OFF-GRID SOLAR AIR QUALITY MONITORING SYSTEM

Team Off-Grid (OG) Air
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ENGR 535: Development Technology
May 05, 2023

Executive Summary

The severity and frequency of wildfires have increased due to climate change, which has raised serious concerns. Particularly in the United States, wildfires have an adverse effect on air quality, posing a severe risk to the public's health and safety. Monitoring air quality (AQ) regularly has become critical to understanding the effect of wildfires and assessing their impacts on people's health. Access to reliable AQ information is often nonexistent for remote communities with limited grid connectivity in wildfire-prone areas. The availability of AQ data can empower individuals and communities to take action to protect themselves and their health from the adverse effects of smoke.

A standalone solar PV air quality monitoring system is a sustainable and innovative solution for monitoring air quality in remote areas and regions with little access to the grid electricity. The system will be an essential tool for monitoring the effects of wildfires and smoke events on the air quality and framing a set of mitigation measures. The system comprises a 30W solar photovoltaic (PV) module, a 128Wh battery, and a Purple air sensor, all integrated into the system. The system continuously measures air pollutants such as particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs). The solar panel charges the battery, and the system sizing ensures that the system can operate independently without needing an external power supply.

The system transmits the air quality data to the Purple air sensor cloud via a wireless network connection, often placed in proximity to inhabited areas. The collection of AQ data allows organizations such as the EPA, researchers, and individuals to access real-time air quality data and ensure that they can make an informed decision to mitigate the hazards of pollutants to the community. The system's low maintenance and cost-effectiveness make it a reliable solution for air quality monitoring in wildfire-prone and remote areas. A standalone solar PV-powered system can be beneficial for monitoring and addressing AQ impacts from wildfire events, especially in areas lacking grid connectivity.

Background

Access to clean air is vital to human health and well-being. Yet, communities across the United States face unprecedented exposure to smoke fueled by climate change and fire suppression. In California, where wildfire severity is at an all-time high, understanding the impact of smoke events on air quality can be vital to protecting human health, particularly for vulnerable populations. Marginalized communities frequently suffer disproportionate effects from exposure to poor air quality and smoke events (Liang, 2021).

Exposure to air pollutants is a public health concern on a global scale (NIH, 2023). Wildfires are a major source of ozone formation and particulate matter emissions, contributing to about 40% of directly emitted $PM_{2.5}$ in the US (NCA, 2018). These fires significantly threaten human health, increasing the risk of respiratory conditions like asthma and chronic obstructive pulmonary disease, cardiovascular disease, and even cancer (WHO, 2023). Climate change is expected to worsen these issues, with longer fire seasons and larger fires leading to reduced visibility (Yue, 2013) and further harm to human health.

The impact of climate change on wildfires is expected to become the primary driver of $PM_{2.5}$ (NCA, 2018). The increase in wildfire exposure to smoke events will likely reduce the amount and quality of time spent on outdoor activities. However, accurate forecasting of smoke events can help mitigate some of the adverse effects. With the significant impact of wildfires on human health and the environment, measures to prevent or minimize their occurrence must be prioritized. To prevent harm to humans and natural ecosystems, the government has been allocating enormous resources toward stopping and minimizing wildfires for decades. Early forest management policy, formed in the 1900s in response to a succession of severe wildfires, may be identified as the origin of wildfire control (Headwaters Economics, 2020).

PurpleAir has created relatively low-cost AQ monitoring devices called PurpleAir sensors, which capture real-time ambient AQ data. These sensors are growing in popularity in the United States and worldwide (Barkjohn et al., 2022). In California, AQ monitoring has become a core resource for better understanding wildfire behavior and informing community response to smoke events. PurpleAir sensors are becoming increasingly important for tribal communities in rural parts of Northern California and in the greater Klamath Mountains (Figure 1A, Figure 1B) region in particular. The Hupa, Yurok, and Karuk tribes have all been affected by devastating wildfires in recent years. Due to the remote nature of many of these communities, emergency response can be slow and ineffective. California ecosystems' long-endured period of fire suppression has prevented Indigenous groups from practicing a traditional regime of prescribed burning, which historically mitigated the potential for severe and destructive large-scale fires (Avitt, 2021; Connor, 2022). AQ data collection can help inform future fire management policy changes. Access to real-time data can help inform individual action, empower community responses to smoke events, and aid our understanding of how prescribed burning can mitigate the severity of large-scale wildfires in California.

The Engineering 535: Development Technology graduate course at Cal Poly Humboldt has partnered with the Schatz Energy Research Center to develop air quality monitoring technology to deploy in remote, wildfire-affected areas. **Our team aims to successfully ideate, design, prototype, construct, and test a solar-powered air quality monitoring system for use in off-grid homes.** Our final products will include the constructed system, a user manual, and a design and construction manual.

Criteria and Constraints

Our criteria and constraints for this project are based on our best understanding of the stated needs of our client. The most important criteria for this system are reliability, durability, and ease of transport. This system must collect $PM_{2.5}$ data reliably and as consistently as possible. It must be resilient to wildlife and moderately resilient to weather. Finally, it must be relatively easy to collapse and transport in the trunk of a car. The final design will be thoroughly assessed using a series of tests to determine fit to the criteria outlined by the team. The testing and results section of this report will provide information on how the system fits the criteria.

Table 1. Criteria and Constraints.

Criteria	***Constraint***	***Weight***
Reliability	Sizing: the system must run 24/7/365. Connectivity: must be able to collect $PM_{2.5}$ data without significant interruptions.	10
Durability	Must be resistant to wildlife, weather, and other external influences.	9
Ease of Transport	Must be relatively easy to transport from place to place in a car.	8.5
Ease of Use	The construction and user manuals must be clear and easy to use. The system must be easy to use.	8
Safety	System must not be a hazard to users during construction or use.	8
Cost	Must stay within budget.	7
Replicability	Easy to replicate/adjust for different projects.	7

Literature Review

PV Systems and Racking

There are countless configurations of PV systems, widely varying depending on size, weight, location, and other factors. Mounting, commonly known as ‘racking’, for PV systems is also widely variable by type of material. Options include metal, wood, and plastic, among others. Racking options can range from expensive and complex to simple, low-cost, and following more of a do-it-yourself (DIY) design. Despite being an essential component of all solar installations, solar racking costs only make up a minority of the overall installation. The National Renewable Energy Laboratory (NREL) estimates that the cost of solar racking will be around $0.10 per watt.

According to EnergySage, the average price of installing solar panels is $2.98/W, thus, the cost of the racking should be about 3% of the whole system cost. (Marsh, 2019). Strategies for DIY-style racking infrastructure can prove to be more economical and more appropriate for solar projects worldwide (Grafman and Pearce, 2021).

System weight is an essential factor in designing a DIY racking structure. Depending on the type of panel, the weight for a 30W panel can range from about 2.5 lbs to about 9 lbs (Amazon, 2023). Typically, the weight of a panel increases along with its wattage, but panels that are older or heavy-duty may weigh more than the average panel of its equivalent wattage.

Panel type will be the largest factor contributing to individual panel weight. Currently, four main types of panels are on the market: monocrystalline, polycrystalline, PERC, and thin-film panels. Monocrystalline panels are the most commonly sold on the market (Forbes, 2023). Panel types have varying costs, efficiencies, and appearances, as well as pros and cons. For instance, thin film panels may have a lower life span and efficiency than conventional alternatives. Still, their low weight and flexibility may be highly convenient for some applications. Different types of panels also have different ratings for hurricanes, hail, fire, temperature, and light-induced degradation (Aurora Solar, 2021).

Air Quality Monitoring

Sensors and monitors are the two main types of devices for measuring air quality data. Ambient air monitors measure the level of common air pollutants such as particulate matter, carbon monoxide, and ground-level ozone. Reference grade monitors, such as the Beta Attenuation Monitor (BAM), are utilized by regulatory agencies, while regulatory agencies acknowledge equivalent monitors to be of comparable accuracy. Monitors are typically expensive and must be consistently maintained via established programs. Agencies can apply for funding to receive these monitors, but it can be difficult for smaller or less-established organizations. The Environmental Protection Agency (EPA) uses monitors to assess the extent of air pollution, provide data to the general public, and gather data for research purposes (EPA, 2022).

Sensors, on the other hand, are cheaper and more accessible but may be less accurate in comparison to monitors. Outdoor sensor performance may decrease with exposure over time and are thus less durable than monitors. Ideally, sensors should be collocated with a reference grade or equivalent monitor to establish quality assurance. Used in congruence with monitors, air sensors can provide important real-time air quality information, which can help protect individuals and communities from the adverse effects of poor air quality. On a local level, knowledge of AQ status can help inform individual and community response to planning activities, emergency response to smoke events, locating leaks at industrial facilities, and is beneficial for conducting research (ENGR 535 Lecture).

Hazardous AQ from high-intensity smoke events can have ravaging impacts on human health. While the long-term effects of exposure to wildfire smoke have been sparsely studied, the short-term and cumulative short-term effects of exposure are widely understood. The EPA states that even short-term exposure to high concentrations of $PM_{2.5}$ and other air pollutants can negatively affect the respiratory and cardiovascular systems causing shortness of breath, reduced lung function, bronchitis, and even heart attack failure (EPA, 2022).

Wildfire and Smoke

Recent increases in yearly concentrations of fine particulate matter, or $PM_{2.5}$, have been attributed to wildfires in the United States (McClure & Jaffe, 2018). Smoke incidents due to wildfires in the Pacific Northwest in 2018 and 2020 led to spikes in $PM_{2.5}$ concentrations significantly higher than the National Ambient Air Quality Standards (Washington State Academy of Sciences, 2019). Wildfires destroyed 10.3 million acres in the United States in 2020, the most forest burned in a single year since 1960. (Hoover and Hanson, 2019). Since the 1980s, the United States' fire season has grown by 78 days, or 64% (Westerling et al., 2006).

In 2013, The Centers for Disease Control reported that wildfire smoke is a dangerous mixture of gasses and fine particles that can cause immediate health effects such as coughing, wheezing, and shortness of breath. It can also affect high-risk groups such as older adults, pregnant women, and people with preexisting respiratory and heart conditions. To protect yourself from breathing in wildfire smoke, paying attention to local air quality reports and the US Air Quality Index is important. If you are told to stay indoors, keep your indoor air clean by closing windows and doors, using an air filter, and avoiding activities that can add to indoor pollution. The California Code of Regulations covers the majority of outdoor workplaces, Title 8, Section 5141.1, where the current Air Quality Index (AQI) for airborne particulate matter 2.5 micrometers or smaller ($PM_{2.5}$) is 151 or higher and where employers should logically anticipate that workers may be exposed to wildfire smoke (DIR, 2021).

Off-Grid Solar Powered Sensors

Air quality monitoring is essential for understanding the health effects caused by air pollution and smoke events. PurpleAir sensors have become a common device for determining the concentration of particulate matter in the atmosphere. Nevertheless, many areas with the greatest need for air quality monitoring, such as off-grid locales, lack reliable electrical infrastructure. Solar energy systems have become an increasingly popular answer to this issue, as they provide a power source that is both reliable and environmentally friendly.

When effectively implementing off-grid air quality sensors, the size and efficiency of the solar panels and batteries have emerged as two of the most important factors to consider. However, shading and smoke can significantly impact the performance of solar systems. This literature review highlights existing research on using solar energy systems to power PurpleAir sensors in off-grid locations in California or the United States.

Compared to the other PM_1, $PM_{2.5}$, and PM_{10} sensors used in the South Coast AQMD Air quality performance study, the PurpleAir PA-II sensors demonstrated accuracy that ranged from moderate to good over the whole concentration range of 0 to 250 g/m^3. PA-II sensors exhibited low levels of intra-model variability, and according to the results of the laboratory investigations, temperature and relative humidity had only a marginal impact on the precision of PA-II sensors. PurpleAir sensor has been rated as quite high, considering its size and low cost (Miller, 2021). It was very straightforward to set up and operate, and it can be utilized even if there is no internet connection as long as the monitor has a micro SD card built-in. On the other hand, the collected data suggest that the monitor has the propensity to report excessively high values, particularly higher ambient concentrations. There is a considerable degree of variation in the data.

In conclusion, previous research indicates that solar-powered sensors, when properly calibrated, can provide accurate readings of particulate matter concentrations even in off-grid regions. Photovoltaic, portable sensor networks are a cost-effective method for monitoring air quality in off-grid settings; however, additional research is required to investigate its effectiveness in powering sensors in various locations and under changing weather conditions.

Air Quality Challenges in Tribal Communities

Analogous to various other regions worldwide, Orleans is also impacted by air pollution, which substantially negatively affects the environment and human health. It is occurring due to several factors, but seasonally severe wildfires in the region have been the main contributor for the past few decades. Respiratory issues, cardiovascular disorders, and harm to agriculture and ecosystems are all outcomes of air pollution in Orleans (Gabbert, 2013). A recent study showed that massive wildfires are becoming more common due to climate change and fire suppression history. The danger of wildfires is enhanced in arid circumstances, such as drought and strong winds (NIDIS, 2023). As stated in the many reports, those who live in rural and suburban regions close to forest will be most severely impacted by the effects of wildfires.

According to a survey conducted by WHO, there are several air contaminants in wildfire smoke, but particulate matter poses the greatest risk to the public's health. WHO survey also mentioned that the potential influence of a wildfire on mortality and morbidity primarily depends on its size, velocity, and proximity to inhabited areas (WHO, 2021). As per the California Air Resources Board (CARB 2023) air monitoring, over 90% of California residents experience harmful levels of one or more air pollutants most frequently during the year. To overcome these dangerous impacts, CARB has established guidelines for eight "traditional contaminants", including ozone and particulate matter. Governmental organizations help tribal communities by putting wildfire prevention measures in place. State wildfire officials have employed both ground and airborne tactics to put out previous flames close to the project site, including using water from the project reservoirs for aerial drops to reduce air pollution in the environment (NWCG, 2023).

Methods

Load Requirement and Solar Sizing

To effectively design, construct and deploy an off-grid solar-powered AQ monitoring system, we measured the power requirements of the PurpleAir II sensor provided by the project instructors. We estimated the sensor's power consumption by connecting the sensor to the Poniie PN1500 power meter provided. The electricity monitor estimated the sensor's power consumption to be approximately 1.44W, resulting in a daily energy demand of 36 Wh. This power consumption was determined for an AC coupling. However, from the Specification Sheets, the PA-II requires a 5V USB Micro, 0.18A continuous, 600mA peak resulting in a DC power requirement of 0.9W and a daily energy demand of 21.6 Wh.

With this data, we designed a system that would meet the requirements and criteria of the project. This includes a system with a generation capacity that can power the PurpleAir II sensor 24 hours per day, 365 days a year, and charge the battery. We used the Global Solar Atlas website to determine the appropriate Photovoltaic electricity production, battery storage, charge controller, and inverter to provide power to the system. The website provides access to high-resolution solar resources and photovoltaic (PV) potential maps for every region of the world. This data includes information on solar radiation, temperature, and other relevant factors and can help design and plan solar energy projects.

Using the geographical coordinates for Orleans, we generated data that includes the system size, irradiation [W/m^2], air temperature, optimum tilt of PV modules, hourly and monthly averages of photovoltaic energy output [Wh] which can be seen in Figures 3A and 4A.

For this project, the team designed the system with the DC-based system based on the power requirement of the PA sensor. The sensor requires a yearly energy demand of 7884Wh. Based on this, we compared 10W, 20W, and 30W PV panel options and selected the 30W option based on the solar generation in the winter months and assuming 30% shading on the panel.

Battery Capacity and Charge Controller Sizing

To determine the battery capacity and charge controller, we considered a battery system that would cover up for the 30% shading of solar radiation. We designed 60Wh, 120Wh, and 300Wh options considering the standard 2 to 5 days of autonomy and 80% DOD (depth of discharge) from other solar experts (Solarlight, 2023). We chose the 128Wh battery because of its estimated six days of autonomy which could effectively substitute any losses or challenges with the solar panel due to snow, wildfire, or other unforeseen circumstances.

Additionally, we did a preliminary test using a 40W panel, a 128Wh battery, an inverter, and a 30A charge controller to estimate how long the battery could power the PurpleAir sensor. We used a 21W AC load for this test, as seen in Figure 1. This charging and discharging test on the system helped us determine how long the 40W panel and 128 Wh battery would last, powering a PurpleAir sensor and a heated seed mat. The 128Wh battery could power the 21W AC load for 5 hours and 20 minutes.

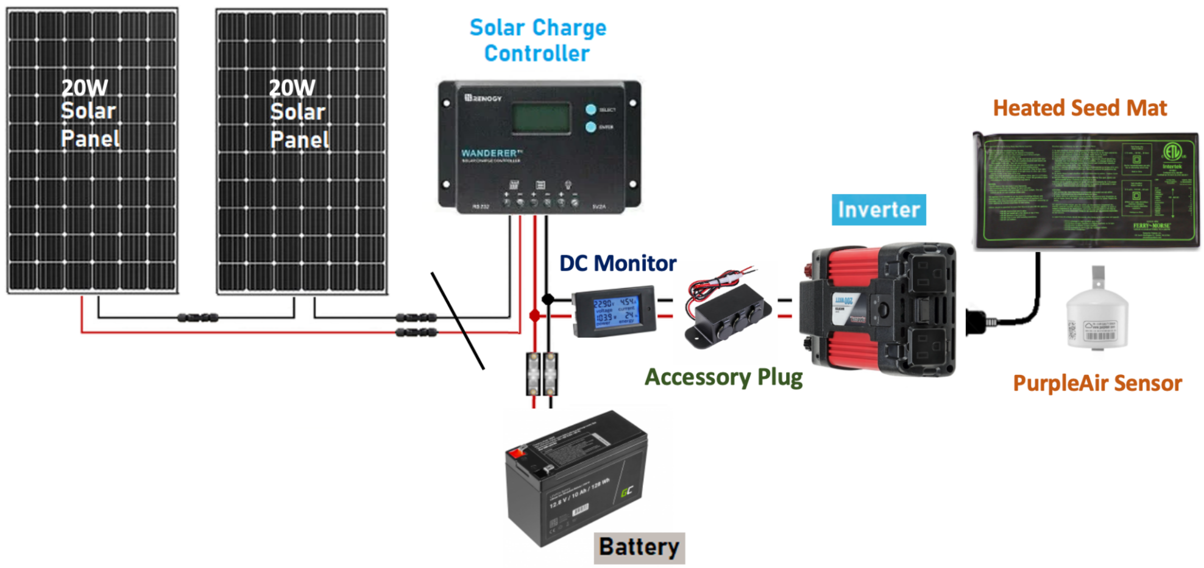

Figure 1. *Discharge experiment setup. The black line demonstrates disconnection from solar panels. Figure altered from CleanEnergyReview.info.*

Final Design

The final design for this project consists of a 30W panel, a 128Wh battery, a 30A charge controller, a DC-DC Buck converter (Figure 2.1), the PurpleAir sensor, and a PVC mounting structure (Figure 2.2). This system is expected to successfully power the PurpleAir sensor 24 hours a day, 7 days a week, and 365 days a year, with expected days of autonomy of approximately 80 hours. The physical system is constructed using schedule 40 1" PVC pipe and fittings, assembled using PVC cement. The final system includes a 14.6"×10.6"×5.9" junction box which holds the battery, charge controller, buck converter, and other moisture-sensitive wiring. A 3-foot USB to micro-USB cord is connected to the charge controller to power the PurpleAir sensor. Both the micro-USB and the PV wires inside the junction box are fed through a PG7 cable gland. Additionally, a set of 16 1.5" galvanized metal U-pins serve to stake the base into the ground to ensure structural integrity. Any loose wires are fastened taunt to the PVC mounting structure using high-quality, outdoor-grade zip-ties. Zip-ties are also used to fasten the junction box and PV panels to the PVC frame. A complete list of materials and cost breakdown is provided in the appendix (Table 1A).

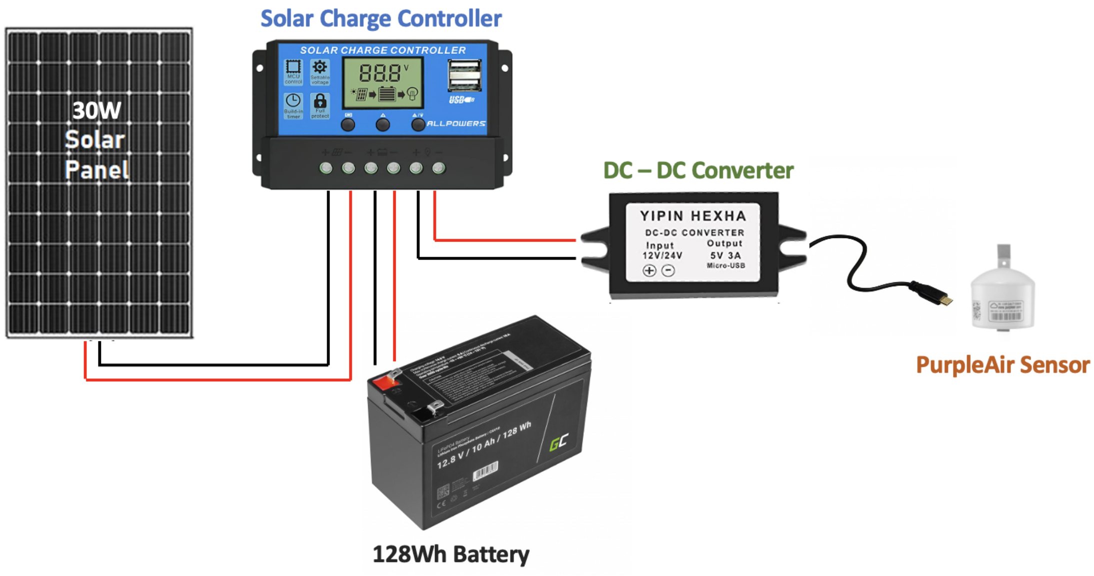

Figure 2.1: *Diagram of the final solar system sizing.*

Figure 2.2: *Final system physical design.*

Decision Alternatives, Justification and Comparison

PV System sizing justification

The team selected a 30W PV panel for this design compared to the 10W and 20W panels, mainly due to the low solar generation in the winter months and a shading consideration of 30%.

Table 2. PV System sizing justification

System Sizing	Pros	Cons
30 W	Solar generation can effectively power the PA sensor and battery every month, with its lowest generation in Dec (63Wh). Free 30W panel from Schatz for testing.	Excess generation is expected in the summer months.
20 W	Solar generation capacity can effectively power the PA sensor and battery in some months.	Low solar generation in Nov, December, and Jan (55, 41 & 49 Wh)
10 W	Cost of 10W is cheaper than others	Low solar generation in Oct, Nov, Dec, Jan, Feb and March (41, 27, 21, 24, 32 & 40 Wh)

In terms of the mounting structure to set up the system, the team considered a PVC pipe structure, a wood mounting structure, and a metal mounting structure (Figure 3).

Figure 3. *The team's solar PVC prototype on the left, the proposed metal system design from WillyGoat.com, and the proposed wood system design by Born to Build from the Autodesk Instructables website.*

Based on the given criteria and constraints, the team conducted a Delphi matrix to justify our PVC mounting structure decision based on the criteria we believe are of the topmost importance to this project. The result of the Delphi Matrix was derived from the votes of each of the team members. Each team member weighed each criterion on a scale of 1 to 100, represented in Table 3.

Table 3. Decision Justification Using a Delphi Matrix Sample.

Rating			
Criteria	*PVC Design*	*Metal Design*	*Wood Design*
Reliability	*300*	*300*	*300*
Durability	*240*	*350*	*320*
Ease of Transport	*330*	*270*	*270*
Ease of Use	*310*	*290*	*300*
Safety	*310*	*270*	*310*
Cost	*340*	*270*	*290*
Replicability	*310*	*260*	*290*
Total	***2140***	***2010***	***2080***

The Delphi matrix shows that the PVC prototype was chosen due to its ability to be easily transported, its ability to fit the budget, and its ability to be easily replicated due to the availability of materials and low barrier of entry to build using PVC. The metal and wood designs are expected to be more durable than the PVC, primarily because the posts are set into the ground. Due to considerations from our client, we chose a free-standing design that would not require concrete or digging despite the moderately lower structural reliability. The PVC design was not preferred for durability, not because of the design, but because lighter materials such as PVCs require additional support to be firm on the ground. The wood design was favorable regarding durability, ease of use, and safety. Depending on the local availability of materials, it could act as an alternative to the PVC design. Overall, the PVC design justified a higher percentage of our criteria.

Results

To guarantee that the final design meets the criteria and objective, our team has conducted a series of tests to ensure transportability, ease of use, replicability, and reliability. The system has been tested in various environmental conditions to ensure it can withstand the elements and function successfully.

Charging/Discharging Test

We have tested the system's 30W PV and 128Wh battery for charging time. The battery charging test was conducted on a day with good solar radiation. The time taken to charge the battery was about 300 minutes from 20% charge, as shown in Figure 4.1. The solar PV module also powered the PA sensor during charging, which indicates that the battery charge will be utilized only during nights or low solar radiation.

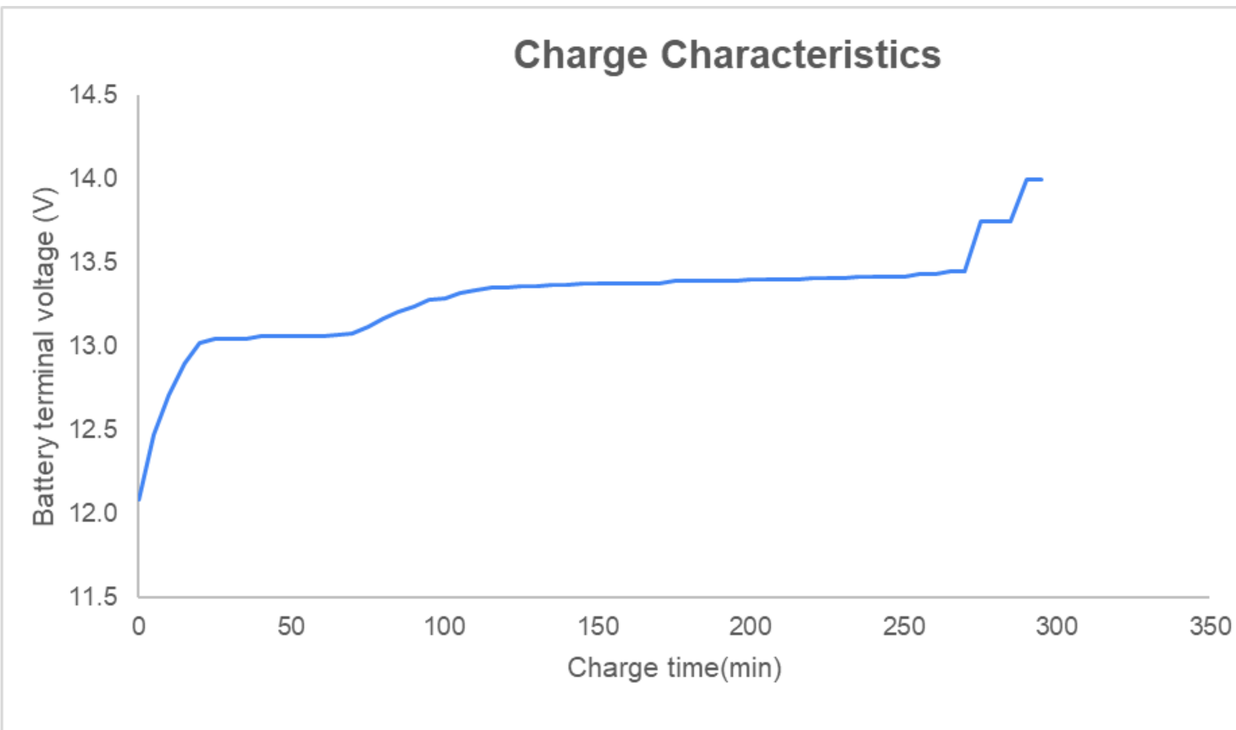

Figure 4.1. *Charge characteristics of 12.8V, 128Wh battery charged with 30W solar PV.*

The ongoing discharging test has shown that 80% of the battery charge is consumed with the PA sensor over 78 hours and 18 minutes. The setup consumes 30Wh over 24 hours, i.e. 1.25Wh/hour. Our system will be autonomous for about three days once the battery is charged and will be kept charging with the available solar radiation. Figure 4.2 shows the discharging characteristics of the system. Based on the discharge test of the final system, the load requirement for the PurpleAir sensor may vary slightly from the manufacturer's specifications.

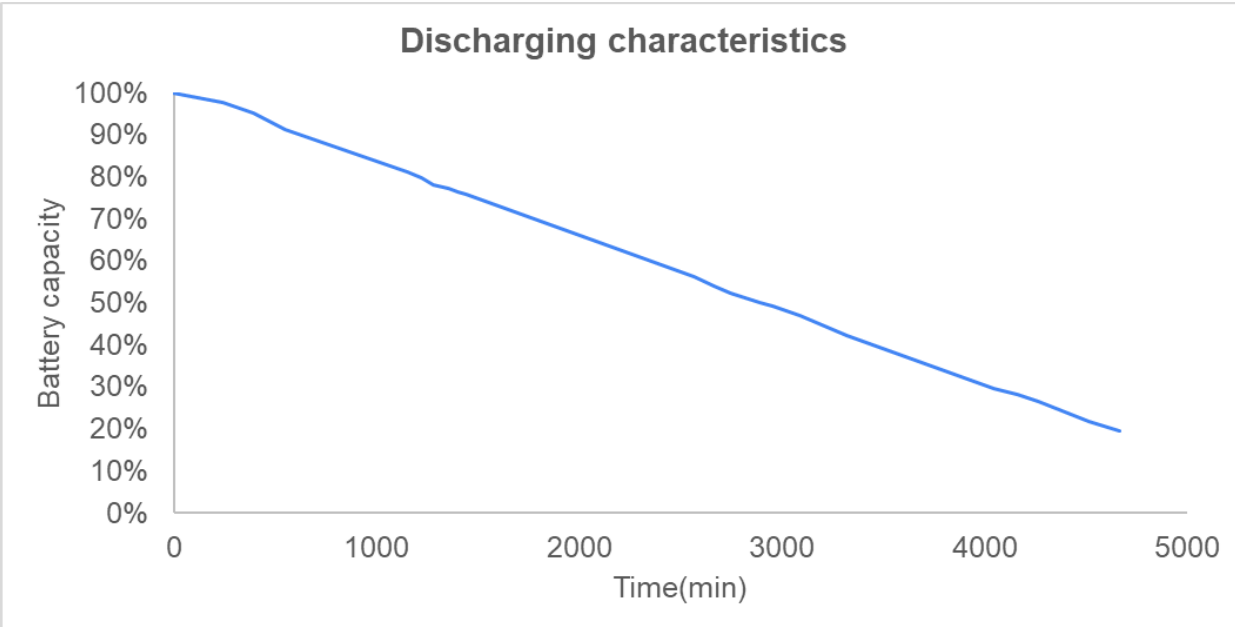

Figure 4.2. *Discharge characteristics of 12.8V, 128Wh battery connected to PA sensor(DC-based).*

The test results suggest that the system is resilient for about three days. The certainty that the system can operate autonomously for up to three days with a fully charged battery and the battery can fully charge within 5 hours with average solar radiation means that the user does not need to monitor the system constantly and adjust the system for proper functioning. Additionally, using a DC-based system in the final product design will make connecting and operating the system easier since it improves efficiency by eliminating AC-DC conversion. Overall these results suggest that the system is both efficient and easy to use, making it a feasible option for users looking for a reliable air quality monitoring system.

Ease of Use/Replicability

The product design has been carefully constructed with ease of replicability in mind. The construction manual includes detailed instructions on each step: cutting pipe to the correct length and joining PVC pipe and fittings using PVC cement. The segment lengths required for the prototype are clearly defined, and users can assemble the prototype without gluing as per the diagram to ensure all pieces are of the correct lengths. Once the user has ensured the assembly of the prototype, the user can glue them along with the fittings using PVC cement. To further enhance replicability, the construction manual has included pictures of all the fittings: the bottom, the top and the support limbs. This will provide the user to visualize the components individually and compare them to their construction.

The product design has been developed with the accessibility of materials in mind. The materials required for the construction of the system are commonly available at hardware stores and online, making it easy for users to get access. The design is relatively simple, consisting of PVC pipes and fittings. The simplicity and low barrier to entry make it easy for users to obtain and work with the materials for designing the product. In addition, users will be provided with an interactive user manual for building the product without any expertise.

Additionally, the team provides a video of the entire construction process, which can be viewed on Appropedia; this will boost the replicability of the design. The construction manual and visuals of each component will make it easy for users to replicate the product design. In addition, the team has tested the construction and user manuals on five subjects with varied experience in building or construction ranging from none to significant experience. The construction and user manuals were given to each participant, who was asked to rate the understandability of the manuals. Participants were provided with the construction manual and pre-cut PVC pipe (labeled) and fittings and asked to fit each piece according to the diagrams in the manual. All 5 participants were successfully dry assembled both the base and the panel mount in varying amounts of time ranging between 15-30 minutes. Due to limited material availability, we could not ask participants to glue the system. The average rating for the construction manual between 5 participants was 8.5 on a 1-10 scale. It is important to note that only the construction of the PVC structure was tested for replicability.

Transportability

Based on our criteria, the system must be easily transported from place to place inside the average passenger vehicle. The system has been physically moved from one location to another in a medium-sized SUV without dismantling (Figure 5A). While the team considers this to successfully fulfill the transportability assessment, transporting the entire system proved to be somewhat burdensome. Upon further adjustments to the final design, the team decided to refrain from gluing the supporting lengths of pipe to the base and panel mount so that the system can be partially disassembled for ease of transportation. The construction manual details exactly which joints are to be left unglued. The team believes that this will not affect the structural integrity of the system as long as enough force is applied when inserting the lengths of pipe into the fittings where glue is not present. To prove this to be the case, the team performed extensive durability testing on the final system.

Durability

The team identified the need for the system to be durable as an important criterion. The region of potential deployment is remote and surrounded by a vast forest ecosystem, meaning that the system must be able to endure interactions with wildlife, sustain expected weather such as rain or snow, and other external influences. Following the construction of the final system, the team tested for structural durability by asking volunteers to physically push, throw, and shake the system to simulate wildlife encounters and high winds. All components of the system remained intact and the system continued to function. Additionally, the system was left outdoors for multiple days, during which it endured strong rain and winds. The zip ties used to fasten the junction box to the base and the solar panel to the panel mount proved satisfactory in securing the components of the mounting structure. The structure may sway side to side during extreme winds, but the team believes this will be to the advantage of the system's durability, as the flexibility of the pipes will reduce the chance of breakage.

Reliability

The system's reliability was tested by ensuring that PM2.5 data were consistently collected and visible on the PurpleAir real-time air quality map. The team conducted a reliability test by simulating power outages by shutting off and turning on the wifi the PurpleAir sensor was paired with and ensuring the sensor would pair back with the wifi and continue collecting data. This test was successful, and the PurpleAir sensor reconnected to the wifi after the wifi was turned back on. Figure 5 shows the data transmitted by the PA sensor installed at 879 Union Street, Arcata, to the PurpleAir cloud. The Wifi was turned off at 19:00 and again turned back on, and after that, the PurpleAir sensor automatically connected to the wifi and started transmitting the data. So it is evident from the test result that the final system is reliable.

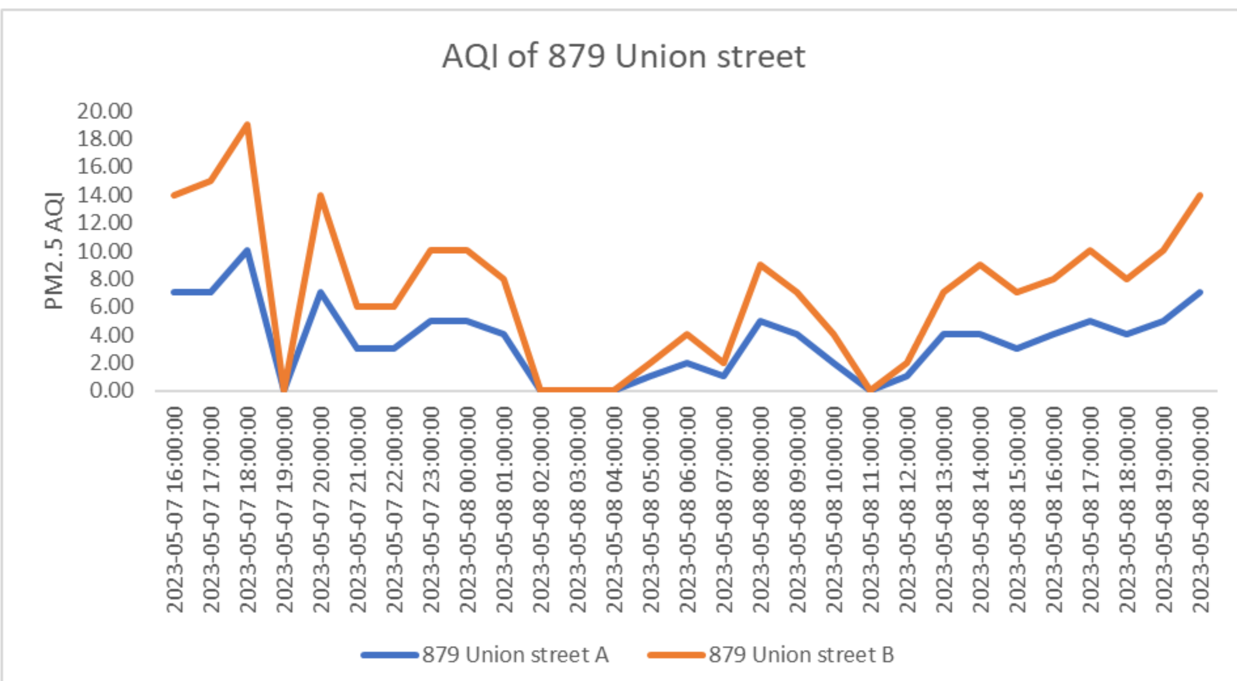

Figure 5. *PurpleAir Sensor data from the final setup installed at 879 Union Street, Arcata*

Discussion

The results suggest that the product design is simple and capable of real-time air quality monitoring, even in places with limited grid connectivity. The other significant advantage of the design is its low cost, making it a highly accessible option for individuals and communities who don't have the resources to afford expensive air quality monitoring systems. Using a PurpleAir sensor and solar PV makes the system highly reliable. Using PVC pipes and fittings for construction also makes replicating, designing and installing easy. The results also demonstrate that the system is easy to use and requires no specialized knowledge or training. The highly interactive user manual provides step-by-step instructions on constructing and operating the system.

Overall the results suggest that the design has the potential to significantly contribute to efforts for monitoring AQ and making informed decisions for protecting public health. The system can be deployed in various places like schools, individual homes and community spaces. The low cost makes it an attractive option for individuals and communities looking for a simple and affordable solution for air quality monitoring. However, the system has certain limitations. For instance, it may be affected by certain environmental factors such as extreme temperatures and heavy snow. Further testing is needed to determine how these factors impact the system's performance.

Additionally, the product design was tested in Arcata, with no shading over the solar PV and moderate wind speed. Testing the system in different locations, such as wildfire-prone areas, is essential to determine its effectiveness. The team also suggests collecting feedback from end users who have constructed and used the system to identify any challenges or issues with the proposed design to make necessary improvements.

Recommendations for Users

We recommend this system to others who want to set up an air quality monitoring system in their homes or communities. The following provides important considerations for users:

- If constructing the system, consult the construction manual and follow the instructions carefully for proper design.
    - Consider that PVC glue is extremely fast drying and irreversible mistakes can be made without dry-fitting all parts prior to gluing.
- Ensure that the setup is placed appropriately so the solar panel gets sunshine without shading. Also, the PA sensor must be connected to the nearby available wifi to visualize the data over the cloud in real time.
- In the event of any issue with the system, consult the user manual for troubleshooting tips and contact customer support if needed.

- While transporting the assembled system, ensure no damage to the sensor and other components. The system can be transported fully assembled in a medium-sized SUV but could be transported partially assembled in a smaller vehicle if needed.
- Ensure the system is functioning properly by regularly checking the system.
- If the system is used for research purposes, it is recommended to validate the accuracy of sensor data with a nearby air quality monitor.

Conclusion

Solar off-grid air quality monitoring systems provide an innovative solution to the difficulties of monitoring AQ in remote or off-grid areas. Key characteristics, such as solar power source and real-time AQ monitoring capabilities, make the team's proposed system a reliable and cost-effective alternative for industries and regions seeking to gather AQ data and safeguard public health. Concerning the project's objective, which includes successfully designing, constructing, and testing a solar-powered air quality monitoring system for use in off-grid homes, our team presented a design and structure that satisfies all the criteria. Based on the testing conducted by the team, future recommendations include testing the system in an off-grid location and further exploring the potential of material alternatives.

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Appendix

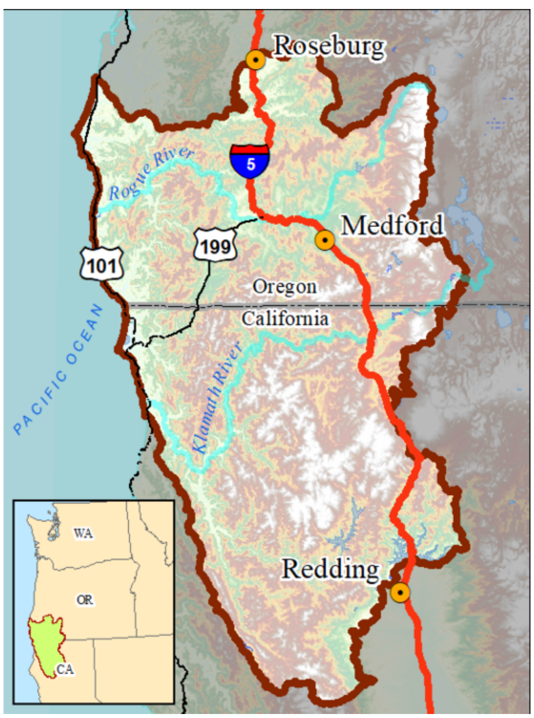

Figure 1A. *Klamath-Siskiyou Region.*

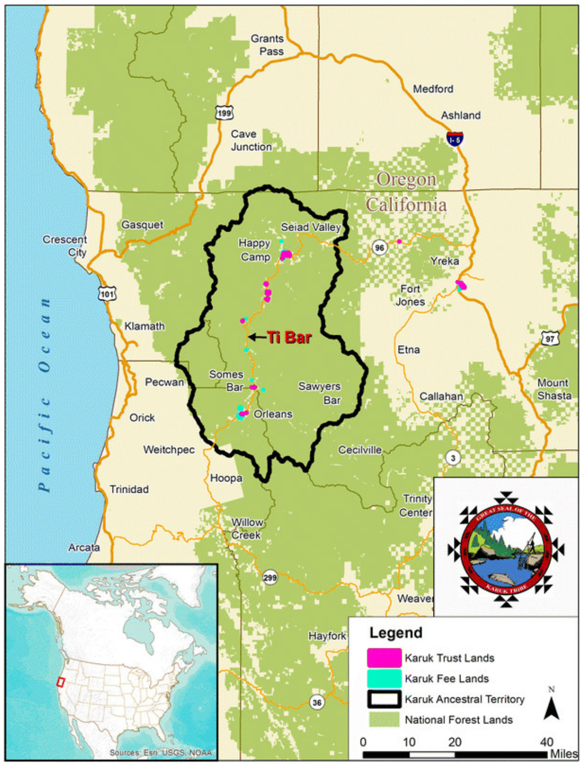

Figure 2A. *Karuk Aboriginal Territory (Diver, 2016).*

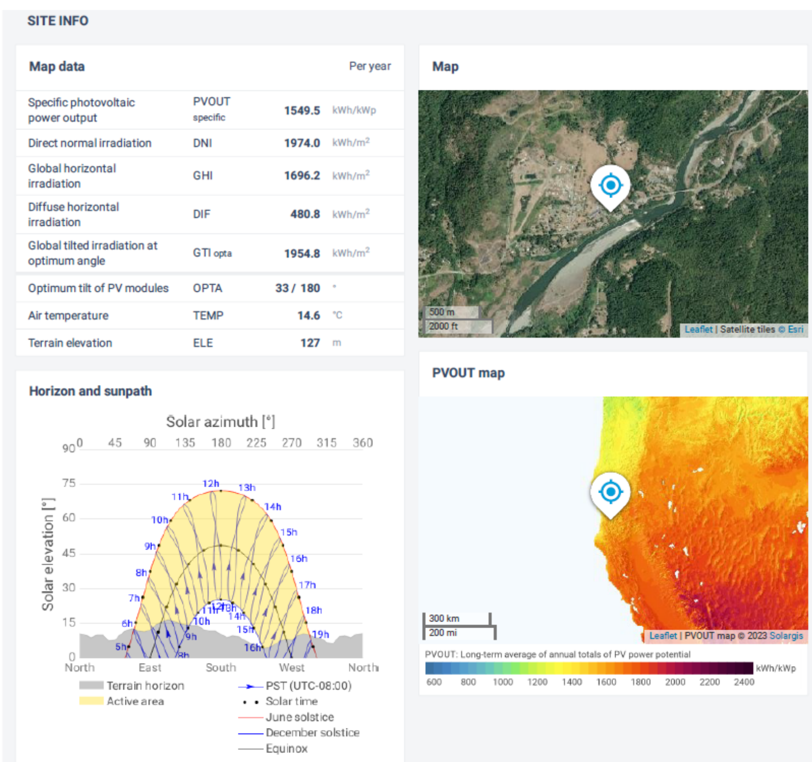

Figure 3A. *Solar Data and Orleans site information generated from Global Solar Atlas website*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5					0	0	0					
5 - 6				0	0	1	0	0	0			
6 - 7			0	1	2	2	2	2	1	0	0	
7 - 8	0	0	1	5	7	7	7	6	5	1	0	0
8 - 9	1	3	7	10	12	13	12	12	12	9	2	1
9 - 10	6	9	11	14	16	17	17	17	17	14	8	6
10 - 11	10	12	15	17	19	20	20	20	20	17	11	9
11 - 12	12	15	17	19	21	21	22	22	21	19	14	11
12 - 13	13	16	17	19	21	21	22	22	22	19	14	12
13 - 14	13	15	16	18	19	20	21	21	20	17	13	11
14 - 15	11	12	14	15	16	18	19	19	17	14	10	9
15 - 16	7	9	11	12	13	14	15	15	13	10	6	4
16 - 17	2	5	6	8	9	10	11	10	8	4	1	0
17 - 18	0	1	2	3	4	4	5	4	2	0	0	
18 - 19			0	0	1	1	1	1	0			
19 - 20					0	0	0	0				
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	74	96	118	143	159	170	176	171	157	124	80	64

Figure 4A. *Average solar hourly profiles generated for Orleans from Global Solar Atlas website*

Figure 5A. *Transportability test in the trunk of an SUV.*

Table 1A. Final System Purchasing List.

Final System Purchasing List				
Item	**QTY**	**Cost $**	**Total $**	**Source**
Elbow 90° 1" PVC Fitting	15	$ 1.99	$ 29.85	ACE Hardware
Tee 1" PVC Fitting	5	$ 2.99	$ 14.95	ACE Hardware
Cross 1" PVC Fitting	3	$ 7.99	$ 23.97	ACE Hardware
Elbow 45° 1" PVC Fitting	2	$ 2.49	$ 4.98	ACE Hardware
1" Socket PVC Cap	7	$ 1.79	$ 12.53	ACE Hardware
Christy's PVC Pipe Cement	1	$ 8.59	$ 8.59	ACE Hardware
1" PVC Pipe 10ft	2	$ 11.99	$ 23.98	ACE Hardware
1.5" Galvanized U Pins	1	$ 8.99	$ 8.99	Amazon
Junction Box 14.6"×10.6"×5.9"	1	$ 59.49	$ 59.49	Amazon
12v 10Ah Battery	1	$ 44.99	$ 44.99	Amazon
30W PV Panel	1	$ 44.79	$ 44.79	Amazon
30A Charge Controller	1	$ 21.99	$ 21.99	Amazon
Zip Ties	1	$ 8.59	$ 8.59	ACE Hardware
12 Gauge Wire 10ft	1	$ 12.98	$ 12.98	Amazon
12v to 5v DC to DC (Buck) converter	1	$ 8.76	$ 8.76	Amazon
PG7 Cable Connectors	1	$ 7.99	$ 7.99	Amazon
Total			**$ 337.42**	

Discharging test data

Discharging test							
Date	Time	Time elasped(min)	Battery Voltage(volts)	Current(A)	power(watts)	Energy(Wh)	Remaining battery capacity(%)
5/3/2023	14:20	0	13.31	0.06	0.7	0	100%
5/3/2023	18:21	241	13.27	0.07	0.9	3	98%
5/3/2023	20:55	395	13.25	0.11	1.4	6	95%
5/4/2023	00:14	549	13.25	0.11	1.4	11	91%
5/4/2023	10:21	1156	13.23	0.11	1.4	24	81%
5/4/2023	11:26	1221	13.22	0.11	1.4	26	80%
5/4/2023	12:26	1281	13.2	0.11	1.4	28	78%
5/4/2023	13:42	1357	13.17	0.11	1.4	29	77%
5/4/2023	14:27	1402	13.15	0.1	1.3	30	77%
5/4/2023	15:07	1442	13.14	0.11	1.4	31	76%
5/5/2023	09:34	2567	13.07	0.11	1.4	56	56%
5/5/2023	11:14	2667	13.09	0.1	1.3	59	54%
5/5/2023	12:34	2747	13.1	0.1	1.3	61	52%
5/5/2023	14:56	2889	13.09	0.12	1.5	64	50%
5/5/2023	16:03	2956	13.08	0.1	1.3	65	49%
5/5/2023	18:13	3086	13.04	0.11	1.4	68	47%
5/5/2023	22:08	3321	12.99	0.1	1.2	74	42%
5/6/2023	10:12	4045	12.76	0.1	1.2	90	30%
5/6/2023	12:09	4162	12.76	0.09	1.1	92	28%
5/6/2023	13:54	4267	12.77	0.07	0.8	94	27%
5/6/2023	17:59	4512	12.41	0.09	1.1	100	22%
5/6/2023	20:34	4667	11.56	0.11	1.2	103	20%
	Total Battery capacity		128Wh(100%)				

Figure 6A. *Discharging test data for the setup(DC-based).*

Table 3A: Reliability testing data

US EPA PM2.5 AQI		
Date Time	**879 Union street A**	**879 Union street B**
2023-05-07 16:00:00	7.00	7.00
2023-05-07 17:00:00	7.00	8.00
2023-05-07 18:00:00	10.00	9.00
2023-05-07 19:00:00	Wifi turned OFF	
2023-05-07 20:00:00	7.00	7.00
2023-05-07 21:00:00	3.00	3.00
2023-05-07 22:00:00	3.00	3.00
2023-05-07 23:00:00	5.00	5.00
2023-05-08 00:00:00	5.00	5.00

2023-05-08 01:00:00	4.00	4.00
2023-05-08 02:00:00	0.00	0.00
2023-05-08 03:00:00	0.00	0.00
2023-05-08 04:00:00	0.00	0.00
2023-05-08 05:00:00	1.00	1.00
2023-05-08 06:00:00	2.00	2.00
2023-05-08 07:00:00	1.00	1.00
2023-05-08 08:00:00	5.00	4.00
2023-05-08 09:00:00	4.00	3.00
2023-05-08 10:00:00	2.00	2.00
2023-05-08 11:00:00	0.00	0.00
2023-05-08 12:00:00	1.00	1.00
2023-05-08 13:00:00	4.00	3.00
2023-05-08 14:00:00	4.00	5.00
2023-05-08 15:00:00	3.00	4.00
2023-05-08 16:00:00	4.00	4.00
2023-05-08 17:00:00	5.00	5.00
2023-05-08 18:00:00	4.00	4.00
2023-05-08 19:00:00	5.00	5.00
2023-05-08 20:00:00	7.00	7.00