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ORIGINAL ARTICLE

IoT-Based Solar-Powered Air Quality Purification and Monitoring Systems

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Abstract

In this paper, we can identify the design, development, and implementation of an IoT-enabled solar-powered air purification and monitoring system, aimed at providing sustainable and real-time solutions for indoor and semi-outdoor environments. The developed system makes use of PM2.5, MQ135, and DHT11 continuing monitoring critical air quality parameters which consist of particulate matter, the concentration of toxic gases, temperature, and humidity; and identifies these parameters before and after the air purifier. Centralized control and data processing are carried out by one ESP32 microcontroller, which controls the operation of the air purifier's blower and transmits sensor data wirelessly to the ThingSpeak IoT cloud platform. Furthermore, the developed system benefits from a solar panel and battery backup which allows for an off-grid energy-efficient system; therefore, the developed. [i.e. solar-powered air purification and monitoring system] is especially suitable because of its energy-efficient design for installation where power is not constant, such as semi-outdoor environments. Information on real-time feedback is available locally (through an LCD display) and remotely (via an SDK cloud platform), so users can be aware of the pollution in the air wherever they are located. For example, it can be useful to compare differences in performance between different types of filters such as HEPA filters and filter paper, showing a meaningful difference in pollution level reductions. A review of the literature highlights an original contribution combining solar power, IOT connections, multi-stage sensors, and filter designs on one platform provides an effective and definitive way to manage air quality. The research findings demonstrated the prototype platform significantly improves air quality with sustainable energy consumption and efficiency in a comprehensive, practical, scalable, and low-cost manner to combat air pollution in home, institutional, and rural communities.

Keywords: IoT; Air Quality Monitoring; Solar Power; Air Purifier; ThingSpeak; Real-Time Monitoring; Renewable Energy; Smart Devices; Indoor Air Pollution; HEPA Filter

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Introduction

Air pollution now has very serious health consequences. It affects millions of people across the planet, contributing to terrible environmental degradation. Fine particulate matter - including PM2.5 (particulates having a diameter of less than 2.5 micrometers) - is even more dangerous as it can enter deep into the tracheobronchial region of the respiratory system which ultimately leads to cardiovascular and respiratory illnesses, reduced lung function, and death [(1)]. Other gaseous air pollutants including ammonia, benzene, nitrogen oxides and smoke, which are included in air pollution, would contribute to environmental challenges and health threats, indicating a strong need for an air quality monitoring and air purification [(2)].

While traditional air purification systems are effective, they lack the ability to leverage real-time data about air pollution levels, which reduces their adaptability and effectiveness in variable pollution conditions. Additionally, because most of these systems are powered by non-renewable energy sources (e.g., electricity), they are also relatively unsustainable. Recently, the emergence of the integration of Internet of Things (IoT) technology has opened up a new, real-time air quality data monitoring approach; and driven away from the electricity-required system model, advanced IoT-based models have allowed us to react dynamically to pollution levels and make decisions based on the air pollution input data [(3)].

However, IoT systems have not been without their power efficiency and scalability issues, especially when deployed in remote or off-grid locations. The authors should make mention of this throughout the paper. In this paper, the authors reviewed the development, design, and utility of a solar-powered air purifier with IoT data monitoring capability. In continual air quality monitoring, particularly for PM2.5 and harmful gases (e.g., measured by sensor MQ135), the author developed a system to purify the air using the blower and filter, all powered by the solar power system so the air purifier could be deployed anywhere, especially in places where electricity is hard to acquire.

This literature review evaluates current IoT-based air quality monitoring and mitigation systems, focusing on solar-powered initiatives, in order to evaluate their effectiveness at pollution reduction, assess energy efficiency, and evaluate possible applications in different sectors. In general, the study adds to the growing literature on sustainable air quality management solutions, and identifies a role for IoT and renewable energy in promoting public health and safety environments.

Literature Survey

M. F. Pu'ad et al. (2018) [(3)] developed a detailed air quality measurement system with Raspberry Pi to monitor real time environmental parameters at various locations. The system incorporates two Arduino Nano boards, a Raspberry Pi 3, a GPS module and three gas sensors to measure temperature, humidity, air quality and geographical location. The design is able to accurately measure PM2.5, PM10 and harmful gases including (sulfur dioxide, carbon monoxide, nitrogen dioxide, ground ozone). The design was tested in both high and low traffic areas and it has a reliable accuracy rate, with a 3.23% error margin when compared to Continuous Air Quality Monitoring Stations (CAQMs) in Malaysia.

Dinesh Panicker et al. (2020) [(4)] developed a system that encompasses air quality monitoring and purification for indoor and outdoor use. The system consists of 2 parts: first a filtering unit with a dust, pre-filter and fine filter and second an air quality monitor using the MQ135 sensor. When the pollutants exceeds the thresholds, the device will automatically begin the air purification process. The MQ135 recognizes pollutants such as NH_3, NOx, alcohol, benzene, smoke, and CO_2. The prototype was successful in detecting contaminants and decreasing pollutants within small spaces; however, past a certain point the sensors were unable to work.

B. Jayasree et al. (2021)[5] developed an indoor space air quality monitoring system built around IoT using a ESP8266 module for seamless data sharing. The inexpensive system consists of basic sensors to measure gas, temperature, humidity, and dust concentrations, sends data to ThingSpeak in real time. The system can notify end user is threshold pollution levels are reached. It measures pollutants CO, CO_2, NO_2, PM10 and environmental measures. Given the simple to implement, wheeled device - designed to be open-source - and the recommended uses in homes, schools, and office.

T. Veeramanikandasamy et al. (2020)[6] developed a real-time air quality monitoring system for industrial environments. The system employed the ESP32 microcontroller, dust optical sensor SDS011, MQ135, temperature and humidity sensors. The pollutants detected included CO_2, CO, ammonia, PM2.5, and PM10. The result was displayed on the Virtuino app and the ThingSpeak platform also updating every five minutes in order to consistently monitor the air quality in industrial situations. Workers and managers were therefore able to be alerted of industrial gas leaks earlier to reduce risk.

Manisha Sharma et al. (2017)[7] developed the I2P (Impure to Pure) system for air quality monitoring, and purification providing suitable means for pollution-afflicted environments such as hospitals, homes, and offices. The I2P system monitored pollution by using a MQ2 sensor for vapours from LPG, combustible gas and smoke, as well as temperature and humidity sensors. In the event that monitored levels of pollutants statistically surpassed a safe threshold, the I2P would inform users, as well as turn on the multi-stage purification process made up of HEPA, activated carbon, silica gel and U/V lamps. It is ultimately a staged process to purify air as thoroughly as practical for indoor spaces, especially more sensitive spaces (e.g., hospitals).

In 2017, Hak Joon Kim and Bangwoo Han[8] developed an electrostatic air purifier for environment application, utilizing both an activated carbon fiber (ACF) sheet with electrostatic forces to capture and neutralize both airborne particles and gases. This purifier was able to provide a 35% higher clean air delivery rate (CADR) than traditional HEPA filters with a faster reduction rate for harmful gases.

In 2018, Kennedy Okokpujie and Etinosa Noma-Osaghae[9] developed an Arduino-based air pollution monitoring system that collects real-time data for air quality recording and transmitting to the cloud. The air pollution monitoring system converts data to Parts Per Million (PPM) to allow the end-user to monitor air pollution levels in real-time via a mobile application on governance laws.

The literature review on air quality monitoring and purification systems has shown significant advancements in creating solutions for various environments including residential, industrial, and mobile. Moreover, with the advancement of the Internet of Things (IoT), these systems have reached the level of performing monitoring and providing data-driven control to users in real-time while also be more accessible. The studies mentioned important insights that were very helpful, and one of these was that sensor based air quality systems were highly successful in measuring pollutants and purifying air, however there were still some challenges to overcome especially with scaling, energy efficiency, and adaptability in different environments.

A. Advancements in Real-Time Monitoring and IoT Integration

Most of the reviewed approaches, such as those by Jayasree et al., and Veeramanikandasamy et al., show that IoT integration significantly enhances air quality monitoring because of the remote capabilities of data and real-time data flow. When utilizing cloud platforms such as ThingSpeak, and mobile applications, users have real-time insight into air quality and can respond quickly to pollution level variations. All of these IoT-enabled approaches help facilitate the continuous monitoring of key pollutants (e.g., CO, CO_2, NO_2, and PM2.5) especially in closed areas where manual checks for air quality would be ineffective.

B. Energy Efficiency and Sustainability

A hopeful advancement regarding air purification systems is that designers really focus on energy efficiency, illustrated by the product created by Hak Joon Kim and Bangwoo Han (2017), an electrostatic air purifier, this system used activated carbon fiber to decrease energy use in confined spaces, like automobiles. Studies such as Sharma et al. study sustainable approaches to air purification systems using natural aspects through building and using HEPA filters and UV lights (which eventually rely on energy sources from the grid), but new systems of purification systems should look more into renewable energy sources. That is, using existing approaches with/and/or solar panels could provide the proper baseline to explore air purification sources that aren't dependant on an outside power source and perhaps more lend themselves to disbursement in remote or energy-poor locations.

C. Application in Dynamic Environment

The mobile air purifier developed by Liang Fan and Chen Hongdou is a significant contribution to the literature. The mobile air purifier uses pedestrian tracking in order to provide localized air purification in densely populated indoor venues like malls and airports. This shift from using static air purification systems provides an improved use of area air quality in grossly dynamic contexts. The method and marginal efficiency are limited when applied to larger scale, open spaces and it requires further improvements.

D. Limitations and Challenges

Many systems experience problems with minimal sensor efficiency and detection range. Sensors that are small platform have less efficiency in large areas according to Panicker et al. Drone-based systems, such as EnviDron, have efficiency limitations due to battery life and coverage. Low-cost sensors also have the limitation of a calibration drift, which may reduce accuracy over time and with change in conditions.

E. The Need for Hybrid Systems and Multi-Stage Filtration

Integrated multi-method purification systems have proven useful in providing integrated air quality treatment as shown in the I2P air purifier design by Sharma et al. The I2P air purifier design included three filtration stages utilizing HEPA, activated carbon, and silica gel filtration that reduced contaminants and people were noticing a difference in the concentration of unwanted particles and gases in the air. These approaches could be reasonably expanded with advanced filtration systems or combined with other purified air systems like electrostatic filtering to improve performance and application in higher pollutant or industrial settings.

Methodology

The solar-powered air purification system proposition overcomes limitations in traditional and battery-powered purifiers by harnessing renewable energy sources and utilizing real-time data monitoring. The system is equipped with PM2.5 sensors and gas recognition sensors to change purification modes based on air pollution levels, therefor being operate in the most energy efficient mode and without being wasteful in energy consumption. After installation the initial costs may be relatively higher but the benefits to the environment and economic savings are instrumental for a smart and sustainable long-lasting air quality management solution. The overall architecture of a solar powered air quality monitoring and purification system framework based on ESP32 microcontroller is exhibited in the Figure 1, which also outlines the power supply components, sensors, air purification and real-time monitoring using IoT sensors.

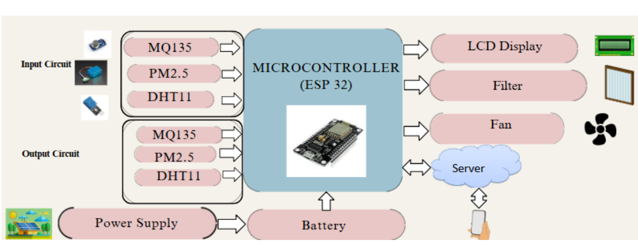

Fig 1. Block diagram of proposed system

The method for development of the IoT-based solar-powered air quality purification and monitoring system is a systematic method that integrates hardware design, software development, and empirical testing. The heart of the system is the ESP32 microcontroller which was chosen for its speed, efficiency, built-in Wi-Fi, and use of a variety of environmental sensors. The air quality monitoring module contains PM2.5 sensors to detect fine particulate matter, MQ135 sensors to measure harmful gases, and DHT11 sensors to gather temperature and humidity readings. These sensors can be located in the trajectory air intake (input) and after the purification module (output) to enable comparative monitoring on sensor readings before and after the purification process.

The purification was facilitated by a blower fan and interchangeable filtration modules such as HEPA filters or standard filter paper to provide options for filtration. The system runs solely on energy harvested by solar panels connected to a rechargeable battery which has a charge controller to monitor and maintain power to the system while protecting the battery from overcharging. As a result, the system can run off renewable energy whether you are on or off the grid; a key benefit for remote locations with low or no energy availability.

The ESP32 collects and processes sensor data continuously. It continuously evaluates air quality and turns the blower system on at predefined pollution threshold levels. The data received by the ESP32 is displayed instantaneously on a local LCD, as well as on the ThingSpeak IoT platform through Wi-Fi. Users can view the trends in air quality from anywhere and receive notifications of pollution events. Sensor communication, data processing, actuator control, and cloud integration were developed in the firmware using the Arduino IDE. The air purification design went through extensive testing in varying environments, some using different types of air filters, to evaluate performance, energy use, and purification effectiveness. The data from the experiments was used to assess the reliability, responsiveness, and appropriateness of the system for real-life air quality management applications.

The Flowchart of the system is shown in Figure 2. The flow chart describes the IoT-based solar-powered air quality purification and monitoring system as it starts by powering the device from a solar panel on a battery, next initialising the ESP32 microcontroller and the sensors that had been connected to the ESP32 microcontroller. The input sensor is at the air intake, and the output sensor is from the outlet. The system continuously captures real time data from the sensor for the two particulate matter sensors - which are PM2.5 - from the gas concentrations sensors - which are MQ135 - and providing real time temperature and humidity values from the DHT11 chip. The real time data is displayed on the LCD screen locally, and to the ThingSpeak IoT platform remotely.

The real-time data is powered by the battery from the initial solar energy capture. The ESP32 Microcontroller is provided with real time data from the input sensors and output sensors simultaneously with the continuous monitoring to determine air quality values from both input sensors and final output sensors. Based on measured concentrations of concentrations of pollution, if any levels of pollution exceeded values set in the ESP32 programming, from the data from the ESP32 microcontroller, that would send a signal to trigger the activation of the blower, and activate the system that there was contamination from pollutants such as PM2.5 - gas and particulate matter to repeat the cycle via purifying the air through HEPA - or filter paper. After purification had been completed, the output sensors would measure the effective performance of the purifier system, and if the air quality was still poor, the system would send signals to communicate the poor air quality via buzzer, and via LCD screen, and also SMS communication if it was in the original specified programming. This process would reoccur continually, so that there are dynamic air quality management in real time, efficient purification of air quality at low cost with remote access and monitoring.

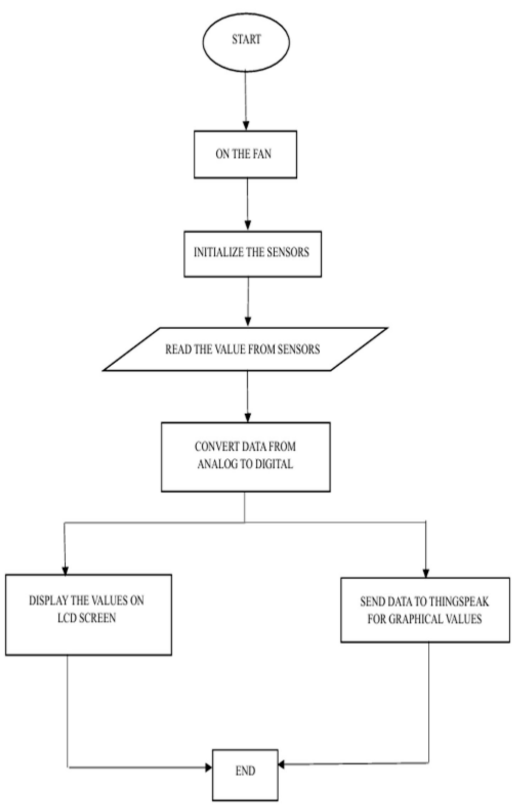

Fig 2. Flowchart of the proposed system

Results

The results section showcases all experimental results and performance tests for the IoT based solar powered air quality purification and monitoring system. After a comprehensive testing program in numerous testing environments, the system demonstrated air quality monitoring, air quality purification, and air quality reporting capabilities. Real-time sensor readings were recorded and the data was represented locally and in the ThingSpeak IoT platform. The sensor data enabled the authors to share with users readings of ambient air for particulate matter, harmful gases, temperature, and humidity before and after the filtration. The test results also compared numerous filter types (HEPA and plain filter paper) to ascertain the system's purification effectiveness. The following results represent the performance reliability measures and the efficacy of the proposed system for providing isolated filtered air with remote monitoring capability.

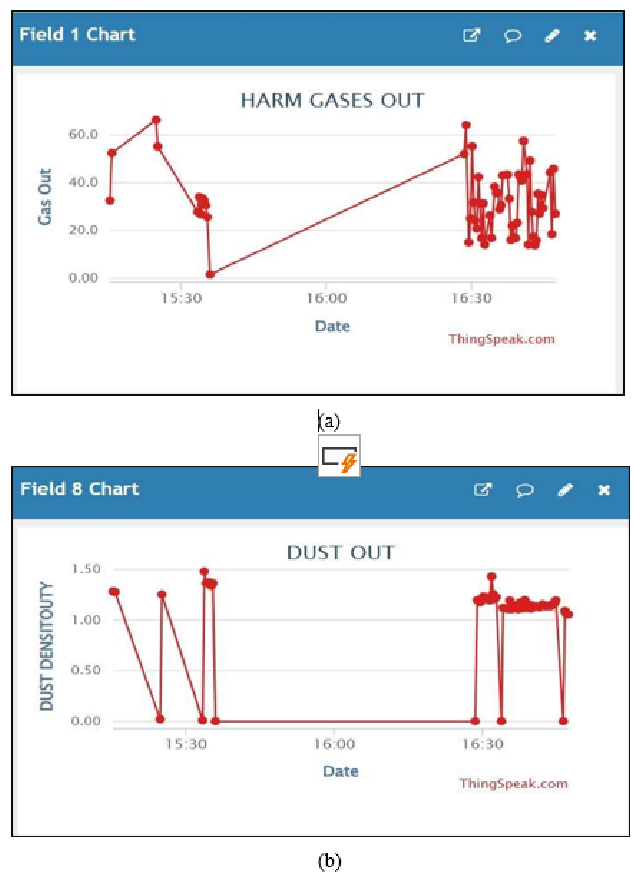

Fig 3. The reading of airpurifier sensors on ThingSpeak cloud platfrom

The results are summarized in Figure 3 and show the successful use of real-time monitoring and remote data logging of the implemented air purifier system using the ThingSpeak IoT cloud platform. The ESP32 microcontroller, continuously uploaded sensor readings of the PM2.5 concentration, harmful gas readings from the MQ135 sensor, and parameters of temperature, and humidity readings form the DHT11 sensor, to ThingSpeak, where these readings could be viewed graphically, and as data trends, from any location by the user. The ease of applying the total air quality measurements and trends of both input and output air quality conditions was possible due to the visualization abilities of the ThingSpeak platform, which permitted easy observation of the trends in effectiveness of the system detecting a change in air quality. The results show an ongoing and continuous drop in the PM2.5 and harmful gas readings were clear data trends after the air had passed through the purification unit, but especially evident with the use of HEPA filters indicating the potential of the units to improve air quality. Finally, the availability of live remote data provided convenience to users, and permitted opportunities for intervention and decision making should air quality measures exceeded thresholds. The results confirm the hoped-for outcomes of the project with a successful, reliable, automated air quality solution with minimal energy usage, and IoT-based monitoring, and reporting capabilities.

The emergency alert obtained on SMS through twilio library is present in Figure 4.

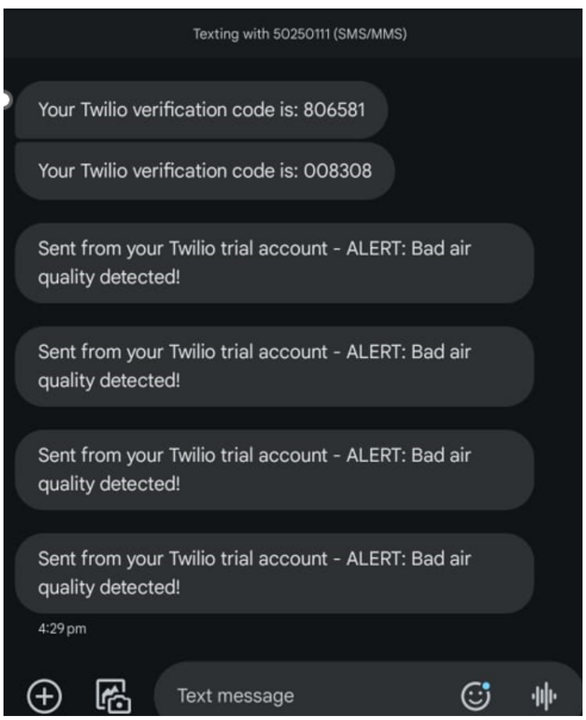

Fig 4. Emergency alerts through sms

Figure 4 demonstrates the system's emergency alert system, in which important air quality data creates real-time alerts over the SMS protocol. When the ESP32 microcontroller detects that any air quality measure is above the safety threshold including PM2.5 concentration, toxic gases, or temperature, it triggers the alert process through a cloud-based service like Twilio (or other service). The ESP32 microcontroller sends an immediate SMS message as notify a registered user on the other side of town, and helps to alert users of potential environmental hazards even when they are not physically present to interact with the device. Rather, the emergency alert system ensures that users are quickly aware of the air quality and can initiate timely actions to safeguard their health and safety in the affected environment. The emergency alert system further demonstrates that the system can perform more than just continuous monitoring and removal, but engage the user at an active level when hazardous air quality conditions occur to reduce possible risks in real-time. This advancement is a huge benefit in providing a needed solution in vulnerable spaces, like homes, classrooms and workspaces, where timely interventions should occur to remediate unhealthy air quality.

Table 1. Air quality obtained from different filters

Filter Paper		HEPA Filter	
Input Air	**Output Air**	**Input Air**	**Output Air**
26.47131	22.00244	18.02198	2.46642
26.64225	22.39316	18.0464	2.51526
26.03175	22.00244	18.14408	2.46642
25.95849	22.00244	18.07082	2.46642
25.34799	22.14896	17.97314	2.39316
24.98169	21.53846	17.9243	2.51526
24.76191	21.92918	18.09524	2.442
24.81075	22.10012	18.33944	2.58852
24.98169	24.90842	17.89988	2.51526
25.27473	24.61539	15.77534	3.95604
25.37241	24.76191	15.77534	3.88278

Table 1 gives comparison of air quality before and after using two filters: Paper and HEPA.

- Paper Filter: slightly improves air quality; output values remain high (around 22–24).
- HEPA Filter: significantly improves air quality; output values drop to around 2.5–3.0.

HEPA filter is much more effective than the paper filter in purifying air.

Conclusion and Future Scope

The research presented in this document describes the successful design and implementation of an IoT-based solar powered air quality purification and monitoring system that can effectively and sustainably address the ambient air quality needs within indoor and semi-outdoor environments. The system consists of multiple environmental sensors (PM2.5, MQ135, and DHT11) paired with an ESP32 Microcontroller that can continuously monitor particulate matter, toxic gases, temperature and humidity of an environment. The system is designed to use renewable solar energy and utilizes live real-time cloud connectivity using the Thingspeak platform to collect and manage environmental air data. The system is efficient and operates off-grid, making it useful for areas with poor electricity supply. Experimental data identified significant on-board pollution levels reductions and publicly available data source and monitoring data indicated reasonably lower pollutant levels when using advanced filter systems such as HEPA filters. The systems abilities to provide continuous web-based data visualization, local and remote alerts (LCD and SMS), and automatic blower control demonstrates the reliability of the system and its smart capabilities. Overall this project presents a cost-efficient air quality management solution that is environmentally friendly, sustainable, public health relevant and can be adapted for larger systems to accommodate for scale of solutions.

The system has many potential avenues for enhancement and applications in the future. Future enhancements might include the incorporation of advanced forms of data analytics with machine learning and other AI components to predict pollution trends and automatically optimize purification cycles. The system can be increased in size for larger environments/environments, or networked with several units (as described previously) for urban and industrial applications. Additional sensors for other air pollutants (e.g., CO, NO_2, or ozone) can also be added to increase coverage for passive air monitoring. Added functionality, such as a mobile app for integration with the system, automated maintenance alerts when filters must be replaced, and real-time mapping capabilities to monitor geographical overlays between set points and corrosion rate tracking, can enhance the panoramic experience and usability. The anticipated ability to integrate solar with other renewable sources (on a one-to-one replacement basis, for example) combined with light, low-power communications (e.g., LoRaWAN) can strengthen the sustainability and operational reach of the system even further. All of these avenues could make the solution even more complete, intelligent, and ready for implementation at scale in smart city deployments and rural communities.

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