Environmental Sensor Network for Wildfire Detection

ECE 499: Design Project II

August 6, 2026

University of Victoria

Group ID: 13

Faculty supervisor: Dr. Homayoun Najjaran

Team Information: Environmental Sensor Network for Wildfire Detection

S. No.	Name	V Number
1	Kohen Butler	V00999075
2	Khephren Gould	V01012827
3	Levi McCulloch	V01038949

Acknowledgment

The authors would like to express their sincere gratitude to everyone who contributed to the successful completion of this capstone project.

First and foremost, we would like to thank our project supervisor, Dr. Homayoun Najjaran, and the Advanced Control and Intelligent Systems (ACIS) Laboratory for supporting our vision throughout this project. Their continuous guidance, feedback, and ideas were critical in shaping the design, implementation, and evaluation of our wildfire detection system.

We would also like to express our appreciation to the Department of Electrical and Computer Engineering technical staff, Paul Fedrigo, Rob Fichtner, and Brent Sirna, for their technical expertise and support. Their willingness to share their knowledge and provide access to equipment played a significant role in the successful completion of this project.

We are also grateful to our course Teaching Assistant, Niloofar Tavahodi, whose excellent organization and coordination helped keep our team on schedule throughout the project. Her guidance and timely communication ensured that project milestones were met and that the course progressed smoothly.

The authors would also like to thank Solaires Enterprises Inc. for generously donating the photovoltaic modules used in this project. These modules were a key component of our sensor nodes and made it possible to demonstrate a self-powered wildfire detection system.

Finally, we would like to thank our families and friends for their encouragement, patience, and support throughout this project. Their understanding and motivation helped us remain focused and committed during the months of design, development, testing, and refinement required to bring this project to completion.

Executive Summary

Wildfires are an increasing threat to Canadian communities, ecosystems, and infrastructure. Although most fires are contained during the initial response, those that escape early containment account for the majority of wildfire damage. Detection time is a major contributor to response delay, creating a need for affordable systems capable of continuously monitoring remote and fire-prone areas.

This project designed and evaluated an open-source environmental sensor network for early wildfire detection. The system consists of distributed sensor nodes that measure carbon dioxide, volatile organic compounds, temperature, and humidity using BME680 and SCD40 sensors. Each node integrates an STM32U5 microcontroller, an SX1262 LoRa transceiver, a rechargeable lithium-ion battery, and a solar energy-harvesting system. Measurements are transmitted to a central gateway, where a weighted scoring algorithm classifies conditions as Normal, Warning, or Danger. The results are then displayed through a remotely accessible web dashboard that provides current readings, historical data, sensor status, and data-export functionality.

Testing demonstrated the capabilities of the major system components. Controlled campfire testing showed measurable changes in carbon dioxide and volatile organic compound readings, supporting the selection of the BME680 and SCD40 sensors. Wireless testing achieved reliable communication over 300 m in an obstructed campus environment, while link-budget analysis indicated that the 1 km design target should be achievable under appropriate radio settings. Power simulations predicted approximately 16 days of battery-supported operation during periods of limited solar charging. The complete prototype was packaged in a compact 3D-printed enclosure designed to support airflow, solar charging, installation, and component maintenance. The estimated component cost of one sensor node is approximately $100 CAD, demonstrating the potential for lower-cost distributed monitoring.

The project successfully produced a functional proof of concept that integrates environmental sensing, long-range wireless communication, autonomous power, wildfire-risk classification, and remote visualization. However, additional validation is required before permanent field deployment. The solar charging current was not experimentally confirmed, the enclosure has not been formally tested for long-term water and dust resistance, and fire-detection testing was limited to small controlled fires at distances up to 10 m. Future work should include longer-range testing in forested terrain, extended outdoor durability testing, validation of the solar charging subsystem, and additional controlled burns to refine the detection algorithm and evaluate false-positive performance.

Table of Contents

List of Tables

List of Figures

Figure D.4 LT Spice Transient Simulation - Load Current vs Time

1 | Introduction

1.1 | Problem Definition

Wildfires pose an increasing threat to communities across Canada as hotter and drier conditions contribute to more frequent and severe fire seasons [1]. While firefighting agencies successfully contain most wildfires during initial attack, the approximately 3% of fires that escape initial attack are responsible for 97% of the total area burned and associated damage [2]. Further analysis of wildfire response timelines reveals that the largest contributor to response delay is not dispatch, mobilization, or travel time, but fire detection itself. Studies estimate that wildfires remain undetected for an average of 10–12 hours, while the combined time required for dispatching and transporting initial attack crews is typically less than two hours [3], [4]. These findings suggest that reducing detection time represents the greatest opportunity for improving wildfire response effectiveness and preventing small ignitions from becoming destructive wildfires.

1.2 | Project Scope and Goals

The objective of this project is to prototype and evaluate an environmental sensor network capable of identifying early-stage wildfires and communicating these alerts to an end user. The prototype will consist of:

- Three sensor nodes to measure and transmit the environmental conditions
- One gateway to receive data, process data, and evaluate if a fire is present
- A user interface in the form of a dashboard hosted as a web application

The scope of this project includes the design, implementation, and testing of the environmental sensor network. Wildfire suppression strategies and resource deployment following detection are outside the scope of this project. The primary goal is to reduce wildfire detection delay while maintaining reliable operation and scalability for deployment across large areas.

1.3 | Project Motivation

Wildfires have created significant financial challenges across Canada, with annual wildfire suppression costs exceeding $1 billion in six of the last ten years [5]. In addition, the Canadian Climate Institute estimates that wildfire-related damages to new housing developments in high-risk areas could contribute an additional $1.1 billion annually by 2030 [6]. These rising costs highlight the economic value of technologies that can improve early wildfire detection.

The increasing financial impact of wildfires has driven investment in innovative detection and monitoring solutions. In 2024, the BC Centre for Innovation and Clean Energy (CICE) launched a $3 million funding program to support wildfire-related technology development in British Columbia [7], demonstrating the growing demand for practical and scalable wildfire mitigation technologies.

1.4 | Relevant EGBC Ethics

The following EGBC ethical principles are relevant to this project and guide its design and development:

- **Hold paramount the safety, health, and welfare of the public, including the protection of the environment and the promotion of health and safety in the workplace**
    - The design, development, and testing of the system will prioritize the safety of the public and the environment at all stages. Any experimental validation or deployment will be carried out in a manner that avoids introducing additional risk, ensuring that the system does not negatively impact communities or ecosystems while aiming to improve wildfire detection.
- **Have regard for applicable standards, policies, plans, and practices established by the government or Engineers and Geoscientists BC**
    - The system design considers relevant communication protocols, safety considerations for field deployment, and applicable guidelines for engineering systems used in public safety and environmental monitoring applications.
- **Undertake work and documentation with due diligence and in accordance with any guidance developed to standardize professional documentation for the applicable profession**
    - The project is developed using structured engineering practices, including validation testing, performance evaluation, and clear documentation of system limitations and assumptions to ensure reproducibility and reliability.

1.5 | Potential User Base

The intended primary user base for this system is wildfire management organizations such as the British Columbia Wildfire Service (BCWS), where improved early detection capabilities could support large-scale wildfire monitoring and response operations. Although BCWS is not currently investing in this technology, they have expressed interest in future installations [8].

In addition to provincial wildfire services, several other potential users may benefit from this system including municipal fire departments responsible for monitoring forested areas. The system may also be valuable for monitoring controlled burns to ensure they remain within designated boundaries. Furthermore, private landowners such as farmers and forestry operators represent a potential user base, where localized early warning and continuous environmental monitoring could help reduce fire-related losses and improve land management practices.

2 | Objectives

This project aims to develop a solution for a wildfire detection solution. The objectives of the project are as follows:

- Conduct a comparative analysis of existing wildfire detection solutions
- Design and assemble an open-source proof of concept for a wireless sensor network including a user dashboard
- Analyze and validate the maximum expected communication range of the solution
- Analyze and validate the expected battery life of the solution
- Analyze the cost-per-unit and develop a cost estimate for complete coverage of a BC wildfire jurisdiction
- Analyze and validate the maximum detection range of the selected sensor suite and detection algorithm

3 | Design Specifications

3.1 | Functional Requirements

This project aims to design and construct a prototype for a low-cost, open source ground based WSN platform. The functional requirements of the solution are listed in Table 1.

Table 1: Wireless Sensor Network Hardware Functional Requirements

Metric	**Requirement**
Coverage & Detection time (FR-1)	Each unit should detect a 0.5x0.5m fire up to 25m away within 1 hour
Uptime (FR-2)	Each unit should operate continuously
Data (FR-3)	Each unit should report temperature, relative humidity, VOC concentration, CO2 concentration, and location
Fire Detection (FR-4)	The system should calculate an internal fire probability and report binary detection notifications (y/n)
Communication (FR-5)	The network should support wireless communication up to 1km

The functional requirements were designed to remain competitive with existing proprietary wireless sensor network solutions. As discussed in *Remote Smoke Sensor End-User Evaluation* by OWTRD [9], the evaluated commercial systems provide coverage areas ranging from 260 ft^2 to 640 ac. With a target coverage of 1 hectare, our system aims to remain competitive with low-cost, high-density deployments.

Commercial systems typically specify detection performance using a reference fire size. For example, Dryad reports a detection time of 60 minutes for a 2 m × 3 m fire at a distance of 100 m. Our design targets detection within 60 minutes of a 0.5 m × 0.5 m fire at 25 m, providing a comparable performance benchmark while complying with BC Wildfire Service testing restrictions, which permit only Class 1 fires [10].

According to the same report, all evaluated wildfire detection systems monitor VOC concentration, temperature, and humidity [9]. As discussed in the environmental sensor literature review, VOC and CO_2 measurements are the primary indicators used for early wildfire detection. Wildfire emissions typically consist of approximately 88% CO_2, 8% CO, 3.8% CH_4, and smaller amounts of other VOC compounds [11]. Monitoring both VOC and CO_2 concentrations can help reduce false positives by identifying emission patterns characteristic of wildfire activity. While temperature and humidity are less effective for direct detection, they are important indicators of wildfire risk and are incorporated into the Canadian Fire Weather Index (FWI) [12]. Together, these measurements provide an effective and low-cost combination for both wildfire detection and risk monitoring.

3.2 | Software Requirements

Table 2: Wireless Sensor Network & Dashboard Software Requirements

Metric	Requirement
Accessibility (SF-1)	The dashboard must be accessible remotely from mobile and desktop platforms
Displayed Live Readings (SF-2)	The dashboard must display the location, live VOC concentration, CO2 concentration, Temperature, and humidity
Displayed Operational Status (SF-3)	The system must display battery state (percentage charged), sensor operation (is data being received from all sensors), and must give an indication of node fault status (display a warning if data is not received from a node)
Displayed Calibration Status (SF-4)	Typical Sensors and detection algorithms require a calibration period over which air quality readings are recorded to establish a baseline. The dashboard must display the calibration status of each node
History (SF-5)	The dashboard must record past readings over a minimum of 2 days and display them in graphical or tabular form. The system must timestamp all received data packets and detection notifications

The dashboard must display live gas concentration and weather data to provide users with remote access to sensor information. Remote monitoring is essential for practical deployments due to the large number of sensor nodes required to cover large areas. In end user evaluations of existing systems, limited availability to view historical data was cited as a major concern [13]. Additionally another end user report cited lack of clarity on the operational status of the sensors as a major barrier [9]. By adding operational status and historical data to the dashboard, the system is made more accessible to the end user which is critical for scaling the design to cover large areas.

3.3 | Non-Functional Requirements

Table 3: Wireless Sensor Network Design Non Functional Requirements

Metric	Requirement
Mounting (NF-1)	The system should be mountable on trees typical of Canadian Wildlands (Spruce, Pine, Maple, Fir, Birch). Mounting equipment required should consist of no more than a ladder, hand tools, and wood screws/nails
Operating Environment (NF-2)	The system should be designed to withstand temperatures ranging from -10ºC to 40ºC
Maintainability (NF-3)	Software updates must be possible without disassembling the enclosure, critical components such as batteries and solar panels must be easily replaceable in the event of failure
Safety (NF-4)	A battery management solution must be employed such that the battery is not exposed to direct sunlight and is never subject to overcurrent, overvoltage or undervoltage conditions
Reliability (NF-5)	The solution should have a system to mitigate false positives

The solution employed should not require specialized mounting equipment. This is important to ensure scalability of the solution at low cost. For example, if installation of a frame or pole is required for each sensor, installation may require multiple people and increased time. This is infeasible when installing dozens or hundreds of units.

The prototype should be targeted for continuous operation in British Columbia. Components used for the design should have temperature ratings suitable for use in the Pacific Maritime, Montane and Boreal Cordillera geographical regions of Canada. The temperature range -10ºC to 40ºC are typical annual maximum and minimum temperatures [14].

Battery powered devices pose a fire risk without proper management. When placed in areas of high wildfire risk, a fire would be catastrophic. The design of a battery management system is critical to ensure safety [15].

False positive mitigation is critical for maintaining confidence in the system and preventing unnecessary emergency responses.

3.4 | Design Constraints

Table 4: Wireless Sensor Network Design Constraints

Metric	**Constraint**
Wireless Communication (DC-1)	The system must adhere to ISED regulations. Only publicly allocated bands should be used for transmission
Detection testing (DC-2)	Testing should be conducted according to BC Wildfire Regulations. Currently, only class 1 fires are permitted on Vancouver Island [10]
Power (DC-3)	The system must not rely on external sources of power

Wireless communication systems are regulated by Innovation, Science and Economic Development Canada (ISED), which governs the use of the radio frequency spectrum in Canada. The prototype must comply with ISED regulations by operating within publicly allocated frequency bands and avoiding restricted spectrum usage.

Testing of wildfire detection performance is constrained by BC Wildfire Service regulations. Currently, only Class 1 fires are permitted for testing on Vancouver Island, limiting the size of experimental fires that can be used for system validation [10].

To support deployment in remote areas, the system must operate without external power sources. This constraint requires the use of energy harvesting and low-power design techniques to enable autonomous operation.

4 | Literature Survey

The three main solution categories for wildfire detection that are actively being researched consist of satellite detection, elevated cameras, and ground based sensors. The suitability of each technology depends on several factors, including detection latency, spatial resolution, coverage area, deployment cost, and scalability. The following sections review the advantages and limitations of existing wildfire detection approaches.

4.1 | Satellite Detection

Satellite-based wildfire detection is one of the most established methods for monitoring large geographic regions. The most widely used sensing platforms are MODIS and VIIRS, infrared spectroradiometers onboard NASA-operated polar-orbiting satellites [16]. These systems detect wildfire activity by analyzing thermal signatures and applying data analysis and pattern recognition techniques to distinguish potential fire pixels from surrounding non-fire areas.

Satellite-based solutions provide exceptional coverage, typically monitoring areas ranging from 2000–3000 km. Additionally, existing satellite datasets containing wildfire thermal signatures and environmental measurements are publicly available at no cost, enabling widespread access to wildfire monitoring data [17]. However, these systems have limitations in early-stage detection due to relatively low spatial resolution (~5ha) and detection latency of up to 12 hours [18]. Small ignitions may therefore remain undetected until they grow large enough to be identified by the satellite sensors.

Improving satellite-based detection capabilities generally requires increasing satellite density, which requires significant financial investment. As a result, these systems are most suitable for large-scale monitoring applications operated by governments or organizations managing large geographic regions. Canada is currently investing in WildfireSat, a dedicated wildfire monitoring satellite system planned for launch in 2029, which aims to improve national wildfire monitoring capabilities [19].

4.2 | Elevated Cameras

Elevated camera monitoring systems provide improved spatial resolution and reduced detection times compared to satellite-based approaches. These systems typically involve mounting cameras on elevated platforms, such as cellular towers or drone platforms, where image processing algorithms are used to identify features such as smoke plumes and flame signatures within captured images [20].

Static camera systems have demonstrated detection ranges of up to 60 miles with a 360° field of view, providing substantially greater coverage than individual ground-based gas sensing systems [9]. However, camera-based solutions require clear line-of-sight to monitored areas and may be affected by environmental conditions such as fog, cloud cover, and lighting variations. Additionally, deployment often requires existing elevated infrastructure or dedicated structures, increasing installation complexity and cost when scaling to large areas.

4.3 | Gas Sensors

While both satellite and camera based techniques are promising areas of research, the focus of this project is on ground based environment sensing techniques. Ground based sensing typically involves the design of a network of sensor nodes connected to a gateway with internet capabilities. A long range communication protocol is used to send data between the sensors and the gateway. Environmental sensors to monitor humidity, temperature, and gases such as CO_2, CO, and CH_4 are employed to detect the gas signature emitted by the fire. Energy harvesting is critical due to the high volume of sensors and remote locations of operation making manual replacement of batteries infeasible.

The following devices are some examples of existing wireless sensor network solutions:

- Dryad Silvanet [21]
- Sensenet [22]
- N5-Shield [23]

While Sensenet and N5 do not provide datasheets for their solutions, Dryad includes the documentation in Table 5 listing the technologies used

Table 5: Existing Solution Component Breakdown

Component	**Solution**
Gas sensing	Temperature, Humidity, Pressure, PM2.5, PM10, CO
Data processing	STM32WL
Energy storage and harvesting	Solar Panel + Supercapacitor
Wireless Communication	915MHz LoRa
Network Design	LoRaWAN (star topology, main base station connected to multiple leaf nodes)

Dryad specifies detection times of under 60 minutes for a 2 m × 3 m fire at 100 m distance with a 1 km communication range. Other commercial systems, such as N5-Shield, require additional mounting infrastructure and larger battery storage solutions, increasing deployment complexity.

Despite industry investment, end-user evaluations have identified several challenges for wireless sensor network wildfire detection, including high deployment costs [9], maintaining continuous autonomous operation, expanding detection range, and reducing false positive rates [11].

5 | Team Duties & Project Planning

5.1 | Team Members & Deliverables

The successful completion of this project requires contributions from all team members in the areas of hardware design, embedded software development, and enclosure design. Each team member has been assigned a key deliverable that is essential to the overall functionality of the wildfire detection system. Table 6 outlines the responsibilities of each team member, their primary deliverables, and the inputs required from other team members to support effective collaboration and successful project completion.

Table 6: Summary of Team Member Roles and Deliverables

Team Member (TM): Kohen Butler (Hardware & PCB Design Lead)	
Critical Deliverable	• Design and construction of a custom PCB integrating the microcontroller, LoRa transceiver, sensors, and power management circuitry.
Requirements for Success	• All sensors communicate successfully with the microcontroller. • Power regulation and battery management systems function as intended. • LoRa transceiver communicates successfully with the base station.
Required Inputs from TMs	• Sensor and communication requirements from the embedded software lead. • Mechanical constraints from the enclosure designer.
Team Member: Khephren Gould (Embedded Software Lead)	
Critical Deliverable	• Development of firmware capable of collecting environmental data and reliably transmitting information to the base station and dashboard.
Requirements for Success	• Environmental data is logged and displayed correctly. • Data packets are transmitted and received successfully through LoRa communication. • Algorithms successfully identify predefined wildfire indicators and generate alerts. • Firmware operates continuously without crashes during testing.
Required Inputs from TMs	• Assembled and tested hardware including the MCU, sensors, and LoRa transceiver. • System requirements including transmission intervals and power consumption targets.
Team Member: Levi McCulloch (Enclosure Design Lead)	
Critical Deliverable	• Design and construction of a prototype enclosure capable of protecting the electronics while allowing accurate environmental sensing
Requirements for Success	• Enclosure securely houses all electronic components. • Sensors remain exposed to ambient environmental conditions through adequate airflow. • The enclosure withstands expected outdoor testing conditions.
Required Inputs from TMs	• PCB dimensions and component placement from the hardware lead. • Antenna and communication requirements from the software lead.

5.2 | Project Planning

The project is scheduled to be completed by July 30th for presentation and will progress through the following major phases:

- Component procurement
- Sensor testing
- PCB design
- Enclosure design
- Final validation

To maximize efficiency, hardware, software, and enclosure development will be completed in parallel whenever possible. Regular field tests will be conducted throughout the project to identify issues early and reduce the risk of delays during the assembly of the final prototype. A Gantt chart for the project was created and is presented in Appendix C.

5.3 | PCB Hardware Challenges

One of the primary hardware design challenges involved the integration of the Sensirion SCD40 CO_2 sensor. At the time of PCB development, the sensor had not yet been experimentally evaluated within our system. However, because CO_2 concentration was identified during the literature review as an important indicator of wildfire activity, the decision was made to include the SCD40 on the initial PCB revision. This represented a calculated design risk intended to avoid the cost and delays associated with a complete PCB redesign if the sensor proved beneficial. To mitigate this risk, the PCB layout was designed such that the sensor could be omitted from future revisions with minimal impact to the remainder of the system. Subsequent testing confirmed that the SCD40 operated reliably and provided useful environmental measurements.

A second challenge arose during power system validation. Initial testing revealed that the energy harvesting circuit was unable to maintain a stable output when the system reached its maximum current consumption, particularly during periods of wireless transmission. Investigation showed that the local energy storage capacitance was insufficient to supply the required transient current. This issue was resolved by replacing several low-value capacitors with larger capacitance devices, increasing the available energy storage and stabilizing the supply voltage during peak load conditions. Following this modification, the power subsystem consistently supported continuous operation of all onboard components.

5.4 | Software Challenges

The software was split into three components:

1. Embedded sensor node software
2. Gateway Software
3. Dashboard Software

While existing arduino libraries could be used for the gateway and the dashboard software was comprised of a web-based client-server (frontend-backend) architecture using standard web development technologies, the most difficult component to develop was the embedded sensor node software. The low power requirements of the node prohibited the direct use of standard drivers. The design required careful integration of the following C libraries:

1. BME68X_Sensor_API (register level i2c driver for BME680)
2. BSEC (Bosch Sensortech Environmental Cluster signal processing library for bme680)
3. libdriver_scd4x (register level i2c driver for SCD40)
4. Loranet_sx1262 (register level spi driver for sx1262 transmitter)

The STM32U5 microcontroller's HAL (hardware abstraction layer) software also required integration. Initially, all .c files and .h files were placed in /src and /inc folders respectively. An immediate issue was encountered when attempting to integrate the software for the sx1262 driver. The driver comprised multiple source files and required the relative file paths between the files to follow a defined structure that did not fit that of the rest of the project. Integration of the BSEC signal processing library posed further issues. The library is pre-compiled and closed source. This means the developer only has access to the object files output from the compiler. Prior to the use of this library, the simple command:

```
arm-none-eabi-gcc -Iinc src/*.c -o firmware.elf
```

was being used to produce the executable. Inclusion of the BSEC library binary required the addition:

```
arm-none-eabi-gcc -Iinc src/*.c /libbsec.a -o firmware.elf
```

however an error was encountered. The binary had been compiled with the VFP (vector floating point) unit enabled and thus could not be linked alongside the rest of the project which was not using VFP instructions. Additional compilation flags would need to be included to resolve the issue.

To resolve the complications in integrating the multiple hardware drivers into a single executable, Cmake was employed as a solution. Cmake is a build configuration software that allows specifications for how a project should be built to be encoded in a Cmakelists.txt file. First, the project was restructured. STM32HAL library files were left in the /src and /inc directories while all additional libraries were moved to a separate /third_party directory. The resulting folder structure can be seen in Appendix E.

CMake allowed the use of the add_subdirectory command to include the relevant third party directories while preserving their expected file structure. It also allowed flags such as -mfloat-abi, -mcpu and -mfpu to be included consistently in the generated compiler commands, ensuring the pre-compiled binaries and the project's own sources shared the same floating point configuration. Through a single CMake build, the entire project could be compiled into one executable, a far simpler and more maintainable process than managing the compiler commands by hand.

5.5 | Enclosure Design and Assembly Challenges

The primary challenge in the enclosure design was balancing adequate airflow with environmental protection. Accurate measurements from the gas, temperature, and humidity sensors require unrestricted airflow, while the enclosure must also protect the electronics from rain and moisture during long-term outdoor deployment. To address these competing requirements, the enclosure was designed with a covered upper section to shield the electronics from direct rainfall, while ventilation openings were concentrated on the underside where water ingress is significantly less likely. This approach maximized airflow to the sensors while improving the enclosure's resistance to adverse weather conditions.

A second challenge was the rapid prototyping of the enclosure. Early design iterations were manufactured using shared 3D printing facilities, where each print required approximately three to four days to complete. As multiple design revisions were necessary and project deadlines approached, this turnaround time became a significant bottleneck. To accelerate development, the team purchased a personal 3D printer, allowing enclosure iterations to be produced on demand. This substantially reduced development time and enabled multiple design refinements before the final enclosure was assembled and field tested.

6 | Design Methodology & Analysis

6.1 | Power Distribution

The objective of the power distribution subsystem was to enable continuous autonomous operation in remote environments without reliance on external power. To achieve this, the system was designed around a solar energy harvesting architecture consisting of a photovoltaic panel, energy harvesting integrated circuit, rechargeable lithium-ion battery, and regulated 3.3 V supply. Figure 1 illustrates the power distribution architecture.

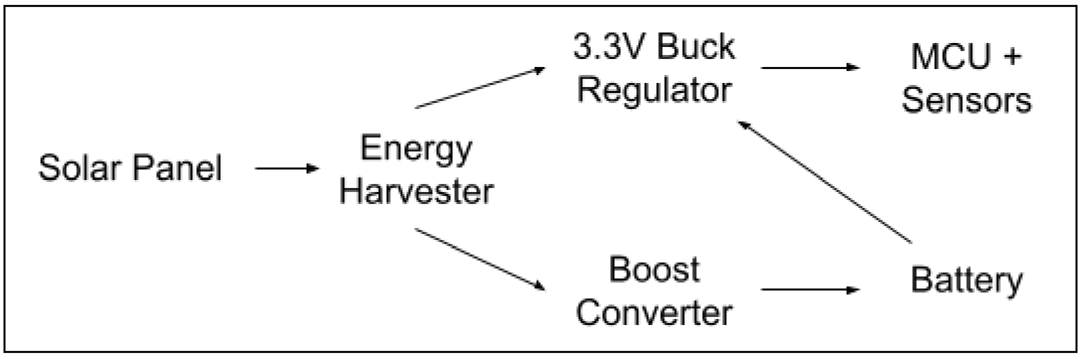

Figure 1: Power Flow Diagram

Solar Panel

The photovoltaic panel serves as the primary energy source for the sensor node, providing power for both operation and battery charging. A solar energy harvesting approach was selected to enable long-term autonomous operation without requiring frequent maintenance visits for battery replacement. This is particularly important for the intended wildfire monitoring application, where sensor nodes may be deployed across large and remote areas.

The selected photovoltaic panel is a perovskite solar panel provided by Solaires Enterprises Inc.. To characterize the available energy generation, the maximum output power of the panel was experimentally measured under full sunlight conditions. These measurements were combined with solar irradiance data from PVGIS to estimate the expected daily energy generation under typical operating conditions [24]. The data was normalized such that the peak irradiance corresponds to the peak expected power output of the modules. Python's *curve_fit* function was used to fit the irradiance data to the function in equation 1 where A, ϕ, and C are parameters to be fit and ω is fixed at $\frac{2\pi}{24h \times (3600s/h)}$ (T = 1 day). The resulting expression used to determine the PV module output in LT Spice is shown in equation 2. The expression clamps the PV module output to zero between 8:00PM and 5:00AM and ensures the battery cannot be charged to a state of charge greater than 1.

$$I_{source} = (A \sin(\omega t + \phi) + C) / V_{batt} \quad (1)$$

I = if(((32.582m * sin(0.00007272 * time) + 11.68m) > 0) & (V(vsoc1) <= 1), (32.582m * sin(0.00007272 * time) + 11.68m) / (V(batt1)), 0) (2)

As shown in Figure 2, the estimated solar input was modeled as a half-rectified sine wave, representing the expected variation in available solar energy throughout the day.

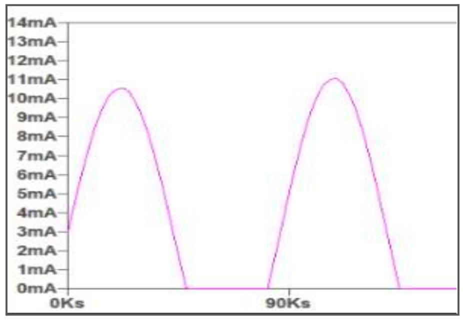

Figure 2: Simulated charge current over 2 days

Based on this analysis, the photovoltaic panel was estimated to provide an average charging current of approximately 5mA to the energy storage system. This value was used during the power budget analysis to determine whether the harvested energy was sufficient to support continuous operation of the sensor node.

Energy Storage

The energy storage system was designed to maintain sensor node operation during periods of insufficient solar generation. An INR18650 lithium-ion cell was selected due to its high energy density, rechargeability, and compatibility with the BQ25570 energy harvesting system. Lithium-ion was selected over lithium polymer batteries due to its improved robustness and safety characteristics, which are important considerations for long-term deployment in wildfire-prone environments.

A supercapacitor-based storage solution was also considered due to its high cycle life and suitability for energy harvesting applications. However, limited available research regarding the performance of the BQ25570 when paired with a supercapacitor introduced additional design uncertainty.

To evaluate the expected operating lifetime of the sensor node, an LTspice battery model was used to simulate the interaction between solar energy generation and system power consumption. The leftmost capacitor in the circuit of Figure E.1 (Appendix E) models the charge stored in the battery. Its value was determined using equation 3.

$$C_{Capacity}(F) = Capacity\,(Ah) \times 3600\,(\frac{sec}{h}) \div 1V \quad (3)$$

The passive components were chosen by fitting experimental data from the CALCE battery dataset. While the authors in [25] suggest the use of SOC (state of charge) dependent components, this is difficult and computationally expensive to model in LT Spice. Instead, the method in [26] was used which simply fits the experimental VOC vs SOC data to a TTC model ("two time constant model" shown in equation 4). MATLAB's *lsqscurvefit* function was used to accomplish this. The TTC model does not capture all transient characteristics of real batteries (an infinite number of exponentials or SOC dependent components are required), however the method yields sufficient accuracy for a behavioral simulation.

$$f(t) = A + Be^{-\alpha t} + Ce^{-\beta t} \quad (4)$$

Equations 22 through 26 from [26] were used to derive the resistor and capacitor values.

Load Modelling

A circuit to model the load was designed. Active digital circuits such as microcontrollers and digital sensors can be modelled as behavioral resistors for the purposes of analyzing power consumption. A circuit with 6 parallel behavioral resistors was used to capture the current consumption from potential sensor candidates at various modes of operation. The datasheet listed currents and supply voltages were used to determine the correct resistance value. The simulation was performed with the parameters of Table 7.

Table 7: LT Spice Transient Simulation Parameters

Parameter	Value
SCD40 Sampling Period	30s
BME680 Sampling Period	3s
MCU sensor measurement execution time	0.5s
MCU data transmission execution time	0.5s
Data transmission period	10s
LoRa transmitter active duration	0.1s

The measured solar charging profile and estimated load power consumption were applied to the model to predict battery performance during operation. Figure 3 shows the simulated battery voltage over time, demonstrating the expected discharge and recharge behaviour of the system. The simulation predicted an operating duration of approximately 16 days, indicating that the selected battery capacity was sufficient to support autonomous operation during extended periods of limited sunlight.

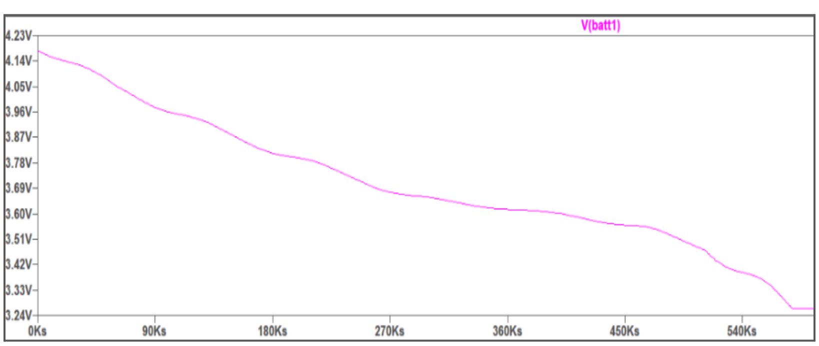

Figure 3: Simulated battery voltage over time

6.2 | Communication Link

The three communication technologies evaluated for use in the communication link between the nodes and sensors were the LoRa,
A link budget analysis was conducted to determine whether the selected LoRa communication system could satisfy the FR-5 requirement. The analysis considers transmitter power, receiver sensitivity, antenna gains, cable losses, and fade margins to estimate the reliability of the communication link under various operating conditions.

Link Budget

The link budget is calculated using the receiver sensitivity (RS), transmitter power (TXP), antenna gains (RXA/TXA), and cable losses (RXC/TXC).

$$Link\ Budget = RS + RXA - RXC + TXA - TXC + TXP$$

For SF7 (spread factor of 7) at a transmit power of 14 dBm:

$$Link\ Budget = 124\ (dBm) + 5\ (dBi) - 1\ (dB) + 5\ (dBi) - 1\ (dB) + 14\ (dBm) = 146\ (dB)$$

Table 8: Link Budget Parameters

Parameter	Value	Units
Frequency (f)	915	MHz
TX Antenna Gain (TXA)	5	dBi
TX Cable Loss (TXC)	1	dB
RX Antenna Gain (RXA)	5	dBi
RX Cable Loss (RXC)	1	dB
Estimated Fade Margin	35	dB
100m Path Loss	71.67	dB
1km Path Loss	91.67	dB
Receiver Sensitivity (SF7) (RS)	124	dBm
Receiver Sensitivity (SF12) (RS)	137	dBm

Note: The receiver sensitivity values used in the link budget analysis were obtained from the SX1262 datasheet [27]

$$Link\ Budget = 124\ (dBm) + 5\ (dBi) - 1\ (dB) + 5\ (dBi) - 1\ (dB) - 9\ (dBm) = 123\ (dB)$$

Table 9: Calculated Link Budget by Spread Factor

Link Budget		
Transmission Power (dBm)	**Spread Factor 7 (SF7)**	**Spread Factor 12 (SF12)**
-9	123 dB	136 dB
14	146 dB	159 dB
17	149 dB	162 dB
20	152 dB	165 dB
22	154 dB	167 dB

Table 10: Link Budget Analysis at 1km (20-35 dB Fade Margin)

Based on 1km Distance (20dB Fade Margin)					**Based on 1km Distance (35dB Fade Margin)**				
Link Margin (dB)		**Available Margin (dB)**		**Pass/ Fail**	**Link Margin (dB)**		**Available Margin (dB)**		**Pass/ Fail**
SF7 -9	31.33	**SF7 -9**	11.33	PASS	**SF7 -9**	31.33	**SF7 -9**	-3.67	FAIL
SF12 -9	44.33	**SF12 -9**	24.33	PASS	**SF12 -9**	44.33	**SF12 -9**	9.33	PASS
SF7 14	54.33	**SF7 14**	34.33	PASS	**SF7 14**	54.33	**SF7 14**	19.33	PASS
SF12 14	67.33	**SF12 14**	47.33	PASS	**SF12 14**	67.33	**SF12 14**	32.33	PASS
SF7 17	57.33	**SF7 17**	37.33	PASS	**SF7 17**	57.33	**SF7 17**	22.33	PASS
SF12 17	70.33	**SF12 17**	50.33	PASS	**SF12 17**	70.33	**SF12 17**	35.33	PASS
SF7 20	60.33	**SF7 20**	40.33	PASS	**SF7 20**	60.33	**SF7 20**	25.33	PASS
SF12 20	73.33	**SF12 20**	53.33	PASS	**SF12 20**	73.33	**SF12 20**	38.33	PASS
SF7 22	62.33	**SF7 22**	42.33	PASS	**SF7 22**	62.33	**SF7 22**	27.33	PASS
SF12 22	75.33	**SF12 22**	55.33	PASS	**SF12 22**	75.33	**SF12 22**	40.33	PASS
Note: naming convention is spreading factor & transmission power, i.e. for transmission power of 14 dBm at a spreading factor of 7: “SF7 14”									

The results indicate that, in ideal conditions, each configuration satisfies the margin requirement for a 20 dB fade margin, while only the SF7 configuration operating at -9 dBm fails under the 35 dB fade margin.

Free Space Path Loss

The free space path loss (FSPL) estimates the amount of signal attenuation that occurs as a radio wave propagates through free space. Path loss increases with both communication distance and operating frequency.

$$FSPL = 32.44 + 20log_{10}(f) + 20log_{10}(d)$$

where d is distance in km and f is 915MHz

For a communication distance of 1 km:

$$FSPL = 32.44 + 20log_{10}(915) + 20log_{10}(1) = 91.67\ (dB)$$

Link Margin

The link margin is calculated by subtracting the expected path loss from the link budget. It represents the amount of additional signal loss that can be tolerated before communication becomes unreliable.

$$Link\ Margin\ (dB) = Link\ Budget\ (dB) - FSPL\ (dB)$$

For SF7 at a transmit power of 14 dBm and a communication distance of 1 km:

$$Link\ Margin\ (dB) = 146\ (dB) - 91.67\ (dB) = 54.33\ (dB)$$

Available Margin

The available margin is calculated by subtracting the assumed fade margin from the link margin. It represents the remaining margin available after accounting for environmental factors such as vegetation, terrain, weather, and antenna misalignment (Fade Margin estimates the environmental factors for now).

$$Available\ Margin\ (dB) = Link\ Margin\ (dB) - Fade\ Margin\ (dB)$$

For SF7 at a transmit power of 14 dBm, a communication distance of 1 km, and a fade margin of 20 dB:

$$Available\ Margin\ (dB) = 54.33\ (dB) - 20\ (dB) = 34.33\ (dB)$$

Pass/Fail Criteria

A communication link is considered acceptable if the available margin remained positive after accounting for the selected fade margin. A positive available margin indicates reliable communication is expected, while a negative value indicates the link may fail.

$$If\ Available\ Margin\ (dB) > 0 \Rightarrow PASS,\ otherwise\ FAIL$$

6.3 | Detection Algorithm

The first step in designing the algorithm was selection of the features to base the detection upon. This is discussed in section 8.2 Gas Detection Testing. The wildfire detection algorithm was designed to identify abnormal environmental conditions associated with early-stage fires while minimizing false positive alerts. Several approaches were considered, including machine learning classification models, fixed threshold detection, and a weighted multi-sensor scoring algorithm. Machine learning approaches were considered unsuitable for the prototype due to the limited availability of datasets and the inability to collect sufficient controlled fire data. A simple threshold-based approach was also considered; however, fixed thresholds alone are susceptible to false positives caused by natural environmental variations.

A weighted multi-sensor approach was therefore selected. This method combines measurements from multiple environmental sensors to generate a fire risk score rather than relying on a single measurement. By considering changes in temperature, humidity, carbon dioxide concentration, and volatile organic compound (VOC) concentration simultaneously, the algorithm improves reliability by requiring multiple indicators of wildfire activity before generating an alert. An additive point-scoring system (scorecard model) was developed for use in detection as discussed in []. The $CO_{2,}$ VOC and temperature features were treated as positive or "bad risks" whereas the humidity was treated as a negative or "good risk". The scoring system assigns thresholds or "bins" to each feature. Each bin has an associated score that is added to the total if a feature falls within a bin. Separate thresholds are established to categorize the output into separate classes. In this case the three classes "Normal", "Warning" and "Danger" were used. Trial and error was performed using the data gathered during testing to establish appropriate bins, scores, and output thresholds. The resulting bins, scores, and thresholds are discussed in section 7.3.

6.4 | Software: Embedded, Gateway, Dashboard

Software development took place across three separate systems including:

1. Embedded software for STM32U5 on the sensor nodes
2. Gateway software for ESP32S3 on the gateway
3. Dashboard software

Software development was managed using Github to track version history. Github issues was used as a ticking system to manage tasks. Tickets were developed based on the requirements discussed in section 3.2. Weekly team meetings were used to "refine" these requirements into tickets that could be implemented as new features. Figure 4 shows a sample ticket.

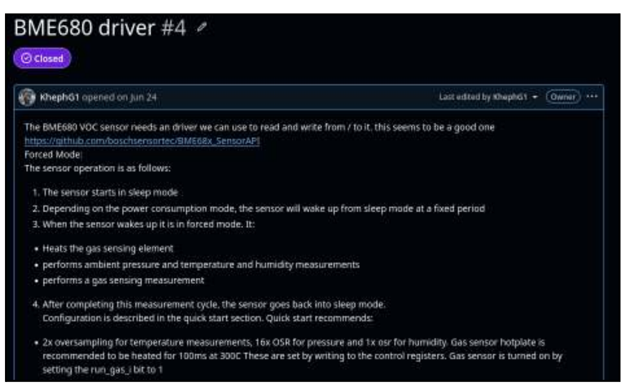

Figure 4: Software Ticketing System

7 | Design & Prototype

7.1 | Sensor Node PCB Design and Specifications

The final sensor node was implemented as a custom two-layer printed circuit board (PCB) integrating the sensing, communication, processing, and power management hardware into a single compact platform. The PCB was designed to support autonomous long-term deployment in remote environments while minimizing physical size, power consumption, and component count. Figure 5 shows a render of the completed PCB layout.

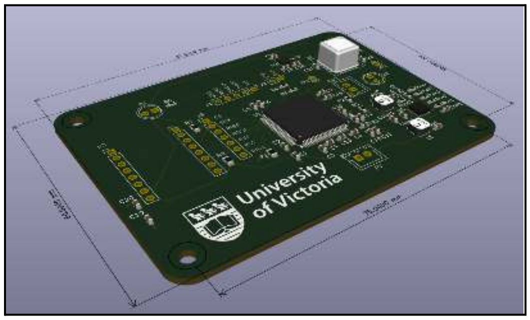

Figure 5: 3D render of PCB layout

Power Management

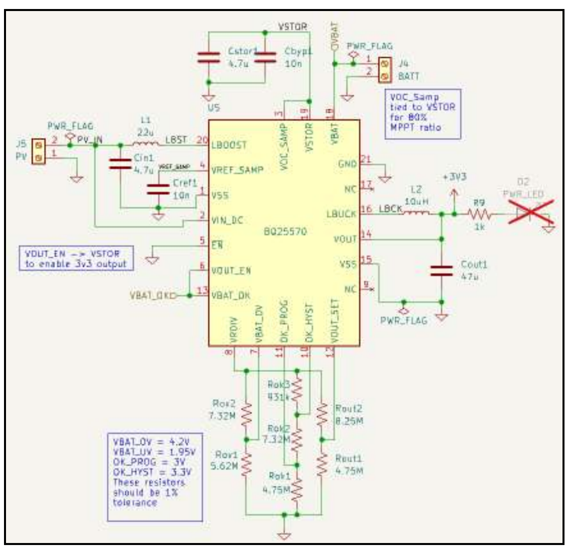

Figure 6: Power management IC schematic

Figure 6 shows the completed power management subsystem schematic. Energy is supplied by a perovskite photovoltaic panel and processed using the Texas Instruments BQ25570 energy harvesting IC before charging an INR18650 lithium-ion battery. The BQ25570 was selected due to its high conversion efficiency, integrated maximum power point tracking (MPPT), battery charging circuitry, and regulated 3.3V output, allowing the complete power management system to be implemented with relatively few external components.

The regulated 3.3V output supplies all remaining circuitry on the PCB, including the microcontroller, sensors, and LoRa transceiver. Decoupling capacitors were positioned adjacent to the BQ25570 and major power rails to improve transient response and maintain supply stability during wireless transmission events.

Microcontroller

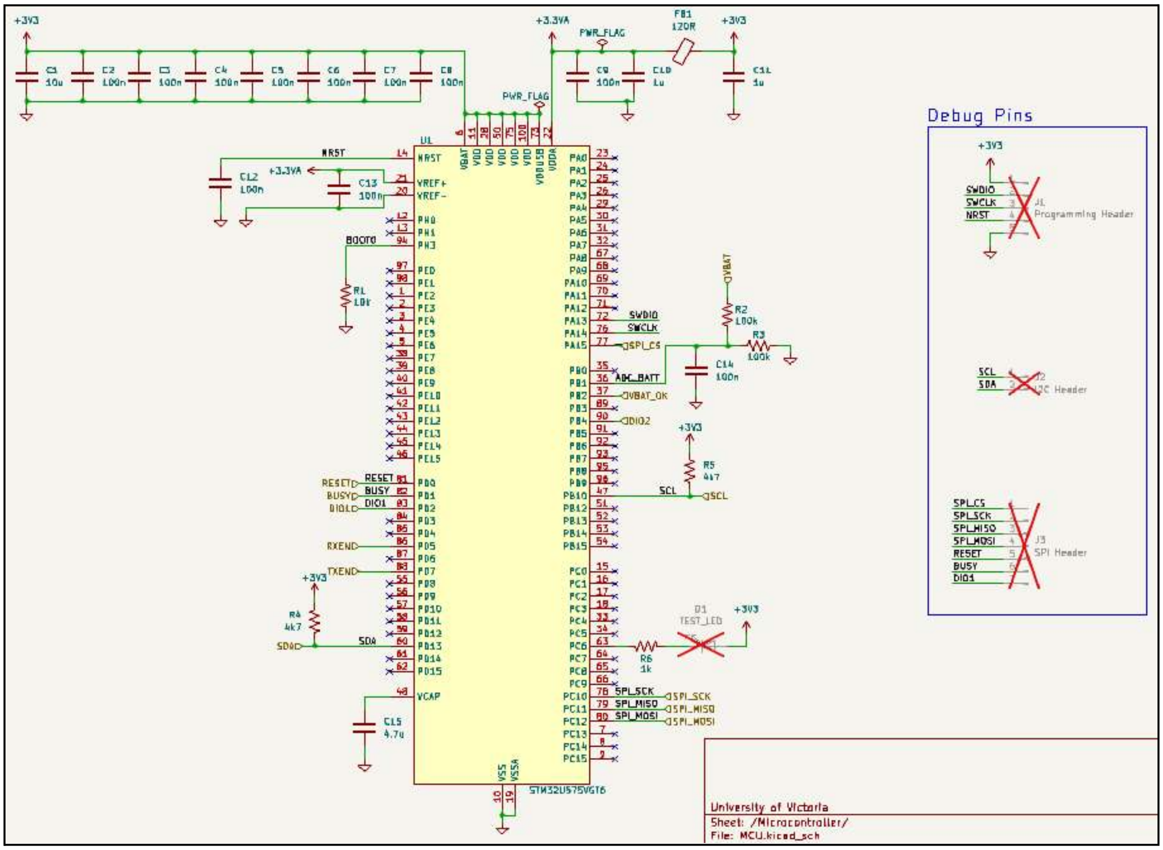

Figure 7: Microcontroller schematic

Figure 7 shows the processing subsystem centered around the STM32U575VGT6 microcontroller. The STM32U5 family was selected due to its ultra-low-power and sufficient processing capability to coordinate sensing and communication tasks while maintaining low average power consumption. During normal operation, the microcontroller periodically wakes from a low-power sleep state to acquire sensor measurements and transmit data to the gateway, then returns to sleep to minimize energy consumption.

The STM32U5 communicates with the environmental sensors over a shared I²C interface, allowing multiple devices to operate on a single bus while minimizing pin count and PCB routing complexity. While communication with the LoRa transceiver is performed over an SPI interface. Additional GPIO pins are used to monitor the status of the energy harvesting subsystem, control peripheral operation, and provide status indication through onboard LEDs.

The supporting circuitry surrounding the microcontroller was designed to ensure reliable operation in an outdoor deployment environment. An internal crystal oscillator provides the system clock required for accurate timing and wireless communication, while reset circuitry ensures the microcontroller initializes correctly following unexpected disturbances. A serial wire debug programming interface was also included on the PCB to simplify firmware development, debugging, and software updates.

To maintain a stable supply voltage, decoupling capacitors were placed immediately adjacent to each power pin of the microcontroller in accordance with the manufacturer's layout recommendations. These capacitors provide local energy backups and reduce voltage ripple, improving stability. The microcontroller also monitors the battery voltage using one of its ADC channels, allowing battery health information to be transmitted to the dashboard and enabling future implementation of low-battery protection features.

Integrated Circuits

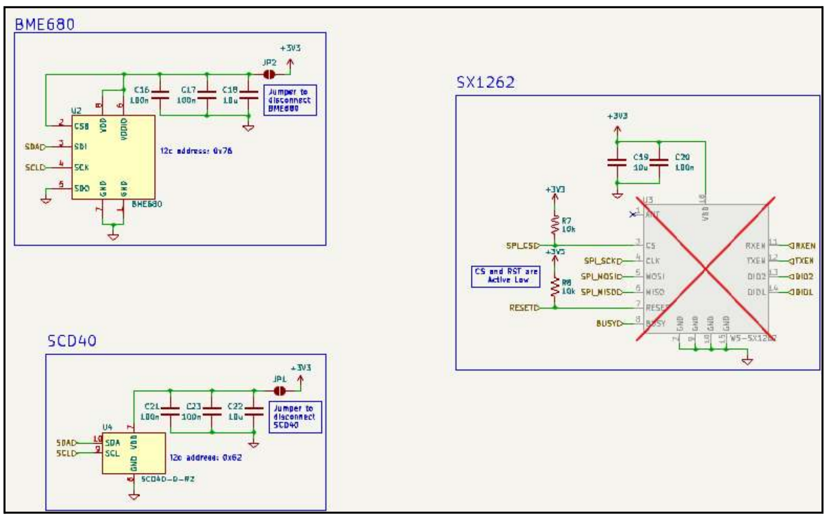

Figure 8: Integrated circuit schematics

Figure 8 shows the integrated circuit subsystem consisting of the environmental sensors and wireless communication hardware. The STM32U5 communicates with the BME680 and SCD40 sensors through a shared I²C bus and communicates with the SX1262 LoRa transceiver through a dedicated SPI interface, as discussed previously.

The environmental sensing subsystem consists of the Bosch BME680 and Sensirion SCD40 sensors. The BME680 measures temperature, relative humidity, atmospheric pressure, and VOC concentration, while the SCD40 measures CO_2 concentration. Together, these sensors provide the environmental data required by the wildfire detection algorithm. Each sensor was provided with dedicated power filtering consisting of a bulk capacitor and smaller ceramic decoupling capacitor to improve supply stability and reduce noise.

To improve system flexibility during development and troubleshooting, both sensors include a jumper in series with their power supply. This allows either sensor to be disconnected from the system without requiring PCB modification, enabling individual components to be isolated in the event of communication or hardware issues.

The wireless communication subsystem is based on the SX1262 LoRa transceiver, selected for its low power consumption and long-range communication capabilities. The internal RF design of the Waveshare SX1262 module was not modified as part of this project due to the specialized requirements and regulatory considerations associated with RF circuit design as outlined by the ISED Canada amateur radio regulations. Instead, the provided module was integrated into the PCB through the SPI interface, power connections, and external antenna connection. The module was positioned close to the antenna connector to minimize transmission losses.

7.2 | Enclosure Design and Specifications

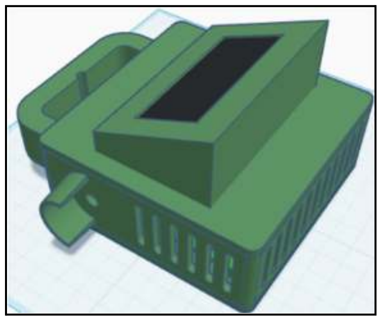

Figure 9: CAD Model of the Final Sensor Node Enclosure

The sensor node enclosure was designed to securely house the PCB, battery, antenna, and photovoltaic module while allowing the environmental sensors to remain exposed to ambient conditions. The primary design requirements were environmental protection, adequate airflow, ease of installation, component serviceability, and a compact form factor suitable for distributed deployment.

The final enclosure uses a covered upper structure to protect the electronics from direct rainfall. Ventilation openings are positioned along the sides and underside of the enclosure, where water ingress is less likely, while still allowing air to circulate around the BME680 and SCD40 sensors. The photovoltaic module is mounted at an angle to improve exposure to sunlight, and a protective cover shields the external LoRa antenna connection.

Figure 10 and 11: Interior of Enclosure and Assembled Prototype

Internally, the PCB is assembled using heat-set inserts and machine screws, allowing it to be removed for maintenance or future revisions. A retaining strap prevents the lithium ion battery from moving during transportation and installation. The enclosure also includes an integrated handle and a rear nail or screw slot, allowing the node to be easily carried and mounted to a tree, post, or similar structure.

The enclosure was manufactured using 3D printing, allowing several design iterations to be produced as component dimensions and mounting requirements changed. The final prototype successfully supported assembly and field testing. However, it has not received an ingress protection rating or been validated for permanent outdoor deployment. Future revisions should use weather-resistant materials, improved seals, and insect screening over the ventilation openings.

7.3 | Detection Algorithm Design

Table 11 summarizes the bins and scores determined and Table 12 summarizes the thresholds used.

Table 11: Bins and Scores by Feature

Feature	Bin	Score
Temperature (°C)	>= 45	35
Temperature (°C)	35 - 44.99	20
Temperature (°C)	30 - 34.99	15
Temperature (°C)	< 30	0
Humidity (%)	<= 20	30
Humidity (%)	21 - 35	15
Humidity (%)	36 - 49	0
Humidity (%)	>= 50	-30
VOC	>= 1.0	10
VOC	0.85 - 0.99	5
VOC	< 0.85	0
CO2 (ppm)	>= 1200	25
CO2 (ppm)	1100 - 1199	20
CO2 (ppm)	1000 - 1099	15
CO2 (ppm)	800 - 999	10
CO2 (ppm)	< 800	0

Table 12: Output Thresholds

Total Score	Risk Level
< 30	Normal
30 - 59	Warning
>= 60	Danger

A python module was developed to perform the computations for the proposed additive scoring system. The module receives as input the sensor data from the serial logger module and annotates it with the risk level. The risk level is then displayed on the dashboard as shown in Figure 12.

Figure 12: Additive Scoring System Dashboard Section

7.4 | Software Design

Embedded Sensor Node

The embedded sensor node software was developed for the STM32U5 Microcontroller using the C programming language. The STM32 HAL library provided by the manufacturer was used for performing all register level operations required for peripheral initialization. Various libraries were used to interface with the external peripherals on the PCB (SCD40, BME680, SX1262) and the UML diagram shown in Figure 13, illustrates the interactions between the library modules utilized.

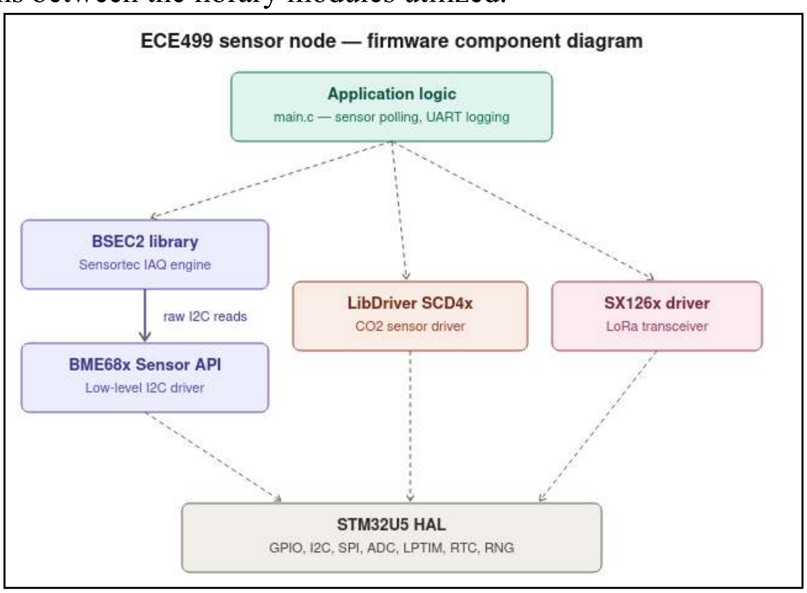

Figure 13: Sensor Node Software Component Diagram

The embedded sensor node software utilized a single process (super loop). After initialization of the peripherals (I2C / SPI) and initialization of the sensors and transmitter, the LPTIM1 low power timer peripheral was configured to generate periodic interrupts with a 10s period. The microcontroller executed a repeated loop in which commands to read data from each sensor were issued over I2C. The BME680 signal processing state machine was stepped each iteration and lastly, data was packed into the packet structure shown in Figure 15. The loop finished by issuing a transmit command to the SX1262 LoRa module before entering low power stop mode. The timer interrupt wakes the MCU from stop mode allowing it to perform another loop iteration. This is illustrated by the flow chart in Figure 14.

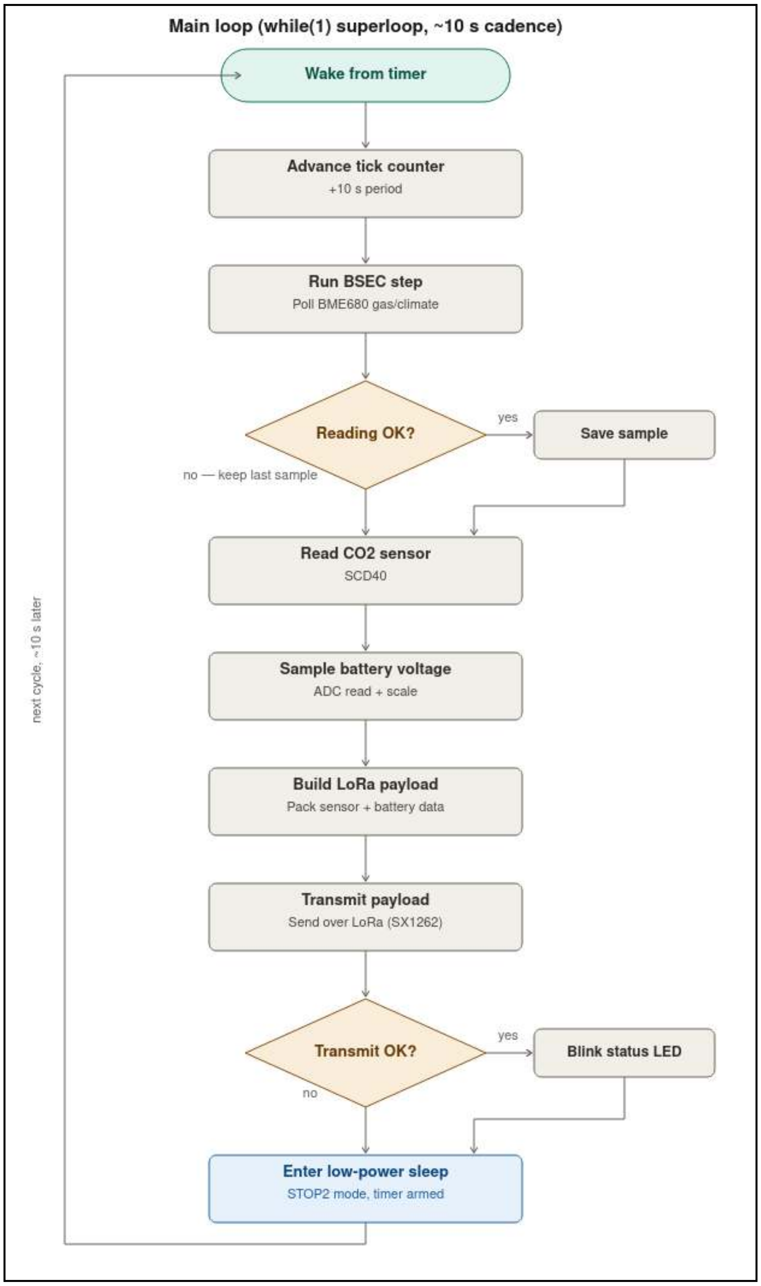

Figure 14: Sensor Node Software Flowchart

Gateway

The gateway software was written in C++ for the HeltecV3 based gateway. It fulfills the functional requirement of receiving data from the sensor nodes over the LoRa protocol, decoding the packets into the respective sections, executing the detection algorithm discussed in section 7.3 and relaying the annotated data to the dashboard over a USB connection. The software relies on two libraries:

1. Espressif Systems esp32 - Handles register level operations on ESP32 microcontroller
2. RadioLib - Handles communication with the SX1262 radio module

The packet structure used by the sensor nodes and decoded by the gateway is shown in Figure 15.

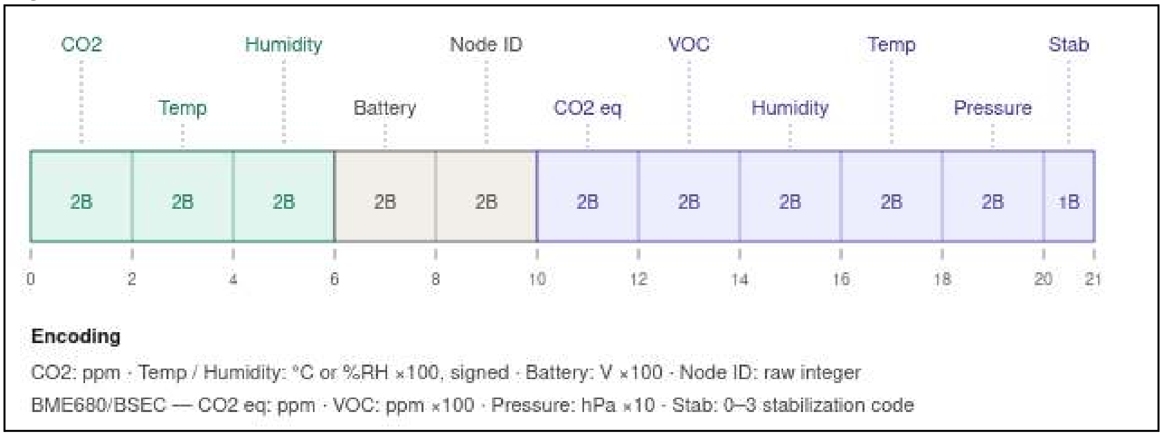

Figure 15: LoRa Packet Structure (21 Bytes)

Dashboard

The dashboard consisted of a web based client server architecture. The frontend was written in pure html, css and javascript while the backend API was written using Flask. SQlite was used as a database for storing the historical data and Cloudflare was used as a cloud tunneling service to make the dashboard available over the internet through the app.wildfiresuvic.ca domain name. The dashboard was designed according to the requirements in section 3.2 and consists of two main views. The "System Overview" page displays sensor locations, status, data from the past reading, as well as a form to allow the user to modify the location of the sensor. This feature allows the user to enter the GPS coordinates of the sensor from an external GPS (phone) during installation and eliminates the need for a GPS on the sensor. The "System Overview" page is shown in Figure 16.

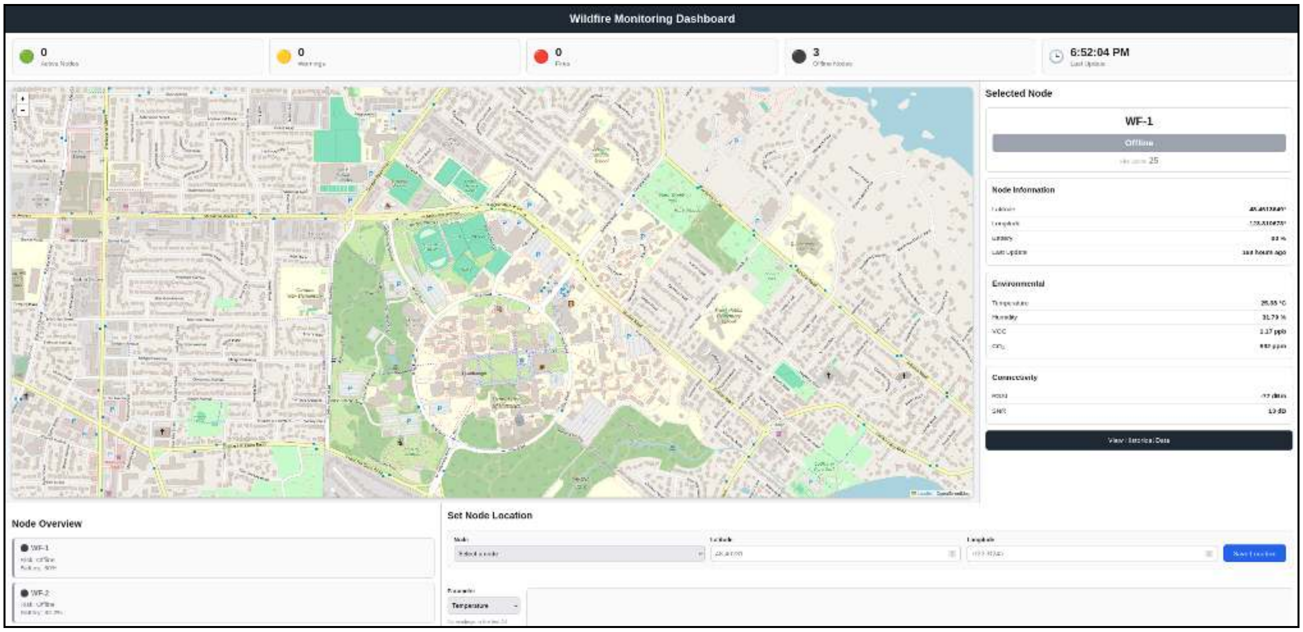

Figure 16: System Overview Dashboard View

The second page is the “Historical Data”. This page displays graphs for all data contained in the sensor packets for the sensor selected upon entering the page. The page allows the user to select the time window over which the data is plotted. Additionally, an option to export the data as a CSV is provided. The “Historical Data” page is shown in Figure 17.

Figure 17: Historical Data Dashboard View

8 | Testing & Validation

8.1 | Range Testing

Wireless range testing was conducted at the UVic Quadrangle to evaluate the performance of the SX1262 LoRa transceiver under realistic outdoor conditions. Two modules were configured in a point-to-point arrangement using a frequency of 915 MHz, spreading factor 9, a bandwidth of 125 kHz, and external 5 dBi antennas. Packets were transmitted at distances ranging from 5 m to 300 m using transmission powers of 22 dBm, 14 dBm, 10 dBm, and -9 dBm. At each distance and power level, the receiver recorded packet delivery, received signal strength, and signal-to-noise ratio. The signal path was mostly unobstructed at shorter distances, while buildings increasingly interfered with communication at longer distances.

Reliable communication was achieved up to 300 m at the higher transmission-power settings despite the increased obstruction. The lowest power setting of -9 dBm achieved zero packet loss over 100 m, demonstrating that shorter-range communication can operate with reduced energy consumption. The project's 1 km communication requirement was not directly validated because the available test site limited the achievable separation between devices. However, link-budget calculations using free-space path loss and a conservative 35 dB forest fade margin predicted reliable communication up to 2 km at -9 dBm using spreading factor 12. Further testing in a forested environment is required to validate this calculated range and quantify the effects of vegetation, terrain, and antenna placement.

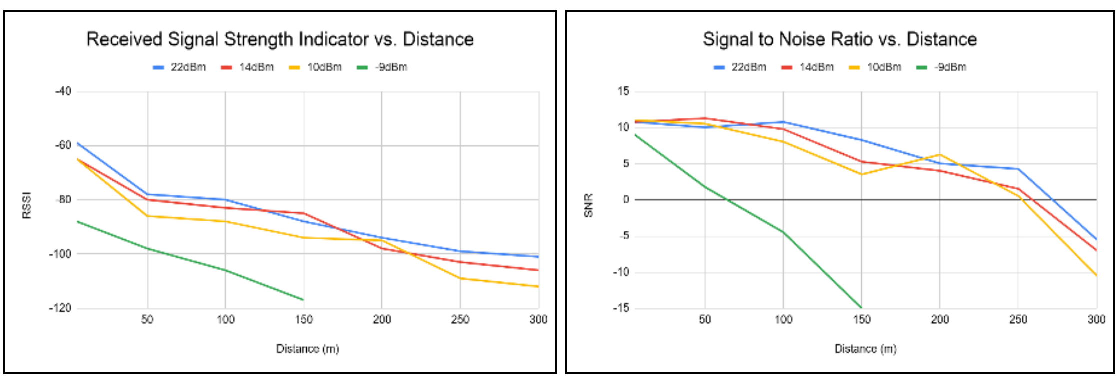

Figure 18 & 19: RSSI and SNR as a function of distance and transmit power

8.2 | Gas Detection Testing

Gas detection testing was conducted to evaluate the ability of the selected environmental sensors to identify changes associated with an early stage fire. The tests used a controlled 0.5m x 0.5m Category 1 campfire in accordance with applicable BC Wildfire Service restrictions [10]. A field test was conducted using 4 of the commonly used sensors derived from the literature review discussed above. These are listed in Table 13:

Table 13: Sensors Considered for Use In Detection

Sensor	Type
BME280	Temperature and Humidity
AHT21	Temperature and Humidity
ENS160	VOC, eCO_2
BME680	VOC, Temperature, Humidity, eCO_2
SCD40	True CO_2

An Arduino Mega was interfaced to communicate with the sensors and the test setup shown in Figure 20 was used to gather test data in both fire and non fire conditions. This was done because many formal classification techniques require training data that is labelled by class (in this case, the two classes are “fire” and “no fire”).

Figure 20: Test Setup for the 2m Test

The test procedure consisted of first gathering ambient data for a period of 5 minutes. Following this, a 0.5 x 0.5m fire was started and the time of ignition was recorded. The fire was allowed to burn for 20 minutes after which it was extinguished. Tests were performed at 1m, 2m and 10m. Sample test data from the 2m test is shown in Figure 21.

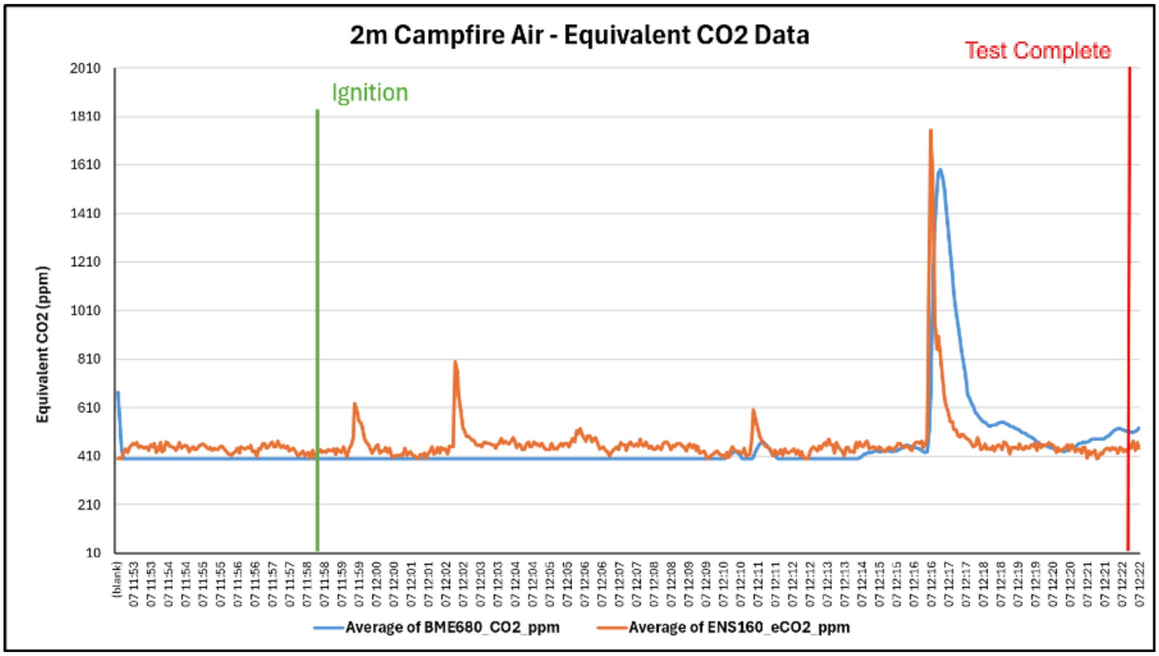

Figure 21: ENS160 & BME680 VOC Data, 2m Distance

The final sensors selected for use were the BME680 and the SCD40. The BME680 was selected due to its accurate VOC readings which correlated well with the readings provided with the ENS160. Additional factors considered were the low power consumption as well as its ability for use as a temperature and humidity sensor in addition to VOC. The SCD40 was selected due to its sensitivity. The SCD40 exhibited large differences in average CO_2 readings in fire conditions when compared to non fire conditions. This is desirable for reducing error in a classifier. The weighted objectives charts used for selection of the sensors are presented in Appendix D.

8.3 | Power Profiling

Following the design and assembly of the PCB, power profiling was performed to validate the expected power consumption of the device. While the power consumption was successfully validated, charge current was not validated. This is discussed further in conclusions and recommendations. The power profiler used was the NRF-PPK2 from Nordic Semiconductor. The results of power profiling with parameters identical to those in Table 7 are shown in Figure 22 and correspond to an average load current of 9mA.

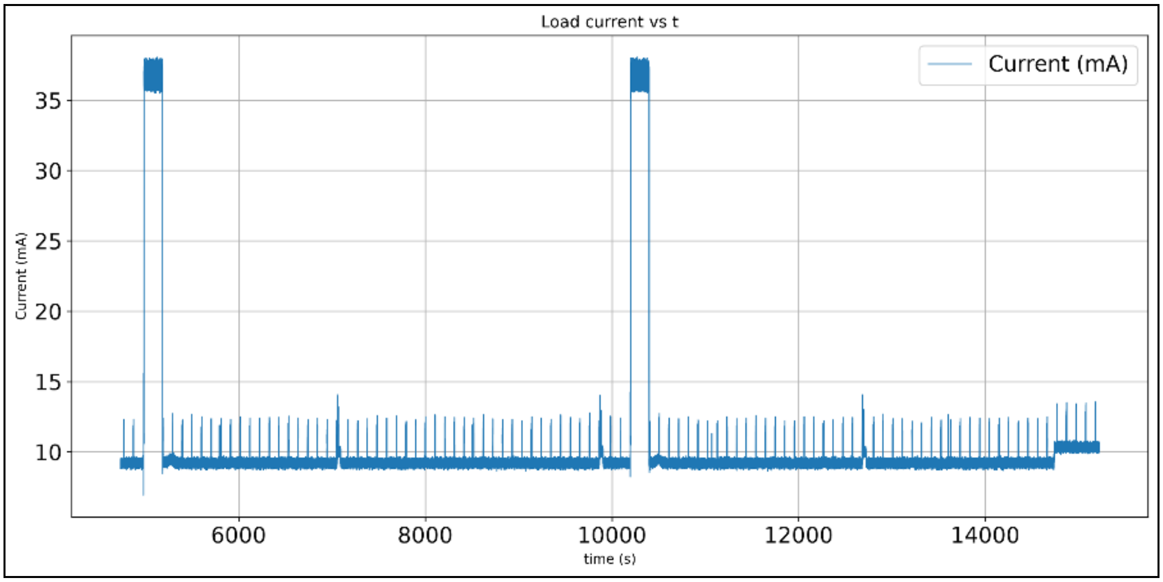

Figure 22: Power Profiler Output

9 | Cost Analysis

To evaluate the feasibility of deploying the proposed wildfire detection system at scale, a cost analysis was performed. The analysis was divided into three stages: the cost per unit, the prototyping costs, and a complete deployment estimate for a representative high-risk community.

9.1 | Cost per Unit

To evaluate the feasibility of deploying the proposed wildfire detection system at scale, the cost per complete sensor node was first determined. The cost per node was calculated using the final bill of materials and includes all components required for a fully operational deployed unit.

Table 14 presents the estimated cost breakdown of a single sensor node. The current prototype design has an estimated unit cost of approximately $100CAD. The largest contributors to the overall cost are the LoRa Transceiver and CO_2 sensor.

Table 14: Bill of Materials

Material	Cost
Battery	$10
Microcontroller	$6
Transceiver	$30
CO_2 Sensor	$20
VOC, Temperature, and Humidity Sensor	$10
Energy Harvester	$4
Enclosure	$5
Miscellaneous	$15
Total	$100 CAD

9.2 | Prototyping Costs

In addition to the estimated production cost of an individual sensor node, several non-recurring expenses were required to develop and validate the prototype. These costs represent the resources required to transition from initial concept to a fully functional wireless sensor network and would not be included in the cost of future deployments.

Early development required evaluation hardware to validate individual subsystems before integrating them onto the custom PCB. This included breakout boards for each environmental sensor, an STM32 Nucleo development board for firmware development and peripheral testing, and prototyping materials used to verify sensor communication, power management, and wireless functionality. A Heltec LoRa gateway was also used during development to validate communication between sensor nodes and the base station.

Additional costs were associated with enclosure development and manufacturing. Multiple enclosure iterations were required to optimize airflow, weather resistance, and component fitment. Due to limited access to external 3D printing resources and the need for rapid design iteration, a 3D printer was acquired to allow in-house fabrication and testing of the final enclosure design.

Including development hardware, prototyping materials, enclosure fabrication, and the components required to assemble three complete sensor nodes, the total prototype development cost was approximately $1000–$1200 CAD. This cost reflects the expenses associated with creating and validating the first functional prototype and is expected to decrease significantly for future production units, where development hardware and iteration costs would no longer be required.

9.3 | Cost of Deployment in a High Risk Area (Lytton, BC)

Figure 23: Municipal boundary of Lytton, BC (673ha)

An ROI calculation was performed using coverage of the Lytton BC wildfire jurisdiction as a target application. The calculation is broken into three steps:

1. Investment Cost Calculation
2. Estimate the Total Benefits
3. Calculate the net benefit

9.3.1 | Investment Cost

The investment costs are broken down into sensor cost, gateway cost, installation and maintenance. The time period analyzed is 5 years. The calculation is based on a sensor cost of $100/node, communication range of 300m to the gateway, and coverage area of 0.25 ha / node. It is assumed that installation will require 40 hours of work per 100 sensors installed with an operator salary of $18.25/hr (BC minimum wage). It is also assumed that maintenance will cost 5% of the upfront sensor cost per year. The resulting total costs are tabulated in Table 15.

Table 15: Investment cost breakdown

Cost Component	Calculation	Total
Sensor nodes	2692×$100	$269,200
Gateways	24×$30	$720
Installation	2692/100×40×$18.25	$19,653
Maintenance (5 years)	2692×$100×0.05×5	$67,300
Total 5-year lifecycle cost	$356,873	

9.3.2 | Estimated Benefits

The estimated benefits were calculated based on the assumption that the detection time reduction from ~10 hours to 1 hour (specified detection time of the sensor nodes) will reduce the frequency of severe wildfire events from 4 to 2 every 5 years (the sensors will prevent ¼ potentially severe fires). The data from 2006 to 2026 indicates Lytton BC experiences 4 severe wildfires (>500ha) every 10 years on average [28]. The estimate suppression costs in BC can be assumed to be approximately $385/ha based on a 2.84M ha suppression cost of $1.095B in BC for 2023 [29]. This equates a 500ha fire with a cost of $413,500. The estimated savings are thus $826000.00 for the 5 year period.

9.3.3 | Net Benefit and ROI

The net benefit over a period of 5 years is:

$$B = \$826000.00 - \$356,873.00 = \$469127.00$$

The ROI is then:

$$ROI = \frac{\$469127.00}{\$356,873.00} x 100\% = 131.45\%$$

10 | Conclusion & Recommendations

This project successfully designed, built, and validated a prototype environmental sensor network for early wildfire detection. A custom PCB integrating the STM32U5 microcontroller, BME680 and SCD40 environmental sensors, and an SX1262 LoRa transceiver was developed alongside embedded, gateway, and dashboard software, and packaged in a 3D printed enclosure. Range testing confirmed reliable LoRa communication up to 300 m in an obstructed campus environment, and link-budget analysis suggests the system can meet its 1 km design target with a 30dB fade margin applied. Gas detection testing using controlled Category 1 fires supported the selection of the BME680 and SCD40 sensors and informed a weighted additive scoring algorithm capable of classifying readings into Normal, Warning, and Danger risk levels, while power system simulations predicted roughly 16 days of autonomous battery-backed operation between periods of adequate solar charging. At the same time, several limitations remain unresolved: the harvester's charge current was not experimentally validated, the enclosure lacks a formal ingress protection rating, and detection performance has only been demonstrated at short range and small fire scale under regulatory constraints. Future work should prioritize forested-environment range testing, experimental validation of the solar charging subsystem, ruggedization of the enclosure for long-term outdoor deployment, and larger-scale or longer-duration fire trials to build confidence in the detection algorithm's false-positive rate before the system is considered ready for pilot deployment with an organization such as the BC Wildfire Service.

11 | References

[1] M. C. Kirchmeier-Young et al., "Human driven climate change increased the likelihood of the 2023 record area burned in Canada," npj Clim. Atmos. Sci., vol. 7, no. 1, p. 316, Dec. 2024, doi: 10.1038/s41612-024-00841-9.

[2] E. Rashidi, H. Medal, and A. Hoskins, "An attacker-defender model for analyzing the vulnerability of initial attack in wildfire suppression," Nav. Res. Logist., vol. 65, no. 2, pp. 120–134, 2018, doi: 10.1002/nav.21792.

[3] F. Brunet, J. Boucher, and M. Bouchard, "Factors influencing travel time and getaway time of helitack crews on wildfires in the province of Quebec," Int. J. Wildland Fire, vol. 33, no. 11, 2024, doi: 10.1071/WF24012.

[4] M. S. Huang and B. Wichmann, "Machine learning estimates on the impacts of detection times on wildfire suppression costs," PLoS ONE, vol. 19, no. 11, p. e0313200, Nov. 2024, doi: 10.1371/journal.pone.0313200.

[5] Natural Resources Canada, "Fighting and Managing Wildfires in a Changing Climate Program." [Online]. Available: https://natural-resources.canada.ca/forest-forestry/wildland-fires/fighting-managing-wildfires-changing-climate-program. Accessed: Jun. 16, 2026.

[6] Canadian Climate Institute, Close to Home: How to Build More Housing in a Changing Climate. Ottawa, ON, Canada: Canadian Climate Institute, Feb. 2025. [Online]. Available: https://climateinstitute.ca/reports/close-to-home/. Accessed: Jun. 23, 2026.

[7] CASupport, "Funding Opportunities: Wildfire Tech Call for Innovation 2024," NorthX. [Online]. Available: https://northx.ca/funding/call-for-innovation-wildfire-tech. Accessed: Jun. 16, 2026.

[8] J. Akers, Research Technician, Research & Innovation, British Columbia Wildfire Service, personal communication, 14 June 2026.

[9] California Department of Forestry and Fire Protection, Office of Wildfire Technology Research and Development, "Remote Smoke Sensor End User Evaluation," Sacramento, CA, USA, Aug. 2024. [Online]. Available: https://34c031f8-c9fd-4018-8c5a-4159cdff6b0d-cdn-endpoint.azureedge.net/-/media/calfire-website/what-we-do/research-and-development/meetings/owtrd_remote_smoke_sensor_end-user_evaluation_08_01_2024.pdf. Accessed: Jun. 23, 2026.

[10] British Columbia Wildfire Service, "Fire Prohibitions and Restrictions," Province of British Columbia, Jun. 19, 2026. [Online]. Available: https://www2.gov.bc.ca/gov/content/safety/wildfire-status/prevention/fire-bans-and-restrictions. Accessed: Jun. 23, 2026.

[11] A. Kumoro et al., "Efficient Wildfire Detection Framework Based on Artificial Intelligence Using Convolutional Neural Network and Multi-Color Filtering," in Proc. IEEE CAI, 2024, doi: 10.1109/CAI62432.2024.10756651.

[12] Natural Resources Canada, "Canada Fire Weather Index System," Government of Canada. [Online]. Available: https://natural-resources.canada.ca/forests-forestry/wildland-fires/canada-fire-weather-index-system. Accessed: Jun. 23, 2026.

[13] U.S. Department of Homeland Security Office of Inspector General, "DHS Wildfire Sensors Did Not Consistently Detect Fires and Provide Early Warning," Report No. OIG-26-05, Apr. 28, 2026. [Online]. Available: https://www.oig.dhs.gov/sites/default/files/assets/2026-04/OIG-26-05-Apr26.pdf. Accessed: Jun. 23, 2026.

[14] Natural Resources Canada, "Forest classification," Government of Canada. [Online]. Available: https://natural-resources.canada.ca/forest-forestry/sustainable-forest-management/forest-classification. Accessed: Jun. 23, 2026.

[15] S. W. Gilbert, H. Fang, D. T. Butry, W. C. Tam, M. Donnelly, and J. F. Fung, Understanding the Risk of Lithium-Ion Battery Fires: Multi-Source Data Analysis, NIST Technical Note 2365. Gaithersburg, MD, USA: National Institute of Standards and Technology, Mar. 2026. doi: 10.6028/NIST.TN.2365.

[16] Y. Kang, E. Jang, J. Im, and C. Kwon, "A deep learning model using geostationary satellite data for forest fire detection with reduced detection latency," GIScience & Remote Sensing, vol. 59, no. 1, pp. 2019–2035, 2022, doi: 10.1080/15481603.2022.2143872.

[17] NASA, "MODIS Web." [Online]. Available: https://modis.gsfc.nasa.gov/data/. Accessed: Dec. 18, 2025.

[18] Q. E. Barber et al., "The Canadian Fire Spread Dataset," Sci. Data, vol. 11, no. 1, p. 764, Jul. 2024, doi: 10.1038/s41597-024-03436-4.

[19] Natural Resources Canada, "WildFireSat: A Canadian operational mission," Government of Canada, May 6, 2026. [Online]. Available: https://natural-resources.canada.ca/forests-forestry/wildland-fires/wildfiresat-canadian-operational-mission. Accessed: Jun. 23, 2026.

[20] A. Mohapatra and T. Trinh, "Early wildfire detection technologies in practice—A review," Sustainability, vol. 14, no. 19, Art. no. 12270, 2022, doi: 10.3390/su141912270.

[21] Dryad Networks GmbH, "Silvanet Wildfire Sensor," Dryad Networks. [Online]. Available: https://www.dryad.net/wildfiresensor. Accessed: Jun. 23, 2026.

[22] SenseNet Inc., "How it works," SenseNet – Wildfire Risk Resilience Intelligence. [Online]. Available: https://sensenet.ai/solution/#how-it-works. Accessed: Jun. 23, 2026.

[23] N5 Sensors, "Wildfire Monitoring," N5 Sensors. [Online]. Available: https://n5sensors.com/wildfire-monitoring/. Accessed: Jun. 23, 2026.

[24] European Commission Joint Research Centre, "Photovoltaic Geographical Information System (PVGIS)," [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/. Accessed: Jul. 28, 2026.

[25] M. Kulkarni and V. D. Agrawal, "A Tutorial on Battery Simulation - Matching Power Source to Electronic System," presented at the 14th IEEE/VSI VLSI Design and Test Symposium, Chandigarh, India, Jul. 2010. [Online]. Available: https://www.eng.auburn.edu/~agrawvd/TALKS/VDAT10/160_ST.pdf

[26] Approaches for credit scorecard calibration: An empirical analysis - sciencedirect, https://www.sciencedirect.com/science/article/abs/pii/S0950705117303568 (accessed Aug. 7, 2026).

[27] Semtech Corporation, *SX1261/2 Data Sheet: Long Range, Low Power, Sub-GHz Radio Transceivers*, Semtech Corp., 2024. Available: https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/RQ000008nKCH/hp2iKwMDKWl34g1D3LBf_zC7TGBRIo2ff5LMnS8r19s. Accessed: Jun. 23, 2026.

[28] Village of Lytton, "Document 9905," Village of Lytton CivicWeb, Lytton, BC, Canada. [Online]. Available: https://lyttonbc.civicweb.net/document/9905/. [Accessed: Aug. 6, 2026].

[29] B. C. Wildfire Service, "Wildfire Averages," Province of British Columbia, Victoria, BC, Canada, 2026. [Online]. Available: https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-statistics/wildfire-averages. Accessed: Aug. 6, 2026.

Appendix A EGBC Code of Ethics

A registrant must adhere to the following Code of Ethics:

Registrants must act at all times with fairness, courtesy and good faith toward all persons with whom the registrant has professional dealings, and in accordance with the public interest. Registrants must uphold the values of truth, honesty, and trustworthiness and safeguard human life and welfare and the environment. In keeping with these basic tenets, registrants must:

1. Hold paramount the safety, health, and welfare of the public, including the protection of the environment and the promotion of health and safety in the workplace;
2. Practice only in those fields where training and ability make the registrant professionally competent;
3. Have regard for the common law and any applicable enactments, federal enactments, or enactments of another province;
4. Have regard for applicable standards, policies, plans, and practices established by the government or Engineers and Geoscientists BC;
5. Maintain competence in relevant specializations, including advances in the regulated practice and relevant science;
6. Provide accurate information in respect of qualifications and experience;
7. Provide professional opinions that distinguish between facts, assumptions, and opinions;
8. Avoid situations and circumstances in which there is a real or perceived conflict of interest and ensure conflicts of interest, including perceived conflicts of interest, are properly disclosed and necessary measures are taken so a conflict of interest does not bias decisions or recommendations;
9. Report to Engineers and Geoscientists BC and, if applicable, any other appropriate authority, if the registrant, on reasonable and probable grounds, believes that:
    a. The continued practice of a regulated practice by another registrant or other person, including firms and employers, might pose a risk of significant harm to the environment or to the health or safety of the public or a group of people; or
    b. A registrant or another individual has made decisions or engaged in practices which may be illegal or unethical;
10. Present clearly to employers and clients the possible consequences if professional decisions or judgments are overruled or disregarded;
11. Clearly identify each registrant who has contributed professional work, including recommendations, reports, statements, or opinions;
12. Undertake work and documentation with due diligence and in accordance with any guidance developed to standardize professional documentation for the applicable profession; and
13. Conduct themselves with fairness, courtesy, and good faith towards clients, colleagues, and others, give credit where it is due and accept, as well as give, honest and fair professional comment.

Appendix B Website Link and Main Page Image

A link to the project website is provided below:
https://sites.google.com/d/141WkM7bfWZDcP9eO7A7KxA5rlQePNjrc/p/1uJ193FiCFZO6hk5LM2p_dg8HGD-oS2L1/edit

The main page of the website is shown in Figure B.1.

Figure B.1: Project Website Main Page

Appendix C Project Timeline

Note: The tasks are colour coded (Kohen - Blue, Levi - Red, Khephren - Green)

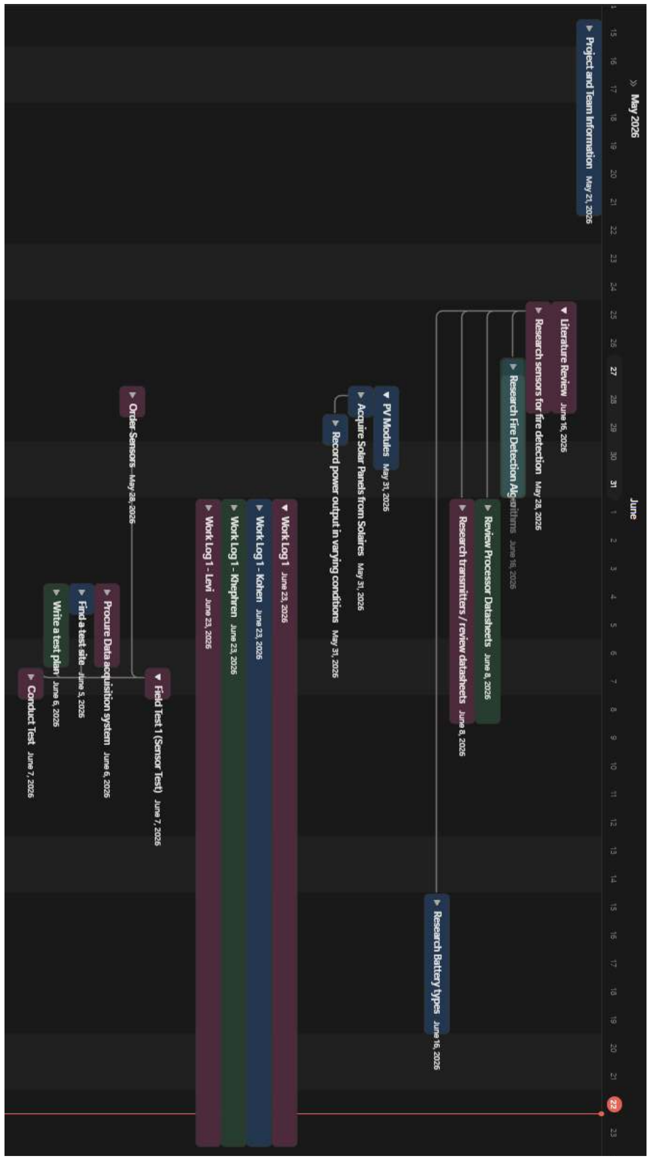

Figure C.1: WSN Gantt Chart - May / June

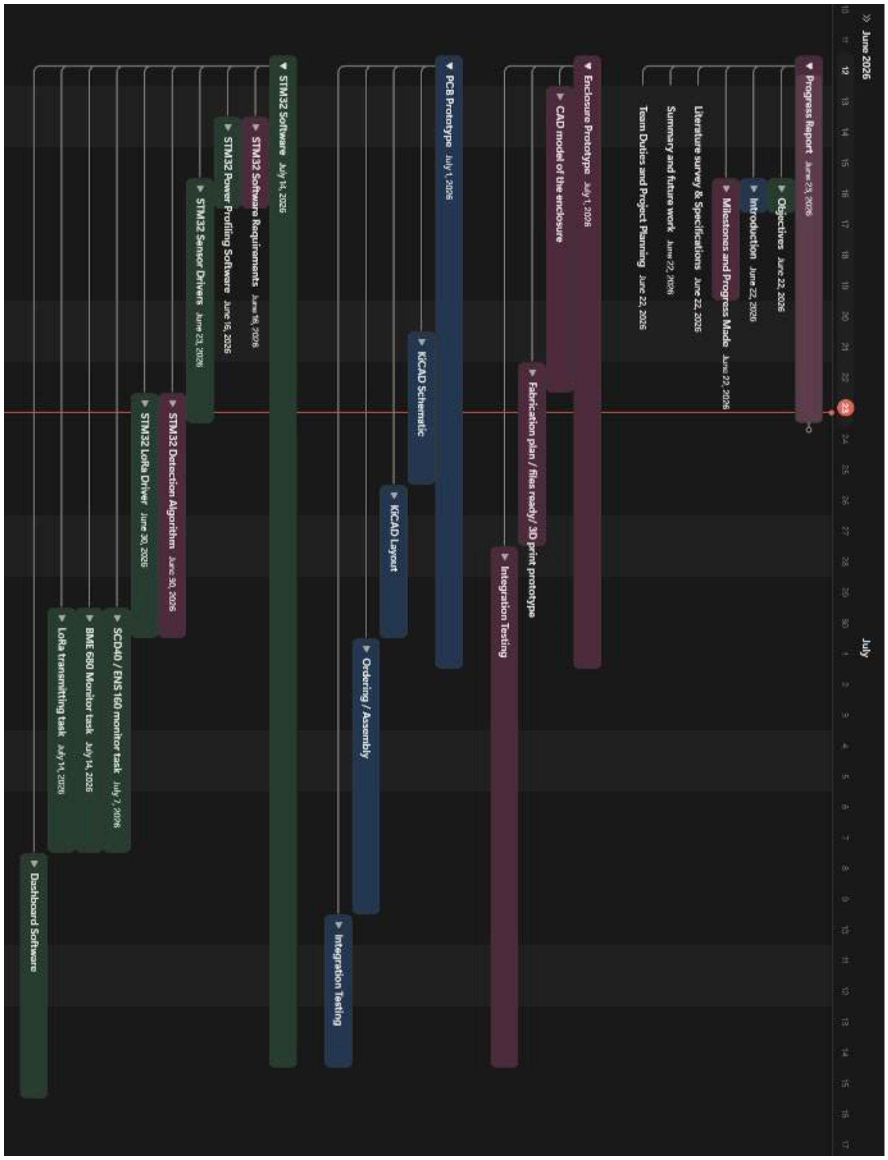

Figure: C.2 WSN Gantt Chart - June / July

Figure C.3: WSN Project Gantt Chart - July

Appendix D LT Spice Simulation Results

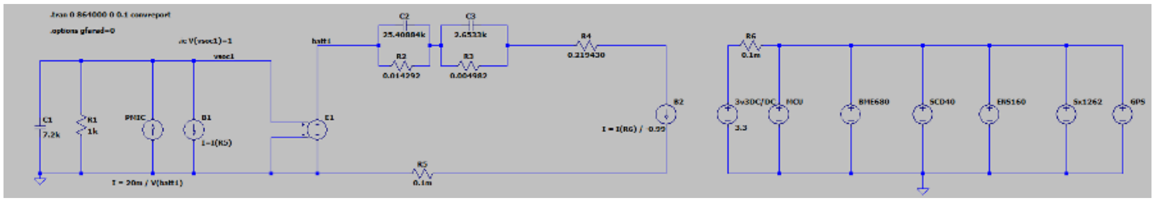

Figure D.1: LT Spice Transient Simulation - Circuit Schematic

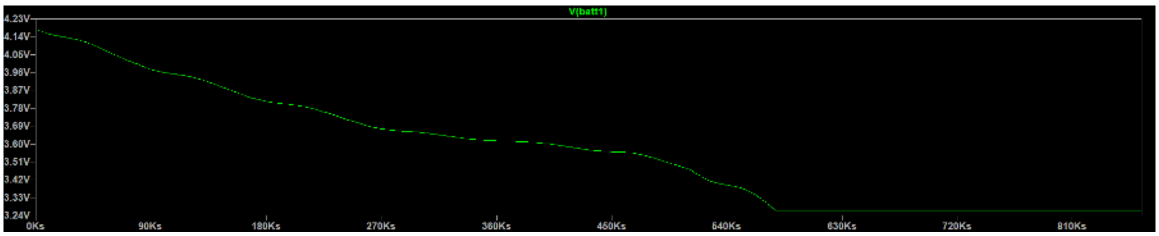

Figure D.2: LT Spice Transient Simulation - Battery Voltage vs time

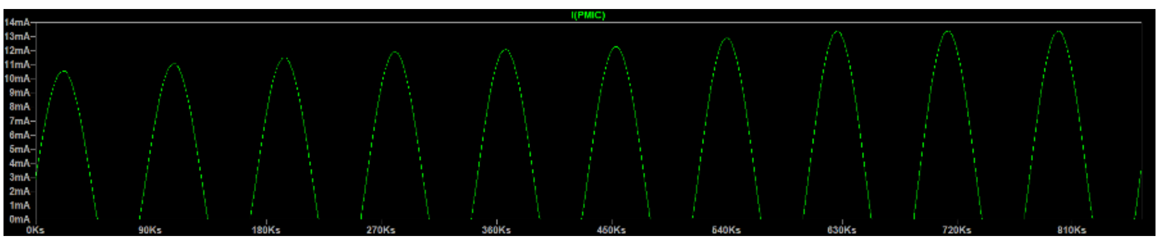

Figure D.3: LT Spice Transient Simulation - PV Module Power Output vs Time

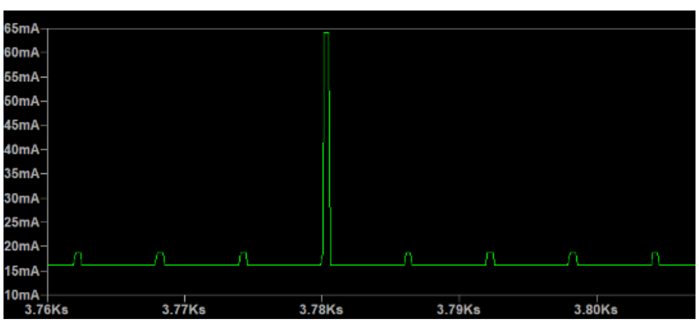

Figure D.4: LT Spice Transient Simulation - Load Current vs Time