoS) has been highlighted. Thus, the potential optimization techniques and task scheduling methodologies are reviewed.

3   Smart Consumer Light Management

Smart consumer light management is often referred as consumer lighting E-CPS. It represents an advanced integration of smart lighting with cyber-physical technologies, enabling consumers to effectively control, monitor, and optimize the energy consumption associated with lighting applications. It integrates sensors, controllers, and advanced control strategies with the physical lighting infrastructure to provide energy savings, convenience, and customizable lighting environments. The advancements in this technology have been remarkable over the past decade. LED technology has completely transformed the lighting industry, providing long-lasting lighting options. In addition, the involvement of IoT in consumer lighting has brought a significant improvement in the technology that has changed the user experience, making it an energy-efficient and sustainable solution. The use of smart consumer lighting systems enables users to conveniently monitor and control their lights from a distance using smartphone applications or voice commands. A smart consumer light management system possess essential characteristics as shown in Fig. 2. These characteristics make them efficiently operate the street light. These characteristics are interdependent and combinedly offer 'smart' tag to consumer light management systems. IoT compatibility is the most significant characteristic that makes it smart in the true sense. It involves the integration of intelligent sensors, actuators, and communication modules with LED lighting to facilitate various functions, including the automatic control of illuminance and remote monitoring. The automatic control feature regulates the illuminance of LED based on several factors, including movement around the light, ambient light level, and weather conditions. Conversely, remote monitoring enables easy supervision of the operational status of the lights for the administrators and responds promptly if any faults are detected. The firmware must ensure that the management system execute its tasks adhering to firm deadlines in order to maintain real-time functionality. Further, the device must be energy autonomous in order to ensure ultra low maintenance, reduced carbon

Fig. 2: Characteristics of Smart Consumer Light Management

footprints, and sustainable operation. Low power consumption is an essential design metric of any IoT device, and it plays an instrumental role specifically in the case of energy-autonomous devices. Low power consumption signifies the high lifespan, low form factor, and low manufacturing cost of the device. The device should be developed with the objective of integrating it into the current LED lighting infrastructure. Therefore, low-form factor is an essential feature that the device must have, as it affects its portability. The advantages of smart consumer light management over traditional systems have been illustrated in Fig. 3.
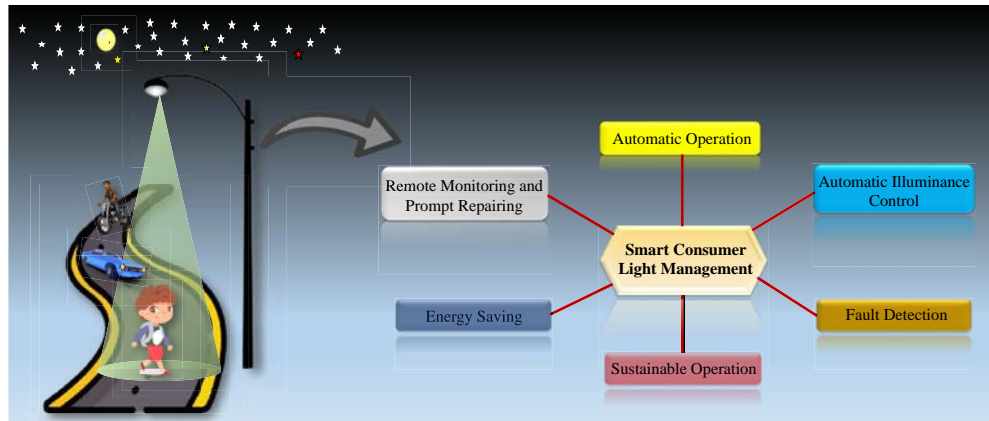

Fig. 3: Advantage of Smart Consumer Light Management over Conventional Light Management

3.1   Architecture of Smart Consumer Light Management Systems

The architecture of smart consumer light management system has been shown in Fig. 4. The architecture is comprised of four layers such as physical layer, network layer, edge-gateway computation layer, and cloud computation layer. The functions of each layer have been outlined below.

- *Physical Layer*: It comprises physical elements such as sensors, along with conditioning circuits, actuators, microcontrollers or microprocessors, and communication units. It additionally encompasses the firmware necessary for the operation of the end device. In this layer, sensors are used for the measurement of various

physical parameters, including occupancy, light intensity, temperature, humidity, and pressure. In this layer, low-level computations like illuminance control and daylight detection are carried out using microcontroller or microprocessor. The control actions, including such as automatic turn on or turn off as well as adjustment of light intensity, are taken using actuator. The measured data is communicated through the communication module integrated with the physical device.

- **Network Layer**: This layer functions as a connectivity layer and typically includes a Wireless Sensor Network (WSN). It collects data from various physical layers and transmits it to the higher layers for processing and analysis. It serves as a conduit between the physical layer and subsequent layers in the architecture. It plays a crucial role in managing the communication between the physical device and the central processing unit, facilitating real-time monitoring and control of the system.
- **Edge-Gateway Computing Layer**: This layer serves a dual purpose, acting both as a gateway and an edge computing device. As an edge computing device, it processes data closer to the source, reducing latency and improving overall network efficiency. This layer offers various significant features such as fault detection and illuminance control through scheduling techniques to street light management systems through edge computing. It connects physical devices with the cloud server as a gateway, allowing for data transfer and communication. This dual role renders this layer crucial for the smooth functioning of an interconnected network.
- **Cloud Computing Layer**: This layer represents the highest tier in the bottom-up architecture of smart consumer light management system. This layer often exists in data centers and is accessible globally via the internet. It is responsible for processing and analyzing the large amounts of data acquired from the sensors in the physical layers. It can make real-time adjustments to lighting systems based on energy consumption goals. Additionally, this layer allows for remote monitoring and control of the entire lighting system, providing a seamless user experience for smart consumer light management.
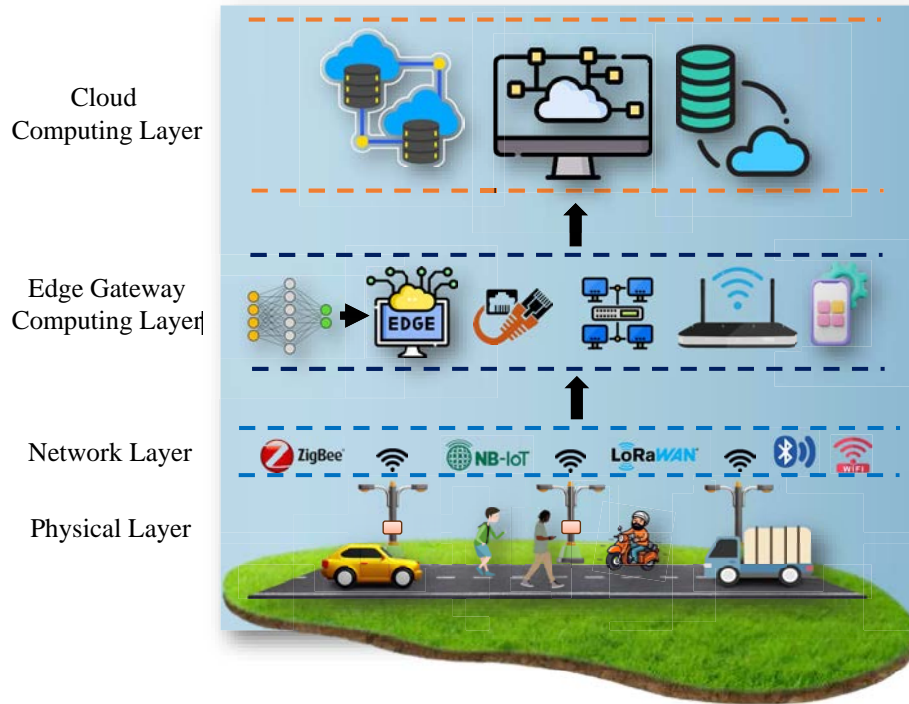

Fig. 4: Architecture of Smart Consumer Light Management

3.2   Application of Smart Consumer Light Management Systems

The aforementioned architecture has often been deployed in outdoor environments and indoor environments. The applications of smart consumer light management have been illustrated in Fig. 5. In outdoor environments, it is often incorporated in street lights, while in indoor environments, it is implemented for indoor light management, particularly
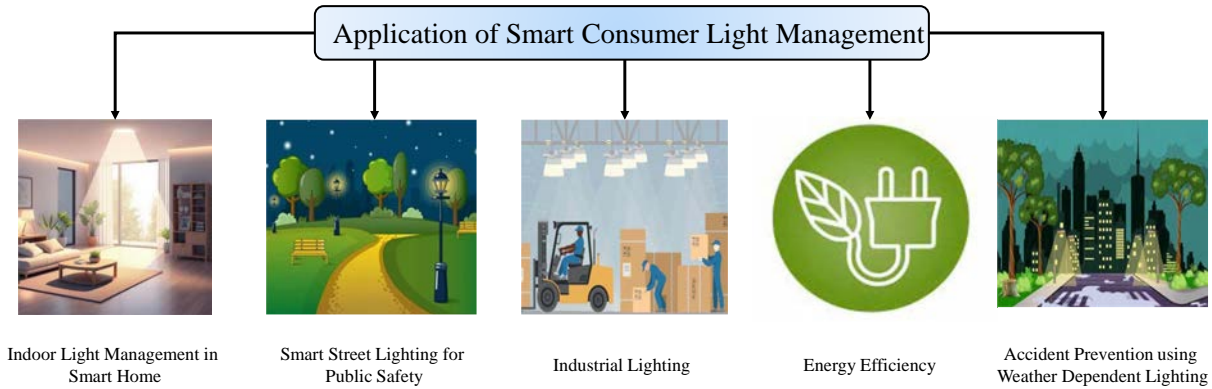
Fig. 5: Applications of Smart Consumer Light Management System

in commercial buildings like offices, shopping malls, and museums. The challenges and solutions are different in both of these environments. A smart and efficient LED lighting system has been proposed using LED technology, sensor application and smart control strategy [15]. A probabilistic approach has been incorporated to analyze traffic patterns over different time intervals in order to control the illuminance of the light. Smart street light management systems have been reported to significantly impact accident prevention [16]. Studies in psychology indicate that variations in color temperature can have a profound impact on the human circadian rhythm. Therefore, the implementation of illumination control based on Correlated Color Temperature (CCT) has been incorporated, enhancing visibility for drivers in areas with low light. Weather conditions, such as heavy rain and fog, can significantly reduce visibility on the road [17]. An IoT-based framework has been proposed to address the visibility challenges caused by harsh weather conditions. It can control the illuminance of the LED light detecting rain in order to solve the visibility issue during harsh weather. Further, an energy-saving scheme has been proposed to save electricity consumption of the street light [18]. In this work, the illuminance of the LED light has been controlled based on ambient light conditions and the speed of the vehicles. The LED light is configured to illuminate with high intensity in case of vehicles moving at a faster velocity. Subsequently, it switches the LED to low-intensity mode. The proposed scheme has been claimed to be efficient than the conventional ambient light intensity based illuminance control of LED lights. This scheme has been reported to reduce energy by 40%. Subsequently, IoT-enabled system has been developed to control the illuminance of the street lights in accordance with two parameters, i.e. occupancy and light intensity [19]. IoT connectivity provides an advantage to the admin in remote monitoring, controlling, and faulty detection in street lights.

Further, similar framework has been developed that can control and monitor the operation of street light energy efficiently [20]. The street light operating firmware has been developed using Artificial Bee Colony (ABC) optimization algorithm. It has been implemented and reported to save 12,615.635 kWh of energy during one year of experimentation. Furthermore, a novel street lighting scheme has been proposed that adjusts the brightness of streetlights based on traffic conditions [21]. It utilizes the signatures of received signal strengths to extract traffic parameters, subsequently used to determine the appropriate lighting level. This scheme effectively controls the illuminance streetlight by adapting to the behaviors of vehicles and pedestrians on the roads. The proposed system has been observed to enhance the performance of existing street light management systems by demonstrating 95% accuracy in detecting road users. On the other hand, it requires 10.5% of the electrical energy compared to other existing methods. In [22], a novel architecture of smart IoT platform that makes use of street lights as computing nodes and incorporates a prediction model for workload management in smart campus environments. Artificial Neural Network (ANN) learning algorithms have been used to analyze the network and determine the resource requirements of each network node. These algorithms enable the nodes to function as a unified network resource allocation service. In addition, it also works as a micro weather station that measures temperature, wind speed, Ultraviolet (UV) index, etc. It also helps in intrusion detection. Subsequently, a weather adaptive control mechanism for street light management has been proposed [23]. It controls the illuminance and CCT of the light based on temperature, humidity and movement of the objects around the road. Furthermore, AI technique has been implemented with street light to detect various object classes such as pedestrian, bicycle, motorbike, and vehicle [24]. The illuminance of the street light is controlled in accordance with these object classes.

Another critical aspect of IoT enabled consumer light management sytsem is communication protocol. Several advanced communication protocols such as Narrow Band Internet of Things (NB-Iot), 5G, Light Fidelity (Li-Fi), Long Range Wide Area Network (LoRaWAN), Bluetooth Low Energy (BLE) have been used in state-of-the-art IoT devices. Efforts have been made to improve communication in street light systems by implementing NB-Iot technology to enhance security and communication range at low-power requirements [25]. Wireless communication based on standard IEEE 802.15.4 has been incorporated into public lighting management systems [26]. This work implements Digital Addressable Lighting Interface (DALI) protocol, which uses bidirectional communication to enable remote monitoring and controlling. The system is reportedly manufactured at low-cost and can be seamlessly integrated with high-pressure sodium lamps to LED lamps. Subsequently, ZigBee protocol is considered as one of the most popular, low-power, low-cost communication protocol that has been used in street light operating systems for short-range communication [27] – [28]. Furthermore, efforts have been made to address the short communication range problem in street light control systems by integrating ZigBee with General Packet Rario Service (GPRS) technology [29]. In order to ensure higher communication range, Wireless Fidelity (Wi-Fi) has been used in designing intelligent automatic street light management system [30]. On the other hand, Long Range (LoRa) communication has been integrated into IoT-assisted fog and edge-based smart lamp posts [31]. The proposed system also has the ability to monitor environmental factors like temperature, humidity, and CO levels aside from its lighting capabilities. In addition, the device utilizes Wi-Fi to transfer the collected data to a cloud server.

Lighting management in residential is also considered as a critical research application as buildings in the USA consume approximately 40% of total energy, among which lighting for residential buildings accounts for approximately 10%, while commercial buildings exhibit a higher proportion of 20%. In [32], a light management system has been proposed considering the spatial characteristics and patterns of occupant behavior to control the lighting parameters effectively. Further, a novel approach has been proposed to manage the color of a multi-channel LED lighting system in a smart home context, implementing camera of smartphone [33]. The algorithm aims to enhance the output spectrum of the luminaires, resulting in light that can be adjusted for CCT, accurate color, and high color rendering index. Subsequently, a control scheme with intelligent power gateway has been introduced for LED based light management in office [34]. The system has been designed with adaptive middleware, which can be modified according to the requirements of the users. The results show a significant potential for power savings, with a maximum reduction of approximately 58%. Furthermore, efforts have been made to improve the energy efficiency of LED light while prioritizing user satisfaction [35]. The system enables regulating the intensity of the light according to user satisfaction. It has been reported to reduce the power consumption by 21.9%. Subsequently, an IEEE 802.15.4-based WSN has been designed to integrate the DALI protocol for lighting automation in buildings [36]. The system is reported to be cost-effective and fully centralized. An energy-saving, easy-to-install, wireless, low-cost IoT-based device has been designed for office light management [37]. It can be easily manufactured with a 10% cost of installing a smart system. Additionally, it provides retrofitting option to consumers. The proposed system has been tested with a commercial 15 W T8 LED tube to save energy maximum up to 28.13%. Further, attempts have been made to design cost-effective indoor lighting management system which is tested in an office [38]. The system controls the intensity of the light depending on the motion and user satisfaction. It has been reported to reduce the energy consumption of the light in the range of 55% to 69%.

3.3   Control Strategies for Smart Consumer Light Management Systems

Consumer light management system helps in conserving energy by controlling the illuminance according to number of factors. Various illuminance control strategies have been adopted in state-of-the-art consumer lighting applications, which have resulted in minimizing energy consumption associated with the light significantly. A comparison of prior works on the basis of energy saving as the impact of several control strategies is presented in Table 2. There are five types of illuminance control strategies implemented in state-of-the-art smart consumer lighting application as outlined below.

- CCT Method: CCT-based illuminance control denotes a system that modulates lighting according to correlated color temperature and illuminance levels. This method is often used in intelligent lighting systems to improve comfort, energy efficiency, and the visual appeal of environments. This method is reported to be specifically useful in case of accident prevention during low visibility.
- Two steps Method: This method is typically implemented to automatically turn on and turn off features in light. It switches the illuminance of the light between 0 and 100%. In this method, the illuminance is regulated according to either daylight or motion. This method is specifically useful in turning off the street lights during day hours eliminating the need for manual operation and consequently conserving energy.

TABLE 2: Related Prior Work on Various Control Strategies and Energy Saving

Research Works	Sensing Parameters	Illuminance Control Strategy	Energy Saving	System Implementation
Byun et al., 2013 [35]	Occupancy and Light intensity	Step dimming	21.9%	Installed in office
Tan et al., 2013 [39]	Occupancy and Light intensity	Step dimming and Scheduling	44%	Installed in office
Nagy et al., 2015 [40]	Occupancy and Light intensity	Two steps	37.9% – 73.2%	Installed in office
Higuera et al., 2015 [41]	Occupancy and Light intensity	Step dimming	13.4% – 43%	Installed in office
Lau et al., 2015 [42]	Occupancy and Light intensity	Zoning and Step dimming	upto 37%	Simulation
Chew et al., 2016 [43]	Occupancy and Light Intensity	Step dimming	55% – 62%	Installed in Classroom
Shahzad et al., 2016 [44]	Light intensity	Step dimming and Group control	68% – 80%	Installed with Street light
Atis et al., 2016 [45]	Occupancy and Light intensity	Group control and Step dimming	33%	Installed with Street light
Juntunen et al., 2018 [46]	Occupancy	Zoning and Two step	60% – 77%	Installed with Street light
Petritoli et al., 2019 [47]	Vision, Occupancy and Inductive loops	Step dimming	59%	Installed with Street light
Bonomolo et al., 2020 [48]	Light intensity	Step dimming	Upto 70%	Simulation
Sifakis et al., 2021 [49]	Occupancy and Light intensity	Step dimming and Group control	56%	Installed with Street light

- Step dimming Method: This method is a simple and economical illuminance control method. It utilizes Pulse Widht Modulation (PWM) technique to regulate the illuminance between 0 to 100%. Step dimming allows for easy adjustment of light levels without the need for complicated controls or systems. It is a reliable option for spaces that require regular changes in lighting intensity.
- Zoning Method: According to this method an area gets partitioned into several zones, each possessing specific lighting needs and controls. This method allows more effective illumination regulation according to the distinct requirements of various zones, improving both functionality and energy efficiency. This method is particularly advantageous in large areas such as offices, conference rooms, or retail establishments, where where different lighting needs may exist within the same area.
- Scheduling Method: This method ensures that the lighting in a space is adjusted based on the time of day, helping to conserve energy and create a comfortable environment for occupants. It is particularly useful in indoor applications such as offices, schools,meuseums etc.

4 Sustainable IoT Framework in Smart Consumer Light Management

The recent developments in smart energy and consumer light technology have not only enhanced the efficiency and convenience of lighting solutions but also contributed to a greener environment by reducing energy consumption and waste. Nevertheless, the increase in the use of IoT devices also raises concerns about powering such a massive number of devices, explicitly considering the wide use of batteries. The global number of active IoT enabled devices deployed on field is estimated as 16.7 billion by 2023 [50]. The number is predicted to reach 29 billion by 2027, according to the same report, as a result of the extensive use of IoT technology. Batteries have a relatively short lifespan, which can result in the need for frequent replacements and higher expenses, implying more maintenance efforts. In addition, improper disposal of used batteries can have detrimental effects on the environment. It has been reported that the increasing reliance on batteries without considering battery life is anticipated to result in a staggering 78 million dead batteries every day by 2025 [51]. Therefore, adhering to sustainability in IoT technology in tandem with Sustainable Development Goal (SDG) 7 of United Nation (UN) has become an impetus. The implementation of E-CPS in consumer lighting is fundamentally supported by sustainable IoT technology. It possesses the advantage of being easily installed on any existing LED based light, allowing for more efficient energy management. The energy harvesting capability

allows it to harness energy from various renewable sources, including artificial light, solar power, thermal energy, and wind power. It eliminates the need for relying solely on the power supply of the connected light source. Furthermore, this characteristic of sustainable IoT-enabled consumer light management system allows it for seamless integration with any LED light without the need for extra circuitry or any impact on the power source of existing lights. Thus, it can be immensely beneficial in converting the conventional lighting infrastructure not only in the case of street lighting but also in offices, smart homes, and commercial buildings. Designing a sustainable alternative for smart consumer light management offers various benefits, as shown in Fig. 6. It primarily overcomes the scalability issues of
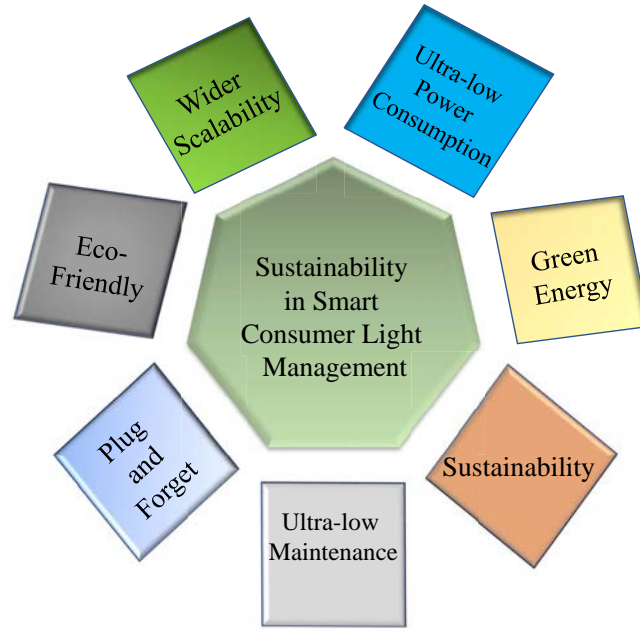

Fig. 6: Advantages of Integrating Sustainability to Consumer Light Management System

IoT-enabled light management systems, making it a plug-and-forget device applicable to any type of LED-based light, such as standalone, on-grid, and hybrid. The inclusion of smart energy technology, specifically the energy harvesting feature, power consumption optimization techniques, and advanced energy storage elements such as supercapacitors and ultra-capacitors, makes it an eco-friendly solution, significantly reducing the maintenance requirement and carbon footprint of the device. According to recent studies, the global count of street lamps is projected to reach 352 million by 2025 [52]. By the end of 2022, the global number of smart street lights has been estimated as 23 million. This number is expected to increase to 63.8 million by 2027, accounting for less than 19% of the total number of street light lamps [53]. Thus, there is a substantial demand for a solution that transforms traditional lights into intelligent lights. Smart consumer light management system is instrumental in achieving the aforementioned goal. The majority of the works conducted on consumer light management systems are in two directions, such as developing control strategies to reduce energy consumption and adding features to LED lights to expand functionality. However, limited research has been conducted on promoting sustainability in IoT-enabled consumer light management systems. Fig. 7 portrays the objective and importance of a consumer light management system enabled by sustainable IoT technology.

Sustainability in consumer light management system involves several advanced interdisciplinary technologies as shown in Fig. 8. The design process of state-of-the-art sustainable IoT framework necessitates in-depth knowledge and skills that align with the specific requirements of the application. The investigation of the energy source should be conducted within the framework of consumer lighting management. The primary performance parameters that must be considered throughout the design process of IoT devices are size, cost, and power consumption. An ideal IoT device should possess the qualities of being cost-effective, energy-efficient, and small. Therefore, in order to design IoT devices that fulfill these requirements, it is necessary to possess a thorough understanding of power management and optimization. Furthermore, the design of such devices requires a thorough understanding of communication protocols. Designers can design a sustainable IoT framework by involving all these techniques that not only fulfill the requirements of the application but also reduce adverse environmental effects, promoting the use of green and sustainable energy.
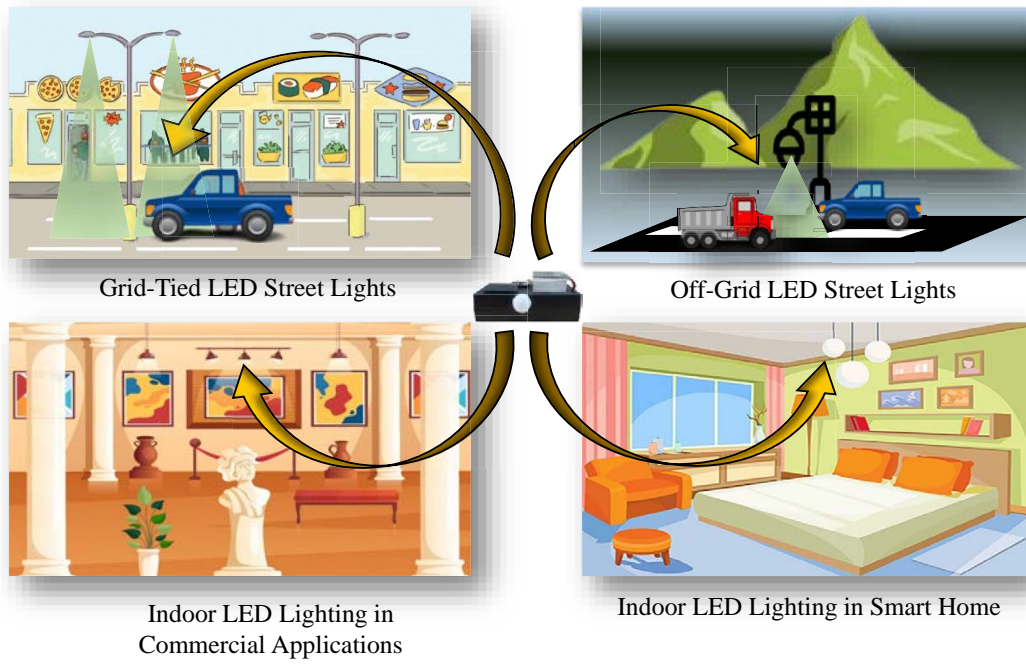
Grid-Tied LED Street Lights

Off-Grid LED Street Lights

Indoor LED Lighting in
Commercial Applications

Indoor LED Lighting in Smart Home

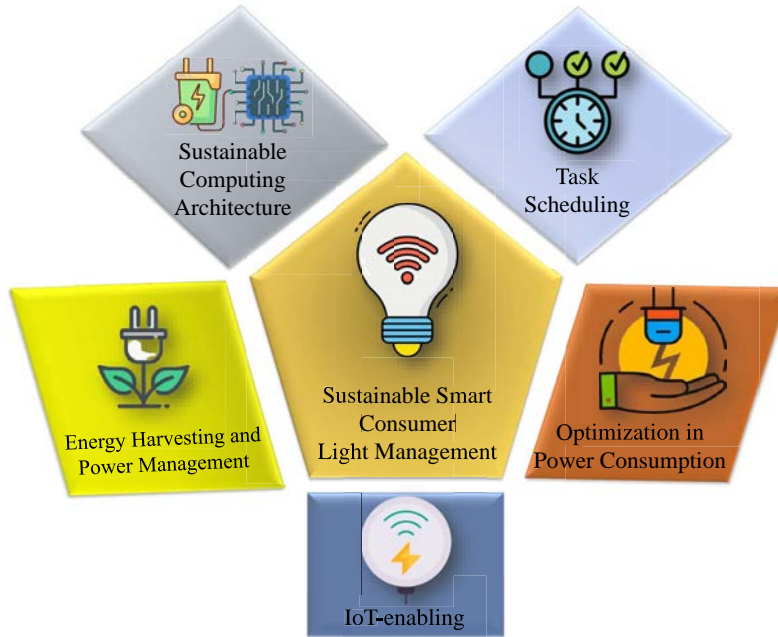Fig. 7: Vision of Sustainable Consumer Light Management System

Fig. 8: Elements of Sustainable Smart Consumer Light Management System

5   Power Management in Consumer Light Management System

Effective power management is a crucial consideration when incorporating smart energy into IoT-enabled devices. Optimal power management is essential for ensuring that the devices can function for long period without frequent maintenance. Power management in consumer lighting applications involves more than just supplying power to the

management system. It also includes protecting it from fluctuating power supply, preserving its lifetime through over-voltage and under-voltage protection, providing backup energy, and optimizing the power supply. There are three power management techniques implemented in state-of-the-art consumer light management systems. Fig. 9 shows the power management scheme implemented in most of the state-of-the-art related works.
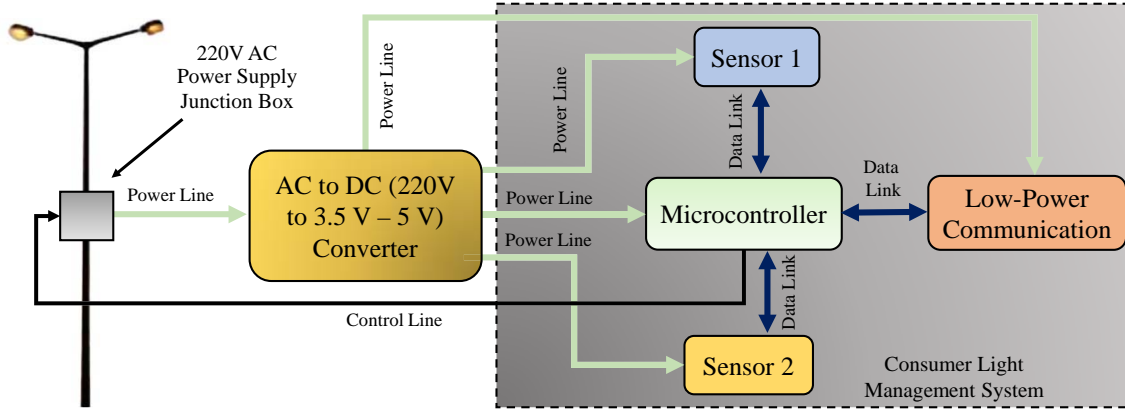

Fig. 9: Power Management Scheme for Grid Tied or Hybrid Street Light Management System

This technique is simple, yet widely applicable. The management system relies on the power supply of the LED for energy. The power supply of LED is mostly 220V AC which gets converted to 3.5V to 5V DC through converter mechanism which is compartible for IoT components. The advantage of this technique is that it doesn't include battery in the management. In [16], the aforementioned technique has been incorporated in street light management system. The power supply circuit is specifically designed to convert 220 V AC into three separate DC supplies: 12V, 5V, and 3V. This conversion is achieved by combining a converter, switching regulator, and linear regulator. A similar power management scheme has been implemented in [20], where the supply voltage is 230V AC. Subsequently, the management system of the street light is powered from the power supply line using a switched mode power supply [26]. The device is designed to convert an input voltage of 230V AC to an output voltage of 3.3V DC. It achieves an accuracy of $\pm 2\%$ and operates with an efficiency of 65%. Further, similar conversion mechnism has been used in [54], which is used to convert the single phase 220V AC to 5V DC to power the sensor node. However, two major limitations have been observed in this power management technique as outlined below.

- There is a significant amount of power leakage during the process of convertion from AC to DC. It leads to increased energy wastage as well as power consumption, ultimately resulting in a decrease in the overall efficiency of the light management system. Additonally, this scheme is less preferred in standalone or off-grid lights due to its higher power consumption.
- This technique is relatively obsolete as it does not eliminate the dependability on traditional grid power promoting sustainability in IoT.
- Power consumption has not been considered for optimization as availability of power is not a constraint here. Nevertheless, it holds significant value as a design metric within the realm of IoT.

Fig. 10 depicts the block diagram of another power management scheme used in state-of-the-art consumer light management systems. This scheme has also been used in standalone solar street lights where power is constrained. It includes a rechargeable battery, mostly lithium-ion type. The charging circuit drags power from the battery of the solar light to charge the mini battery of the management system. The charging circuit typically includes a DC-DC converter. However, the management system depends on the energy storage unit of the light for power, which does not make it a sustainable device. The protoypes of LED light management system developed in [55] and [56] have been powered by the solar panel of the light following the scheme depicted above. The major drawback of this power management scheme is the inclusion of batteries. Additionally, the issue of high power consumption has not been addressed in case of consumer light management systems that follow this power management scheme.

Fig. 11 illustrates the block diagram of a sustainable consumer light management system. The drawbacks cited in the aforementioned power management schemes has been solved using this technique. It can be implemented in any LED
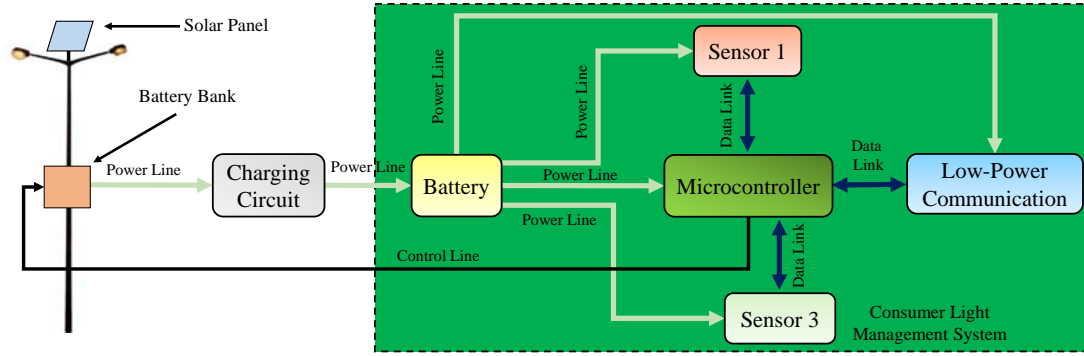
Fig. 10: Power Management Scheme in Stand-alone for Off-grid Street Light Management System
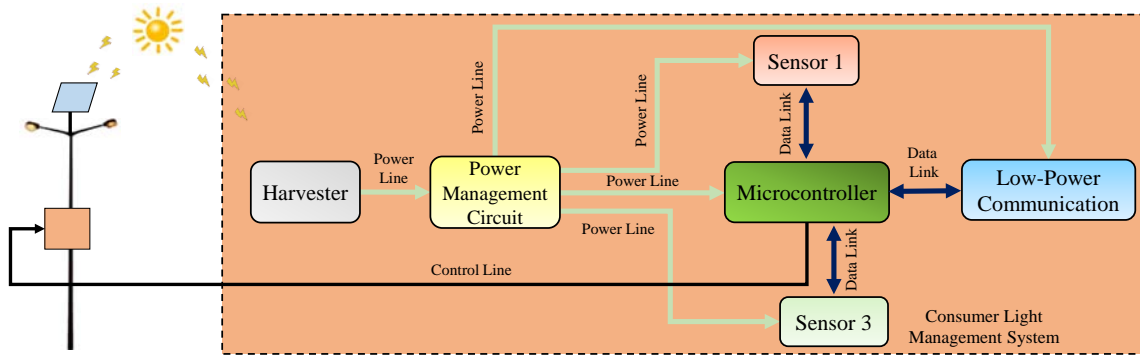

Fig. 11: Energy Autonomous Power Management System for Consumer Light Management

light. It harvests energy from various renewable sources such as solar, thermal, artificial light, etc., using its energy harvester to power the sensor node, achieving sustainability. This feature makes it an ideal solution to retrofit it to existing LED lighting systems without disrupting the entire infrastructure. It enhances energy-efficiency and enables IoT compatibility in consumer light.

Efforts have been made to develop self-powered street light management system that utilizes a smaller solar panel to collect solar energy [57]. It is energy autonomous and operate the LED light to bring energy efficiency. Further, attempts are made to reduce the size of the solar cell by optimizing the power consumption of the management system to achieve the same goal [4]. In this work, the device harvests energy from artificial light sources in order to perform its tasks autonomously. Duty cycle optimization technique has been employed to minimize power consumption. It incorporates battery-less framework. Subsequently, hybrid power management system for harvesting energy from solar and solar thermal energy has been proposed [5]. It can power the management system in order to operate the street light energy efficiently.

6   Energy Harvesting and Power Management Technology in Smart Energy

Energy harvesting and power management techniques are the core of smart energy. Designing an efficient energy harvesting subsystem to power the IoT devices through ambient energy sources is the primary design step towards achieving sustainability. Subsequently, implementing optimized power management techniques that effectively regulate and distribute energy across a smart energy network possesses equal importance. Thus, the combination of energy harvesting and power management technologies is crucial for developing a reliable and effective smart energy system capable of fulfilling the needs of sustainable IoT. It deals with harnessing energy from natural sources, conditioning it according to the requirement of the application and storing it for powering the electronics components of the device. It helps a device to sustain its operation uninterruptedly without the requirement of maintenance.

6.1 Energy Harvesting Technology

There are two important terminologies associated with energy harvesting technology which are important to be understood i.e. energy scavanging and energy harvesting. Energy scavenging includes the search for reusable sources. It is obtained from natural sources and the untapped portion of the discarded energy [58], [59]. It helps alleviate a certain amount of strain on the primary system in terms of activity and cost, serving a specific purpose to promote sustainability. Energy scavenging is a perfect solution for sensors located near machinery, like industrial equipment, household appliances, and vehicles. Table 3 presents the energy sources available for powering IoT devices.

TABLE 3: Sources of Energy used to Power IoT devices

Type of Energy	Source of Energy
Mechanical Energy	Vibration or Deformations
Solar Energy or Light Energy	Sun or Artificial light
Thermal Energy	Temperature difference
Acoustic Energy	Vibration due to sound wave
Radio Frequency	Electromagnetic radiation

Energy harvesting is a comprehensive process that involves a range of activities aimed at utilizing and storing energy scavanged from renewable energy sources. The size of the global energy harvesting system market has been assessed at 0.6 billion USD in 2023, with an estimated growth to 0.9 billion USD by 2028 [60]. It indicates a steady increase at a compound annual growth rate of 10% throughout the forecast period. As technology advances, integrating renewable energy sources into IoT devices will become even more widespread, further promoting a greener and more sustainable future. Table 4 summarises energy sources with its harvesting methods used in state-of-the-art energy autonomous IoT devices. Light, vibration, heat, Radio Frequency (RF), and air/water flow are the most common energy sources used for harvesting energy for IoT devices [61].

TABLE 4: Characteristics of Ambient Energy Sources used to Power IoT Devices

Research Works	Energy Source	Harvesting Method	Power Density	Merit	Demerit
Orrego et al., 2017 [62] Wang et al., 2017 [63] Sardini et al., 2011 [64]	Wind	Piezo Turbine	4–50 μW/cm^2 [62]	Predictable and even low-speed is sufficient to power	Not Steadily Available
Rossi et al., 2015 [65] Russo et al., 2017 [66]	Light	Photovoltaic	0.5–1000 μW/cm^2 (Indoor) [65] 5–100 mW/cm^2 (Solar) [66]	Predictable and Mature	Not steadily Available and Expensive
Song et al., 2016 [67] Monti et al., 2014 [68] Goudar et al., 2014 [69]	Mechanical	Electromagentic, Piezoelectric	0.819 μW/cm^2 [67]	Highly efficient and Controllable	Risk of Material Breakage
Visser et al., 2008 [70] Shah et al., 2016 [71], Xiao et al., 2016 [72]	RF	Rectenna	0.01–0.3 μW/cm^2 [70]	Continuous Available and Process Information and Simultaneously	Short Operating Range
Yuan et al., 2014 [73] Kumar et al., 2012 [74], Yuan et al., 2017 [75]	Sound	Coherence Resonance	6.02 μW/cm^2 [73]	Harvestable at Low Sound Level	Not Steadily Available

Energy source for powering electronics devices typically depends on the application. Solar, wind, and thermal are commonly chosen sources for energy harvesting enabled devices used in outdoor environments. Harvesting energy from mechanical vibration, such as wind and human movement has been reported to feature energy autonomy to IoT devices deployed in various crucial applications [76], [77]. Solar energy has been recognized as a proven energy source for powering energy autonomous IoT devices deployed in a wide range of applications such as health care [78], environmental monitoring [79], agriculture [80], solid waste management [81], air pollution monitoring [82], and underground water monitoring [83]. It is considered as the most convenient renewable energy source in street light management systems as solar energy is a mature technology with high power density. A self-powered street light management system has been designed that harvests energy from sunlight [57]. Furthermore, the utilization of thermal energy generated by direct sunlight has been harnessed as an energy source for powering a smart consumer light management system [5]. On the otherhand, solar energy is not applicable in case for indoor applications. RF and artificial light are widely utilized to power IoT devices in indoor environments. Energy harvesting that implements Near Field Communication (NFC) has been used in various energy autonomous devices deployed in indoor environment such as livestock farming [84], pH measurement of drinking water [85], soil health monitoring

in indoor plants [86], freshness monitoring in fishes and packed food [87], [88]. Subsequently, there is potential for energy harvesting from artificial light using high-efficient thin-film solar cells. It has been particularly used for batteryless devices, which require energy uninterruptedly. The ability to harness energy from sunlight and artificial light using a single, specially designed harvester is a significant advantage of light as an energy source. Therefore, several energy autonomous devices that depend on solar energy are also capable of harnessing energy from artificial light sources [78], [79]. It has also been used for sustainable consumer light management systems [4], [5].

The energy acquired then needs to be converted into electrical energy to be compatible with the intended use. The conversion process requires power conditioning circuits. In certain instances, the conversion process is straightforward, while for other resources, it necessitates complex circuitry and machinery to become functional. Fig. 12 illustrates the comprehensive block diagram of energy harvesting and power management technology used to power IoT devices.
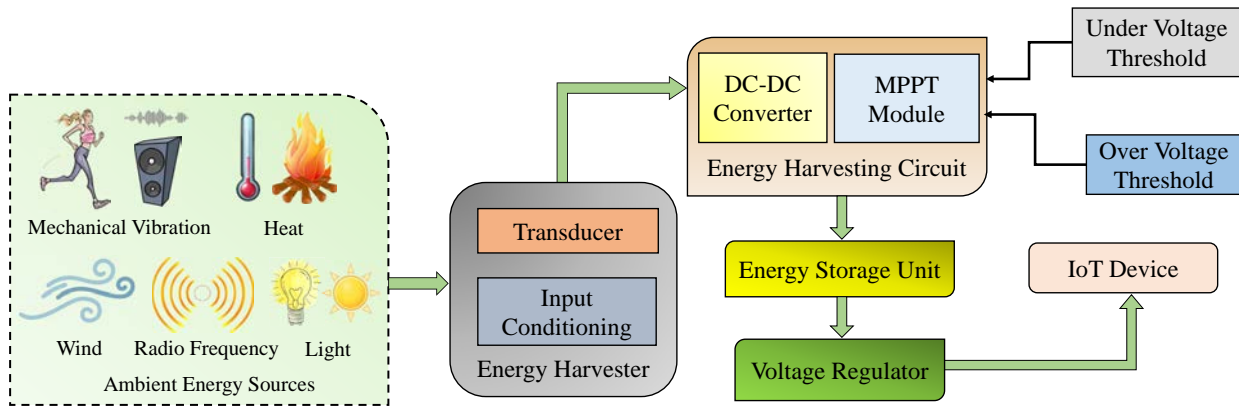

Fig. 12: Comprehensive Block Diagram of Energy Harvesting and Power Management Technology

6.2 Power Management and Energy Storage Technology

DC-DC conversion mechanism is used to convert the harvested energy through energy harvested into electrical energy. Specifically, it involves taking the variable voltage and current generated by the energy harvester and converting it into a stable and regulated voltage suitable for powering IoT devices. The DC-DC conversion mechanism is essential for maximizing the efficiency of the energy harvesting system and ensuring a consistent power supply for the connected devices [89]. There are mainly three types of converter mechanism used in state-of-the-art energy autonomous IoT devices which are boost converter, buck converter and buck-boost converter.

- Boost Converter: It is used to step up the voltage obtained from the harvester. The increase in voltage is crucial to guarantee the efficient storage or utilization of the generated energy for devices that demand a higher voltage. It optimizes the efficiency of the energy harvesting process, enabling the efficient use of the harvested energy by increasing the voltage. It is highly adaptable and easily handles input voltages in a range for which it can generate output voltage compatible with IoT devices i.e. 0V to 5V, making it an essential component in energy harvesting systems.
- Buck Converter: It is used to lower the output voltage of an energy harvester. This type of converter is known for its high efficiency and is frequently used in energy harvesting systems to control voltage levels to power low-power devices. By reducing the voltage, the buck converter guarantees that the energy obtained from various sources like solar panels or vibration sensors is converted and stored at the most suitable voltage for the specific application. Furthermore, buck converter can prevent battery overcharging and protects sophisticated electronics from being exposed to excessive voltage levels.
- Buck-Boost Converter: It is used in a wide range of applications where there is a substantial variation in the input voltage, such as in the case of solar energy harvester. It converts efficiently and regulates the output voltage, even when the input voltage fluctuates, ensuring the smooth operation of the overall system. In addition, it has the ability to adjust voltage levels for various components in a circuit, making them a crucial and adaptable part of today's electronics.

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In addition to DC-DC converter, Maximum Power Point Tracking (MPPT) controller serves vital role in managing the process of enery harvesting in power management unit. MPPT is used with variable power sources to maximize energy extraction as weather conditions vary. It is specifically useful in cases of devices that rely on solar energy. MPPT technology can increase energy output to a great extent compared to traditional fixed voltage systems by continuously adjusting the electrical load to match the optimal operating point of the power source. This not only maximizes the energy production of renewable sources but also improves the overall performance and longevity of the power system. MPPT controller can be designed using several techniques such as hill-climbing, Perturb and Observe (PO), incremental conductance, Fractional Open-Circuit Voltage (FOCV), fuzzy logic control, constant voltage, Neural Network (NN), and Generic Algorithm (GA). Subsequently, the harvested energy gets stored in energy storage unit after being conditioned. There are several energy storage elements such as fuel-cell, non-recharable battery, solid-state battery, recharable battery, capacitor, supercapacitor, lithium-ion capacitor that are used depending on specification of applications. A comparision between energy storage units is presented in Table 5.

TABLE 5: Comparison of Energy Storage Units used in Energy Autonomous IoT Devices

Energy Storage Element	Advantages	Limitations
Fuel Cell	Reliable and portable	Expensive
Lithium-ion Battery	Rechargeable and Cost effective	Limited charge cycle, Less power density, Harmful to environment
Solid State battery	Thin and flexible	Less power density
Supercapacitor	Environmental friendly, Huge charge-discharge cycle, High power density	Affected by self-discharge, Low energy density
Capacitor	Low cost, Compact size, Long life span, High power density	Low energy density
Lithium-ion Capacitor	High power density, Better energy density compared to supercapacitor	Costly, Limited energy density compared to battery

7 Sustainable Computing Architectures for Consumer Light Energy Cyber Physical Systems

Sustainable computing architecture is the basic building block of smart consumer light management system. It is responsible to minimize the energy consumption of the consumer light management systems thereby contributing to reduction in the size of energy harvesters, storage elements, device footprint, and overall manufacturing costs. Sustainable computing architectures reduce and optimize the energy consumption of the device by means of efficient use of hardware and software combinations. Consumer light management systems have been reported to attain enhanced energy efficiency with reduced ecological footprint through the implementation of various sustainable computing architectures. Recent development, testing, and validation of many sustainable IoT devices have exhibited their ability to provide satisfactory functionality when used in real-world scenarios. These devices have been proven reliable, effective, and environment friendly, making them highly suitable for various applications. Fig. 13 shows the block diagram of a sustainable computing architecture which is simple yet mostly opted in various devices. In this architecture, energy can be harnessed using a suitable harvester based on application and then conditioned with a power management unit. The harvested energy is typically stored in an energy storage element, such as battery or supercapacitor bank. The sensor node draws power from the energy storage unit. Therefore, the storage unit effectively stores sufficient energy to help the sensor node to sustain its operation for longer duration. This architecture is commonly utilized for energy autonomous IoT devices that are deployed in outdoor applications and incorporate batteries as energy storage. The higher energy density of batteries compared to other energy storage elements enables the storage of harvested energy for extended durations, allowing the sensor node to operate uninterruptedly when the energy source is unavailable. The architecture has been used in a self-powered IoT-enabled street light management system with energy autonomous capability has been developed [57], . A single PV harvester has been used to harvest energy, and a lithium-ion battery of 1200 mAh has been incorporated as an energy storage unit. The system manages the operation of LED based street light. In [80], an IoT system has been designed to monitor soil conditions continuously. The proposed system includes end nodes that are powered from solar energy. These units can be easily deployed on the field for long period. The system measures temperature, moisture, electrical conductivity, and carbon dioxide of the
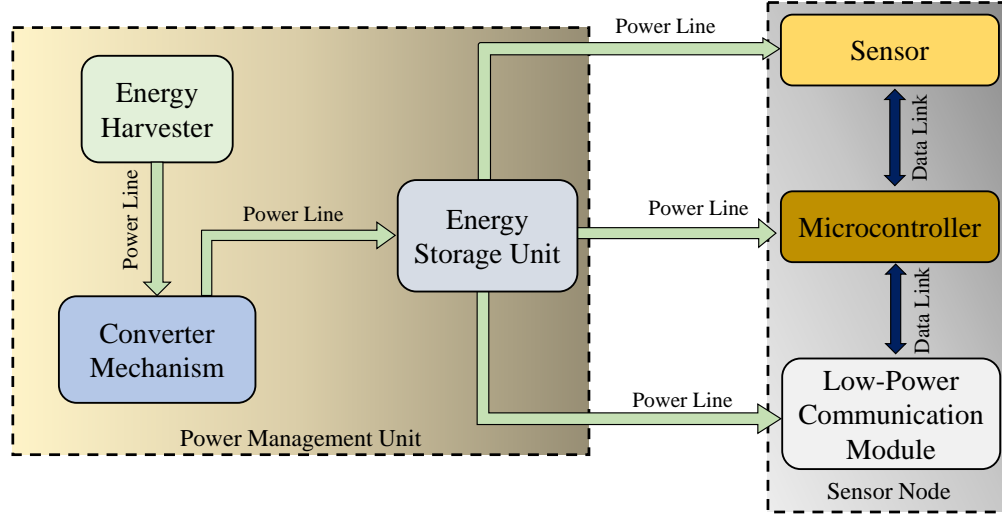
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Fig. 13: Sustainable Computing Architecture for Energy Autonomous IoT Devices for Battery Powered Energy Autonomous IoT Devices Deployed in Outdoor Application

soil and transmits the information along with the geolocation of the end node using LoRaWAN. The manufacturing cost of an end node is claimed to be 179.34 USD. Similarly, in [81], an solar powered energy autonomous device has been proposed incorporating the aforementioned architecture for trashbin monitoring. LoRaWAN has been used for low-power communication. Power consumption has been optimized using duty cycle technique. The proposed system operates in real-time to assist the authority in effectively managing solid waste. Further, an IoT-compatible low-cost sensor system has been designed to monitor air pollution [82]. The device relies on solar energy with a rechargeable battery for power, and it is designed to withstand various weather conditions. It measures carbon monoxide, nitrogen dioxide, PM10, temperature and humidity. ANN has been implemented to calibrate the sensor.

TABLE 6: State-of-the-art Energy Autonomous IoT Devices incorporating Sustainable Computing Architecture

Reference Works	Energy Source	Energy Storage	Target Application	Average Consumption
Zhang et al., 2019 [90]	Sunlight	Rechargeable Battery, 10000 mAh	Soil Health Monitoring	N/A
Sadowski et al., 2020 [91]	Sunlight	Rechargeable Battery, 6600 mAh	Soil Health Monitoring	29.33 mW
Bhusal et al., 2020 [92]	Sunlight	Rechargeable Battery, 2000 mAh	Air Quality Monitoring	7 mA
Mohanty et al., 2021 [57]	Sunlight	Rechargeable Battery, 1200 mAh	Street Light Management	N/A
Kombo et al., 2021 [83]	Sunlight	Rechargeable Battery, 5000 mAh	Soil Health Monitoring	104.081 mW
Ramson et al., 2021 [80]	Sunlight	Rechargeable Battery, 2500 mAh	Soil Health Monitoring	13 mA
Ali et al., 2021 [82]	Sunlight	Rechargeable Battery, 4000 mAh	Air Pollution Monitoring	$\approx$ 14.306 mW – 14.97 mW
Houssaini et al., 2020 [93]	Sunlight	Rechargeable Battery, 6600 mAh	Soil Health Monitoring	29.33 mW
Ramson et al., 2022 [81]	Sunlight	Rechargeable Battery, 2500 mAh	Solid Waste Management	1.5 mA

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A cost-effective and efficient wireless sensor network has been designed to monitor groundwater levels in Zanzibar, Tanzania [83]. It can harvest energy from sunlight and reserves the energy using lithium-ion battery. This network provides timely data to aid in making decisions regarding groundwater resource management. The manufacturing cost of the system ranges from 350 USD to 400 USD. Duty cycle technique has been implemented to optimize power consumption, keeping it below 1%. In constrast, similar system has been designed for the same application which is capable to harvest energy from artificial light in addition to sunlight [92]. One of the limitation in the state-of-the-art energy autonomous systems is limited communication range. Efforts have been made to enhance the communication range by incorporating LoRa and NB-Iot technology into a soil health monitoring system [90]. The system harvests energy using a solar panel and relies on recharagble battery as energy storage unit. It has been reported that the communication range has been increased up to 1.6 KM in complex environments. The system requires an average of 2 mA to achieve this range with a packet loss rate of approximately 3%. Subsequently, further attempts have been made to enhance communication in solar energy powered IoT devices using three major IoT communication protocols such as Zigbee, LoRaWAN, and Wi-Fi [91]. The proposed device in this work has undergone experimental testing in an application related to monitoring soil health. A state-of-the-art comparision among the devices designed with afformentioned architecture, has been provided in Table 6.

There is a growing focus on reducing reliance on battery technology due to its negative environmental impact. It has become a significant area of research. Therefore, supercapacitors, capacitors, and lithium-ion capacitors have emerged as the leading alternatives to rechargeable batteries. Nevertheless, the energy density of these elements is significantly lower than that of batteries, making it extremely difficult to utilize them in IoT devices. In order to achieve sustainability in a battery-less system, it is crucial to ensure continuous energy harvesting. Fig. 14 illustrates the advanced architecture of battery-less sustainable IoT devices. In this architecture, the harvester serves
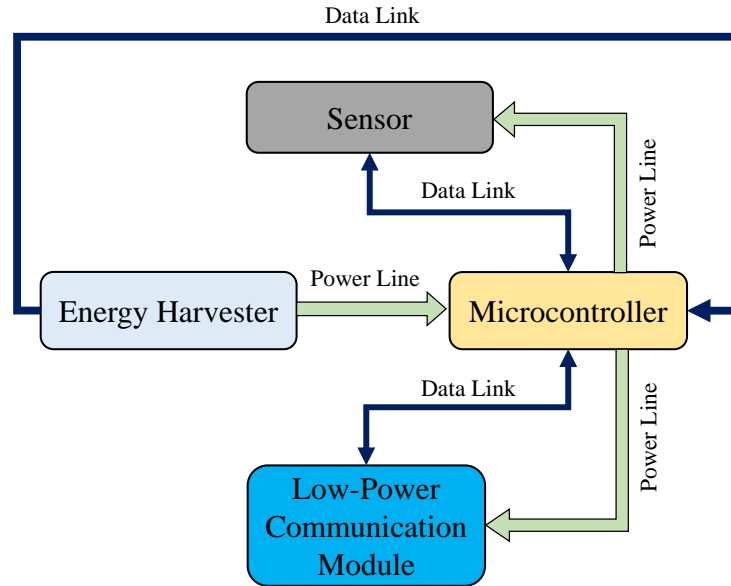

Fig. 14: Sustainable Computing Architecture Utilizing Harvester as Transducer

a dual purpose by functioning as a transducer within the system while also harvesting energy. Furthermore, there is no use of external complicated power management unit. Instead, it utilizes the internal power management of the microcontroller called Power Voltage Detector (PVD) to accurately determine the output voltage level of the harvester. This architecture utilizes an in-built low-power timer along with PVD for measurement operations. This architecture provides the benefit of reducing the number of sensors in a system and eliminating the need for additional power management, resulting in a simpler design. Ambient light powered wireless sensor platform using a single photovoltaic transducer has been designed to measure the same ambient light [94], [95]. This wireless system offers a convenient and efficient solution. Additionally, it can measure temperature and humidity. The device is BLE-enabled and has been implemented in measuring indoor light intensity up to 200 lux. Furthermore, the system has undergone thorough testing to demonstrate its compatibility in smart agriculture applications [96]. Furthermore, a system has been developed based on the aforementioned architecture to measure electrical impedance for evaluating the water

stress level in plants [97]. Experimental tests demonstrated a reading error rate of less than 15% when working with impedance modules up to 180 kΩ. The major limitation in these systems is the communication range due to the use of BLE as communication module. Therefore, LoRaWAN has been implemented as a communication unit to address the mentioned problem [98]. The proposed system can communicate a maximum of 30 bytes subject to the Spreading Factor (SF), and the bandwidth of LoRa is set at 7 and 125 KHz, respectively. The implementation of such architecture has also been achieved in the healthcare system, specifically in monitoring human metabolism through glucose monitoring [99].

Communication unit in an IoT device accounts for over 50% of the energy consumption of the device. It is a significant issue, especially in IoT devices that rely on energy harvesting. The availability of energy is crucial in these devices. Therefore, a range of low-power communication protocols, including LoRaWAN, BLE, SigFox, and NB-Iot, alongside suitable power optimization techniques, are incorporated into these devices to minimize overall power consumption. It can be achieved with systems capable of harnessing energy from renewable sources with a high power density, such as sunlight and wind. Conversely, when addressing energy sources characterized by low power density such as RF, acoustic, and vibration, there can be drawbacks. These drawbacks may result in decreased communication range and lower QoS. Fig. 15 shows a state-of-the-art architecture used in energy harvesting enabled IoT devices to overcome the aforementioned issue. In [100], a battery-less Radio Frequency Iddentification (RFID) wirless sensor has
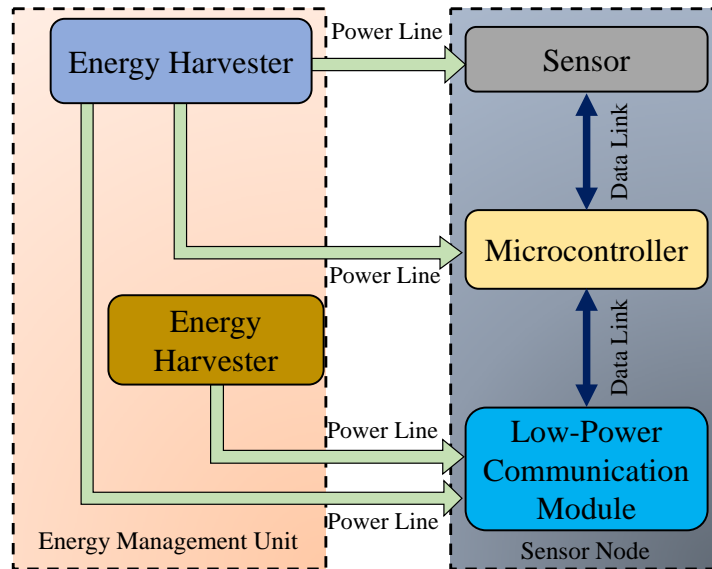

Fig. 15: Sustainable Computing Architecture Leveraging Multiple Harvesters to Overcome Communication Range Issue in Energy Autonomous IoT Devices

been designed which is tested with environment temperature monitoring and golf ball tracker application. The device primarily harvests energy from RF source in backscattering principle, and additonally, thin-film solar cell has been incorporated to harvest energy from artificial light to power the device to enhance communication range. The reported range has been improved to 15 meters to 20 meters with a variation of +/-2 meters, achieved through a frequency sweep from 800 to 1000 MHz. The performance is significantly higher compared to passive RFID, with a boost of 6-10 times. Subsequnetly, a perovskite solar cell has been fabricated of 10.1% efficiency to additionally power the RFID sensor [101].

One of the main challenges faced by battery-less IoT devices is their extremely limited energy storage capacity. Supercapacitors and capacitors, unlike batteries, have lower energy storage density. Therefore, if the energy source experiences fluctuations or interruptions, the performance of the device is often gets affected due to insufficient energy. This issue has been solved in two approaches as outlined below in state-of-the-art energy autonomous IoT devices.

- Primary energy storage elements along with secondary storage element can be utilized to ensure a continuous power supply in situations where energy availability from renewable sources is limited. Consider, for instance, the crucial importance of energy availability during the rainy season for a solar energy powered IoT device.

Therefore, the primary energy storage component guarantees an uninterrupted power supply to the sensor node, resulting in unaffected performance of the device.

- Integration of multiple harvesters allows for continuous energy harvesting from same or various energy sources, regardless of the time. Thus, the device can ensure that the sensor node gets power uninterruptedly irrespective of time.

Fig. 16 illustrates the achitecture of state-of-the-art energy autonomous IoT device which uses hybrid storage element to overcome the issues reported in battery-less devices. A dual energy harvesting enabled battery-less street light
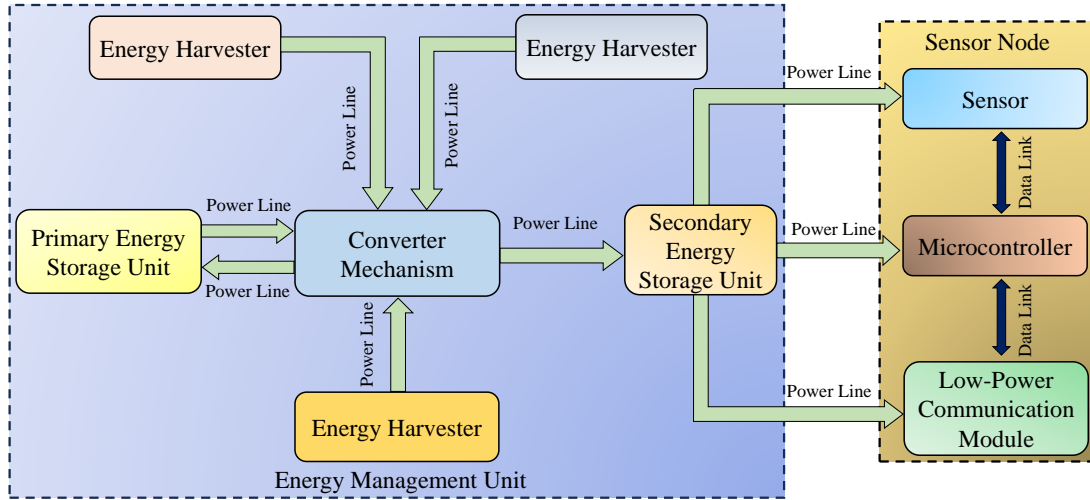
Fig. 16: Sustainable Computing Architecture Based on Hybrid Power Management Unit for Energy Autonomous IoT Devices

management system has been proposed to operate street lights energy efficiently [4]. It incorporate a single thin-film solar cell which can harvest energy under sunlight as well as artificial light i.e. from the street light. It incorporates supercapacitor as energy storage unit and utilizes LoRaWAN for long-range communication. Subsequntly, similar system has been proposed that can harvest energy from solar and solar thermal energy [5]. This work addresses the issues encountered in [4], thus dual-energy storage elements, including a capacitor and lithium-ion capacitor, have been incorporated into the proposed hybrid energy management scheme. The system employs the capacitor to provide power to the sensor node during day and relies on the lithium-ion capacitor for power during night. Furthermore, a battery-less LoRaWAN enabled IoT device has been developed and evaluated for monitoring environmental parameters [79]. It can harvest energy from solar and artificial light. This device implements supercapacitor as its energy storage unit and the size of the supercapacitor has been optimized to meet the specific requirements of the application. A hybrid energy storage and management solution has been proposed for a LoRaWAN enabled sensor [102]. It harvests energy from sunlight using a 330 mW PV panel. Supercapacitor has been used along with lithium-ion battery as storage unit. Battery has been used as a secondary energy storage element for power backup. The device has undergone thorough testing and validation for a specific application related to monitoring environmental parameters like temperature, humidity, and pressure on LoRaWAN. Furthermore, a dual thermal energy harvesting scheme has been proposed for water flow rate measurement device [103]. It employs a specially designed energy management unit to manage energy consumption effectively. It incorporates ultrasonic sensors, a task-based computing scheme, and a LoRa module to sense and report the flow rate independently. In [104], a LoRaWAN enabled environmental data and water quality monitoring device has been proposed. In this work, energy has been harvested combinedly from sunlight and thermal differences created between water surface and materials exposed to sunlight through Thermo Electric Generator (TEG) for powering LoRa enabled device. There has been an ongoing trend toward utilizing the output signals from energy harvesters to extract contextual information instead of using specific sensors. The harvester provides valuable contextual information about the deployment environment due to the diverse nature of the harvested energy. Fig. 17 shows the typical sustainable achitecture energy autonomous IoT devices in which harvester has been used as transducer in addition to powering the device. The architecture has the potential to provide cost-effective design, minimal use of electronics, simple design, and a smaller form-factor. In this direction, TEG has been used to harvest energy from heat to power the device and additionally provide temperature information to the same [105], [106], [107]. It has proven to be valuable in a range of important applications, including detecting human
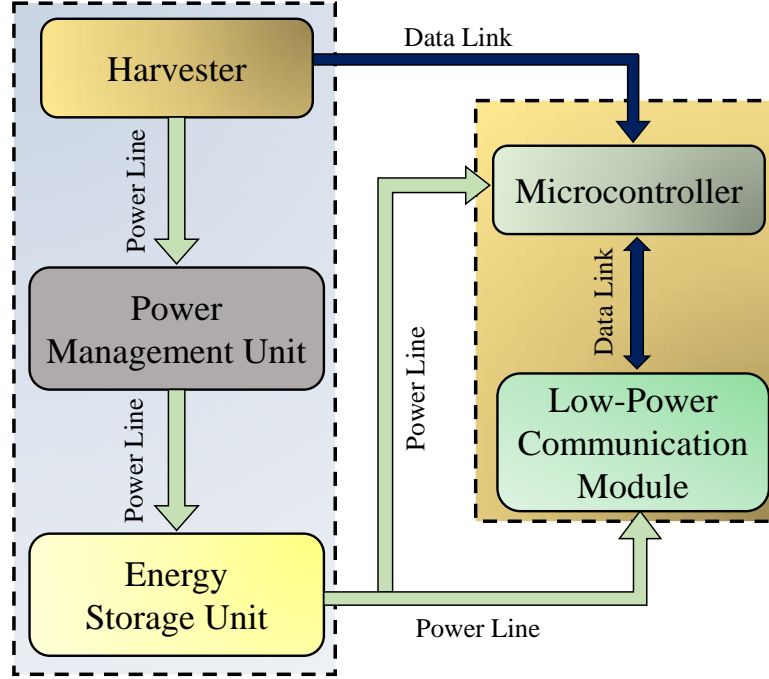
Fig. 17: Sustainable Computing Architecture Employing Harvester as Transducer in Addition to Powering the Device

activity, monitoring chemical reactions, and measuring water flow. On the other hand, in addition to measuring light intensity through PV harvester [94], [95], monitoring or detecting human activity and gesture recognition has been accomplished in PV harvester integrated devices designed using the aforementioned sustainable architecture [108], [109], [110].

Subsequently, a system has been proposed utilizing RF harvesting to monitor hand hygiene in humans [111]. It shows results in detecting hand gestures, with an error rate of less than 8%. The device has the potential to be highly beneficial in healthcare applications. Furthermore, efforts have been made to recognize hand gestures in humans using RF harvester through back-scattering principle [112]. A battery-less RF device has been designed in [113], which employs an RF harvester to detect touch and gesture applicable to various real-world scenarios. Further, Kinetic Energy Harvester (KEH) has been used for transportation mode detection in addition to power the device. It has the ability to detect and analyze the vibrations that passengers experience while using various modes of transportation. Further, KEH has been used for transportation mode detection in addition to powering the device [114]. It has the ability to detect and analyze the vibrations that passengers experience while using various modes of transportation. The device demonstrates an impressive overall accuracy of over 92% in classifying five modes while significantly reducing system power consumption by more than 34% compared to traditional accelerometer-based approaches. Battery-less energy autonomous wearable device incorporating kinetic energy harvester has been designed to detect human activity with 95% accuracy [115]. It has been reported that the device consumes 57% less power than the conventional motion sensor-based approaches. Further efforts have been made toward gait detection using KEH enabled energy autonomous device [116]. This technique of gait detection has been proven more energy efficient, specifically achieving 82.5% less energy consumption compared to the accelerometer-based approach. The device detects gait against spoofing attackers, achieving minimum Equal Error Rate (EER) of 11.2%. A summary of the latest advancements in the field has been compiled in Table 7.

8   Task Scheduling and Energy Optimization Techniques for Consumer Light Energy Physical Systems

A significant limitation in state-of-the-art IoT enabled consumer light management systems is the lack of efforts provided to power consumption. Power consumption is currently a major focus of research for designers and scientists

TABLE 7: Energy Autonomous IoT devices Designed using Harvester as Sensor or Transducer

Research Works	Energy Source	Target Application
Campbell et al., 2014 [105]	Thermal	Water and applience metering
Zarepour et al., 2017 [106]	Thermal	Detection of chemical reaction
Proto et al., 2018 [107]	Thermal	Activity detecion of human
Varshney et al., 2017 [108]	Sunlight	Hand gesture recognition of human
Ma et al., 2019 [109]	Sunlight	Gesture recognition of human
Sandhu et al., 2021 [110]	Sunlight	Activity detection of human
Khamis et al., 2020 [111]	RF	Hand hygiene monitoring in human
Wang et al., 2018 [112]	RF	Hand gesture recognition of human
Pradhan et al., 2017 [113]	RF	Touch detection of human
Lan et al., 2020 [114]	Kinetic	Transport mode detection
Lan et al., 2020 [115]	Kinetic	Activity detection of human
Xu et al., 2019 [116]	Kinetic	Activity detection of human

due to its impact on the overall performance and lifespan of IoT devices. Addressing power consumption issues in IoT devices demands a focus on developing energy-efficient algorithms and optimizing hardware design. Devices can operate for longer periods of time without needing to be recharged or have their batteries replaced by reducing power consumption. As a result, it lessens the environmental impact of discarded batteries and enhances user experience. In addition, it offers designers a competitive advantage by allowing them to seamlessly integrate energy harvesting technology with IoT. Further, power consumption in IoT devices is influenced by their task scheduling to a great extent. Optimizing task scheduling can decrease power consumption by ensuring that devices are only active when needed. IoT devices can enhance their operational efficiency and prolong battery lifespan through strategic management of task completion. In addition, implementing a well organized task schedule can effectively prioritize essential tasks and optimize resource allocation, resulting in significant long-term power savings. There are three most standard energy optimization and task scheduling strategies implemented in state-of-the-art IoT devices as outlined below.

- Dynamic Voltage Frequency Scaling (DVFS)
- Decomposing and Combining of Tasks
- Duty cycle

Fig. 18 illustates stategies using which energy consumption optimization and task scheduling can be achieved in consumer light management systems. Implementing these techniques is not only restricted to help optimize energy consumption but also enables the designer to maintain high QoS in the device by executing tasks as per priority level.

8.1 Dynamic Voltage and Frequency Scaling (DVFS)

The power consumption of the sensor nodes is impacted by the factors such as the supplied voltage, current flow, and the operating frequency, specifically the clock frequency. Thus, it can be optimized by adjusting both of these parameters in real-time. The objective DVFS technique is to either optimize performance within the constraints of a finite energy budget or to reduce energy consumption within a performance bound. This technique offers a dynamic approach to lower power consumption of microprocessor or microcontroller in the sensor node by adjusting the supply voltage and frequency according to the specific performance needs of the application. There are certain applications in which the system achieves high performance for very short period of time. Thus, it presents an oppertunity to save a significant amount of energy [117]. Real-time applications may exhibit variations in Actual Execution Time (ART) which often finish earlier than the estimated Worst Case Execution Time (WCET). DVFS technique takes advantage of these variations in the workload to adaptively modify the supply voltage and frequency of the system [118]. The relation between dynamic power consumption (P_{dyn}) of the sensor node with clock frequency and supplied voltage can be expressed as:

$$P_{dyn} \alpha f_{clock}(V_{supply})^2; \tag{1}$$

P_{dyn} decreases quadratically upon supply voltage (V_{supply}) gets reduced linearly. On the other hand, a decrease in V_{supply} also leads to a decrease in the switching speed of the CMOS transistors. As a result, the maximum clock frequency of the microprocessor or microcontroller eventually gets reduced. The clock frequency below which the microprocessor or microcontroller is not capable to execute tasks is called as critical frequency. Thus, it automatically adjusts its frequency to a higher level if the requested frequency is unavailable. It is crucial for the microprocessor or microcontroller to be aware of the duration of the idle period, or at least, its minimum size in order to select the most
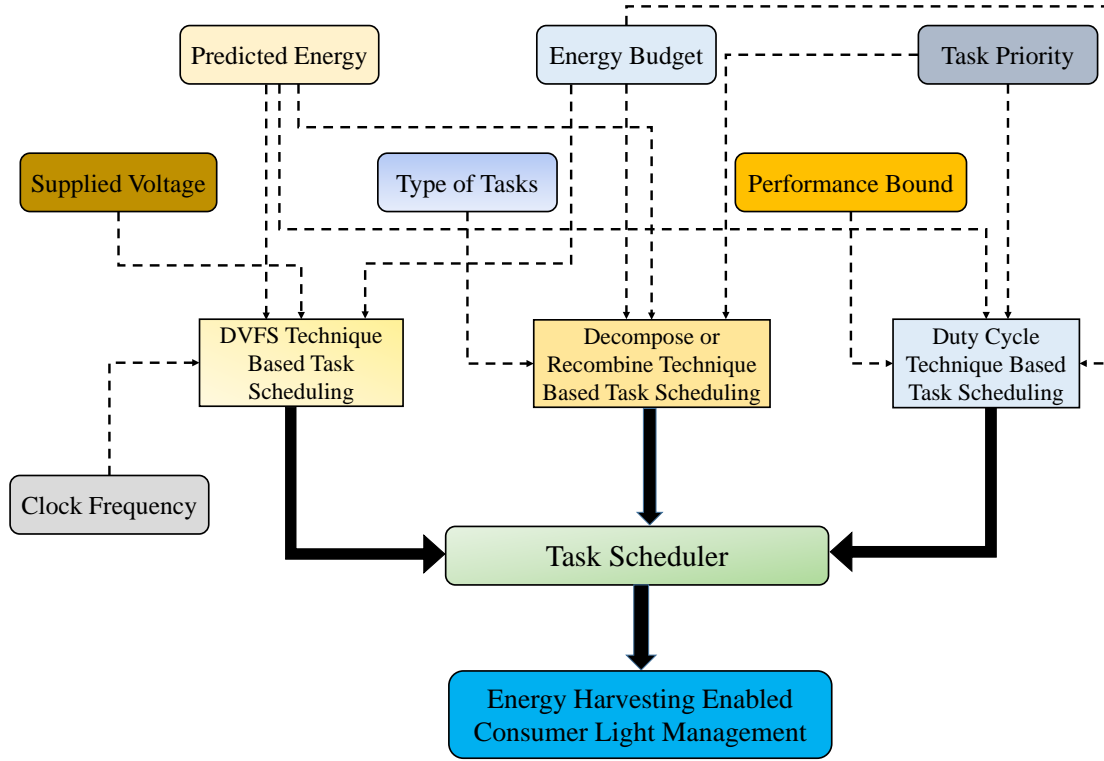
Fig. 18: Strategies for Power Consumption Optimization and Task Scheduling in IoT Enabled Consumer Light Management System

effective low-power state. DVFS has been gradually incorporated into most smart handheld devices and it has been widely adopted by laptop computers, server processor, and mobile devices to conserve energy.

In [119], a method has been proposed combining DVFS and workload scheduling. The method has been implemented in an heterogeneous multi-core WSN device. Work load of tasks has been adjusted with power mode of the hardware in order to satisfy the varied real-time power budget. Machine Learning (ML) based DVFS framework has been proposed in [120]. The framework decides the voltage-frequency scaling suitable to characteristics of the task and configuration of processor. It strikesout the requirement of explicit modeling of processor configuration and is capable to suit itself to various environments without the support of any external supervisor due to the learning ability. Further, DVFS has been implemented on ARM-based off-the-shelf microcontroller [121]. It has been reported that the aforementioned approach is better in terms of energy saving than DVFS being applied only for Central Processing Unit (CPU). Attempts have been made to implement DVFS technique for ultra-low power embedded devices [122]. The proposed method ensures the system can seamlessly adjust energy levels based on load requirements in real time. It enables the system to regulate its operating frequency based on computational demand, operating at lower levels when demand is low and scaling up for maximum efficiency when more power is required. The overall energy consumption of the system has been reduced to 24.74% to 47.74%.

Efforts have been made to minimize the power consumption of wireless sensor nodes by meticulously selecting low-power microcontroller and implementing DVFS technique in the power management scheme [123]. The implementation of the DVFS technique is not only restricted to WSN or IoT devices but is also used in cloud computing. In [124], supply voltage and frequency for servers in cloud computing is tunned incorporating DVFS technique. As a result, the energy consumption of the server has been reported to be reduced significantly maximum upto 25% during the period when the server handles light workloads. Further, DVFS has been used for scheduling tasks in various IoT devices. In [125], DVFS has been explored for task scheduling in a power management framework.

The proposed algorithm efficiently schedules tasks based on forecasted energy, energy budget, and task deadlines. A task scheduling algorithm has been proposed, which has the capability to decide whether the tasks should be offloaded to a cloud server or executed locally [126]. This algorithm utilizes DVFS to adjust the frequency of the cores in a multi-core heterogeneous processing architecture of mobile devices. Reinforcement Learning (RL) based DVFS method has been proposed in [127] for task scheduling. This approach has been found to reduce power consumption in multi-core embedded systems while maintaining reliability for executing sporadic tasks and meeting deadlines.

DVFS algorithm is not suitable for scheduling tasks on energy harvesting-based battery-less sensors because of the limitations of resource-constrained hardware. The energy harvesting circuits are intentionally designed to be simple in order to minimize energy losses. However, this simplicity may limit the availability of different voltage levels for performing tasks on the sensor node. As a result, alternative task scheduling algorithms can be used to seamlessly minimize energy consumption in resource-constrained sensor nodes, without any additional overhead in terms of energy and resources.

8.2   Decomposing and Combining of Tasks

This algorithm breaks down the energy-intensive tasks into smaller subtasks, resulting in reduced energy consumption during their execution. Typically, this technique involves four phases that involve decomposing and combining such as decomposition, combining, admission control and optimization. The functioning of this technique has been graphically presented in Fig. 19.
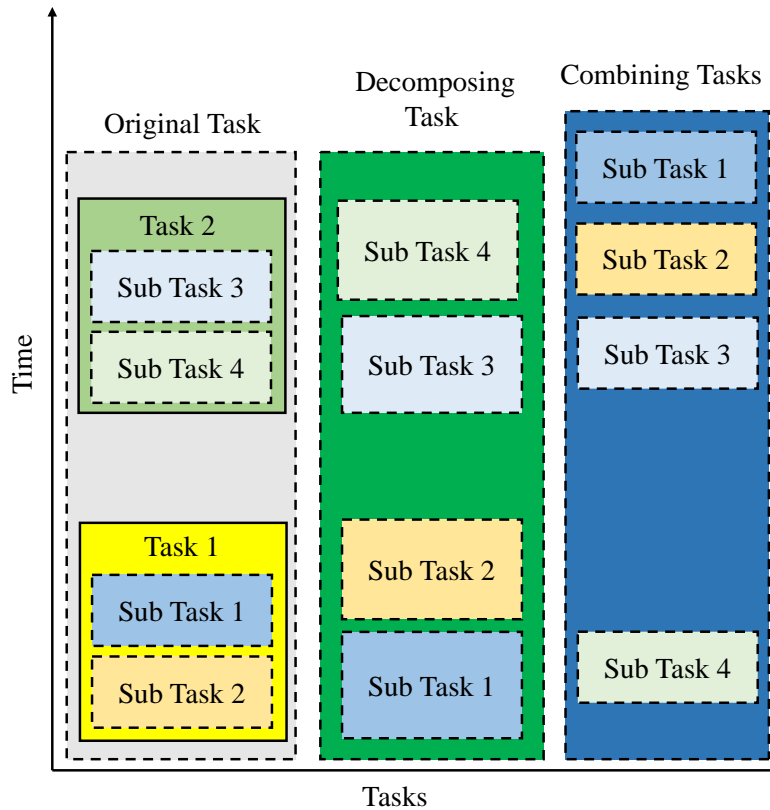

Fig. 19: Decomposing and Recombining Tasks

- Decomposition: Energy intensive tasks are broken down into various subtasks based on their potential to be combined with other subtasks to save energy. If the energy harvested is insufficient to sustain continuous high-powered tasks, the subtasks can still be carried out using the limited energy available.
- Combining: This phase involves the integration of various subtasks that can be performed on a single processor in order to reduce energy usage. Furthermore, there are certain tasks which can be simultaneously

executed and reduce the idle time of the processor. Simultaneous execution offers the benefit of decreased delay and lower latency in task execution. However, it also necessitates more energy, which is only available intermittently in energy harvesting enabled IoT sensor nodes.

- Admission Control: During this phase, the tasks are sorted based on their priority and the energy consumed when executed. While efforts are made to optimize the energy consumption of the system; still, harvested energy is very often insufficient to ensure that all the ready-to-go tasks are executable. Thus, admission controller takes into account the priority of tasks, the amount of harvested energy available, and the energy consumption of tasks to filter the tasks. It considers two major aspects of tasks in order to arrange the tasks i.e. task priority and task deadline. Task priority has significant importance specifically in time-critical real-time applications. Task deadline is categorized into two types such as hard deadlines and soft deadlines. Hard deadlines are very critical and missing hard deadline can cause major loss to the system and often can be fatal. On the other hand, soft deadlines are critical for the application; however, unlike hard deadlines, violation of soft deadlines does not create severe consequences.

- Optimization: In this phase, the execution of tasks is optimized by considering the available energy, the number of task executions, and the energy consumption of each task. This phase further filters the tasks to ensure the efficient utilization of the harvested energy. The availability of additional energy is crucial in determining the implementation of time-sensitive tasks in the future. The system needs to ensure sufficient energy is stored in the storage unit in order to ensure the execution of future tasks with hard deadlines.

Multicore processors are widely used in various computing systems, including general-purpose computers and real-time embedded systems. In [128], a decomposition based scheduling algorithm has been proposed for real-time tasks. The proposed technique showcases a solution to address the issue of dividing subtasks into multiple parts, resulting in a reduction of the overall density of the Directed Acyclic Graph (DAG) tasks following decomposition. In [129], a scheduling technique for parallel real-time tasks has been proposed. The decomposition algorithm takes the structural characteristics of each task into account with the objective of enhancing schedulability. Schedulability tests have been done for the global Earliest Deadline First (EDF) scheduling algorithm using decomposition techniques. A combination of Global EDF with restricted migration and density separation has been reported to perform better in terms of schedulability. Further, a method based on granularity is proposed for task decomposition analysis for manufacturing systems [130]. In this method, small subtasks are recombined and organized based on the desired level of detail, resulting in the decomposition of the manufacturing tasks. This work introduces a mathematical model and an algorithm to solve the problem of subtask scheduling efficiently. Subsequently, multi-granularity task decomposition and hierarchical task scheduling have been investigated within a collaborative computing network spanning the cloud, edge, and end devices [131]. Long Short Term Memory (LSTM) based resource prediction scheme has been used for task decomposition in this work. Nevertheless, in the case of energy harvesting-enabled and batteryless IoT devices, it is challenging for the device to execute multiple tasks simultaneously rather than a specific portion of a task at a time due to the availability of limited energy [132]. Thus, this technique is not typically considered to be incorporated for task scheduling in state-of-the-art energy autonomous IoT devices.

8.3 Duty Cycle

One of the most effective approaches to reduce energy consumption and task scheduling in state-of-the-art energy-autonomous devices is implementing the duty cycling technique, which is widely recognized and employed. It involves periodically turning off the device to conserve energy when it is not actively used. The functioning of this technique has been graphically presented in Fig. 20. This technique enables the device to switch between diffrent energy saving modes. Primarily, it puts the device in active mode for a short period of time, during which the device executes the energy consuming tasks such as wireless communication, sensing, and control actions. Subsequently, the device goes into low-power modes for the rest of the time in an operation cycle. The device usually consumes power in the milli range when it's active and in the micro range when it's in low-power or sleep mode. Solar energy powered battery-powered LoRaWAN based IoT devices proposed in [133] – [134]. implements the duty cycle technique for power consumption. On the other hand, battery-less IoT devices proposed in [135], [136] have incorporated the afformentioned technique for energy optimization and scheduling.

However, the duty cycle in state-of-the-art energy autonomous IoT devices is configured considering various factors such as number of tasks, energy consumption of tasks, and the remaining energy of the node. The common major drawback of these works is the variability of harvested energy caused by changes in environmental conditions, affecting ambient energy availability. Thus, the duty cycle of a node should be adjusted based on the amount of energy it receives to effectively utilize the energy for future tasks. The sleep period of a node can be regulated based on the amount
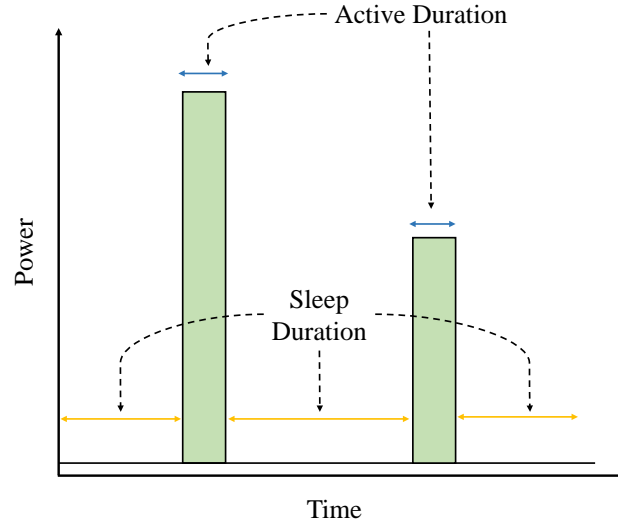
Fig. 20: Duty Cycle based Power Consumption Optimization

of energy that will be harvested in the future in order to strategically manage the energy consumption for task execution.

Thus, duty cycle has been devided into two categories as outlined below.

- Energy Budget-Based Duty Cycling
- Predicted Harvested Energy-Based Duty Cycling

8.3.1   Energy Budget-Based Duty Cycling

The duty cycling mechanism in a sensor network relies on factors such as the amount of harvested energy, energy consumed, and the distance between nodes and the data receiver. In a typical IoT system, nodes close to the central point often experience faster resource depletion due to the additional workload of relaying data from distant nodes through multiple hops. However, the nodes with energy harvesting capability can sustain and operate continuously. The duty cycle of a sensor node is determined by the average amount of energy harvested and energy consumed in both high power mode or active mode and low power mode or sleep mode. The duty cycle should be tuned to ensure the total energy consumption does not surpass the harvested energy. Correspondingly, harvested more energy leads to elevate the duty cycle to enhance performance while staying within the allocated energy budget.

In [137], a model for determining the appropriate size of an energy storage unit for sustainable embedded systems has been proposed. An optimization scheme based on the duty cycle technique has been implemented on an embedded device to validate its performance experimentally. Furthermore, a mathematical model is introduced for optimizing the power consumption and task scheduling in sensor nodes based on the available energy [138]. An emperical model has been introduced for maximizing performance improvement and task scheduling in sensor nodes, considering the available energy. The model optimizes system performance by adapting to the dynamics of the renewable energy source, enabling energy neutral operation. In this work, the harvestable energy in the future has been predicted using the Exponentially Weighted Moving Average (EWMA) technique. In [139], a duty cycle based Media Access Control (MAC) protocol has been proposed to optimize energy usage in cooperative WSNs. The proposed algorithm can schedule the active period and sleep period of the sensor node considering the remaining energy of the node, and data needs to determine when they should be active or in sleep mode.

Subsequently, duty cycle technique has been used in determining the optimal sensing scheduling policy for a sensing system with energy harvesting capability equipped with limited size battery [140]. The proposed work dynamically chooses the next sensing epoch based on the battery level at the current sensing epoch. Furthermore, energy allocation schemes for energy harvesting enabled sensing devices have been proposed to maximize the utilization of periodically harvested solar energy and minimize fluctuations in energy allocation [141]. On the other hand, novel online sensing

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scheduling policy has been proposed for an energy harvesting enabled sensing system considering both finite and infinite battery cases [142]. The policy selects the subsequent sensing epoch based on the battery level during the current sensing epoch. A duty cycling technique based event-driven strategy is proposed for efficient power management in a device deployed on the roadside [143]. The system harvests energy from sunlight and sends data packets using EDF algorithm depending on the traffic flow. The proposed approach results in a significant reduction in power consumption, implying maximizing the lifetime of the device.

8.3.2 Predicted Harvested Energy-Based Duty Cycling

The amount of harvested energy has often been reported as insufficient to enable the energy harvesting devices to execute high energy consuming tasks. Thus, estimating the amount of harvestable energy in the future is crucial for effectively managing tasks during periods of energy scarcity. This allows the devices to schedule the tasks considering forecasted energy, ensuring deadlines are met without interruptions. Fig. 21, illustrates the working principle of the technique. The first five tasks are carried out when there is sufficient energy available. However, even though task 6 is scheduled, the level of harvested energy falls below the lower cutoff threshold. Therefore, it has been delayed until the energy level from harvesting is adequate. Since the scheme can predict future energy availability, task 6 is scheduled based on the predicted energy. Implementation of this approach results in more efficient energy utilization and a reduction in the number of missed task deadlines.
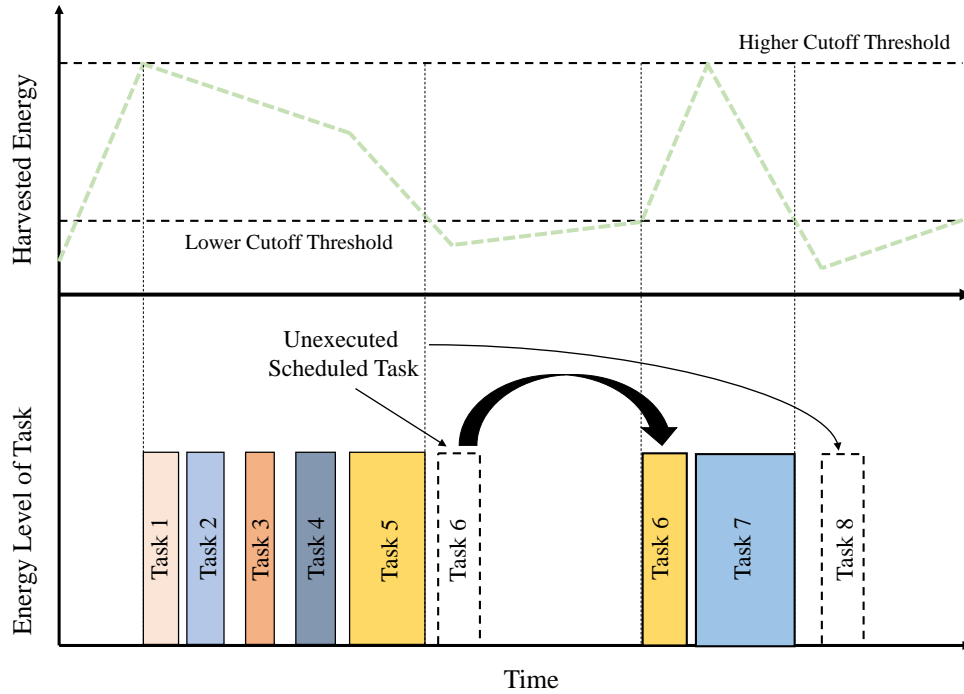

Fig. 21: Duty Cycle based Power Consumption Optimization

A fuzzy logic based adaptive duty cycle task scheduling strategy has been developed [144]. The proposed approach considers three input parameters such as current residual energy, predicted harvesting energy and predicted residual energy parameters for estimating the duty cycle of a sensor node. A prediction model has been used to forecast future available energy. The remaining energy has been estimated for future time slots depending on forecasted energy and energy consumption of the tasks. The amount of harvestable energy can be predicted using various techniques including ML, Deep Learning (DL), and statistical techniques [145], [146], [147]. Furhter, a scheduling framework has been proposed that considers real-world dynamics to optimize long-term tracking performance, considering both energy and mobility factors [148].

The framework utilizes EWMA filter to calculate a virtual energy budget for the remaining forecast period, enabling accurate energy predictions. Further, the proposed information-based Global Positioning System (GPS) sampling

approach utilizes this virtual energy budget to estimate the current tracking error through dead-reckoning. It then schedules a new GPS sample when the error surpasses a threshold. In [149], attempts have been made to efficiently schedule non-uniform samples, both in terms of time and space. It is essential to consider the estimated energy that will be harvested when developing a sampling method. It is particularly crucial when the estimated energy is low. This algorithm also considers the information from neighboring sources when determining the duty cycle. It enhances the duty cycle of nodes in the area surrounding a location where an event has taken place. The other nodes operate at their usual duty cycle to save power. A prediction based adaptive duty cycle MAC protocol has been proposed for energy harvesting enabled WSN devices [150]. Nonlinear Autoregressive Neural Network (NARNET) has been used to forecast future harvestable energy based on historical solar irradiance. The proposed approach efficiently manages the available energy through a duty cycle adjustment scheme. Further, a MAC protocol based on prediction based adaptive duty cycle mechanism has been proposed [151]. The adaptive duty cycle is determined by the predicted amount of energy harvested and the geographical distance to the cluster head or sink.

9 Open Research Direction in Smart Consumer Lighting

This section discusses the open research direction in smart consumer light management systems. These directions are outlined below.

- AI techniques for forecasting traffic patterns and alleviating the load on lighting systems are expected to be a significant future trend. Various advanced AI techniques, including DL and ML, can be implemented on cloud based, cloud-edge based, or cloud-fog-edge based frameworks to evaluate real-time data from sensors and cameras to forecast traffic patterns and modify lighting parameters accordingly [152].
- The increasing deployment of smart technologies emphasizes the critical significance of cybersecurity in smart lighting systems. Thus, integrating cybersecurity into the design of future smart lighting systems is a prominent trend. Securing smart lighting systems against malicious cyber attacks such as denial of service or unauthorized control is essential for safeguarding critical infrastructure, averting outages, and reducing the risks of criminal activities in a smart city environment [153]. Stringent encryption methods and comprehensive authentication mechanisms can be used to protect consumer light management systems against cyber attacks [154].
- Exploring energy harvesting sources such as vibration and wind for powering management systems integrated with street lighting presents a promising avenue for research. It has the potential to yield more sustainable and economically viable solutions for consumer light management systems.
- The battery serves as the primary energy storage component in off-grid street lights; hence, developing a battery health monitoring system for these lights presents a compelling research opportunity [155]. This monitoring system may facilitate the detection of possible battery concerns, such as degeneration or malfunction, prior to a total failure of the street light. Continuous monitoring of battery health enables proactive repair scheduling, minimizing downtime and assuring the operational status of street lights. Implementing a battery health monitoring system in off-grid street lighting might significantly enhance reliability and efficiency.

10 Conclusion

Smart consumer lighting management serves a significant part in the development of smart cities. Over the last decade, it has been shown as a solution that enhances safety, security, and energy efficiency for consumers in public places and indoor environments. Despite ongoing research and development aimed at enhancing various facets of this application, more than 80% of conventional public lights are yet to be replaced with smart solutions. In recent times, vigorous efforts have been undertaken to incorporate IoT compatibility into consumer lighting. The pursuit of sustainability in IoT devices has garnered worldwide interest since most IoT devices rely on batteries for power. These batteries have been identified as the primary source of carbon emissions from IoT nodes, resulting in several detrimental environmental impacts. This manuscript presents a comprehensive review of consumer lighting technology and emphasizes the importance of sustainability in it. The primary distinction of this manuscript lies in reviewing the essential technologies involved in featuring sustainability in consumer light management systems. It provides a comprehensive resource for researchers and industry experts working on consumer light management systems, addressing notable gaps in the current literature and providing a significant reference for the academic community.

The advancement in ICT and Industry 5.0 is expected to introduce significant evolution in smart consumer light management, making it more adaptive, user-friendly, and sustainable, with an emphasis on human-centric technology. It focuses on customization, enabling lighting systems to adjust to individual preferences, needs, and even moods. It may signify lighting that modulates lighting parameters according to user behavior and preferences, improving

well-being and productivity. In addition, the integration of AI in smart consumer light management can ensure light management according to individual preferences for visual comfort, minimizing eye fatigue by implementing task-based illumination control for particular tasks such as reading, working, or relaxing according to the time of day or specific circumstances. The emphasis on sustainability in Industry 5.0 is going to shape the choice of materials for lighting products, leading manufacturers to adopt recyclable and eco-friendly materials, along with manufacturing processes designed to reduce environmental impact.

Acronyms

ABC	Artificial Bee Colony
AI	Artificial Intelligence
ANN	Artificial Neural Network
ART	Actual Execution Time
BLE	Bluetooth Low Energy
CAGR	Compound Annual Growth Rate
CCT	Correlated Color Temperature
CPU	Central Processing Unit
DAG	Directed Acyclic Graph
DALI	Digital Addressable Lighting Interface
DL	Deep Learning
DVFS	Dynamic Voltage Frequency Scaling
E-CPS	Energy Cyber-Physical System
EDF	Earliest Deadline First
EER	Equal Error Rate
EWMA	Exponentially Weighted Moving Average
FOCV	Fractional Open-Circuit Voltage
GA	Generic Algorithm
GPRS	General Packet Rario Service
GPS	Global Positioning System
ICT	Information and Communication Technologies
IoT	Internet of Things
KEH	Kinetic Energy Harvester
LED	Light Emitting Diode
Li-Fi	Light Fidelity
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LSTM	Long Short Term Memory
MAC	Media Access Control
ML	Machine Learning
MPPT	Maximum Power Point Tracking
NARNET	Nonlinear Autoregressive Neural Network
NB-Iot	Narrow Band Internet of Things
NFC	Near Field Communication
NN	Neural Network
PO	Perturb and Observe
PVD	Power Voltage Detector
PWM	Pulse Widht Modulation
QoS	Quality of Service
RF	Radio Frequency
RFID	Radio Frequency Iddentification
RL	Reinforcement Learning
SDG	Sustainable Development Goal
SF	Spreading Factor
TEG	Thermo Electric Generator
UN	United Nation
UV	Ultraviolet
WCET	Worst Case Execution Time
Wi-Fi	Wireless Fidelity
WSN	Wireless Sensor Network

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