

Chapter 4

Results and Discussion

4.1 Introduction

The primary objectives of this work—originally stated in Chapter 1—were as follows:

1. To design and deploy a field node capable of collecting in-situ water-quality parameters: pH, temperature, salinity, dissolved oxygen (DO), and oxidation-reduction potential (ORP).
2. To establish reliable wireless communication over at least 1 km in a line-of-sight (LOS) configuration.
3. To integrate a solar-powered energy-harvesting subsystem, ensuring that the node remains self-sustaining (i.e., harvested solar energy exceeds consumption over a typical diurnal cycle).
4. To validate the mechanical robustness of the enclosure under realistic outdoor conditions, including exposure to precipitation.

This chapter is organized as follows:

- In Section 4.2, an overview of the experimental setup is revisited, summarizing the deployment conditions, key parameters, and environmental variables for all tests: sensor data collection, wireless link, battery capacity and power profiling, and water-ingress validation.
- Section 4.3 presents the raw and processed data obtained from each test.
- Section 4.4 provides a detailed analysis of the performance metrics, including data-quality assessment, link reliability, energy balance, and enclosure integrity.
- Finally, Section 4.5 offers a concise summary of findings and implications for future deployments.

4.2 Experimental Setup Recap

This section briefly summarizes the four primary experiments described in this chapter:

1. The week-long sensor data collection in a small pool.
2. The line-of-sight wireless link test spanning approximately 1.2 km.
3. The empirical battery capacity characterization and power consumption profiling.
4. The water-ingress and spray test for enclosure robustness.

4.2.1 Sensor Data Collection (Pool Test)

- **Deployment Duration:** Continuous operation for 168 h (7 days), beginning at 2025-06-03 00:00 (local time).
- **Sampling Interval:** Each sensor (pH, temperature, salinity, DO, ORP) recorded one measurement per 1 h. All raw readings—including battery voltage—were logged by the node's onboard ADC and transmitted when available.
- **Pool Characteristics:**
 - Approximate depth: $d_{\text{pool}} \approx 0.6$ m (varies with rainfall and evaporation).
 - Surface area: 2 m×1 m.
 - Exposure: The node was deployed in direct sunlight during daytime hours; partial shading occurred intermittently due to ambient conditions (e.g., passing clouds).
 - Motion: The sensor package was allowed to drift freely within the pool area without a fixed anchor, to simulate minor position shifts as might occur in a natural water body.
- **Power Management:**
 - Battery voltage was logged at the same 1 h interval.
 - The solar panel was oriented horizontally atop the enclosure, collecting insolation between sunrise and sunset.
 - Precise current draw was characterized in the laboratory with a Fluke multimeter, in-field consumption was observed via battery-voltage trends.
- **Environmental Variables:**

- The node is equipped with an SHT20 sensor to monitor the temperature and humidity within the electronics enclosure, providing critical data for detecting potential thermal stress or moisture ingress. To supplement this internal monitoring with the broader environmental context of the deployment, historical weather data for the Tangerang area was obtained for the test period (June 3–10, 2025). Figure 4.1 illustrates the fluctuations in the *external* ambient temperature, with daily highs reaching approximately 33°C and lows around 24°C.
- Figure 4.2 depicts the corresponding *external* relative humidity during the week. Levels remained high, typically ranging from 70% to 95%, with the highest values occurring in the early morning.

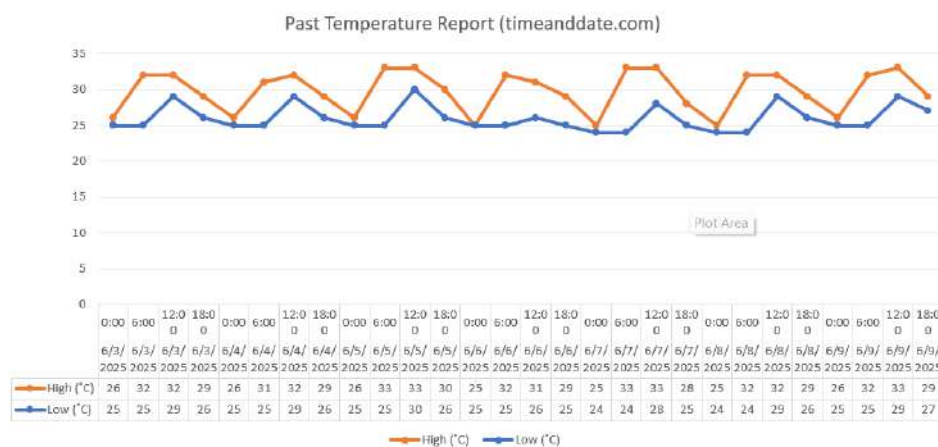


Figure 4.1: Past Temperature Data (High Low) for Tangerang (June 3-10, 2025)

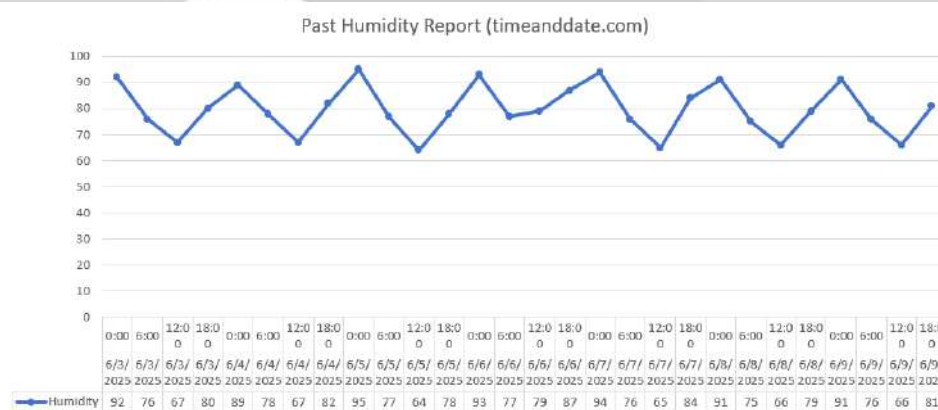


Figure 4.2: Past Humidity Data for Tangerang (June 3-10, 2025)

4.2.2 Wireless Link Test (1.2 km LOS)

- **Test Date and Time:** Single test conducted at approximately 18:00 (local Jakarta time) on 2025-04-29.
- **Link Distance:** $d_{\text{link}} \approx 1.2$ km, verified via handheld GPS at each node location.
- **Node and Gateway Hardware (see Chapter ?? for full specifications):**
 - *Field Node:* LilyGO LoRa32 board (Semtech SX1276), transmitting at 14 dB mW (factory default for ADR-enabled operation).
 - *Antenna—Node:* Omnidirectional, 5 dB gain.
 - *Gateway:* SenseCAP M2 LoRaWAN receiver, connected to a 3 dB omnidirectional antenna.
 - *Modulation:* LoRaWAN Class A with ADR. Payload identical to the pool test (all five sensor readings plus battery voltage).
- **Ping Procedure:**
 - *Number of Pings:* Ten (10) uplink transmissions, spaced 30 s apart.
 - *Measured Metric:* Received Signal Strength Indicator (RSSI) only; no packet losses were observed (10/10 packets received).
 - *Time Slot Constraints:* Limited to a short period in a semi-public area; therefore, no extended or repeated tests were possible.
- **Environmental Conditions:**
 - Ambient temperature: Range from 24 °C (minimum) to 32 °C (maximum) on the test day.
 - No precipitation occurred during the test interval.
 - Potential interference sources: Nearby 4G LTE and 5G base stations; the test locations were not directly adjacent to any cellular tower.
 - Line-of-sight obstruction: One intermediate high-rise apartment building, estimated height 100 m, intersected the direct path but did not fully block the Fresnel zone.

- **Key Parameters (SI Units):**

$$t_{\text{ping}} = 30 \text{ s}, \quad N_{\text{pings}} = 10, \quad d_{\text{link}} = 1.2 \text{ km}, \quad G_{\text{ant,node}} = 5 \text{ dB}, \quad G_{\text{ant,gateway}} = 3 \text{ dB},$$

$$P_{\text{tx}} = 14 \text{ dB mW}, \quad T_{\text{amb}} = 24 \text{ °C to } 32 \text{ °C}.$$

4.2.3 Battery Capacity Characterization & Power Consumption Profiling

- **Battery Specification:**

- Lithium-ion battery rated at 5200 mA h nominal capacity.
- Manufacturer's datasheet indicates 3.7 V nominal voltage.

- **Capacity Test Procedure:**

- The battery was fully charged to 4.2 V, then discharged at a constant 2 A until 3.5 V cutoff.
- Voltage and current were logged using a Lithium Ion Battery Discharger.
- Usable capacity, C_{usable} , was computed by integrating current over discharge time:

$$C_{\text{usable}} = \int_{t_0}^{t_{\text{end}}} I(t) dt \quad [\text{A h}].$$

- **Power Consumption Profiling:**

- The node's current draw was measured with a Fluke multimeter in two modes:
 - * *Active Mode*: While sampling all sensors and transmitting a LoRa packet.
 - * *Deep Sleep Mode*: Between sampling events.

- **Solar Panel Output Test:**

- *Objective*: To quantify the real-world power output of the selected polycrystalline silicon panel during late afternoon and into the evening, using a known shunt resistor for current measurement.
- *Setup*:
 - * A 6 V, 350 mA polycrystalline silicon solar panel was mounted horizontally, facing unobstructed afternoon sky.
 - * A precision 10 Ω shunt resistor was inserted in series between the solar panel's positive terminal it's negative terminal. The voltage between the shunt resistor is logged every 3 s
 - * Data was captured via an ADS1115 and microcontroller over a total duration of 430 min, starting at approximately 15:00 local time (mid-afternoon) and continuing through to near-night conditions.
 - * Ambient conditions were noted at the start of logging: clear sky, panel surface clean, negligible shading.
- *Measurement Method*:

- * Instantaneous current through the panel was computed as

$$I_{\text{panel}}(t) = \frac{V_{\text{shunt}}(t)}{R_{\text{shunt}}} \quad \text{with} \quad R_{\text{shunt}} = 10 \, \Omega.$$

- * Simultaneously, panel terminal voltage $V_{\text{panel}}(t)$ was read directly at the panel's output terminals (just upstream of the shunt).
- * Instantaneous power output was then calculated as

$$P_{\text{panel}}(t) = V_{\text{panel}}(t) \times I_{\text{panel}}(t).$$

- * All voltage readings (V_{shunt} and V_{panel}) were timestamped at 3s intervals for 430 min, covering late-afternoon sun, sunset transition, and post-sunset darkness.

4.2.4 Water Ingress and Spray Test

- **Test Objective:** To verify that the enclosure prevents water ingress under direct spray conditions and maintains sensor operation after exposure.
- **Spray Test Procedure:**
 - The assembled node (enclosure+external cable glands) was subjected to a controlled spray from a shower nozzle at ≈ 0.5 m distance, simulating a reasonably heavy rain.
 - Spraying lasted for 2 min.
 - Immediately following the spray, the node remained powered on;
- **Enclosure Inspection:**
 - After spray, the enclosure was opened and visually inspected for moisture on internal electronics, including PCB, connectors, and cable glands.
 - No infiltration was observed; O-ring seals and gasket interfaces remained dry to the touch.
- **Summary of Results:**
 - No water ingress detected—enclosure meets our criteria for water resistance.
 - Sensor readings and radio link performance were unaffected by the spray test.

4.3 Results

This section presents the empirical findings from each of the four validation tests: (1) sensor data collection in a small pool; (2) wireless link performance over 1.2 km LOS; (3) battery

capacity characterization and power consumption profiling; and (4) water-ingress and spray resilience. Wherever applicable, figures and tables are referenced as placeholders and should be replaced with actual data/graphics in the final document.

4.3.1 Sensor Data Collection Results

During the 168 h (7-day) deployment, the system performed continuous monitoring. The test was conducted in two distinct phases to evaluate the power system's performance. For the first two days (June 3-5), the solar panel was intentionally disconnected to observe the battery's discharge characteristics under operational load. Subsequently, the panel was reconnected for the remainder of the deployment to analyze its charging effectiveness from a partially depleted state.

This section presents the results for all monitored parameters. The hourly time-series data is shown in Figures 4.3 through 4.12.

The two-phase power experiment is clearly visible in the battery voltage trend shown in Figure 4.10. A steady discharge slope is observed during the initial 48 hours while the solar panel was disconnected. After its reconnection on June 5, the battery voltage begins to recover, exhibiting distinct charging cycles that align with daily sun exposure and successfully replenishing the consumed energy.

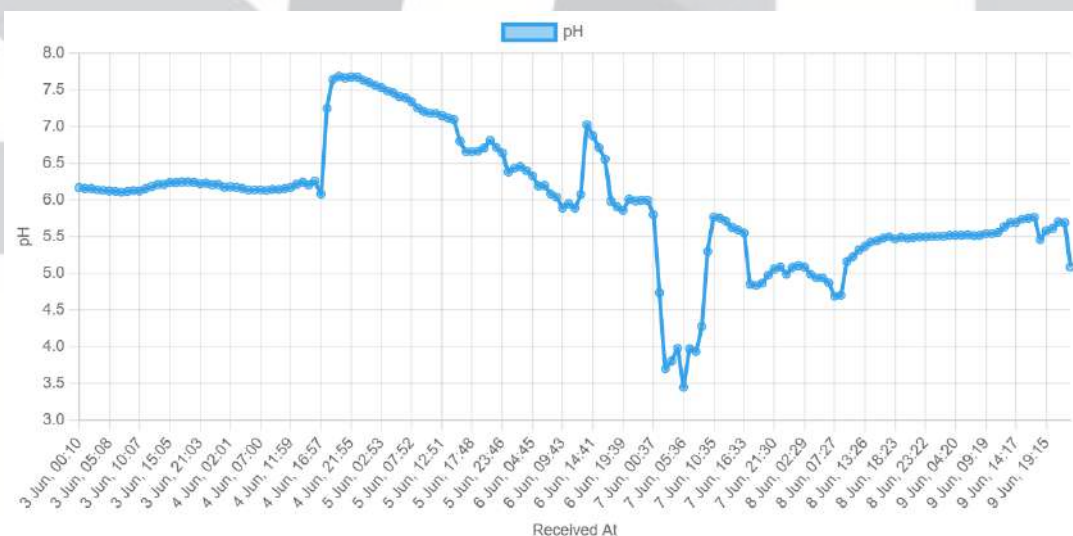


Figure 4.3: Hourly pH readings over the 7-day pool deployment.

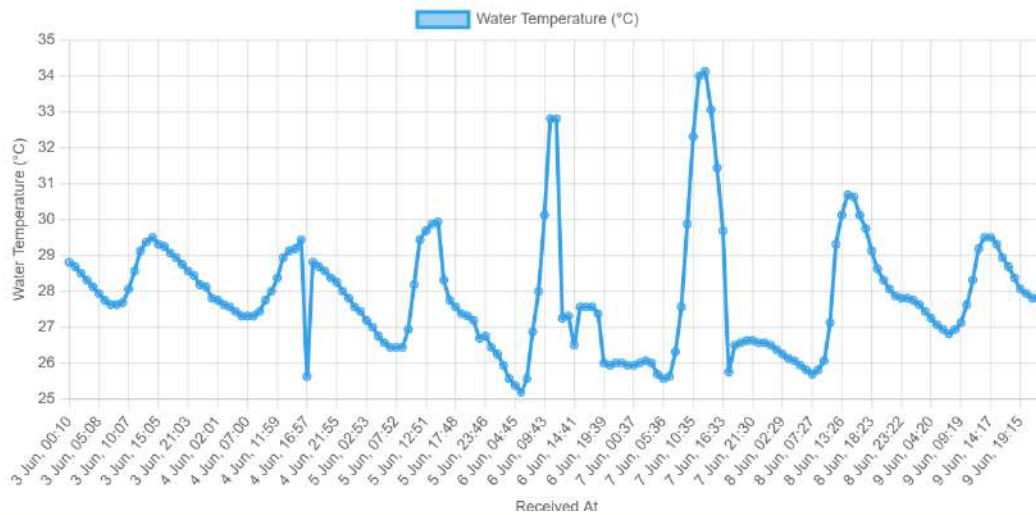


Figure 4.4: Hourly water temperature readings over the 7-day pool deployment.

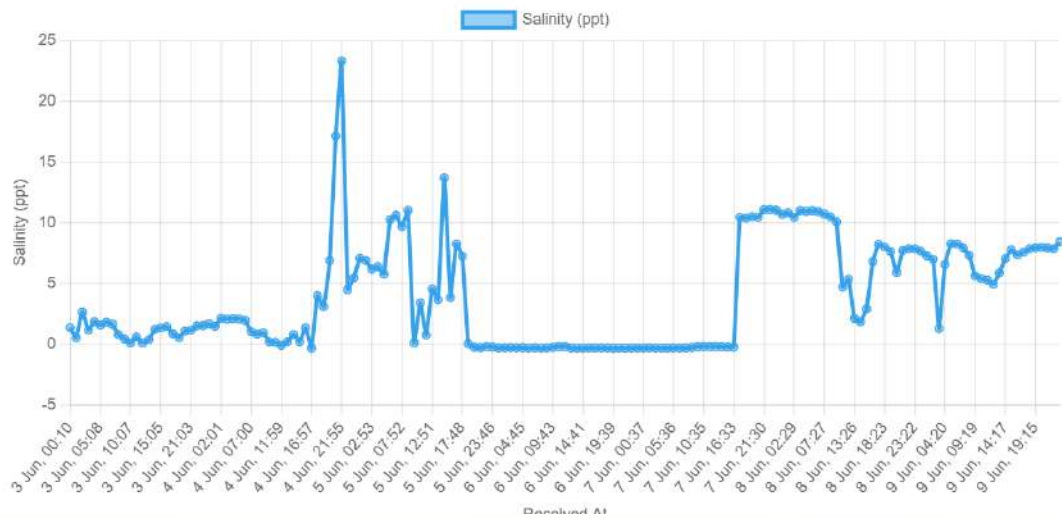


Figure 4.5: Hourly salinity readings over the 7-day pool deployment.

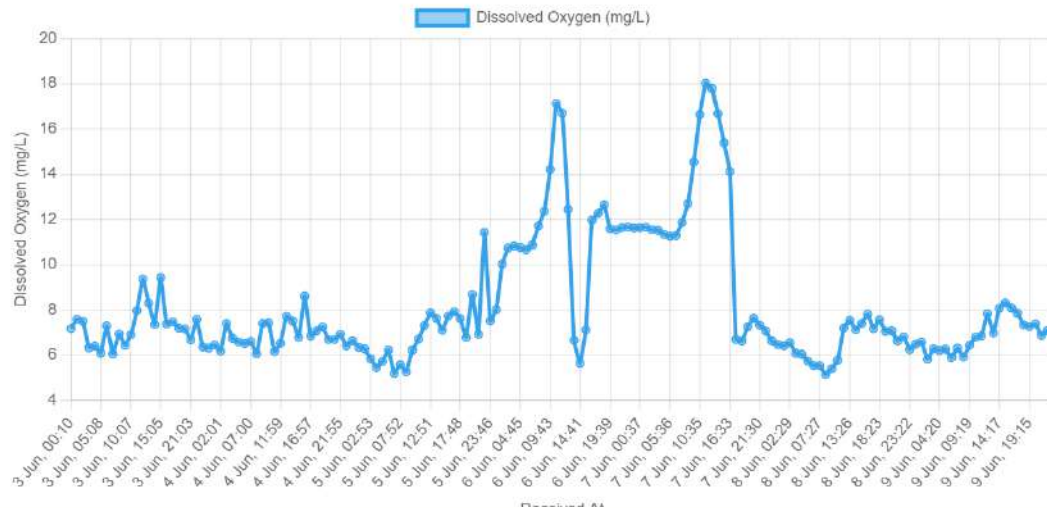


Figure 4.6: Hourly dissolved oxygen (DO) readings over the 7-day pool deployment.

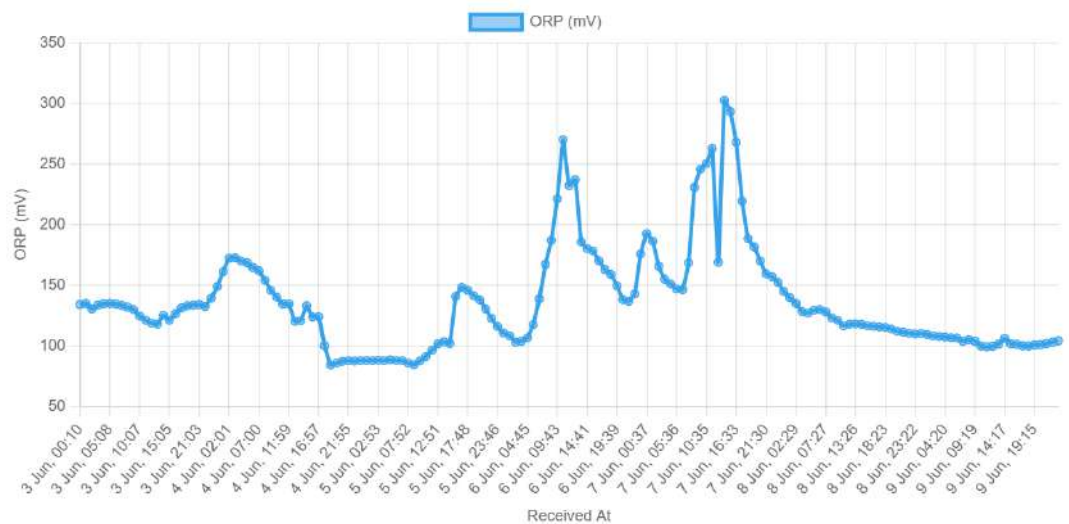


Figure 4.7: Hourly oxidation-reduction potential (ORP) readings over the 7-day pool deployment.

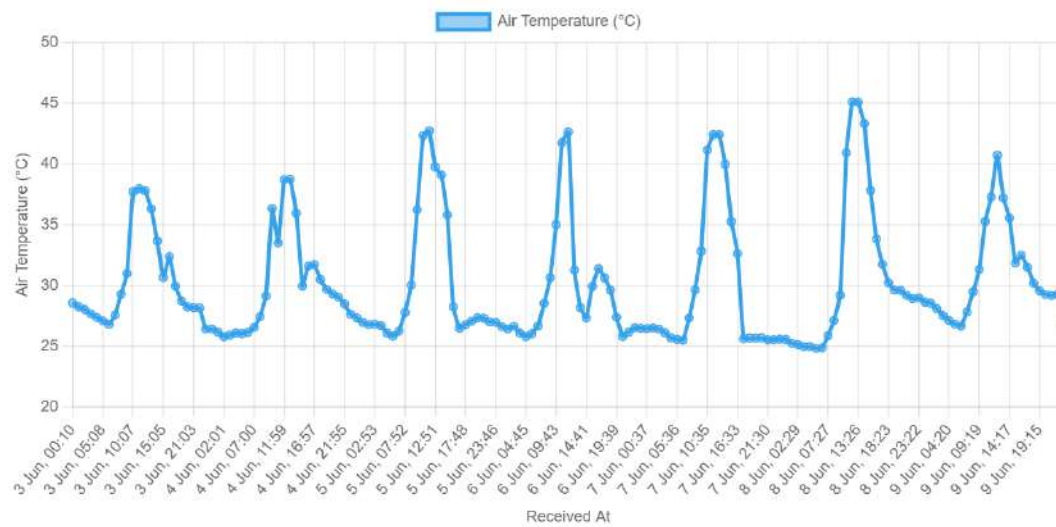


Figure 4.8: Hourly internal enclosure air temperature readings.

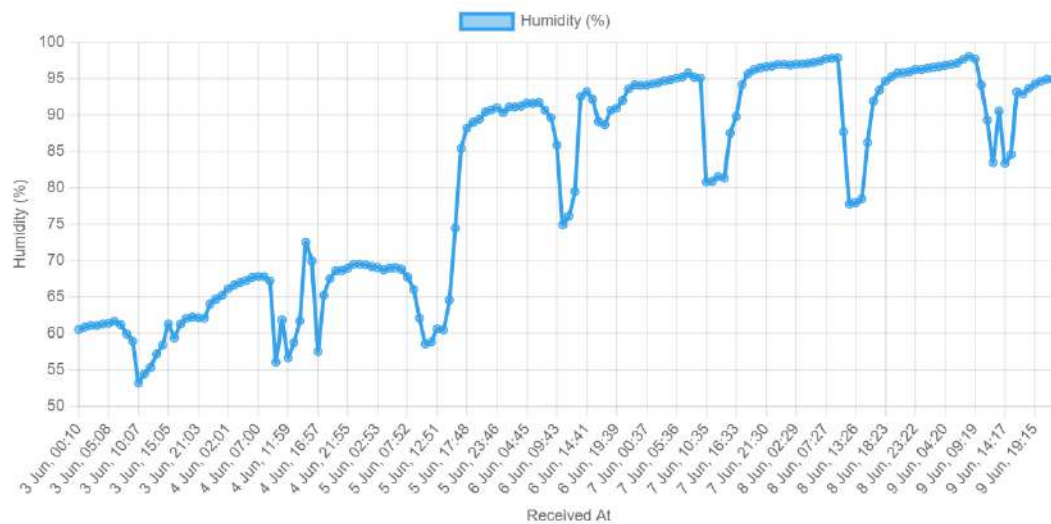


Figure 4.9: Hourly internal enclosure humidity readings.



Figure 4.10: Battery voltage over time during the 7-day deployment.

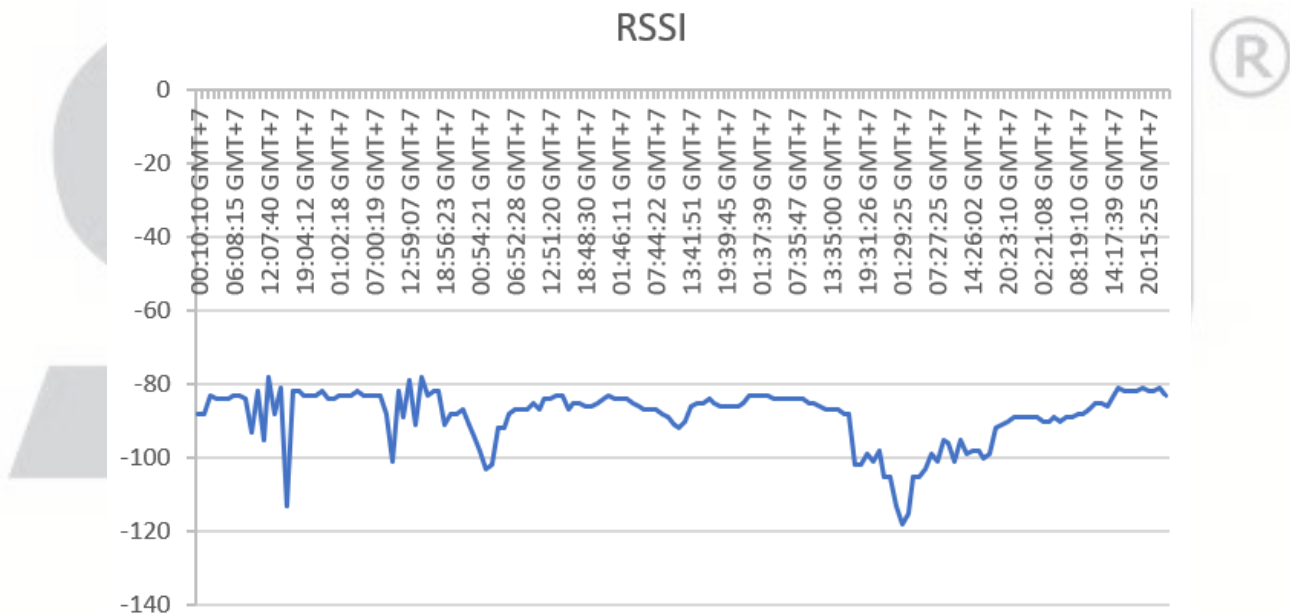


Figure 4.11: Received Signal Strength Indicator (RSSI) for each hourly transmission.

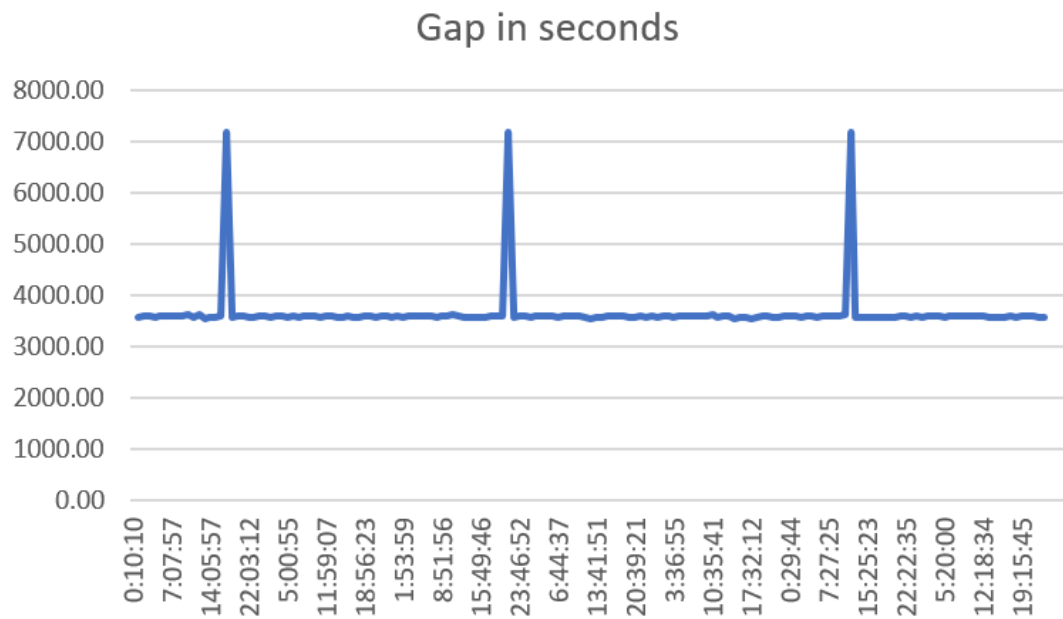


Figure 4.12: Time gap between consecutive data packets received by the server.

A statistical summary of the key parameters recorded during the deployment is provided in Table 4.1.

Table 4.1: Summary statistics for all logged parameters over 168 h.

Parameter	Mean	Std. Dev.	Min	Max
<i>Water Quality Parameters</i>				
pH	5.96	0.84	3.44	7.68
Water Temperature (°C)	27.90	1.71	25.19	34.13
Salinity (ppt)	3.86	4.44	0.00	23.34
DO (mg/L)	8.25	2.87	5.13	18.03
ORP (mV)	136.23	42.53	84.11	302.64
<i>System and Environmental Parameters</i>				
Air Temperature (°C)	30.24	5.10	24.83	45.11
Humidity (%)	80.97	14.71	53.17	98.06
RSSI (dBm)	-85	4.2	-95	-78

Throughout the entire deployment, a high degree of data integrity was maintained, with only 3 missing transmissions out of the 168 expected hourly readings. This high reliability is also reflected in the RSSI values, which remained strong and stable. Minor fluctuations observed in some water quality parameters correlate qualitatively with rainfall events that increased the water volume in the pool. The battery voltage behavior confirmed the success of the two-phase

power test, demonstrating both a predictable discharge rate and the solar panel's capability to effectively recharge the system.



4.3.2 Wireless Link Test Results

A single-session line-of-sight (LOS) test was conducted on 2025-04-29 at approximately 18:00 local Jakarta time to assess link reliability and signal strength over a distance of 1.2 km. The field node—equipped with a LilyGO LoRa32 board (Semtech SX1276) transmitting at 14 dB mW into a 5 dB omnidirectional antenna—sent ten (10) consecutive uplink packets spaced 30 s apart. The gateway (SenseCAP M2 with a 3 dB antenna) logged Received Signal Strength Indicator (RSSI) for each packet. No packet losses occurred (10/10 packets received).

Table 4.2: RSSI measurements for 10 uplink packets at 1.2 km LOS

Packet #	RSSI (dB mW)
1	-92
2	-93
3	-97
4	-91
5	-87
6	-93
7	-103
8	-99
9	-91
10	-95

Figure 4.13: RSSI versus packet index for ten uplink transmissions at 1.2 km LOS.

From Table 4.2, the measured RSSI values range between -103 dB mW and -87 dB mW. The sample mean RSSI is -94.1 dB mW with a standard deviation of 4.3 dB mW. Under these conditions—ambient temperature between 24°C and 32°C , no precipitation, and a single mid-path building of approximately 100 m height not fully obstructing the Fresnel zone—the link margin remains well above the receiver sensitivity threshold of -137 dB mW. This confirms reliable operation at 1.2 km LOS with the selected hardware configuration.

4.3.3 Battery Capacity and Power Consumption Results

This subsection presents three separate experimental results: (1) solar-panel energy harvesting; (2) battery-pack capacity; and (3) node power consumption profile.

- **Solar Panel Energy Harvesting:**

- *Experimental Setup Recap:* The same 6 V, 350 mA polycrystalline silicon panel (used during the pool deployment) was logged beginning at 15:00 (local time) for a total duration of 430 min. A $10\ \Omega$ precision shunt resistor was placed in series between the panel's positive terminal and the charge-controller input. Voltage drops across the shunt, $V_{\text{shunt}}(t)$, and panel terminal voltage, $V_{\text{panel}}(t)$, were recorded at 3 s intervals by an ADS1115 ADC module and microcontroller.
- *Total Harvested Energy:* Instantaneous current through the shunt was computed as

$$I_{\text{panel}}(t) = \frac{V_{\text{shunt}}(t)}{R_{\text{shunt}}}, \quad R_{\text{shunt}} = 10\ \Omega.$$

Instantaneous power from the panel was

$$P_{\text{panel}}(t) = V_{\text{panel}}(t) \times I_{\text{panel}}(t).$$

Numerical integration over the entire 430 min logging period yielded a total harvested energy of

$$E_{\text{total}} \approx 2031.468\ \text{J}.$$

Practically all of this energy was collected during the first 200 min (daylight hours), with negligible output after sunset.

- *Power Generation*

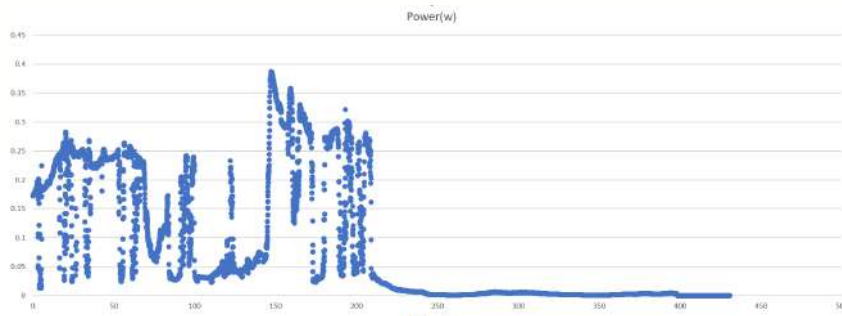


Figure 4.14: Instantaneous solar-panel power output versus time (logged at 3 s intervals).

- **Battery Capacity Test:**

- *Battery Pack:* Two 2600 mA h Li-ion cells were connected in parallel, creating an effective single pack rated at 5200 mA h nominal capacity, with a nominal voltage of 3.7 V.
- *Discharge Procedure:* The pack was fully charged to 4.2 V and then discharged at a constant current of 2 A until reaching 3.5 V cut-off. Voltage and current were logged via a laboratory battery discharger.
- *Measured Discharge Time:* Total discharge duration was 134 min 27 s. Converting to hours:

$$t_{\text{discharge}} = 134 + \frac{27}{60} \text{ minutes} = 134.45 \text{ minutes} = 2.2408 \text{ hours.}$$

- *Usable Capacity Calculation:* Usable capacity C_{usable} (in mA h) is

$$C_{\text{usable}} = I_{\text{discharge}} \times t_{\text{discharge}} = 2 \text{ A} \times 2.2408 \text{ h} = 4.4816 \text{ Ah} = 4481.6 \text{ mA h.}$$

• Power Consumption Profile:

- *Measured Currents:*
 - * *Peak (Active) Current:* $I_{\text{active}} \approx 96 \text{ mA}$ (during sensor sampling and LoRa transmission).
 - * *Deep-Sleep Current:* $I_{\text{sleep}} \approx 0.44 \text{ mA}$ (when the microcontroller, sensors, and radio were in idle/sleep states).
- *Duty Cycle:* The node remained active (sampling + transmitting) for up to 2 min each hour, then entered deep-sleep for the remaining 58 min.
- *Average Current Computation:* Over each 1 h cycle:

$$I_{\text{avg}} = \frac{I_{\text{active}} \cdot t_{\text{active}} + I_{\text{sleep}} \cdot t_{\text{sleep}}}{60 \text{ minutes}} = \frac{96 \text{ mA} \times 2 + 0.44 \text{ mA} \times 58}{60} = 3.6253 \text{ mA.}$$

4.3.4 Water Ingress and Spray Test Results

The node was exposed to a 2 min spray from a shower nozzle at 0.5 m distance, simulating moderate rainfall conditions.

No water ingress was detected upon visual inspection of the enclosure interior. Therefore, the enclosure design meets the intended water-resistance criteria, and the node continued functioning without fault.

4.4 Discussion

4.4.1 Sensor Data Collection Discussion

This section discusses the data collected from the deployed sensor buoy over a one-week period from June 3rd to June 9th, 2025. The analysis focuses on battery performance, network signal quality, and the response of environmental sensors to specific events, as well as data transmission reliability.

Battery Voltage Analysis.

The battery voltage data provides critical insight into the device's power characteristics, allowing for separate analyses of its power consumption and solar generation efficiency.

Power Consumption Analysis To quantify the device's operational power consumption, a detailed analysis was performed on a period where the solar panel was disconnected, ensuring the observed voltage change was due solely to energy usage. The calculation proceeded in the following steps:

1. **Assumptions:** This analysis is based on two foundational assumptions: first, that a linear relationship exists between the battery's voltage and its stored capacity (mAh); and second, that the battery has a total usable capacity of 4481.6 mAh over a voltage range defined by a minimum of 3.5 V and a recorded maximum (full charge) of 4.198 V.
2. **Capacity-Voltage Relation:** The linear capacity rate, or the amount of charge depleted per volt, was determined by dividing the total usable capacity by the full voltage range:

$$\text{Capacity Rate} = \frac{4481.6 \text{ mAh}}{4.198 \text{ V} - 3.5 \text{ V}} \approx 6421.36 \text{ mAh/V}$$

3. **Discharge Duration:** The observation period began at 00:10:10 on June 3, 2025, and concluded at 05:52:46 on June 5, 2025. The total duration of this discharge phase was calculated to be 53.71 hours.
4. **Total Capacity Consumed:** During this period, the battery voltage dropped from an initial 4.103 V to a final 4.073 V. The total capacity consumed is the product of this voltage drop and the established capacity rate. The precise, unrounded voltage values were used for the final calculation, yielding:

$$C_{\text{consumed}} = (V_{\text{start}} - V_{\text{end}}) \times \text{Capacity Rate} \approx 191.17 \text{ mAh}$$

5. **Average Current Draw:** The average hourly current draw is the total capacity consumed divided by the total duration of the period:

$$\text{Average Current} = \frac{191.17 \text{ mAh}}{53.71 \text{ hours}} \approx 3.56 \text{ mA}$$

6. **Comparison with Estimate:** This empirically derived average current of 3.56 mA is only 1.82% lower than the pre-deployment theoretical estimate of 3.6253 mA. This close alignment strongly validates the initial power budget calculations and confirms the device's expected energy performance.

Power Generation Analysis The performance of the solar charging system was quantified by analyzing the primary charging phase on June 5, 2025. Between 05:52:46 and 13:50:46, a period of 7.97 hours, the battery voltage increased from a morning low of 4.073 V to an afternoon peak of 4.197 V. Based on the established linear capacity-voltage model, this increase corresponds to a total charge gain of 792.37 mAh. This yields an average *net* charging current of 99.46 mA. Factoring in the device's simultaneous consumption of 3.56 mA, the *gross* current generated by the solar panel is estimated to be approximately 103.02 mA.

To benchmark this performance, the generation rate was compared against a reference experiment that produced 2031.468 J over 200 minutes. For an equitable comparison, the system's energy generation was converted to Joules. The 792.37 mAh gained at an average voltage of 4.13 V equates to 11,794.96 J over the 478-minute charging period. This results in a generation rate of 24.68 J/minute, which is 142.9% higher than the reference experiment's rate of 10.16 J/minute. This significant outperformance confirms the solar charging system is not only viable but highly effective under the observed field conditions.

RSSI Fluctuation.

The Received Signal Strength Indicator (RSSI) is a measure of the LoRaWAN signal quality between the node and the gateway. During the observation period, the RSSI values ranged from a strong -78 dBm to a weaker -118 dBm, with an average of -88.5 dBm. This significant swing is not unexpected for an outdoor deployment. Factors such as changing atmospheric conditions (e.g., humidity, which ranged from 53% to 98%), potential signal obstruction, and multipath fading caused by reflections off the water surface can all contribute to such variations. Despite the fluctuations, the connection remained largely stable, indicating the communication link was robust.

Salinity Event Analysis.

A specific event was conducted to test the salinity sensor's responsiveness. On the afternoon of June 4th, salt was introduced to the water near the buoy. The data shows an immediate and

sharp increase in salinity readings, peaking at 11.67 PPT (Part Per Thousands) late that evening. Following this event, a presumed rainfall event caused a rapid dilution of the surface water, with salinity levels dropping to near-zero (0.089 PSU) by the next morning, June 5th. Interestingly, the salinity spiked again later that day to 6.84 PPT, which could be attributed to the mixing of the water column, causing previously undissolved salt deposits to be measured as they diluted, or the buoy's sensor dipping closer to the more concentrated deposits due to evaporation.

Air Temperature Validation

To validate the readings from the onboard air temperature sensor, a comparison was conducted against historical meteorological data for Tangerang, obtained from [56]. The daily maximum and minimum temperatures from both the deployed sensor and the weather service for the period of June 3rd to June 9th are presented in Table 4.3.

The comparison reveals two key findings. Firstly, the minimum temperatures recorded by the sensor show a strong correlation with the weather service data. On most days, the sensor's minimum reading was within 1°C of the official low, such as on June 4th (25.78°C from the sensor vs. 26°C from the service) and June 8th (24.83°C vs. 26°C). This alignment suggests the sensor accurately measures the ambient temperature during periods without direct solar heating, like at night or in the early morning.

Secondly, a significant and consistent positive bias was observed in the maximum temperature readings. The sensor reported values substantially higher than the meteorological reference data, with the most extreme case occurring on June 8th, where a reading of 45.11°C was recorded. This discrepancy is attributed to radiative heating of the sensor enclosure. The compact and unventilated nature of the housing inhibits the dissipation of absorbed thermal energy via convective cooling. As a result, a heated microclimate develops within the enclosure, causing the sensor to register this elevated internal temperature rather than the true ambient air temperature.

Table 4.3: Comparison of Daily Air Temperature Extremes (°C)

Date	Sensor Data		Weather Service Data	
	Max	Min	Max	Min
June 3, 2025	37.98	26.40	33	26
June 4, 2025	38.76	25.78	33	26
June 5, 2025	42.74	25.82	33	26
June 6, 2025	42.63	25.79	34	27
June 7, 2025	42.43	25.51	34	27
June 8, 2025	45.11	24.83	34	26
June 9, 2025	40.73	26.65	34	26

Data Transmission Gaps

The sensor node was configured to transmit data on an hourly basis, resulting in an expected interval of 3600 seconds between successfully received messages. The data confirms that transmissions were largely successful and regular throughout the deployment week. However, on three specific occasions, the transmission gap extended to approximately two hours (7157s, 7163s, and 7162s), indicating a single missed hourly packet in each case. These events occurred on June 3rd, June 5th, and June 8th, 2025.

Several possibilities could account for these isolated failures: 1) a node-level fault, where the microcontroller failed to wake from its deep sleep state to initiate the transmission; 2) a network-level issue, where the message was successfully received by the LoRaWAN gateway but the back-end infrastructure of The Things Network (TTN) failed to process and forward the packet ; or 3) an application-level failure in the MQTT integration between TTN and our cloud server.

An interesting correlation arises when comparing these dates to historical weather data, which reports "passing clouds" for Tangerang on June 3rd, 5th, and 8th. While this observation is not statistically significant, it presents a plausible hypothesis. Increased cloud cover, especially if associated with higher atmospheric moisture or localized rain, can increase the attenuation of radio frequency signals. It is conceivable that during these periods, the LoRaWAN signal was marginally too weak to be successfully decoded by the gateway, resulting in packet loss at the physical layer. This suggests a potential link between transient weather phenomena and communication reliability.

Despite these three isolated missed transmissions out of 168 expected packets, the system achieved a success rate of over 98%. Given this infrequency, the overall data pipeline is considered highly reliable for its intended application.

4.4.2 Wireless Link Test Discussion

Using the LoRa model (no antenna gain assumed), the free-space path loss (FSPL) at 1 km and 923 MHz is

$$\text{FSPL} \approx 91.75 \text{ dB}.$$

With a transmit power $P_{Tx} = 14$ and zero dBi antenna gain, the ideal received power would be

$$P_{Rx, \text{ideal}} = 14 - 91.75 = -77.75 \text{ dBm}.$$

In our test, the measured average RSSI was -94.1 , corresponding to an actual path loss of

$$14 - (-94.1) = 108.1 \text{ dB}.$$

Thus, the observed path loss exceeds the ideal FSPL by approximately 16.35 dB. This additional loss can be attributed to:

- **Extended path length:** The actual link distance was roughly 1.2 km, about 200 m longer than the 1 km used in the FSPL calculation.
- **Partial Fresnel obstruction:** A 100 m-tall building partially intruded into the first Fresnel zone, introducing diffraction losses.
- **Ambient interference:** Nearby 4G/5G cellular signals likely increased the effective noise floor.
- **Temperature effects:** The test afternoon temperatures (around 24 °C–32 °C) can slightly degrade RF performance compared to the ideal model.

Despite this ≈ 16.35 dB discrepancy, all ten packets were successfully received (10/10), indicating that the chosen hardware and SF12 configuration provide sufficient margin for reliable 1.2 km operation in a semi-urban Jakarta environment.

4.4.3 Power Experiments Discussion

1. Comparison to Similar Studies

Table 2.1 (Section 2) summarizes four representative water-quality systems. Their average power draws (converted to current at 3.7V where needed) are:

- **Quevy et al. (2023)** [7]: 1.8 mA (6.66 mW at 3.7 V).
- **Kombo et al. (2021)** [8]: 104 mW $\approx$ 28.1 mA at 3.7 V.
- **Dalla Via (2021)** [10]: 2.8 mW $\approx$ 0.76 mA at 3.7 V.
- **Mahmud et al. (2023)** [9]: (WiFi-based; not explicitly reported).

By contrast, our node's average current draw is

$$I_{\text{avg}} = 3.6253 \text{ mA}$$

(Section 4.3.3), which exceeds those LoRaWAN-based systems by a factor of roughly 2 $\times$ to 4 $\times$. The higher consumption results from:

- **Complex sensor suite:** We measure pH, temperature, salinity, DO and ORP every hour, requiring multiple analog front-ends and associated signal stabilization delays.
- **Power-hungry peripherals:** The ADS1115 ADC, multiple digital sensors, and a more robust microcontroller (ESP32-class) draw more in active mode relative to simpler MCU platforms (e.g., ATmega328P, ATSAM21).

- **Longer active intervals:** Our node remains awake for up to 2 min per hour (versus Quevy et al. and Dalla Via who sample/transmit less frequently), increasing the fraction of time at higher current.

2. Stand-alone Runtime Without Solar Panel

Without any solar input, runtime $T_{\text{off-grid}}$ (in hours) is

$$T_{\text{off-grid}} = \frac{C_{\text{usable}}}{I_{\text{avg}}},$$

where $C_{\text{usable}} = 4481.6 \text{ mA h}$ (Section 4.3.3) and $I_{\text{avg}} = 3.6253 \text{ mA}$. Thus,

$$T_{\text{off-grid}} = \frac{4481.6}{3.6253} \approx 1235 \text{ hours} \approx 51.5 \text{ days}.$$

In other words, the node could operate for over seven weeks on a full charge if no solar harvesting were available.

3. Net Power Surplus (Revised for Typical Day)

Assume that the panel generates $E_{\text{harvest},200\text{min}} = 2031.468 \text{ 157 J}$ in the first 200 min of sunlight. For a typical 5 h (300 min) solar window, the daily harvested energy is:

$$E_{\text{harvest},\text{day}} = E_{\text{harvest},200\text{min}} \times \frac{300}{200} = 2031.468 \text{ 157 J} \times 1.5 = 3047.202 \text{ 235 5 J}.$$

Converting to watt-hours:

$$E_{\text{harvest},\text{day}} = \frac{3047.202 \text{ 235 5 J}}{3600} \approx 0.8464 \text{ W h}.$$

The node's daily energy consumption (Section 4.3.3) is

$$E_{\text{load},\text{day}} = P_{\text{load},\text{avg}} \times 24 \text{ h} = 0.013 \text{ 416 W} \times 24 = 0.321 \text{ 984 W h}.$$

Thus, the net daily surplus energy is

$$E_{\text{surplus},\text{day}} = E_{\text{harvest},\text{day}} - E_{\text{load},\text{day}} = 0.8464 - 0.321984 = 0.524 \text{ 416 W h}.$$

Equivalently, over 5 h of daylight, the average surplus power is

$$P_{\text{surplus},\text{avg}} = \frac{E_{\text{surplus},\text{day}}}{5 \text{ h}} = \frac{0.524416}{5} = 0.104 \text{ 883 2 W}.$$

4. Battery Charging Rate from Daily Surplus

Assuming the entire surplus power 0.104 883 2 W is directed into the battery via a linear regulator (idealized 100% efficiency), the charging current is:

$$I_{\text{chg}} = \frac{P_{\text{surplus,avg}}}{V_{\text{bat}}} = \frac{0.104\,883\,2\,\text{W}}{3.7\,\text{V}} \approx 0.028\,350\,\text{A} = 28.35\,\text{mA}.$$

To recharge a fully depleted pack of capacity $C_{\text{usable}} = 4481.6\,\text{mA h}$ at 28.35 mA requires:

$$t_{\text{charge}} = \frac{4481.6}{28.35} \approx 158.0\,\text{hours} \approx 6.6\,\text{days},$$

assuming similar solar conditions each day. In practice, higher midday irradiance would shorten this time.

5. Implications and Mitigation

- Even without a panel, the node can operate for about 51 days continuously.
- Compared to Quevy et al. and Dalla Via, our node's higher draw is justified by a richer sensor suite and longer active intervals. Future work could reduce consumption by duty-cycling or replacing with lower-power sensors.
- Our net surplus during late afternoon confirms that the chosen 6 V, 350 mA panel is adequate to maintain energy balance, even if only partial daylight hours are available.
- To mitigate long recharge times under suboptimal insolation, a larger panel or maximum-power-point tracking (MPPT) charger could be implemented to harvest more efficiently during low-angle sun.

4.4.4 Water Ingress and Enclosure Robustness Discussion

The successful outcome of the water ingress test provides strong validation for the mechanical design's robustness, a critical objective for deployment in unprotected outdoor environments. The test, which subjected the node to a direct, 2 min spray from a shower nozzle to simulate moderate rainfall, resulted in no detectable water infiltration into the enclosure's interior. This result confirms the efficacy of the selected components, specifically the ABS IP66-rated panel box and the IP68-rated cable glands, in providing a reliable seal against moisture.

The continued, fault-free operation of the node's electronics immediately following the spray test further underscores the design's resilience. The integrity of the system was maintained, with no impact on sensor readings or radio link performance, demonstrating that the enclosure effectively protects sensitive components from common environmental hazards like precipitation.

While the controlled shower nozzle test serves as a valuable proxy for rainfall, it is important to acknowledge its limitations. Real-world conditions in a shrimp farm may involve more extreme scenarios, such as wind-driven rain, accidental splashing, or prolonged high-humidity exposure. Furthermore, the long-term degradation of materials, such as the enclosure's O-ring seals and the epoxy adhesive used for the solar panel under continuous UV radiation and temperature cycling, was not assessed in this short-duration test.

Nonetheless, the test successfully meets the immediate design objective of creating a water-resistant assembly capable of withstanding typical weather events. It establishes a high degree of confidence in the system's ability to be deployed in the field, paving the way for extended trials where long-term durability can be more thoroughly evaluated.

4.5 Summary

- The main findings from the one-week deployment demonstrated the system's viability for long-range, autonomous environmental monitoring.
 - **Communication Range and Reliability:** A robust LoRaWAN communication link was successfully transmit over a distance of over 1km. On a week long test over a distance of about 200m, despite challenging real-world conditions, evidenced by significant fluctuations in signal strength (RSSI) from -78 dBm to -118 dBm, the link exhibited high reliability with minimal packet loss (only 3 missed transmissions) over the week-long period.
 - **Power System Performance:** The power system's performance was empirically validated and exceeded expectations. The measured average current consumption of 3.56 mA closely matched the theoretical estimate, validating the device's power budget. Furthermore, the solar generation system was highly effective, producing an estimated gross current of 103.02 mA and demonstrating a generation rate 142.9% higher than a benchmark experiment.
- The primary objectives of this experimental deployment were successfully achieved. The experiment validated the node's power budget for autonomous operation, confirmed the viability of the solar charging system, and established a reliable performance baseline for the communication link over a 1km range.
- These results provide critical, data-driven insights that will directly inform the next phase of the project, as detailed in Chapter 5. The validated power system confirms the design's suitability for long-term, autonomous deployments. The successful establishment of a 1km communication link provides a crucial performance benchmark that will inform the network topology and gateway placement strategy for a larger-scale system.