

# Development and Field Validation of an IoT-Based Smart Beehive Monitoring System for Precision Apiculture

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## Research Article

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# Abstract

Even though honey bee colonies are experiencing record losses, the majority of beekeepers continue to conduct laborious, time-consuming manual hive inspections hence need for continuous, non-invasive, and cost-effective monitoring technologies that can support timely beekeeping decisions. The Bee-Hive Project, a low-cost solar-powered Internet of Things (IoT) system for ongoing smart hive monitoring, is the subject of this paper's case study. A conventional embedded-systems design cycle was employed during the development process, encompassing requirements specification, architectural design, component selection, bench prototyping, PCB manufacturing, mechanical integration, firmware creation, and field validation. The system is configured with a five-stage data path (Fig. 1). An Arduino MKR WAN 1310 interrogates multiple sensors within the hive. The microcontroller transmits the data via a LoRaWAN uplink after encoding it into a compact binary payload. The Arduino MKR WAN 1310 is surrounded by sensors for temperature, humidity and weight. Data is sent via LoRaWAN to The Things Stack and subsequently to the Ubidots and BEEP cloud platforms for alerting and visualization. A LoRaWAN gateway acquires the uplink, subsequently transmitting it to The Things Stack (TTN), a LoRaWAN network server, where the binary payload is decoded into designated fields via a bespoke decoder function. The weatherproof solar-powered enclosure and custom printed circuit board were constructed and put through a two-week field test. In addition to discussing the advantages and disadvantages of the system in light of the precision-beekeeping literature, the paper reports on the design, implementation, and field results. The proposed system successfully enabled real-time hive monitoring by transmitting environmental, weight, and battery data at ten-minute intervals, demonstrating a low-cost, solar-powered, weather-resistant IoT solution for precision beekeeping in off-grid environments.

## 1. Introduction

Notwithstanding their crucial role as pollinators that underpin a substantial fraction of global food production and biodiversity, managed honey bee populations have recently faced extraordinarily elevated mortality rates. The 2024–2025 national beekeeping survey in the United States revealed an estimated loss of 55.6% of managed colonies during the survey period, approximately fourteen percentage points higher than the fourteen-year average, representing the highest annual loss rate since monitoring commenced in 2010–2011 (Aurell et al., 2024). Commercial migratory activities documented even greater average losses during the same timeframe (Gil-Lebrero et al., 2020), with winter losses alone estimated at 40.2%, exceeding the historical average for that season (Bixby et al., 2023). These figures underscore the necessity for instruments that aid apiarists in early problem detection, despite being confined to a particular country and survey technique. They are typically in agreement with accounts of the rapid deterioration of colonies globally. Direct, tactile examination is the traditional approach to assessing colony vitality. This entails accessing the hive, examining the frames, and visually assessing the status of the stores and brood. This technique can only be employed as often as the apiarist can attend to each apiary; it provides valuable insights but is labor-intensive and disruptive to the hive. Besides generating honey, a considerable fraction of the fruit, vegetable, nut, and seed harvests that

constitute a nutritionally adequate food supply are pollinated by honey bees, whose pollination services are universally recognized as economically vital to global agriculture. The decline of colonies predominantly impacts smallholder and subsistence farmers, who often depend heavily on both managed and wild pollinators and possess the least resilience to adverse seasons. This promotes the evaluation of initiatives such as the Bee-Hive Project regarding their appropriateness in resource-limited environments, a topic reexamined in Section 6, and highlights the relevance of economical, low-maintenance monitoring instruments particularly in non-commercial apiaries of affluent nations. This limitation has resulted in the emergence of precision beekeeping, which employs IoT sensors, wireless communication, and data analysis to incessantly observe colony metrics without the need to open the hive. The Bee-Hive Project, a cost-effective, solar-powered system for monitoring hives, is detailed in this paper, which also assesses it as a case study in relation to the broader literature on precision beekeeping.

## 1.1 Related Work

Precision beekeeping (PB) is typically defined as a management approach that utilizes continuous sensor monitoring rather than sporadic manual inspections to assess colony conditions and inform beekeeper decisions (Kashumba, 2025; Ratnayake et al., 2026). Field assessments reveal that the most commonly evaluated metrics are hive weight, internal temperature, and relative humidity, as these three elements collectively provide an extensive insight into thermoregulation, food reserves, and general activity without disturbing the colony (Gil-Lebrero et al., 2020; Kashumba, 2025). More advanced systems additionally incorporate acoustic or vibration sensors to detect swarming or the lack of a queen, alongside gas sensors to assess carbon dioxide levels as a measure of metabolic activity, though these enhancements elevate costs and complicate calibration. A recent systematic analysis of forty-six studies on precision beekeeping indicated a notable surge in research endeavours since 2016, predominantly featuring systems that employ single-board microcontrollers such as Arduino or ESP32 variants, coupled with Lora, Wi-Fi, or GSM connectivity to a cloud infrastructure. A contemporary monitoring system relevant to the ongoing case study incorporated DHT22 humidity and temperature sensors, a HX711 load-cell weighing module, and a LoRa radio link powered by an ESP32 microcontroller, relaying data to a dashboard through MQTT. The Bee-Hive Project follows a comparable sensor and communication philosophy but sets itself apart by pairing each DHT22 with a dedicated waterproof DS18B20 probe employing the LoRaWAN-certified Arduino MKR WAN 1310 with The Things Stack as its network server, and transmitting data via a dual-stage cloud pipeline designed for beekeepers. Thorough assessments of IoT-based hive monitoring reveal that energy efficiency, reliable long-range communication, and sensor calibration remain the foremost practical obstacles for operational systems in the field (Sad et al., 2025). This case study distinguishes itself from many published PB research not mainly due to its selection of sensors, but rather because of the meticulousness of its design: a custom two-layer PCB, a weatherproof enclosure, and an outdoor field trial, all documented transparently. It is advantageous to situate the data management choices of the Bee-Hive Project within context. A multitude of analyzed systems store and assess sensor data either locally or within a singular

proprietary cloud framework, complicating transitions for beekeepers among service providers or obstructing research teams from repurposing a dataset (Alleri et al., 2023; Guruprasad & Leiding, 2024). Conversely, routing data first through a standards-compliant LoRaWAN network server (TTN) and then into commercial dashboards preserves a distinction between the radio and network layers and the presentation layer, enabling the same sensor node to be redirected to an alternative dashboard without requiring any hardware or firmware alterations. This layered approach signifies a modest yet practically advantageous architectural selection that is frequently lacking in the more cohesively unified commercial or research models recorded in the literature (Alleri et al., 2023; Sad et al., 2025). In conclusion, most systems evaluated in recent reviews are primarily tested through bench evaluations, short trials, or simulations, with a limited number providing a thorough, outdoor, multi-week field deployment along with a complete disclosure of materials, schematics, and firmware. The Bee-Hive Project's open GitHub repository and its two-week apiary trial establish it as one of the more reproducible and empirically substantiated examples in this field, notwithstanding the trial's short duration and primarily qualitative results, as detailed in Section

## 1.2 System Objectives

### *Functional Objectives*

The architecture of the solar-powered intelligent beehive monitoring system was influenced by a blend of functional and non-functional goals, each enhancing the overall efficacy and sustainability of the solution. From a practical perspective, the system needed to record temperature and humidity levels both within and outside the hive, offering crucial information regarding the microclimate that influences colony well-being and efficiency. Furthermore, the aggregate weight of the hive was assessed utilizing a load cell, acting as an indicator of honey reserves and colony dynamics. To guaranty accessibility in distant apiaries, all sensor data was conveyed wirelessly over distances appropriate for areas devoid of traditional infrastructure.

### *Non Functional Objectives*

A visual dashboard was incorporated to display the gathered data in an accessible, user-centric manner, allowing beekeepers to oversee conditions remotely. Additionally, the system integrated threshold-driven notifications, enabling the automatic identification of anomalous readings, thus diminishing the necessity for constant manual supervision. The non-functional objectives, which highlighted cost-effectiveness, durability, and reproducibility, were equally important. To achieve a minimal unit cost, the design employed commercially accessible development boards and sensor breakout modules instead of bespoke silicon. Energy independence was attained via the incorporation of solar power, guaranteeing continuous functionality under varying climatic conditions without the need for human oversight. Durability was ensured through the utilization of a weatherproof casing designed to endure precipitation, moisture, and severe temperatures characteristic of outdoor beekeeping environments.

Ultimately, replicability was emphasized by providing schematics, firmware, and a bill of materials at no cost, thus fostering open-source collaboration and allowing other practitioners to recreate and modify the system. Collectively, these design factors underscore a harmonious strategy that incorporates IoT technology, renewable energy, and sustainable methodologies to enhance contemporary beekeeping.

## 2. Methodology

A conventional embedded-systems design cycle was employed during the development process, encompassing requirements specification, architectural design, component selection, bench prototyping, PCB manufacturing, mechanical integration, firmware creation, and field validation. The system is configured with a five-stage data path (Fig. 1). An Arduino MKR WAN 1310 interrogates multiple sensors within the hive. The microcontroller transmits the data via a LoRaWAN uplink after encoding it into a compact binary payload. A LoRaWAN gateway acquires the uplink, subsequently transmitting it to The Things Stack (TTN), a LoRaWAN network server, where the binary payload is decoded into designated fields via a bespoke decoder function. The interpreted information is transmitted via HTTP webhook from TTN to Ubidots, a versatile IoT dashboard platform, and subsequently to BEEP, a dashboard platform tailored for beekeepers. The BEEP interface, as indicated by the project's field notes, refreshes approximately every ten minutes in the field, enabling the beekeeper to observe trends and, ultimately, receive threshold alerts (Ratnayake et al., 2026). Two stages of validation were accomplished: an external field deployment of the finalized, enclosed unit and individual bench testing of each sensor, as well as testing the entire breadboard prototype. The system is particularly relevant to dry regions because it treats climate, limited forage, pests, theft and inadequate training as interconnected management challenges. It demonstrates that a smart-hive system should measure the colony and fit the physical and socio-economic conditions in which the colony is kept.

### 2.1 Methodology Validation

Before integration, bench validation was performed on each sensor individually, a conventional practice in embedded systems development that confines errors to a specific subsystem instead of the entire assembly. Prior to transferring the electronics from the breadboard to the finalized PCB, each DHT22 and DS18B20 measurement was validated for consistency with environmental conditions, the HX711 load-cell channel was zeroed and calibrated using known reference weights, and the LoRaWAN connection was confirmed to integrate with The Things Stack and transmit decoded data to Ubidots. The complete system underwent indoor retesting following the completion of the PCB-based assembly and its placement within the enclosure to ensure that soldering and assembly did not result in any regressions. Subsequently, it was relocated to the apiary for the field experiment. The suggested validation protocol for solar-powered outdoor IoT nodes, where rectifying issues in a completely sealed, field-installed unit incurs significantly higher costs than early fault detection, is reflected in this phased methodology, which includes component-level bench testing, breadboard system evaluation, PCB system assessment, and field testing.

### 3. Technology Description

Table 1 summarises the principal hardware subsystems used to implement the architecture described in Section 2.

Table 1  
Hardware Components and Their Function

| Subsystem        | Component                                                        | Function                                                                                                                                                                                                       |
|------------------|------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Microcontroller  | Arduino MKR WAN 1310 (SAMD21 Cortex-M0+)                         | Sensor acquisition, payload encoding, LoRa radio control. The hive system's brain is this microcontroller. It gathers, processes, and transmits data from various sensors to the communication module.         |
| Humidity         | 2 × DHT22 (indoor / outdoor)                                     | Relative humidity and coarse temperature reference                                                                                                                                                             |
| Temperature      | 2 × DS18B20 (waterproof, One Wire)                               | Precision in-hive / probe temperature                                                                                                                                                                          |
| Weight/Load Cell | HX711 24-bit ADC + strain-gauge load cell                        | Hive mass for honey-store estimation. situated below the hive to ascertain its mass. This facilitates the monitoring of honey yield and the detection of hive activities including resource usage or swarming. |
| Power supply     | SOL2W solar cell, LiPo Rider Pro, 1000 mAh Li-Ion, TPL5110 timer | Autonomous charging and low-power duty-cycling.                                                                                                                                                                |
| Power Panel      | 30 Watt power panel                                              | To capture sunlight and transform it into electrical power energy.                                                                                                                                             |
| Communication    | Integrated LoRa transceiver, LoRaWAN, TTN                        | Long-range, low-power uplink to the network server enables remote monitoring of hive conditions from any location by providing internet connectivity.                                                          |

The build additionally relied on the following tools and materials:

KiCad for schematic capture, footprint assignment, and PCB layout.

A 3D printer for sensor housings and mounting brackets.

A temperature-resistant plastic enclosure with cable-gland ports and heat-shrink tubing for waterproofing.

A soldering iron and helping-hand tool for board and cable assembly.

#### 3.1 Sensing Subsystem

The Arduino MKR WAN 1310 was chosen due to its built-in LoRa transceiver, Bluetooth Low Energy capabilities, and minimal active/sleep current, rendering it ideal for a battery- and solar-operated field

sensor node. The SAMD21 Cortex-M0 + microcontroller possesses adequate capability for connecting with various digital and analogue sensors, performing fundamental calibration calculations, and managing the LoRaWAN stack within a single duty cycle. Two DHT22 sensors provide humidity readings from both inside and outside the hive, with the external sensor housed in a 3D-printed protective casing that shields it from rain and direct sunlight while allowing free airflow to the sensing element. Juxtaposing the two measurements allows the system to differentiate between humidity generated by the hive, associated with brood maturation, ventilation efforts, and nectar handling, and humidity affected by external meteorological factors. Accurate temperature assessment is conducted independently from the DHT22 devices using two waterproof DS18B20 digital sensors that utilize a single One Wire bus, thereby minimizing wiring intricacies compared to an Analog channel for each probe. The cable of each probe is sufficiently lengthy to extend from the enclosure into the hive body, while the electronic components are situated externally in a location shielded from direct weather conditions. The weight of the hive is assessed using a HX711 24-bit Analog-to-digital converter along with a strain-gauge load cell situated beneath the hive support. The HX711's high resolution allows the system to detect minute fluctuations in weight, such as the daily nectar intake and honey output of an active colony, which would be difficult to identify with a less accurate scale, making weight one of the most informative individual metrics in the complete sensor array (Alleri et al., 2023; Guruprasad & Leiding, 2024). An NSL-19M51 photoresistor mounted on the solar-panel bracket completes the sensing subsystem, providing an ambient light reading derived from a fixed resistor voltage-divider circuit. Beyond its primary role of clarifying solar-charging patterns, this channel offers a basic day/night and cloud-cover indicator that can be examined alongside other environmental channels when evaluating dashboard trends.

## 3.2 Power Subsystem

A SOL2W solar panel supplies energy to a 1000 mAh Li-Ion battery through a LiPo Rider Pro charge-management circuit, thus forming a dedicated solar power bank for the device. This setup removes dependence on grid electricity at the apiary, which is essential as hives are frequently situated far from buildings or electrical networks. The firmware assesses the battery's charge level by evaluating an Analog voltage measurement through a resistive divider, calibrated between defined voltage limits to produce an estimated percentage, which is subsequently relayed alongside environmental data, offering the beekeeper an understanding of both the power subsystem's status and the hive's condition. An AdaFruit TPL5110 low-power timer regulates the electronics during measurement intervals, improving firmware-driven sleep modes to reduce average current usage — a significant constraint often emphasized in the precision-beekeeping literature for solar-powered field nodes (Sad et al., 2025). Incorporating a hardware timer with software sleep offers two independent levels of energy efficiency: the timer can entirely sever power to the sensor and radio elements during intervals, while the microcontroller's sleep mode reduces power consumption during brief moments of activation without transmission.

## 3.3 Mechanical Design and Enclosure

The electronic components were integrated onto a bespoke PCB crafted in KiCad, subsequent to schematic capture, footprint and enclosure selection, bill-of-materials creation, and board layout. Following fabrication, the board underwent continuity verification before soldering, and the assembled board was evaluated as part of the complete system prior to its final integration into the weatherproof enclosure. The finished electronics were encased in a heat-resistant plastic shell. Waterproofing was accomplished by creating cable-gland ports for every sensor cable, employing heat-shrink tubing to secure cable-to-connector junctions, and utilizing custom 3D-printed brackets to firmly attach the solar panel, photoresistor, and internal circuit board within and around the enclosure. This integration of a commercially available weather-resistant casing with bespoke cable organization and internal supports presents a pragmatic, economical solution for replicable outdoor IoT nodes that does not necessitate access to industrial enclosure production.

## **3.4 Cloud system and data management**

The cloud system receives data from many apiaries and stores it in a time-series database. It maintains records for the beekeeper, apiary, hive, sensor, calibration, inspection, treatment, feeding, harvest and alert. Linking sensor data with management records is essential. A sudden weight reduction that follows a recorded harvest should not be classified as colony loss. Similarly, a change after hive relocation must be interpreted differently from an unexplained movement. The server provides application programming interfaces for mobile and web applications, generates reports and supports cooperative or extension dashboards. Data retention policies distinguish high-frequency raw data from long-term summaries. Audio and image data, which require more storage, may be processed at the edge and uploaded only when an event is detected or when the user requests it.

## **4. Developments**

### **4.1 Firmware and Communication Protocol**

The read-encode-transmit-sleep sequence is followed by the embedded firmware, which was created in C/C++ for the Arduino platform. Using the device's AppEUI, DevEUI, and AppKey identifiers, the firmware initiates the load-cell scale, establishes calibration parameters, and establishes an Over-The-Air Activation (OTAA) connection to the LoRaWAN network. The two DS18B20 probes, the load cell, the battery voltage divider, the indoor and outdoor humidity and temperature, and the photoresistor are all sequentially processed by the primary loop upon activation. Each floating-point measurement is converted into a succinct 16-bit integer before the entire array of readings is combined into a single LoRaWAN uplink packet. Due to LoRaWAN's duty-cycle and airtime constraints, minimizing the uplink payload is essential. By representing each measurement as a scaled integer rather than a full floating-point number, a compact packet is maintained while guaranteeing two decimal places of accuracy. The firmware will attempt a retry during the next wake cycle rather than staying in a perpetual block if the attempt to join or transmit fails. This allows the node to recover on its own from a temporary loss of gateway connectivity without requiring a manual reset in the field. Before the data leaves the network

server, The Things Stack uses a payload-decoder function on the network side to reconstruct the designated fields—temperatures, humidities, weight and battery percentage—from the raw binary uplink.

## 4.2 Cloud Dashboard and Data Visualisation

An HTTP webhook forwards decoded data first to Ubidots and then to BEEP, the beekeeper-facing presentation layer. Thus, two complementary cloud services are used downstream of TTN: BEEP displays the same data through hive-oriented dashboard views, while Ubidots receives the decoded payload first and offers general-purpose widgets and data storage. The parameters provided to the beekeeper are summarized in Table 2.

Table 2  
“ Parameters Exposed on the Beekeeper Dashboard

| Parameter                    | Sensor                         | Update Interval | Destination   |
|------------------------------|--------------------------------|-----------------|---------------|
| Indoor / outdoor temperature | DHT22, DS18B20                 | ~ 10 min        | Ubidots, BEEP |
| Indoor / outdoor humidity    | DHT22                          | ~ 10 min        | Ubidots, BEEP |
| Hive weight                  | HX711 + load cell              | ~ 10 min        | Ubidots, BEEP |
| Battery level                | Analog divider on MKR WAN 1310 | ~ 10 min        | Ubidots, BEEP |

The weight trend serves as a consistent, non-intrusive indicator of foraging behaviour and honey production, which would typically necessitate hive inspection for assessment; concurrently, the display of indoor and outdoor temperature and humidity as correlated trends allows beekeepers to visually differentiate hive-induced thermoregulation from external climatic conditions. Routing identical decoded data through two dashboards, rather than being superfluous, signifies a deliberate developmental choice. BEEP was selected as the preferred production interface due to its dashboard terminology—centered around hives, colonies, and beekeeping-specific thresholds—which is more accessible to the intended end user compared to a standard IoT dashboard, whereas Ubidots functioned as a versatile platform during development to verify the proper functioning of the payload decoder and webhook chain, as its widgets and raw data tables facilitate straightforward validation of values on a field-by-field basis. As of the time of composition, it was indicated that the automatic threshold-based alert setup for the BEEP platform was still in progress (Ratnayake et al., 2026).

## 5. Results

After bench validation—first on a solderless breadboard and later on the finished PCB — the enclosed unit was installed at an apiary site and monitored for approximately two weeks (Catania and Vallone, 2020; Ratnayake et al., 2026). Over this period, the system delivered continuous hive telemetry to the

BEEP dashboard, with successful, easy remote access to hive data and graphical trends showing how conditions evolved over the deployment window.

The published documentation for the project is primarily qualitative: it reports that the dashboard displayed indoor/outdoor temperature and humidity trends, a hive-weight trend, and battery percentage, and that the ten-minute update cadence was maintained in the field, but it does not report quantitative sensor-accuracy figures, a formal packet-delivery-rate statistic, or a measured battery-autonomy figure under field solar conditions (Ratnayake et al., 2026; Souza Cunha et al., 2020). Within these bounds, the two-week trial can reasonably be read as a successful proof of the end-to-end pipeline described in Section 2, rather than as a statistically powered evaluation of sensor accuracy or long-term reliability.

The project met its original technical objectives and provided hands-on experience across the full embedded-systems development cycle: firmware development, LoRaWAN network integration, PCB design, 3D-printed mechanical design, power-budget-conscious hardware selection, and configuration of two cloud dashboards (Bine and Aylon, 2025).

Table 3  
:Objectives from Section 1.2 against Reported Outcomes

| Objective                                         | Outcome as Reported                                                     |
|---------------------------------------------------|-------------------------------------------------------------------------|
| Indoor / outdoor temperature and humidity sensing | Achieved – delivered continuously to the dashboard                      |
| Hive weight sensing                               | Achieved – delivered continuously to the dashboard                      |
| Long-range wireless transmission                  | Achieved – LoRaWAN uplink via TTN maintained throughout the trial       |
| Remote graphical dashboard                        | Achieved – Ubidots and BEEP both operational                            |
| Threshold-based alerting                          | Partially achieved – reported as still in progress (Bine & Aylon, 2025) |
| Autonomous solar power                            | Achieved qualitatively – no quantified autonomy figure reported         |
| Weatherproof enclosure                            | Achieved – unit survived a two-week outdoor deployment                  |

## 6. Discussion

### 6.1 Business Benefits

Relative to the broader precision-beekeeping literature, the Bee-Hive Project's sensor selection, dual temperature/humidity sensing, load-cell weight, and a supporting environmental channel, sits squarely within the mainstream of published PB systems (Alleri et al., 2023; Catania and Vallone, 2020; Guruprasad and Leiding, 2024). The practical advantage for a beekeeper is the substitution of frequent,

intrusive physical inspections with ongoing, remote monitoring of hive conditions, facilitating earlier identification of stress and minimizing unnecessary visits to the apiary. The deliberate incorporation of a hardware timer with firmware-based sleep modes, in conjunction with solar charging, aims for prolonged autonomous functionality at minimal operational expenses, a crucial factor for smallholder or resource-limited beekeeping practices, aligning with the power efficiency focus prevalent in precision-beekeeping research. The publicly available schematics, firmware, and bill of materials further diminish the obstacles to replication for students, enthusiasts, or small-scale apiarists who may find a commercial turnkey system unjustifiable.

## **6.1 .1 Relevance to Low-Resource and Off-Grid Settings**

The design choices made in the Bee-Hive Project are, in several respects, well matched to beekeeping contexts where mains electricity, broadband connectivity, and commercial PB products are not readily available, conditions common across much of the smallholder beekeeping sector, including in many parts of Africa. Solar-only power removes any dependency on grid connection at the apiary; a LoRaWAN uplink can cover a rural apiary from a single, relatively inexpensive gateway rather than requiring cellular data coverage at the hive itself; and a bill of materials built from generic, globally available modules avoids reliance on a single proprietary vendor or service subscription.

Because the full design, schematics, firmware, bill of materials, and enclosure approach, is published openly, it can, in principle, be reproduced or adapted locally rather than purchased as a closed commercial product, which matters where import costs, currency constraints, or after-sales support for imported electronics are limiting factors. Realising this potential in practice would still require local access to basic PCB fabrication or an equivalent hand-assembly approach, a LoRaWAN gateway within range of the apiary, and a stable path to the chosen cloud dashboards, none of which are guaranteed in every deployment context; the point is that the architecture does not itself introduce unnecessary barriers beyond these general IoT-deployment prerequisites.

## **6.1 .2 Significance for Low-Resource and Off-Grid Environments**

The design decisions implemented in the Bee-Hive Project are, in numerous ways, appropriately aligned with beekeeping environments lacking access to mains electricity, broadband internet, and commercial PB products, circumstances prevalent in many regions of the smallholder beekeeping industry, particularly in various areas of Africa. According to Bine and Aylon (2025) utilizing solar energy eliminates reliance on grid connectivity at the apiary; a LoRaWAN uplink can effectively service a rural apiary from a singular, cost-effective gateway instead of necessitating cellular data access at the hive; and a materials list composed of universally accessible modules mitigates dependence on any singular proprietary supplier or service subscription. The comprehensive design, including schematics, firmware, bill of materials, and enclosure strategy, is made publicly available, allowing for local reproduction or adaptation instead of acquiring it as a proprietary commercial item, which is significant in contexts where import expenses, currency limitations, or after-sales service for imported electronics pose

challenges. Actualizing this potential in practice necessitates local access to fundamental PCB fabrication or a comparable hand-assembly method, a LoRaWAN gateway within proximity of the apiary, and a reliable connection to the selected cloud dashboards, none of which are assured in every deployment scenario; the key point is that the architecture does not impose superfluous obstacles beyond these general IoT deployment requirements.

Several limitations temper these benefits and outline directions for further work. The two-week field trial is short relative to the seasonal cycles that most influence hive weight and thermoregulation, so results speak to short-term system function rather than long-term seasonal performance. The system does not include acoustic or vibration sensing, used elsewhere to detect swarming or queenlessness (Guruprasad and Leiding, 2024; Sad et al., 2025).

Threshold-based alerting, arguably the feature that most directly reduces the need for physical inspection, was not yet configured at the time of writing. Finally, the design as documented targets a single hive; scaling to a multi-hive apiary would require a LoRaWAN gateway with adequate capacity and per-node addressing, and, at larger scale, a review of ongoing data and connectivity costs across the Ubidots and BEEP subscriptions used downstream of TTN.

## 7. Conclusions

This paper has presented a case study of the Bee-Hive Project, an open, solar-powered IoT system for smart beehive monitoring built around an Arduino MKR WAN 1310, a compact sensor suite for temperature, humidity, weight and a LoRaWAN-to-cloud data pipeline terminating in a beekeeper-facing dashboard. The system's custom PCB, weatherproof enclosure, and solar power management demonstrate a complete, low-cost path from sensor node to usable hive telemetry, and its two-week field deployment shows the pipeline functioning end to end outside laboratory conditions.

Further work should extend field trials across a full season to capture build-up, nectar flow, and overwintering behaviour; complete and validate threshold-based alerting; add acoustic or entrance-traffic sensing to broaden the set of detectable colony events; conduct a quantified energy budget and battery-autonomy study under real solar conditions; and generalize the single-hive design to a multi-hive apiary deployment coordinated through a shared LoRaWAN gateway.

More broadly, this implementation suggests that a fully documented, low-cost, solar-powered hive-monitoring node of this kind is a realistic building block for wider precision beekeeping adoption in resource-constrained and off-grid apiary settings, provided the outstanding items identified above, particularly completed alerting and a properly quantified energy budget, are addressed before wider deployment is attempted.

## Declarations

## Acknowledgements

*Declaration of use of content generated by artificial intelligence (AI) (including but not limited to generative AI) in the paper. The authors acknowledge the use of content generated by artificial intelligence (AI) in the paper entitled “IoT-Enabled Smart Beehive Monitoring: Design, Implementation, and Field Evaluation of the Bee-Hive Project” in the following ways: Claude (Anthropic) was used to check document coherence, references, and any grammar issues. All AI-assisted content was reviewed, verified against cited sources, and edited by the author(s) prior to submission.*

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## Figures

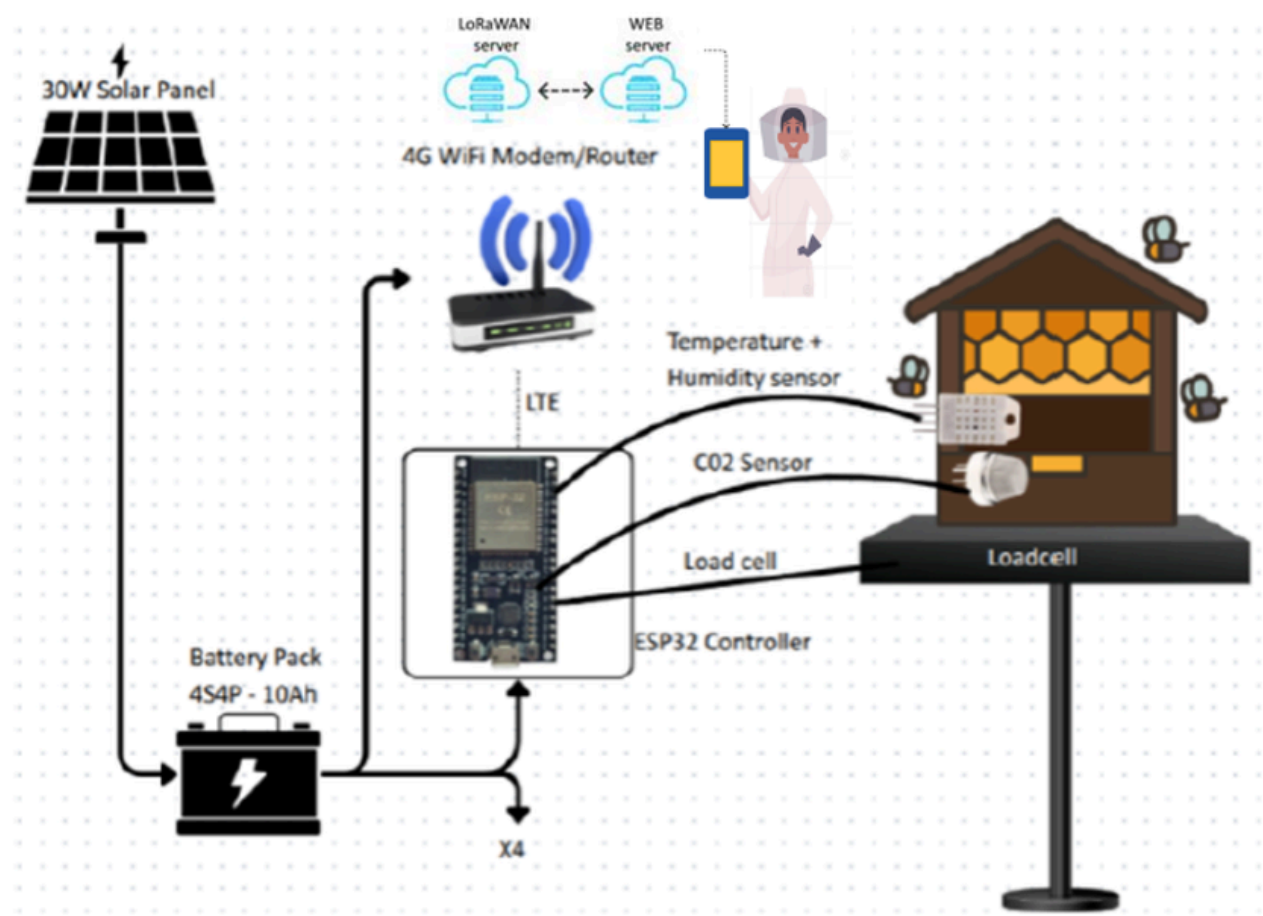


**Figure 1**

Station Architecture, Solar Panel, battery pack, ESP 32 Controller and shared 4G uplink.