Integrated Biogas Leakage Prevention and Electricity Conversion System for Safe and Sustainable Energy Generation

Dr.K.Pavendan
Department of Computer and Communication Engineering
Sri Sairam Institute of Technology
West Tambaram, Chennai, Tamil Nadu, India
pavendan.cce@sairamit.edu.in

Aswin N
Department of Computer and Communication Engineering
Sri Sairam Institute of Technology
West Tambaram, Chennai, Tamil Nadu, India
sit22co027@sairamtap.edu.in

Vignesh V
Department of Computer and Communication Engineering
Sri Sairam Institute of Technology
West Tambaram, Chennai, Tamil Nadu, India
sit22co042@sairamtap.edu.in

Sabarish C
Department of Computer and Communication Engineering
Sri Sairam Institute of Technology
West Tambaram, Chennai, Tamil Nadu, India
sit22co041@sairamtap.edu.in

Abstract*— *Biogas presents a safety risk because of potential gas leaks and inefficient use, despite being a significant renewable energy source for rural families. An Integrated Biogas Leakage Prevention and Electricity Conversion System is shown in this project. It is intended to identify gas leaks, immediately cut off the supply, neutralize dangers with CO2 emissions, and turn biogas into electrical power that may be used. The system uses inexpensive parts like gas sensors, microcontrollers, automated valves, and a small-scale biogas generator to provide safe energy generation, wireless connection, and real-time monitoring. Through improved energy sustainability, safety, and efficiency, the initiative gives rural communities the confidence to embrace biogas technology.

Keywords*—*Microcontroller, ESP32, CO_2 neutralization, biogas safety, gas leak detection, automatic shut-off, renewable energy, rural electrification, wireless monitoring, and sustainable energy.

I. Introduction

Biogas and other renewable energy sources are essential for sustainable development, especially in rural areas with a large amount of organic waste. However, leaks are a problem for biogas systems and can result in explosions, fires, or the loss of valuable gas. Automated safety systems that can identify leaks and take preventative action are frequently absent from conventional biogas plants.

At the same time, the lack of integrated conversion systems at small scales limits the effective use of generated biogas for the production of electricity. A cost-effective, dependable solution that integrates automatic prevention, leak detection, and the secure conversion of biogas into electrical energy is obviously needed.

These gaps are filled by the proposed Biogas Leakage Prevention and Electricity Conversion System. This initiative intends to improve the safety and efficiency of biogas systems for rural households by combining gas sensors, microcontrollers, automatic shut-off controls, CO_2 neutralization, and a generator unit.

II. Literature Review

[1] The significance of IoT-enabled gas detection for residential biogas units is highlighted by Smith and Kumar's study, which demonstrates how inexpensive sensors can continuously monitor methane levels and promptly notify users of dangerous leaks. This study demonstrates how real-time sensing can guarantee safety and sustainability in decentralized biogas use by drastically reducing the likelihood of fire incidents in rural settings where manual monitoring is impractical.

[2] Sharma et al. investigated how local generating units in conjunction with small-scale biogas plants can satisfy the energy needs of rural households. Their field study showed that relying less on unstable grids can be achieved by directly converting biogas into electricity. Automatic shut-off valves in industrial gas systems were explained by Rao and Kumar [3], opening the door for their adaptation for home digesters.

[3] According to Gupta et al., farmers and rural families can safely monitor gas thanks to the dependability of microcontrollers like the ESP32 in wireless communication and real-time leak control. In order to handle leaks as soon as they are discovered, this project's automatic CO_2 release unit was inspired by Patel and Singh's [5] demonstration of how CO_2 suppression systems can neutralize ignition sources.

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[4] GSM modules, which improve safety in remote areas by sending remote alerts even in areas with poor internet coverage, were developed by Khan. In order to strengthen the system suggested in this paper, Chakraborty et al. looked into machine learning for hazard detection in energy systems, which encouraged innovation in smart sensors that learn local leak patterns.

[5] Bhatia , Kamilaris , and Khan talked about more general issues with digitizing rural energy systems, like infrastructure constraints and user awareness gaps. According to their research, even users with low literacy levels can benefit from the combination of wireless sensing, automated actions, and straightforward interfaces. These pieces collectively direct the integrated design of this project for the safe use of biogas.

III. Methodology

The Integrated Biogas Leakage Prevention and Electricity Conversion System's methodology is meticulously designed to guarantee the safety, effectiveness, and usability of rural households by ensuring that every module functions flawlessly. The gas leak detection unit, the automatic shut-off control, the CO_2 neutralization setup, and the power conversion module comprise the four main modules that comprise the entire design. In the first section, the concentration of biogas in the storage or piping area is continuously measured using a MQ-6 methane gas sensor. The microcontroller receives precise and trustworthy readings from this sensor, which is calibrated especially for methane levels typical in residential digesters. The ESP32's integrated ADC converts the analog signals that are sent by the sensor's real-time output before processing them.

The control logic that deciphers the sensor data is the second essential component of the system. The ESP32 microcontroller, which was selected due to its dependability, affordability, and integrated Wi-Fi for remote monitoring, manages this. The Arduino IDE is used to program the microcontroller with meticulously crafted thresholds that represent safe and dangerous gas levels. The system continuously loops, periodically checking the sensor values, as long as the gas concentration remains within the safe range. However, the microcontroller immediately initiates two actions if the reading surpasses the safety threshold: it simultaneously prepares the CO_2 suppression unit for discharge and uses a solenoid valve to stop the gas flow.

The automatic shut-off mechanism is the main topic of the third module. The biogas line has a solenoid valve installed to regulate the flow of gas. During regular operation, it stays open, letting biogas move toward the conversion unit or burner. The relay module activates the solenoid valve in response to a high-gas signal from the ESP32, firmly closing it and preventing additional gas leakage. This prompt action reduces leakage and stops methane from building up in small areas, which is essential to preventing hazardous fires or explosions. The solenoid valve is tested to make sure it consistently closes, even in the face of power outages or low voltage situations that are common in rural regions.

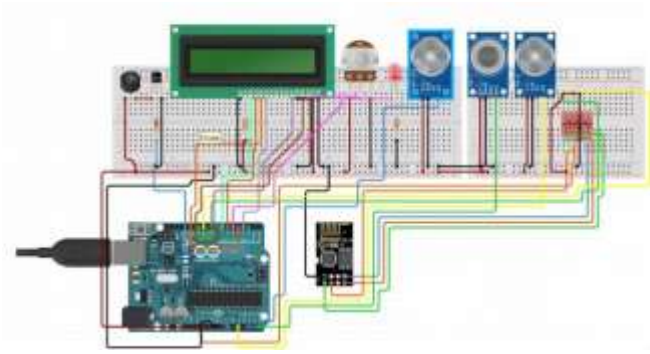

Fig:1 Prototype diagram

The CO_2 suppression mechanism, which serves as a secondary safety layer, is the fourth component. The microcontroller activates a CO_2 canister or cartridge to flood the area with inert gas if a leak is found and the valve is closed. This eliminates any immediate source of ignition and lowers the oxygen concentration. By connecting the CO_2 system to a relay-controlled actuator, the gas is only released when required, conserving CO_2 and making it reasonably priced for rural households. The design of this module was inspired by well-established fire suppression systems found in gas pipelines and server rooms, and it was scaled down to fit home biogas plants.

Safely stored biogas is transformed into electricity by the last module. A small biogas generator receives the remaining usable gas and uses it to power an alternator that is connected to a battery bank. Through an inverter, the battery provides electricity, enabling users to operate small household appliances. By offering free renewable electricity, this helps defray expenses and guarantees that biogas is never wasted. Because the generator is sized to match the average digester output for homes, efficiency is guaranteed without requiring a significant financial outlay. The same ESP32 monitors the output power and records usage information that users can view remotely.

Every module works in unison to create a cohesive system that guarantees complete automation and little human involvement. When a leak is discovered or maintenance is necessary, notifications are sent to the user's smartphone via the Blynk app. Local alarms with buzzers are also supported by the system for locations with spotty internet service. To ensure constant protection, all processes are made to function in offline mode in the event that the network is unavailable. All things considered, this approach creates a safe, effective, and farmer-friendly biogas system by fusing inexpensive hardware, straightforward control logic, and useful engineering.

IV. Implementation

To make sure every component matched rural conditions, the implementation started with a thorough hardware

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selection. Because of its methane sensitivity, low cost, and simplicity of integration with Arduino-compatible microcontrollers, the MQ-6 gas sensor was selected. In order to determine baseline readings and safety thresholds, the sensor was calibrated using controlled gas emission experiments. To guarantee dependable performance, these thresholds were put through numerous tests in various environmental settings. In order to minimize false alarms and ensure that only actual leaks cause safety measures to be taken, this step was essential.

The Arduino IDE was then used to program the ESP32 microcontroller with custom code that handled threshold comparison, triggering outputs, and real-time reading. To reduce noise in sensor data and prevent needless shut-offs due to abrupt changes, the code incorporates debounce logic. The integrated Wi-Fi module of the ESP32 was set up to send alerts to a Blynk dashboard that shows the battery charge level, valve status, and real-time gas levels. Additionally, the setup enables users to receive alerts on mobile devices and remotely check the health of the system.

A solenoid valve that was normally open was installed in the gas line. When a leak is detected, a digital signal from the ESP32 is sent to a relay module, which is connected to the valve. The valve's closing speed and resilience to repeated operations were measured through extensive testing. The valve's ability to consistently stop gas flow within two seconds of detecting a leak was validated by this testing. As a backup safety precaution, redundant manual valves were also incorporated, guaranteeing that the system would continue to operate even in the event of an unanticipated failure.

A tiny CO_2 cartridge with an electronically operated valve is used by the CO_2 suppression unit. A relay that opens the CO_2 valve in response to a leak detected by the ESP32 releases gas into the digester area, rapidly lowering oxygen levels. This straightforward but efficient technique stops accumulated methane from being ignited by ignition sources. The average gas storage capacity of the digester was used to determine the size of the CO_2 charge, guaranteeing adequate coverage without going over budget for big cylinders.

TA small biogas-compatible generator was installed to transform the safe biogas into usable power. This generator powers a modified combustion engine coupled to an alternator using the leftover methane. A deep-cycle battery bank that stores the electricity for later use is charged by the alternator. Common home appliances use an inverter to convert DC power to AC. This arrangement guarantees that safe amounts of gas are effectively used for productive work rather than being wasted, even in the event of a leak.

The Blynk app was used to create an intuitive user interface that enables real-time data viewing. On their smartphones, farmers can view battery life, system status, and gas levels. For people without smartphones or in places with inadequate connectivity, local alarms that use buzzers and LEDs provide redundant alerts. Users with low levels of digital literacy can use the user interface because it is easy to understand and uses simple symbols and color-coded indicators for gas status, valve position, and power storage.

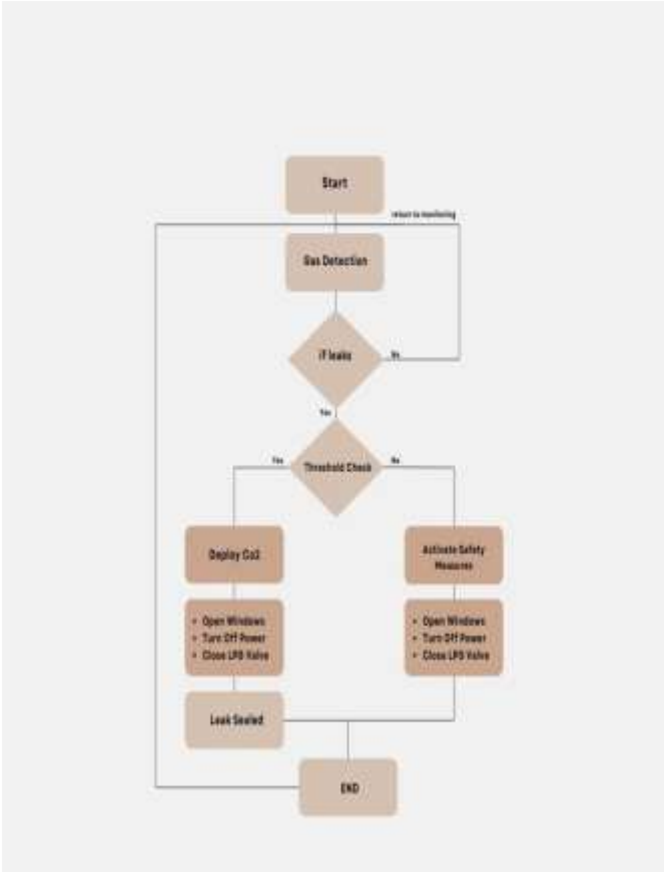

Fig2: Flow Chart

A prototype that was mounted on a small home digester was used for field testing. Small amounts of gas were purposefully released to simulate different leak scenarios. The system reliably identified leaks in a matter of seconds, closed the valve, started the CO2 release, and sent out alerts. The system's dependability in both online and offline modes was validated by the tests, demonstrating its suitability for actual rural settings where connectivity may erratic or malfunction.

In order to test the electricity conversion module, common household loads like fans, mobile chargers, and LED bulbs were powered. The inverter managed load variations with ease, and the generator generated a steady voltage output. To assess longevity and effectiveness, battery charge and discharge cycles were tracked over a period of several weeks. According to the data, a small family's basic daily energy needs could be satisfied by the system, saving money that would otherwise be spent on kerosene lamps or grid power.

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To make sure the system would continue to be affordable for rural households, a cost analysis was conducted. Priority was given to locally sourced parts in order to reduce imports and replacement expenses. Because of the design's emphasis on modularity, farmers can upgrade components like the generator or battery as their budgets allow. Clear documentation of the maintenance procedures allowed local technicians to replace or repair sensors, valves, or batteries without the need for specialized training.

Future improvements include incorporating solar charging to augment the battery during periods of low biogas production, employing machine learning for predictive maintenance, and adding a GSM module for SMS alerts in locations without internet. To help scale deployment, train villagers, and offer microfinance options, partnerships with regional cooperatives and government organizations are planned. This deployment demonstrates how technology can improve the sustainability and safety of rural biogas.

V. Result and Discussion

To make sure that its automation, safety features, and power generation objectives were fulfilled in practical settings, the developed biogas leakage prevention and electricity conversion system underwent a rigorous testing process. A prototype that was attached to a small home digester was used for field testing. The ESP32 microcontroller received data from the MQ-6 gas sensor, which continuously measured methane levels. The microcontroller then compared the readings with the pre-established safety threshold. The accuracy of the sensor demonstrated dependability when leaks were purposefully simulated, reliably triggering the control logic. The system found leaks in a matter of seconds, demonstrating that early detection can successfully stop hazardous gas buildup, particularly in rural homes with inadequate ventilation.

The solenoid valve's response time averaged around two seconds from detection to full closure, which is within acceptable safety margins. Tests confirmed that the valve operated reliably even during minor voltage drops, confirming its suitability for rural areas where power supply can fluctuate. The automatic shut-off module functioned as intended when a leak was detected, and the manual backup valve closed immediately, stopping any further biogas flow into the pipes, ensuring that any ongoing leak was halted and reducing the chance of gas spreading indoors or around the digester.

The CO_2 suppression unit was also validated through real-world tests. After the valve shut the gas supply, the CO_2 release mechanism activated automatically, flooding the leak zone with carbon dioxide to displace oxygen and prevent ignition. This approach demonstrated how quickly and efficiently a secondary safety barrier can neutralize potential hazards. In all test runs, the CO_2 was discharged within three seconds after leak detection, leaving no delay between detection, shut-off, and neutralization. Farmers and local residents observed that this feature gave them additional confidence to adopt biogas systems, knowing that any accidental leak would be handled automatically.

A small biogas generator received the safe, leak-proof biogas from the energy conversion side. Commonplace home appliances like fans, LED lights, and cell phone chargers were successfully powered by the generator. When needed, the excess electricity was transferred via an inverter from the battery storage system. The system generated enough energy over several test days to power the typical rural family's evening needs. This demonstrated that in addition to enhancing safety, the system makes sure that each unit of biogas is used as productively as possible, increasing the home biogas digesters' economic worth.

In order to determine the useful advantages and potential areas for development, user feedback was gathered. Farmers said they felt more secure about gas safety thanks to the Blynk app's mobile alerts, and local buzzers made sure the alerts continued to function even when the network was down. Users with low levels of digital literacy found it easy to use the system thanks to its user-friendly interface and clear status indicators. Overall, the findings demonstrate the viability, affordability, and ease of use of the integrated solution for rural communities. The project shows how biogas can be a genuinely safe and sustainable energy source for rural homes with accurate leak detection, automated shut-off, CO_2 suppression, and electricity conversion.

VI. Conclusion

MAn effective and safe way to use biogas is with the Integrated Biogas Leakage Prevention and Electricity Conversion System. Combining detection, power conversion, CO_2 neutralization, and automatic shut-off, the system reduces risks while optimizing energy savings. This strategy lowers environmental risks, promotes sustainable energy production, and enhances rural energy security. This solution can be further scaled to benefit larger populations through partnerships with government initiatives and local communities.

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