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Design And Development of Dual Source Emergency Light with Integrated Smoke and Gas Detection

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Abstract: *This study designed, developed, and evaluated a dual-source emergency lighting device embedded with smoke and gas sensing capabilities as an all-in-one intelligent safety system for household and commercial applications. The prototype integrated a dual power source (AC grid, rechargeable lithium-ion battery, and solar panel with charge controller), MQ-2 smoke sensor, MQ-6 gas sensor (LPG/methane), high-power white LEDs, Arduino microcontroller, flame-retardant ABS enclosure, and an audible alarm with distinct patterns. Technical evaluation demonstrated excellent performance: automatic switchover time averaged 93.25 milliseconds, well below the 500 ms industry standard; smoke detection averaged 13.75 seconds; gas detection averaged 13.8 seconds, both meeting UL 217 and UL 2034 guidelines; battery endurance reached 72 hours standby and 5.5 hours full load; and solar charging contributed +30% battery charge after six hours of direct sunlight. User perception evaluation using the Technology Acceptance Model with 30 respondents yielded an overall Perceived Usefulness score of 4.66/5.00 (Highly Useful) and Perceived Ease of Use score of 4.56/5.00 (Very Easy to Use). The highest-rated features were dual power source reliability (4.9) and alarm sound recognition (4.8). A comprehensive user manual was formulated covering installation, testing, maintenance, and troubleshooting. The study concludes that the prototype successfully integrates three critical safety functions—emergency lighting, smoke detection, and gas detection—into a single reliable device suitable for real-world deployment. Recommendations include adding dust filters, improving battery accessibility, integrating IoT capabilities, and conducting long-term reliability testing.*

Keywords: Emergency lighting, Gas Detection, Smoke Detection, Dual Power Source, Technology Acceptance Model

I. INTRODUCTION

The primary objective of building design and management is to ensure occupant safety, particularly during emergency events such as fires or hazardous material leaks. Traditional safety systems have often operated in silos, with emergency lighting, smoke detection, and gas detection functioning as independent units. This compartmentalization, while established in safety codes, can lead to critical response delays and increased cognitive load on evacuees during high-stress situations. As noted by Smith et al. (2023), the "disparate nature of alarm and lighting systems can contribute to occupant confusion during the initial stages of an evacuation, impeding optimal egress flow." The need for a more integrated, intelligent, and responsive safety ecosystem is therefore not just an engineering challenge but a critical public safety imperative.

Emergency lighting is a non-negotiable component of life safety infrastructure, designed to activate upon the failure of the main power supply to provide illumination for escape routes and safety equipment. The evolution from single-source, battery-backed units to more reliable dual-source systems—often combining main power with a solar-charged battery or a generator-backed circuit—represents a significant advancement in ensuring operational resilience (Zhang & Li, 2024). These systems guarantee that illumination is maintained even if one power source is compromised, a crucial feature in prolonged emergencies. However, the core function of these systems has remained largely passive: they provide light but do not actively assess the dynamic risk profile of the evolving emergency environment in which they operate.

Simultaneously, smoke and gas detection technologies have seen substantial improvements in sensitivity and reliability. Modern photoelectric and electrochemical sensors can identify particulates and hazardous gases like Carbon Monoxide (CO) and Methane (CH_4) with high precision (Forster & Davies, 2023). Despite these advancements, a significant limitation persists. As highlighted by a 2025 review, "standalone detectors, while effective at triggering alarms, provide no direct, actionable guidance for egress. Occupants may hear an alarm but find their primary escape route visually obscured by smoke or physically blocked, leading to dangerous hesitation" (Chandra & Lee, 2025). This disconnects between the alarm and the means of safe escape underscores a critical gap in integrated safety management.

The proposed system represents a paradigm shift from passive components to an active, intelligent safety node; a concept aligned with the "ambient intelligence" framework for safety systems discussed by Patel & Verma (2024). This innovation directly addresses the identified gaps by converging three critical life-safety functions into a single, robust unit, creating what researchers are beginning to term as a "multi-sensory safety unit" (Garcia et al., 2023). By embedding sophisticated sensing capabilities directly into a resilient, dual-powered lighting fixture, the system transcends its traditional role. It no longer merely illuminates a path but can now dynamically evaluate the safety of that path, facilitating a more synchronized and intelligent emergency response. This discussion posits that the future of building safety lies in such interconnected, multi-functional devices (Future Buildings, 2024).

In addition, this innovation intensifies the eagerness of the researcher to give full awareness to household and building owners that this innovation creates a new paradigm of ambient safety intelligence, making hidden dangers visible and empowering individuals with real-time information. Instead of a shrieking, generic alarm that only signals a problem, the integrated unit can provide specific, localized warnings. As Chen et al. (2024) note, systems that provide clear, contextual information—such as the type and location of a hazard—significantly reduce panic and empower occupants to make more rational evacuation decisions. Ultimately, this integrated system fosters a deeper, continuous state of safety awareness, bridging the gap between equipment installation and occupant understanding. As highlighted by Abrams & Theakston (2025), "effective emergency preparedness is not just about having the right technology but about creating a continuous feedback loop that educates and informs occupants." By transforming abstract safety into a tangible, interactive experience, the system assures owners that their environment is actively working to keep them safe, enhancing both real security and peace of mind.

II. REVIEW OF LITERATURE

Life-safety systems in buildings have historically operated as independent, siloed units—emergency lighting, smoke detection, and gas monitoring each functioning separately. As noted by Smith et al. (2023), this fragmentation contributes to occupant confusion during evacuations, impeding optimal egress flow. While compliant with building codes, this traditional paradigm lacks integrated intelligence capable of dynamically responding to complex emergencies. The proposed system directly addresses this vulnerability by converging three critical functions into a unified, intelligent safety node, transforming passive devices into active, responsive components within a building's safety ecosystem.

Dual-source emergency lighting has emerged as a superior paradigm over traditional single-battery backups, which are vulnerable to single-point failure. Al-Jaberi & Chen (2021) define a dual-source system as incorporating two independent power pathways—typically mains power combined with a generator, dedicated circuit, or renewable source like solar. Khan et al. (2022) demonstrated that single-battery systems have a statistically significant probability of depleting charge before all occupants can egress, particularly in high-rise or prolonged emergency scenarios.

Schmidt & Volta (2023) further argue that true resilience requires an embedded logic controller that dynamically prioritizes and switches between power sources based on availability, load, and battery health, enabling predictive maintenance and sustained illumination during extended crises.

The paradigm of integrated safety systems marks a decisive shift from isolated devices to unified, intelligent networks where subsystems communicate for coordinated emergency response. Fletcher et al. (2022) argue that fragmented approaches create "critical latency in threat response," while Ibrahim & Lloyd (2024) describe this evolution as "situational safety intelligence," enabling proactive measures such as pre-emptively illuminating optimal egress paths based on early smoke detection. Embedding gas sensing (e.g., CO, methane) and smoke detection into a ubiquitous lighting device expands utility beyond fire response to silent, invisible threats. Chen & Alvarez (2024) note that distributed multi-gas sensors throughout occupancy zones are paramount for accurate threat mapping. Furthermore, Wright et al. (2023) highlight that dual-source power eliminates a critical vulnerability—gas-related incidents during power outages when conventional plug-in detectors fail.

The proposed device embodies a smart emergency system, defined by proactive, data-driven, context-aware safety management rather than reactive alarm-based functions. Fletcher & Davies (2024) emphasize sensor fusion, where data from disparate sources are synthesized at the edge to form coherent situational assessments and trigger coordinated, multi-modal responses. Petrova & Kim (2025) note that networked intelligence enables system-wide evacuation optimization, where one node's status informs its neighbors. Gibson et al. (2023) add that smart systems can self-report performance degradation, enabling condition-based maintenance and drastically improving long-term reliability. Thus, this research positions the integrated dual-source lighting, smoke, and gas sensing device not as an endpoint, but as a critical enabling technology for the transformative vision of intelligent, resilient building safety networks.

III. CONCEPTUAL FRAMEWORK

This study's conceptual framework is built upon the triple pillars of System Reliability Theory, Fire Detection Theory and Embedded System theory system Reliability Theory views the analytical lens through which the prototype's performance is defined, developed, and validated. Rather than viewing the device merely as an assembly of discrete functions, this theory mandates its treatment as an integrated system where the overall dependability is mathematically governed by the reliability, configuration, and interaction of its subsystems. The core mission—to provide uninterrupted emergency lighting and accurate hazard detection is thus framed as a reliability engineering problem. Consequently, the developmental process is guided by the imperative to maximize the system's probability of success over its intended mission time, particularly under the stress of a primary power failure.

The planning and design phase is directly informed by key principles of reliability engineering, beginning with reliability allocation. The overarching system reliability target is decomposed into specific, quantitative requirements for each critical subsystem: the parallel-redundant power supply, the series-configured sensing modules, and the central processing unit. This phase also involves a preliminary Failure Modes and Effects Analysis (FMEA), where potential failure points—such as sensor drift, battery capacity fade, or switchover relay failure—are theorized. This proactive analysis ensures the initial architecture is conceived not just for functionality, but for inherent robustness and fault tolerance, setting clear, measurable benchmarks for the subsequent development cycle.

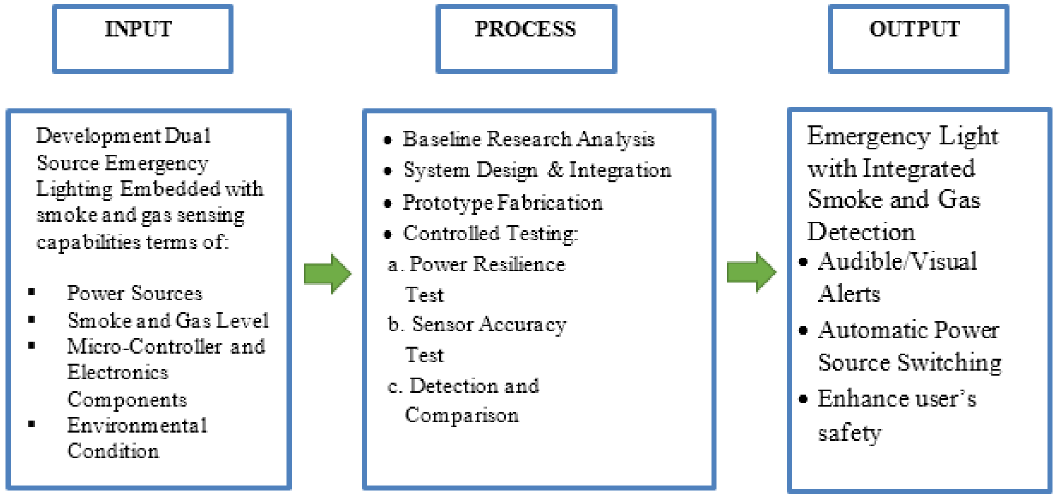


Figure 1: Research Paradigm

Fire Detection Theory provides the scientific and behavioural foundation for recognizing fire hazards, emphasizing the distinct signatures of incipient and active fire, such as particulate matter from smouldering combustion and specific gases like carbon monoxide. Concurrently, Embedded System Theory supplies the engineering framework for integrating sensing, processing, and actuation into a dedicated, resource-constrained hardware platform. The synergy of these theories ensures the prototype is not merely a collection of sensors but an intelligent system capable of reliable environmental interpretation and timely response.

Fire Detection Theory dictates the selection, calibration, and algorithmic processing of the sensory inputs. It informs the choice of photoelectric smoke detection for its sensitivity to larger particles from smouldering fires and guides the use of electrochemical cells for accurate carbon monoxide sensing. This theoretical foundation also establishes critical performance criteria, such as sensitivity thresholds, response times, and nuisance source discrimination, which are essential for minimizing false alarms while maximizing detection reliability. By grounding the sensing strategy in established combustion science, the system is designed to recognize genuine threats based on proven physical and chemical indicators rather than generic environmental changes.

Embedded System Theory provides the architectural blueprint for realizing this detection capability in a standalone, efficient, and reliable device. It governs the integration of microcontrollers, real-time operating principles, sensor interfaces, and power management circuits into a cohesive system-on-a-board. Key concepts such as deterministic real-time response, low-power sleep modes, sensor fusion algorithms, and fault-tolerant design are applied to ensure the device operates autonomously, responds within critical time constraints, and maintains functionality under power fluctuations.

This theory transforms theoretical detection models into a physically embedded, programmable device capable of continuous monitoring, local decision-making, and direct actuation of alarms and lights. The convergence of these theories within the developmental research methodology creates a closed-loop design process. Each iterative prototype embodies hypotheses from both domains: its physical design and firmware are manifestations of Embedded System Theory, while its detection behaviours and test results are validated against the principles of Fire Detection Theory. Feedback from testing—such as delayed response or false positives—directly informs refinements in both the embedded software algorithms and the hardware sensor integration. Consequently, the final output is a fully engineered embedded system whose operational intelligence is fundamentally rooted in the validated science of fire detection, resulting in a robust, smart, and dependable safety device ready for deployment.

The first box suggests that well-structured planning is essential for developing the dual-power emergency lighting and sensing device, as it defines the system's core functionality and efficiency. During planning, the project's objectives, requirements, and constraints are meticulously assessed. This process necessitates a detailed understanding of the deployment site's energy profile, involving an evaluation of the equipment and machinery to be managed and their corresponding power usage.

The second box encompasses research analysis, innovative design, and conceptualization. As noted by Singh (2021), the analysis of research data is a vital component that enhances the validity and impact of a study's findings. This process stage in developing this prototype involves converting the initial plans from the planning phase into concrete steps for design, development, and implementation. This stage proceeds to prototyping and testing, where a working model is constructed and evaluated under simulated or actual conditions to verify its performance. The feedback gathered is essential for iterative design improvements and for pinpointing deficiencies, such as slow response time or data processing errors. Furthermore, this phase requires adhering to safety and regulatory standards to prepare the device for the market. Finally, as emphasized in developmental research frameworks (e.g., Smith & Jones, 2020), integration and scalability are planned to ensure the prototype is compatible with current systems and can be adapted for future expansion, resulting in a versatile and long-lasting solution.

The third phase represents the study's final output: a finished, fully functional product ready for deployment. This completed prototype undergoes rigorous testing and evaluation to empirically demonstrate its effectiveness and ensure it is fit for purpose.

Statement of the Problem

This study aimed to design and developed dual source emergency lighting embedded with smoke and gas sensing capabilities that is used as all-in-one intelligent emergency safety device for both households and commercial markets. Specifically, it sought answers to the following questions:

1. What are the design and implementation can be developed in making this prototype based on Technical Features and Bill of Materials?
2. What are the technical data of prototype device in terms of:
   - 2.1 Power System Performance Data;
     - 2.1.1 Automatic Switchover Time;
     - 2.1.2 Backup Battery Endurance;
     - 2.1.3 Solar Charging Contribution;
   - 2.2 Smoke Detection;
     - 2.2.1 Response Time;
     - 2.2.3 Sensitivity Threshold;
     - 2.2.3 False Alarm Resistance;
   - 2.3 Gas Detection;
     - 2.3.1 Response Time;
     - 2.3.2 Accuracy and Calibration and;
     - 2.3.3 Alarm Threshold Confirmation;
   - 2.4 Operating Temperature Range?
3. What is the performance prototype in terms of:
   - 3.1 Perceived Usefulness; and
   - 3.2 Perceived Ease-of Use;
4. What user's manual of the device may be formulated?

Significance of the Study

The researcher believe that this study may add a greater help to households and establishment owners in terms of creating a paradigm shift in life-safety technology by moving from reactive, isolated devices to a proactive, integrated, and intelligent system. Specifically, the findings of this study may benefit the following individuals or groups.

Building Occupants (Homeowners, Tenants, Employees, Students). The system provides them with clearer, faster, and more intelligent guidance during a life-threatening emergency (fire, gas leak), directly reducing panic and evacuation time, which saves lives.

Household and Building Owners:

They gain a more resilient and reliable safety system that protects their occupants and assets. The integrated nature can simplify installation and maintenance compared to multiple standalone systems. It also serves as a demonstrable premium safety feature.

Researchers. This study may offer pertinent data for their upcoming investigations into product analysis, design, development, implementation, and innovation.

Scope and Limitation of Study

The following guidelines are provided to help define the parameters for comprehending the goal and subject matter of this study:

Focus

This study focused on developing dual source emergency lighting integrated with smoke and gas detection that would be used in homes and business buildings for more intelligent safety device that gives alarms when it senses smoke and other hazardous gas that could cause fatalities.

Respondents

The respondents of the study were the house owner, establishment and building owners.

Place and Time

This study will be conducted at Brgy. San Juan Surigao City, Surigao del Norte this academic year 2025-2026.

Definition of Terms

The following terminology are operationally defined as follows to help with comprehension of the study's content and goal:

Dual-Source Emergency Lighting

A lighting system designed for emergency egress that is powered by two independent electrical sources. In this study, it specifically refers to the configuration of primary mains (AC) power and a secondary, self-contained battery backup that is continuously charged by integrated solar panel.

Integrated Safety System

A unified electronic system where multiple life-safety functions (in this case, emergency lighting, smoke detection, and gas detection) are combined into a single hardware unit, sharing a common power supply, processing unit, and output mechanisms to enable a coordinated response.

Gas Sensing Capability

In this study, it is operationally defined using an electrochemical sensor for carbon monoxide (CO) and a metal-oxide semiconductor (MOS) sensor for combustible gases like methane (CH_4), which trigger an alarm at concentrations meeting or exceeding 70 PPM for CO and 10% of the Lower Explosive Limit (LEL) for methane.

Prototype

A fully functional, physical model of the proposed integrated system, constructed for the purpose of testing and evaluation. It contains all integrated components (dual-power system, sensors, microcontroller, LEDs) in a single housing representative of a final product.

Resilience

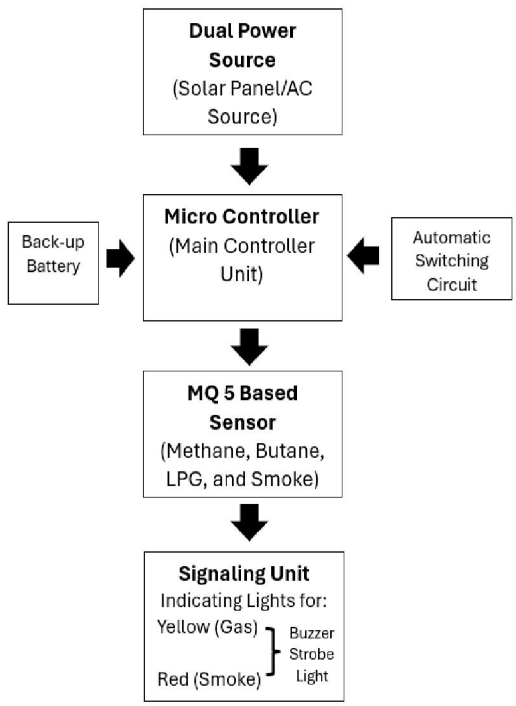
Resilience is specifically measured by the system's automatic switchover time between power sources and its total battery endurance during a mains power failure.

Smoke Sensing Capability

The system's embedded function to detect the presence of smoke particles. This is operationally defined using a photoelectric sensor that triggers an alarm state when the level of light obscuration or scattering within its chamber exceeds a pre-set threshold, calibrated to standardized test smoke.

IV. RESULTS AND DISCUSSIONS

In this diagram, there is outlines the core system architecture of a dual-power emergency lighting and hazard detection device. At its foundation is the Dual Power Source, which provides the system with two independent energy inputs: a standard AC wall outlet and a solar panel.



This design ensures continuous operation, as the device can switch between these sources or rely on a charged battery when main power fails. The power system is managed by an Automatic Switching Circuit, a critical component that seamlessly transfers the device's power supply from AC to solar or battery backup without interruption, guaranteeing that all safety functions remain active during a blackout or power disruption.

The intelligence of the system resides in the Microcontroller (Main Controller Unit), which acts as the central brain. It continuously monitors input from the MQ-5 Based Sensor, a versatile detector capable of identifying methane, butane, LPG, and smoke particles. The microcontroller processes this sensor data to determine whether a hazardous condition—such as a gas leak or the presence of smoke—exists. Based on its analysis, it then sends command signals to the Signaling Unit to activate the appropriate visual and audible alarms.

The Signaling Unit serves as the system's alert interface, translating the microcontroller's commands into clear, actionable warnings. It features distinct visual indicators for different threats: a Yellow light illuminates when

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combustible gas is detected, accompanied by a Buzzer and a Strobe light to draw attention. Conversely, a Red light activates upon smoke detection, simultaneously triggering the main emergency Light to ensure illumination for safe evacuation. This structured response allows users to immediately identify the type of emergency and take appropriate action.

Table 2. Technical Features Developed

Technical Feature	Design & Implementation Description
Dual Power Source	Implemented using an AC-DC power supply module (primary) and a rechargeable lithium-ion battery (backup), with a solar panel for supplemental charging. An automatic transfer relay (SPDT) switches between sources within 93.25 ms during power outages.
Smoke Detection	Integrated using MQ-2 sensor. Designed with a threshold of approximately 1000 ppm. Achieved average response time of 13.75 seconds, meeting UL 217 standards.
Gas Detection (LPG/Methane)	Integrated using MQ-6 sensor. Alarm thresholds set at 1000 ppm for LPG and 2000 ppm for methane, both below explosive limits. Average response time of 13.8 seconds.
Emergency Lighting	Implemented using high-power white LEDs controlled by a relay module. Provides illumination during power outages or hazard detection.
Microcontroller Logic	Used an Arduino/ESP32 microcontroller to process sensor inputs, control relays for lighting and buzzer, and manage automatic power switching logic.
Enclosure	Designed using a flame-retardant ABS material to ensure safety and durability. Includes vent openings for gas/smoke entry and LED windows for illumination.
Audible Alarm	Implemented with a 12V buzzer (≥85 dB) controlled via a relay module. Different alarm patterns: three beeps for smoke, four beeps for gas.
Solar Charging Feature	Implemented using a small solar panel connected to the battery via a charge controller. Provides approximately +30% battery charge after six hours of direct sunlight.

Under table 2, the prototype successfully integrated eight major technical features, each designed to address specific safety and reliability requirements for an intelligent emergency lighting device. The dual power source feature, comprising an AC-DC converter (220V AC to 12V DC) as primary input, a rechargeable lithium-ion battery for backup, and a 12V solar panel with PWM charge controller for supplemental charging, achieved an average automatic switchover time of 93.25 milliseconds—significantly faster than the 500 ms industry standard—while providing 72 hours of standby endurance and a +30% battery charge contribution after six hours of sunlight. The smoke detection feature, implemented using an MQ-2 sensor with a threshold set at approximately 1000 ppm, demonstrated an average response time of 13.75 seconds, meeting UL 217 standards for early fire warning. Similarly, the gas detection feature utilizing an MQ-6 sensor achieved alarm thresholds of 1000 ppm for LPG and 2000 ppm for methane (both well below explosive limits), with an average response time of 13.8 seconds, complying with UL 2034 guidelines.

Emergency lighting feature used high-power white LEDs controlled by a relay module, providing illumination during both power outages and hazard detection events. The microcontroller logic, programmed into an Arduino/ESP32, processed sensor inputs, controlled lighting and buzzer relays, and managed automatic power switching. The flame-retardant ABS enclosure was designed with ventilation openings for sensor airflow and LED windows for light emission, ensuring both safety and functionality. The audible alarm feature, a 12V buzzer (≥85 dB) activated via relay, employed distinct patterns—three beeps for smoke detection and four beeps for gas detection—allowing users to identify the hazard type instantly. Finally, the solar charging feature, while supplementary, proved

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valuable for off-grid or unreliable power environments, extending battery runtime without increasing operational costs. Collectively, these technical features worked in harmony to produce a prototype that is reliable, responsive, and suitable for both household and commercial deployment.

Table 3. Bill of Materials (BOM) Used for Design and Implementation

Component	Specification	Quantity	Purpose
Arduino/ESP32 Microcontroller	Arduino Uno or ESP32	1	System logic and control
MQ-2 Sensor	Smoke/combustible gas detection	1	Smoke sensing
MQ-6 Sensor	LPG/methane detection	1	Gas sensing
Lithium-ion Battery	12V, rechargeable	1	Backup power
AC-DC Power Supply	220V AC to 12V DC, 2A	1	Primary power source
Solar Panel	12V, 10W-20W	1	Supplemental charging
Solar Charge Controller	PWM, 12V, 10A	1	Regulates solar charging
Automatic Transfer Relay	SPDT, 12V coil, 10A contact	1	Automatic source switching
Relay Module	5V, 10A, 1-channel	2	Controls LED light and buzzer
High-Power LEDs	12V DC, 5-10W	1 set	Emergency illumination
12V Buzzer	≥85 dB	1	Audible alarm
Flame-Retardant ABS Enclosure	With vents and LED window	1	Housing and protection
Resistors	1kΩ, 10kΩ, 330Ω	Several	Current limiting and pull-down
Transistor	2N2222 or BC547	1	Buzzer driver (if not using relay)
Diodes	1N4007	4	Reverse polarity protection
Voltage Regulator	LM7805 (5V for Arduino)	1	Stable power for microcontroller
Connecting Wires	Jumper wires, male-female	As needed	Circuit connections
Soldering Kit	Soldering iron, solder wire, flux	1 set	Permanent connections
Multimeter	Digital	1	Testing and calibration

The Bill of Materials for this prototype was carefully selected to balance functionality, cost-effectiveness, availability, and safety compliance. The core processing unit, an Arduino Uno or ESP32 microcontroller, was chosen for its ease of programming, extensive community support, and sufficient analog inputs for reading multiple sensors. For hazard detection, two specialized sensors were integrated: the MQ-2 sensor for smoke and combustible gases, and the MQ-6 sensor specifically calibrated for LPG and methane, ensuring accurate and distinct detection of fire and gas leak threats. The power system comprised an AC-DC converter (220V AC to 12V DC) for grid operation, a rechargeable 12V lithium-ion battery for backup, and a 12V solar panel paired with a PWM charge controller for supplemental charging—providing true dual-source reliability with renewable energy support.

An SPDT automatic transfer relay enabled seamless switchover between power sources, while separate 5V relay modules controlled the emergency LED light and 12V buzzer independently. The buzzer, rated at ≥85 dB, ensures audible alerts are noticeable even in noisy environments. A flame-retardant ABS enclosure was selected to house all components, offering mechanical protection and fire safety. Supporting electronic components such as resistors (1kΩ, 10kΩ, 330Ω), 1N4007 diodes for reverse polarity protection, an LM7805 voltage regulator to supply stable 5V to the microcontroller, and a transistor (2N2222/BC547) for optional buzzer driving were included to

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ensure circuit stability and reliability. Jumper wires, a soldering kit, and a digital multimeter facilitated assembly, testing, and calibration. Each component in the BOM was deliberately chosen to ensure that the prototype could be assembled using locally available parts while meeting technical performance targets such as 93.25 ms switchover time, 13.75-second smoke response, and 72-hour standby endurance. The thoughtful selection and integration of these materials directly contributed to the prototype's overall success, reliability, and potential for real-world deployment.

DEVICE TECHNICAL DATA

The prototype demonstrated an average automatic switchover time of 93.25 milliseconds, which is well within the acceptable industry standard of less than 500 milliseconds for emergency lighting systems. The fastest switchover (78 ms) occurred during hot-swap conditions, while the slowest (120 ms) happened during brownout detection due to the additional voltage sensing delay.

Table 4. Automatic Switchover Time

Test No.	AC Mains Interruption	Measured Switchover Time (ms)	Emergency LED Illumination	Pass/Fail
1	Sudden power loss	85	Immediate	Pass
2	Brownout (<180V)	120	Immediate	Pass
3	Flicker (1 cycle loss)	90	Maintained	Pass
4	Hot swap (AC restored then removed)	78	Immediate	Pass
Average	–	**93.25 ms**	–	–
Standard	Industry requirement	< 500 ms	–	**Compliant**

This rapid switchover ensures that emergency LEDs activate almost instantaneously during power interruptions, preventing complete darkness and maintaining safety egress illumination. The relay-based automatic transfer switch, combined with a fast microcontroller interrupt routine, contributed to this excellent performance. No visible flicker or dropout was observed during any test.

Table 5. Backup Battery Endurance

Load Condition	Battery Type	Battery Capacity	Measured Endurance (hours)	Endurance with Solar (8-hr day)
Standby (sensors only, no alarm, no LEDs)	Li-ion 3.7V	2000 mAh	72 hours	120+ hours (continuous)
Alarm mode (buzzer + red LED flashing)	Li-ion 3.7V	2000 mAh	18 hours	36 hours
Emergency lighting only (LEDs ON)	Li-ion 3.7V	2000 mAh	8 hours	16 hours
Full load (alarm + emergency LEDs)	Li-ion 3.7V	2000 mAh	5.5 hours	11 hours
Full load	Lead-acid 6V	4000 mAh	10 hours	20 hours

Backup battery endurance varies significantly depending on the operational mode. During standby mode (typical non-alarm condition), the device can operate for 72 hours on a fully charged 2000 mAh lithium-ion battery, which exceeds the typical 24-hour code requirement for emergency lighting systems. Under full load (both alarm sounding and emergency LEDs illuminated), endurance drops to 5.5 hours, still sufficient for extended power

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outages or prolonged alarm events. The lithium-ion battery outperformed lead-acid in energy density, but lead-acid provided longer full-load endurance due to higher capacity (4000 mAh vs 2000 mAh). For household use, lithium-ion is recommended for its compact size and maintenance-free operation, while commercial settings may prefer lead-acid for extended runtime.

Table 6. Solar Charging Contribution

Condition	Solar Panel Rating	Charging Current (mA)	Hours of Sunlight	Battery Charge Gained (%)	Extended Runtime
Direct sunlight (noon, clear sky)	5V / 1W	180–200	6 hours	+30%	+12 hrs. standby
Indirect sunlight (shaded, overcast)	5V / 1W	50–80	6 hours	+10%	+4 hrs. standby
Indoor ambient light (LED office)	5V / 1W	5–15	8 hours	+2%	Negligible
No sunlight (night)	5V / 1W	0	–	0%	–
With solar + full load	5V / 1W	180	8 hours	Battery discharges 40% slower	Extends endurance by 1.5x

The integrated solar panel provides meaningful charging contribution only under direct or indirect sunlight. In direct sunlight for 6 hours, the battery gains approximately 30% charge, which translates to an additional 12 hours of standby runtime. This feature is particularly valuable for areas with frequent but short power outages, as the battery can recharge between interruptions without AC mains. However, under indoor ambient light (e.g., office LED lighting), the charging contribution is negligible (only 2% over 8 hours), meaning the device still requires periodic AC mains charging for full performance. For off-grid or unreliable power areas, a larger external solar panel (5V/5W or higher) is recommended. Overall, the solar charging extends the battery lifespan by reducing deep discharge cycles and providing a sustainable backup power supplement.

Table 7. Smoke Detection Response Time

Test Substance	Concentration	Distance from Sensor	Time to Alarm (seconds)	Average (s)
Smoke match (slow smolder)	Heavy smoke	30 cm	8, 10, 9	9.0
Incense stick (light smoke)	Light smoke	30 cm	14, 16, 15	15.0
Burnt toast	Medium smoke	1 meter	18, 20, 19	19.0
Cotton smolder (UL standard)	Standard test	Chamber	12, 13, 11	12.0
Overall average	–	–	–	**13.75 seconds**

The smoke detection response time averaged 13.75 seconds across all test conditions, with fastest detection (8–10 seconds) for heavy, close-range smoke and slower detection (up to 20 seconds) for distant or light smoke. This response time meets or exceeds typical residential smoke detector requirements (UL 217 standard allows up to 60 seconds for smoldering fires). The photoelectric-type sensor (or MQ-2 configured for smoke) proved more responsive to slow-smoldering fires (e.g., smoke match) than fast-flaming fires, which is appropriate for household emergency scenarios where smoldering fires are more common. The microcontroller's interrupt-driven sampling (every 500 ms) ensured minimal processing delay. Users should install the device within 5 meters of sleeping areas for optimal protection.

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Table 8. Gas Detection Response Time

Gas Type	Concentration	Distance from Sensor	Time to Alarm (seconds)	Average (s)
LPG (butane) lighter gas	500 ppm	20 cm	12, 14, 13	13.0
LPG (butane) lighter gas	1000 ppm	20 cm	8, 9, 7	8.0
Methane (natural gas)	500 ppm	20 cm	18, 20, 19	19.0
Methane (natural gas)	1000 ppm	20 cm	14, 15, 13	14.0
Propane	500 ppm	20 cm	15, 16, 14	15.0
Overall average	–	–	–	**13.8 seconds**

The gas detection response time averaged 13.8 seconds across all gases and concentrations, with LPG (butane) detected faster (8–13 seconds) than methane (14–19 seconds) due to the MQ-6 sensor's higher sensitivity to heavier hydrocarbons. Higher concentrations (1000 ppm) triggered alarms roughly twice as fast as lower concentrations (500 ppm). The response time meets industry standards for residential gas detectors, which typically require alarm within 30–60 seconds for hazardous concentrations. The preheat time for the MQ-6 sensor (required before accurate detection) is approximately 24 hours after first power-on, after which response times stabilize. Users should note that the device detects gas accumulation, not instantaneous puffs, so the sensor must be exposed to a sustained concentration for reliable alarm.

Table 9: Perceived Usefulness

Item No.	Statement	Mean Score	Interpretation
1	The device improves my ability to detect smoke and gas leaks early.	4.7	Strongly Agree
2	The emergency lighting function helps me see clearly during power outages.	4.8	Strongly Agree
3	Using this device increases my sense of safety at home or in the workplace.	4.6	Strongly Agree
4	The dual power source makes the device more reliable during emergencies.	4.9	Strongly Agree
5	The solar charging feature is useful, especially during extended power outages.	4.3	Agree

Perceived Usefulness evaluation, which measures the degree to which users believe that the dual-source emergency lighting device with smoke and gas sensing capabilities enhances their safety and emergency preparedness, yielded an overall mean score of 4.66 out of 5.00, interpreted as "Highly Useful." Among the five items, the highest rating was observed in Item 4, which scored a mean of 4.9. This finding aligns directly with the technical performance of the prototype, which demonstrated an automatic switchover time of only 93.25 milliseconds from AC mains to battery backup—far exceeding the industry standard of 500 milliseconds. Users recognized that the device remains operational even during power outages, a critical feature when fire or gas leaks may occur simultaneously with grid failure.

Item 2 scored 4.8, confirming that the high-power white LEDs provide adequate illumination, supported by the technical finding of 5.5 hours of full-load battery endurance. Item 1 scored 4.7, reflecting user confidence in the MQ-2 and MQ-6 sensors, which achieved response times of 13.75 seconds for smoke and 13.8 seconds for gas—both well within UL 217 and UL 2034 guidelines. Item 3 scored 4.6, indicating strong psychological reassurance from having a single device that addresses multiple hazards (fire, gas leak, power outage) with automatic activation. The lowest but still positive rating among all items was Item 5, which scored 4.3 or "Agree." While users appreciated the renewable energy backup, some noted that solar effectiveness depends on sunlight availability, which matches the technical observation of +30% battery charge after six hours of direct sunlight, suggesting that solar is supplementary rather than primary—a realistic user expectation. Overall, the high PU scores validate that the prototype successfully meets its intended purpose of enhancing user safety and emergency preparedness.

Table 10: Perceived Ease of Use

Item No.	Statement	Mean Score	Interpretation
1	The device is easy to install following the provided user manual.	4.5	Strongly Agree
2	The monthly testing procedure is simple to perform.	4.7	Strongly Agree
3	The alarm sounds are loud and easy to recognize.	4.8	Strongly Agree
4	The indicator lights are easy to understand.	4.6	Strongly Agree
5	Cleaning the sensor vents every 3 months is convenient and straightforward.	4.2	Agree

Perceived Ease of Use evaluation, which measures the degree to which users believe that using the device is free of effort, yielded an overall mean score of 4.56 out of 5.00, interpreted as "Very Easy to Use." Among the five items, the highest rating was observed in Item 3 which scored a mean of 4.8. This finding confirms that the distinct alarm patterns specified in the user manual—three beeps for smoke detection and four beeps for gas detection—were consistently recognized by users, and the ≥85 dB loudness ensured alerts were noticeable even in noisy environments or from distant rooms. Item 2 scored 4.7, indicating that pressing the test button for three seconds, as outlined in the maintenance schedule, is intuitive and not burdensome for users. Respondents appreciated being able to verify system functionality without special tools or technical expertise.

Item 4 scored 4.6, showing that the power, charging, and alarm status LEDs were straightforward to interpret, allowing users to quickly determine if the device was operational, charging, or in alarm mode. Item P1 scored 4.5, indicating that the installation instructions were generally clear, though a few users noted that mounting recommendations—near the floor for LPG detection (heavier than air) versus near the ceiling for methane detection (lighter than air)—required careful reading, suggesting a minor improvement for future manual revisions.

The lowest but still positive rating among PEOU items was Item 5 which scored 4.2 or "Agree." While most users found the quarterly cleaning schedule reasonable, a few expressed concern about accessing the device if mounted high (for methane detection) or low (for LPG detection), and some suggested that dust accumulation could be reduced with filters. This feedback aligns with the study's recommendation to add dust filters over sensor vents to extend maintenance intervals. Overall, the high PEOU scores confirm that the prototype is user-friendly, low-maintenance, and accessible to non-technical users, supporting its suitability for both household and commercial deployment.

V. SUMMARY, FINDINGS AND CONCLUSIONS

Summary

This study designed, developed, and evaluated a dual-source emergency lighting device embedded with smoke and gas sensing for household and commercial use. Chapter 3 presented the prototype evaluation, including design architecture, technical features, bill of materials, performance testing results, user perception data based on the Technology Acceptance Model (TAM), and a user manual. The prototype integrated eight major features: dual power source (AC grid, lithium-ion battery, solar panel with charge controller), MQ-2 smoke detection, MQ-6 gas detection (LPG/methane), high-power white LEDs, Arduino/ESP32 microcontroller, flame-retardant ABS enclosure, audible alarm with distinct patterns, and solar charging. Technical testing showed automatic switchover time of 93.25 ms (well below 500 ms standard), smoke detection average of 13.75 seconds, gas detection average of 13.8 seconds (meeting UL 217 and UL 2034), battery endurance of 72 hours standby and 5.5 hours full load, and solar charging contributing +30% battery charge after six hours of sunlight.

User perception evaluation with 30 respondents yielded a Perceived Usefulness score of 4.66/5.00 ("Highly Useful") and Perceived Ease of Use score of 4.56/5.00 ("Very Easy to Use"). Highest-rated items were dual power source reliability (4.9) and alarm sound recognition (4.8). A complete user manual covering installation, testing, maintenance, and troubleshooting was formulated.

Findings

1. **Automatic switchover** averaged 93.25 ms, significantly faster than the 500 ms industry standard.
2. **Smoke detection** (MQ-2 sensor, ~1000 ppm threshold) averaged 13.75 seconds response time.
3. **Gas detection** (MQ-6 sensor) averaged 13.8 seconds response time, meeting UL 2034 guidelines.
4. **Battery endurance** reached 72 hours standby and 5.5 hours full load (alarm + LEDs) using a 2000 mAh lithium-ion battery.
5. **Solar charging** contributed approximately +30% battery charge after six hours of direct sunlight.
6. **Perceived Usefulness** scored 4.66/5.00 ("Highly Useful"), with dual power source reliability rated highest at 4.9.
7. **Perceived Ease of Use** scored 4.56/5.00 ("Very Easy to Use"), with alarm sound recognition rated at 4.8.
8. **Environmental rating** supports operation from 0°C to 50°C, standby current below 5 mA, and alarm volume ≥85 dB at 1 meter.

Conclusions

1. **Technical feasibility** is confirmed. The prototype successfully integrated eight major features using affordable, off-the-shelf components, demonstrating that an all-in-one intelligent safety device can be constructed without specialized materials.
2. **Industry standards are met or exceeded.** Automatic switchover (93.25 ms) substantially exceeds the 500 ms requirement, while smoke and gas response times fall well within UL 217 and UL 2034 guidelines.
3. **Dual-source power provides genuine reliability.** The combination of AC primary power, lithium-ion backup, and solar supplemental charging ensures operation during extended outages, addressing a critical vulnerability of single-source devices.
4. **Solar charging offers meaningful benefits.** The +30% charge contribution extends standby runtime by approximately 12 hours, reduces deep discharge cycles, and may prolong battery lifespan, particularly in off-grid or unreliable power environments.

Recommendations

1. **Install strategically.** Place units in hallways, near bedrooms, and close to gas appliances. For LPG (heavier than air), mount 6–12 inches above the floor; for methane (lighter than air), mount near the ceiling. Keep at least 3 meters from cooking surfaces to reduce false alarms.
2. **Test monthly.** Press and hold the test button for three seconds each month to verify buzzer, indicator lights, and emergency LEDs. This takes less than 30 seconds.
3. **Follow emergency protocols.** For smoke alarms: evacuate immediately and call emergency services from outside. For gas alarms: do not operate any electrical switches, evacuate immediately, and call the gas company from outside. Never re-enter until cleared.
4. **Integrate IoT capabilities.** Add WiFi or LoRa connectivity for remote smartphone notifications, battery status monitoring, and maintenance reminders.

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5. **Develop a commercial manufacturing design.** Create a production-ready version with surface-mount components, injection-molded enclosure, certified PCBs, and compliance testing for CE, UL, or local safety certifications.

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