Aurora

working to advance road weather information systems technology

Review Synthesis of Alternative Power Supply

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Aurora Project 2015-04

Final Report
August 2017

About Aurora

Aurora is an international program of collaborative research, development, and deployment in the field of road and weather information systems (RWIS), serving the interests and needs of public agencies. The Aurora vision is to deploy RWIS to integrate state-of-the-art road and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures. It is hoped this will facilitate advanced road condition and weather monitoring and forecasting capabilities for efficient highway maintenance and real-time information to travelers.

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16. Abstract

The deployment of different alternative power sources and low-power sensors and equipment packages for remote (off-grid) road weather information system (RWIS) sites in the Aurora Program states in recent years has resulted in a number of system configurations and operational strategies. This report provides a comprehensive review, investigation, and analysis of alternative power sources and power budgets for sensors and associated components used in remote RWIS applications.

Through a literature review, investigation of recent developments, and a survey of the Aurora Program states, this study explored alternative power sources and power budgets of sensors and associated components and provides recommendations on existing remote RWIS configurations and methodologies.

The study found that a variety of alternative power sources, low-power sensors, and associated equipment are currently available for remote RWIS applications. The survey results showed that a combination of fossil fuel-based and renewable power sources tied to a battery bank are employed as a viable means of reliable year-round operation of remote RWIS sites.

The survey results also showed that many of the remote RWIS sites are using weather sensors, cameras, and associated equipment with a much higher power budget than products currently available on the market. These findings suggest that the reliability and efficiency of some remote RWIS sites could potentially be improved through the deployment of low-power sensors and associated equipment combined with alternative power sources.

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REVIEW SYNTHESIS OF ALTERNATIVE POWER SUPPLY

Final Report
August 2017

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The point of contact with the Alaska Department of Transportation and Public Facilities (ADOT&PF) for this research was Lisa Idell-Sassi, Geospatial Engineering Services, Information Systems and Services Division. The author would like to thank Lisa as a key contributor of information through surveys distributed to the Aurora Program states regarding alternative power sources, sensors, and associated equipment.

The author would also like to thank those individuals in the state department of transportation (DOT) offices in the Aurora Program states who provided information about the alternative power sources and budgets, sensors, and associated components used at their remote weather information system (RWIS) sites.

Lastly, the author would like to thank Billy Connor of the Alaska University Transportation Center for information on and images of the all-in-one weather sensor packages being developed and tested for remote RWIS sites.

EXECUTIVE SUMMARY

This project explored alternative power sources and power budgets for sensors and associated components used in remote (off-grid) road weather information systems (RWIS) through an investigation of recent developments and technologies for remote RWIS applications and a survey of remote RWIS configurations and methodologies across the Aurora states.

A review of current power sources found that propane or natural gas-fired internal combustion (IC) generators used to charge battery banks are either being supplemented or replaced by alternative power sources. These alternative power sources include renewables, such as solar photovoltaics and small wind turbine generators; propane- or natural gas-fired fuel cells; and thermoelectric generators.

The review also found that remote RWIS sites include sensors in separate packages to measure various weather-related parameters, such as air temperature, humidity, wind, precipitation, road temperature, visibility, and road surface temperature; provide visual observations (via camera); and include communications equipment. Some of these sensors and associated components have been integrated into individual packages with a lower power budget (e.g., power-over-ethernet and wireless cameras). All-in-one low-power wireless weather stations powered by small batteries are being developed for year-round operation but need to be adapted for the harsh climatic conditions that tend to exist at many remote RWIS sites.

The results of the Aurora survey showed that, generally, a combination of fossil fuel-based and renewable power sources for charging battery banks are employed to maintain year-round operation of remote RWIS sites. Power sources used at remote RWIS sites included propane- or natural gas-fired internal combustion generators, solar photovoltaics, small wind generators, fuel cells or thermoelectric generators, and batteries. The type and capacity of the power sources largely depend on the power budget of the weather sensors, camera(s), and associated components and the renewable resources available at the site.

General findings from the survey suggest that the operation of some remote RWIS sites could be improved by incorporating a combination of alternative power sources and sensors, cameras, and equipment with a lower power budget. Based on these findings, it is recommended that remote RWIS sites be evaluated for the potential use of alternative power sources and low-power sensors with wireless technology.

CHAPTER 1 – INTRODUCTION AND RESEARCH APPROACH

1.1 Problem Statement and Research Objective

The deployment of different alternative power sources and low-power sensors and associated equipment packages for remote road weather information system (RWIS) sites in the Aurora states in recent years has resulted in a number of system configurations and operational strategies. Consequently, the Aurora states have a research need for a comprehensive review, investigation, and analysis of alternative power sources and power budgets for sensors and related RWIS equipment. The objective of this study was to make recommendations and draw conclusions on alternative power sources and power utilization based on a wide array of methodologies, recent developments, and operational experience.

1.2 Scope of Study

This research project reviewed the power supply problem for remote RWIS applications and explored alternative power sources and low-power weather sensor technology. A survey (see Appendix A) of the Aurora states was conducted to determine methods of power generation, sensor technologies used, and power budgets for remote RWIS sites. For each state that responded to the survey, the researchers reviewed existing power sources, sensor technologies, and power budgets and made recommendations for improvements in four areas:

- Replacement or supplementation of fossil fuel-based internal combustion (IC) generators
- Use of currently available alternative power sources, such as wind, solar, fuel cells, thermoelectric generators, and batteries
- Use of weather sensors and associated components with lower power budgets, including all-in-one sensors, cameras, and wireless communications
- Operating scenarios that could allow for more efficient and optimal use of power

The expected outcomes of this project were (1) a review of current and developing power sources, weather sensors, and associated equipment for remote RWIS applications and (2) a comprehensive report that documents findings and makes recommendations on alternative power sources and power budgets based on a wide array of methodologies, recent developments, and operational experience across the Aurora states.

1.3 Research Approach

This study was completed using the following research methods in the order listed:

1. A literature review on methodologies and past work relevant to the remote RWIS power supply problem using available department of transportation (DOT) and online resources

2. Investigation of recent developments in alternative power sources for remote RWIS applications

3. Analysis of the results of a survey of the Aurora states (conducted by Aurora) regarding remote RWIS sensors and equipment power budgets to determine (1) alternative power sources and (2) sensors (and associated power budgets) used for remote RWIS

4. Analysis of the current alternative power sources and power budgets of sensors and associated remote RWIS components used in the Aurora states

5. A report that documents the alternative power sources and power budgets of the sensors and associated components used for remote RWIS applications and provides recommendations and conclusions based on the review, investigation, and analysis

The University of Alaska-Fairbanks (UAF) issued a draft final report to the project team for review and a final report to the Iowa DOT and Aurora Program containing the results of the investigation and recommendations for alternative power sources, low-power sensors, and power budgets for remote RWIS sites.

1.4 Review and Evaluation Methods

Information about the power sources, weather sensors, and associated components used at existing remote RWIS sites in the Aurora Program states was collected using an online survey developed by the researcher and Lisa Idell-Sassi at the Alaska Department of Transportation and Public Facilities (ADOT&PF). Past methodologies and investigations, including current and potential alternative power sources, weather sensors, and associated components used at remote RWIS sites, were reviewed (Chapter 2). This was followed by an analysis of the alternative power sources, weather sensors, and associated components reported in the survey results (Chapter 3). Recommendations and conclusions were developed for implementing alternative power sources and reducing power budgets at remote RWIS sites (Chapter 4). A discussion of future research and development for remote RWIS is presented at the end of Chapter 4.

CHAPTER 2 – REMOTE RWIS POWER SOURCES AND SENSORS

The following chapter (1) reviews the remote RWIS power supply problem; (2) documents power sources, sensors, and associated equipment used for remote RWIS; and (3) explores recent developments in alternative power sources and low-power sensors for remote RWIS applications.

2.1 Remote RWIS Power Supply Methodologies and Past Investigations

The challenges of implementing and operating remote RWIS sites have been investigated previously in Alaska (Wies 2014) and other Aurora Program states, including Idaho, Michigan (URS 2007), and New York. The reliability (continuous operation) of remote RWIS sites is of particular importance to states with harsh winter weather conditions. Strategies for continuous unattended operation of remote RWIS sites have included the use of fossil fuel-based IC engine generators coupled with solar photovoltaics (PV) and/or small wind turbine generators (WTGs) to charge battery banks, with power budgets in the 200 to 500 W range. A major portion of the power budget (over 75%) comes from the resistive heating required on weather sensors (precipitation gauges) and cameras required during periods with near- to sub-freezing temperatures. Some of these systems have suffered from reliability issues due to failure of the IC engine and the complexity of the control systems and converters required to operate multiple power supplies and sensors at a single site.

More recently, thermoelectric generators (TEGs) and fuel cells (FCs) have been implemented at a few very remote sites in combination with low-power weather sensors and associated equipment. These types of power sources are operated using natural gas or propane, which must be high grade to prevent corrosion of the highly susceptible materials used to create the power cells. While TEGs have initially proven to be a good alternative power supply for low-power RWIS applications, some FCs have experienced problems with corrosion from contaminated fuel supplies, fracturing of the ceramic cells in shipment, repeated failures of internal bundles, and inconsistent operation of the control equipment used to provide data for remote diagnosis. However, other FCs have provided uninterrupted service in remote RWIS applications. If the problems with FCs are solved, they could prove to be a good alternative for low-power remote RWIS applications.

Low-power RWIS have become more prevalent in recent years as weather sensors and associated equipment (cameras and communication devices) with power budgets below 50 W have become more readily available. This has been accomplished through the development of all-in-one sensor packages and low-power camera technologies. In fact, one company has been developing an all-in-one weather sensor and smart phone-style camera package that is completely self-contained with its own battery power supply (WeatherCloud/Fathym 2017). The system is designed not only to provide weather-related information from sensors at the remote RWIS site, but also to be fully integrated with the current GPS and weather sensor technology used in modern vehicles. Prototypes of the all-in-one technology minus the camera have already been developed and are currently being tested by the ADOT&PF and DOTs in other states. This is likely the future of remote RWIS, which will allow for both point source and nearby roadway and weather information while also providing weather information directly to vehicles.

2.2 Power Sources for Remote RWIS

The current and alternative power sources, including IC engine generators, solar PV modules, wind turbine generators, batteries, fuel cells, and thermal electric generators, used at remote RWIS sites in the Aurora Program states are discussed in the following sections, with information drawn from interactions with DOT personnel and the survey developed by the authors and conducted by Aurora. As an example, power sources and associated converter equipment for a remote RWIS site in Alaska are listed in Table 1, with some representative photos shown in Figure 1.

Table 1. Power sources and converters at a remote RWIS site in Alaska

Power Source/Charge Controller/Inverter	Power Rating (W or Amp-hr)
8340K-WG972 propane DC generator with Kubota WG972 engine and 8340 alternator (24 V DC, 8 kW)	8000 W
6-Kyocera 120 W solar PV modules	120 W per module
4-Rolls 12 V DC, deep-cycle marine batteries	275 Amp-hr
4-Trojan 12 V DC, deep-cycle marine batteries	230 Amp-hr
Acumentrics RP500 fuel cell DC generator	500 W
Gentherm 5060 Thermoelectric Generator	50 W
Outback Flexmax 80 Charge Controller	1000 W
Outback VFX2812 inverter	2800 W

Figure 1. Power supplies at a remote RWIS site in Alaska, from left to right: overall site, 8340K-WG972 propane DC generator, and six Kyocera 120 solar PV modules

2.2.1 Internal Combustion Engine Generators

IC engine generators for remote RWIS applications (see Figure 1 center) include small-format diesel-, propane-, and natural gas-fired units rated at 1 to 2.5 kW. While the IC engine generators can be used to directly power the RWIS, they are typically used to recharge the battery banks when solar PV or wind does not provide sufficient charging capability. The capacity of the generators is also normally two to five times more than that required to directly power the RWIS because they are used to recharge a higher capacity battery bank that can sustain the RWIS for long periods of time.

IC engine generators have historically been problematic for remote RWIS sites due to the routine maintenance required and operational issues, particularly because many of the remote RWIS sites are difficult to access in the winter. Operational problems have consisted of the generator engine running continuously until running out of fuel, the low battery voltage switch not triggering the generator on so that it can recharge the batteries, gas concentration safety sensors tripping the system off, and mechanical engine and generator failures. Mechanical failures are often compounded by limited or no availability of replacement parts and units that are not serviceable on site. Furthermore, in order to manage proper air flow into the engine and exhaust gases, IC engine generators must be mounted outside or in a well-ventilated enclosure with gas concentration safety sensors to control ventilation.

Many of the previous small-format IC engine generators used an alternating current (AC) output, which needs to be rectified to direct current (DC) and use a common charge controller for charging the batteries. Newer models of these small-format IC engine generators have a DC output and integrated charge controller and have shown promise for remote RWIS applications. However, the introduction of low-power all-in-one sensors and associated equipment to the weather monitoring market has significantly reduced power budgets for RWIS. This has allowed a transition to to alternative power supply technologies with lower power output capacities, as discussed in the following sections.

2.2.2 Solar Photovoltaics

Solar PV modules (see Figures 1 left and 1 right and Figure 2) are generally employed at remote metrological sites to charge the battery bank during daylight hours when solar energy is available.

Shyla Keays, UAF INE undergraduate assistant

Figure 2. Alaska DOT RWIS site at Little Coal Creek, Parks Highway MP 163.2

The installed solar PV capacity at a remote RWIS site typically ranges from 0.2 to 0.9 kW and uses three to six modules (75 to 150 W each) with nominal 12 or 24 V DC outputs depending on the configuration of the connections of the individual modules. However, the actual power output and voltage level depend on the available solar energy impacting the surface of the modules, which is dependent on the season, hour of the day, and weather conditions. Therefore, a charge controller is needed to maintain maximum charging power at a voltage above the nominal battery voltage when the solar PV output voltage is lower than nominal. Additionally, an advantage in efficiency is achieved in winter months due to lower operating temperatures of solar cells, but reduced daylight hours and increased cloud and snow cover (see Figure 1 right) has significantly more impact, reducing the overall solar PV power output.

The current PV modules used in many remote RWIS sites are polycrystalline due to their lower capital cost than thin-film technologies. Thin-film solar PV technologies typically cost between 1.5 and 2 times more per watt than standard polycrystalline and amorphous silicon technologies. Thin-film copper indium gallium selenide (CIGS) solar PV modules, such as the Stion STN series, offer improved performance in capturing the available solar energy due to a higher efficiency (15% to 18%) than standard polycrystalline or amorphous silicon-based modules (10% to 14%) (Stion 2012). However, the small efficiency improvement with thin-film CIGS modules does not provide enough additional output power to offset the increased capital cost in cases where replacement of existing functional solar PV modules is considered. Therefore, thin-film CIGS solar PV modules are suggested as possible power supplies for the development of new remote RWIS sites or as a point of failure replacement at an existing site.

2.2.3 Wind Turbine Generators

A variety of small-format wind turbine generators are used for power supply applications at remote meteorological sites. These small-format wind turbine generators, with typical power output capacities of 100 W or less, are commonly used in conjunction with solar PV modules to charge batteries at remote RWIS sites where wind resources are available. The actual power output from wind turbine generators, which is normally three-phase AC rectified to DC at 12 to 48 V, can be quite variable based on the wind resource, which is dependent on the seasonal and diurnal weather patterns. The DC output is generally held constant by the rectifier and can be directly connected to the system's battery charge controller. Also, because wind turbine generators are often used in conjunction with solar PV, the variability in wind and the times when wind is available may not complement solar PV resources. A more complex controller is required to manage the power generated from wind and solar PV to sustain the charge in the batteries.

Other significant challenges with employing small-format wind turbine generators at remote RWIS sites include the generators' durability and reliability in harsh weather conditions, such as extremely high winds and conditions in which ice covers the blades. A small-format harsh weather-rated wind turbine, such as the WT10 (see Figure 3), could be installed at sites with good wind potential. The turbine has been used by the Federal Aviation Administration (FAA) on its meteorological modules (discussed in Section 2.4.1), which are designed for monitoring extreme weather conditions at remote airports.

APRS World, LLC

Figure 3. WT10 wind turbine, from left to right: on FAA module, brochure view, and remote mountaintop application

However, such small-format harsh weather wind turbine generator systems have not provided a cost-effective alternative as a remote RWIS power source. For example, the cost of the basic WT10 turbine is listed from $3,000 to $3,500 depending on the blade, yaw, and mast connection types. Cabling ($100 to $150) for power output to the RWIS module and quick coupler mounts ($300 to $500) and an associated mast for mounting the turbine would also have to be installed, given that the current anemometer is already mounted on top of the existing meteorological sensor mast.

When the addition of a wind turbine generator to a new or existing remote RWIS site is considered, a meteorological study of the site should be performed to determine if wind is even a viable power source, and, if so, to determine the best wind turbine for the site. Even if meteorological studies have shown a consistent and complementary wind resource at the site, the system's complexity and the cost and reliability of small-format wind turbine generators need to be considered. Consequently, it was found in this study that wind turbine generators have not been historically used at remote RWIS sites, which is supported by the fact that only one failed wind turbine generator was reported in the survey (see Section 3.1). However, wind turbine generators could still be used in critical remote RWIS applications where a viable wind resource is available and additional alternative power sources are available to supplement the charging of the batteries.

2.2.4 Batteries

Deep-cycle lead-acid and, more recently, lithium ion have been the most common battery chemistries used for remote meteorological applications. The number of batteries required for a remote RWIS application depends on the power budget and the length of time the batteries are expected to provide power without being recharged. A battery bank with a nominal 12 or 24 V DC output (depending on the configuration) is connected to the system through a bidirectional converter/charge controller. The bidirectional converter/charge controller is used for charging the batteries from all available power sources and delivering power to the RWIS loads (sensors, cameras, and associated equipment).

Both battery chemistries have exhibited failures due to their inherent limitations in remote meteorological applications. Batteries have generally suffered from decreased charge potential as the number of charge/discharge cycles increases. In the case of lithium ion batteries, a specialized battery management system is required to monitor and regulate the cell voltage and temperature. Overcharging or completely discharging a lithium ion battery can result in individual cell damage or potential catastrophic failures of the entire bank due to thermal runaway. With these limitations in mind, the push has been towards the use of lithium ion battery technology for remote RWIS applications, especially considering the decrease in power budgets for sensors and associated equipment.

2.2.5 Fuel Cells

Fuel cells using propane, natural gas, or methanol as a fuel source could be added to keep the system operational when solar PV and/or wind do not produce enough energy to maintain the charge on the battery bank. Fuel cells have been coveted as a non-mechanical and non-combustive fossil fuel-based power source. In general, fuel cells are designed to use hydrogen extracted from a fuel source to combine with oxygen across a ceramic cell membrane, thus producing electrical energy and water as a byproduct. However, there have been issues with cells fracturing during transport due to their fragile ceramic cell membranes and operational challenges due to corrosion from fuel impurities and the need to keep the fuel cell active once operational to prevent the cell from freezing up in cold climates, given that water is a byproduct of the process.

Two types of fuel cells, solid oxide and methanol (see Figure 4) have been deployed as primary power sources on remote RWIS platforms.

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Figure 4. Fuel cells for RWIS, from left to right: Atrex ARP500 (formerly Acumentrics RP 500), EFOY 600, 1600, and 2200 Pro, and EFOY 800 and 2400 Pro

The Atrex Acumentrics RP500 (Figure 4 left), fueled by propane or natural gas, was designed as a solid oxide fuel cell (SOFC) with a 500 W maximum power output capacity, ideal for use with traditional RWIS applications with higher power budgets. It was deployed at the Klondike Highway remote RWIS site in Alaska on the US/Canada border in 2012, but it failed due to a fractured ceramic cell during shipment. There were also problems with an oversensitive fuel sniffer sensor relay shutting off the system, though these problems were later resolved. The cost of the RP 500 is estimated at about $30,000 for remote RWIS applications based on the deployment in Alaska. The EFOY 800 and 2400 Pro series (Figure 4 center) were designed as methanol fuel cells (MFCs) with 45 W and 110 W maximum power output capacities, ideal for use with currently available low-power sensor packages and associated equipment. The units were designed to use up to two pre-charged methanol cartridges using an adapter, with the ability to double the number of fuel cartridges (Duo model) for extended operation. The first-generation EFOY Pro series (600, 1600, 2200) MFC was replaced in June 2013 by a second-generation EFOY Pro series (800 and 2400) MFC (Figure 4 right). An EFOY 1600 Pro fuel cell (65 W maximum power output capacity) was deployed at the Fourth of July Pass remote RWIS site in Idaho and has been operational ever since. The EFOY Pro MFC has also been used in a variety of remote applications in Alaska and northern Canada, such as remote oil platforms and communication sites. The EFOY pro series fuel cells were designed for cold climate operation, with temperature ratings to -40 °C (-40 °F) and heat regulation aided by a special insulated enclosure provided by the manufacturer. The cost of the EFOY 800 Pro fuel cell with a cold climate enclosure is estimated to range from $15,600 to $21,000 depending on the amount of fuel required to achieve the desired autonomy in terms of hours of unattended operation.

2.2.6 Thermoelectric Generators

TEGs, which are fueled by propane or natural gas, could be added to a remote RWIS site for continuous operation through winter months or as the primary power supply for low-power

RWIS. TEGs are designed to use the Seebeck effect by combusting fuel to heat one side of a thermoelectric material while the opposite side is exposed to ambient air (Wikipedia 2016). A potential difference (voltage) between the two sides of the thermoelectric material is generated due to the large temperature difference. These units must either be mounted outside or in a well-ventilated enclosure due to the combustion of gases. This has presented problems in some RWIS power supply applications that employ a completely enclosed utility container to house the power supply converters and associated communications equipment.

In particular, the Gentherm Global Power Solutions 5060 TEG (see Figure 5) has been deployed as a power source on remote meteorological platforms in Alaska and Canada.

Gentherm Global Power Technologies

Scrimshaw 2016

Figure 5. Thermoelectric generator for RWIS: Gentherm GPS 5060 (left) and GPS 5060 as installed outside the Divide remote RWIS module near Seward, Alaska (right)

The GPS 5060 TEG was designed to generate a maximum of 55 W. This particular TEG was installed at the Divide remote RWIS site near Seward, Alaska (see Figure 5 right), in early 2016 and has operated reliably as the site's primary power source ever since. These TEGs have also been deployed by the FAA at its remote meteorological platforms (discussed in Section 2.4.1) in Alaska to provide approximately 50 W of power to keep the batteries charged during the winter season when sunlight for PV arrays is minimal and wind speeds are low. The cost of the GPS 5060 TEG is estimated at about $6,000 but could be as much as $500 higher with additional costs for mounting hardware (pole mast versus stand), depending on the application.

2.2.7 Summary of Alternative Power Sources

Alternative power sources such as thin-film solar PV, small-scale harsh weather-resistant wind turbines, lithium ion battery banks, fuel cells, and TEGs, discussed in Sections 2.2.2 through 2.2.6, were evaluated for use in remote RWIS applications. The alternative power sources reviewed in this study, their power capacities, capital costs, and fuel consumption rates (when applicable) are listed in Table 2.

Table 2. Alternative power sources, power capacity, cost, and fuel consumption rates

Power Source	Power Capacity (W)	Capital Cost ($)	Fuel Rate (gal/kWh)
Stion STO-135A Thin-Film CIGS Solar PV Framed Module	135 W	$105/module	NA
APRS World WT10 Wind Turbine (24 VDC)	75 W @ 40 mph and 12 VDC	$4,000	NA
Acumentrics RP500 Fuel Cell	500 W @ 12 VDC	$30,000	0.12
EFOY Pro 800 Fuel Cell	45 W @ 12 VDC	$21,500	0.24
Gentherm Global Power Solutions 5060 TEG	54 W @ 12 VDC	$6,500	1.16

2.3 Weather Sensors, Cameras, and Associated Communications Equipment

Weather sensors, cameras, and associated communications equipment used at remote RWIS sites in the Aurora Program states are documented in the following sections, with information drawn from interactions with DOT personnel and the survey developed by the authors and conducted by Aurora.

2.3.1 Weather Sensors for Remote RWIS

Weather sensors typically used for remote RWIS and their power budgets are listed in Table 3, with a representative image of an RWIS-based meteorological tower in Figure 6.

Table 3. General weather sensors with power budget for RWIS

Weather Sensors	Power Budget (W)
Air Temperature/Humidity/Dewpoint	0.1 W
Barometric Pressure	0.1 W
Wind Speed/Direction	0.25 – 0.5 W
Snow Depth	0.6 – 1 W
Pavement Temperature Sensors	0.1 W
Precipitation (Accumulation and Occurrence)	0.75 – 3 W; 250 – 400 W (w/ heater)
Soil Moisture	0.1 W
Soil Temperature	0.1 W
Pyranometer (Solar Irradiance)	0.1 – 0.5 W

Figure 6. Weather sensors and communications equipment at remote RWIS site in Alaska, from left to right: meteorological tower, satellite dish, and communications antenna

Weather sensors used at remote RWIS sites include ambient air temperature, humidity, barometric pressure, wind speed and direction, dew point, pavement surface temperature, snow depth, precipitation (gauges), soil moisture, and solar irradiance (pyranometer).

2.3.1.1 Individual Weather Sensors

Individual weather sensors rather than all-in-one sensor packages are still used at a number of remote RWIS sites. While some temperature sensors have always offered the three basic measurements of ambient air temperature, humidity, and barometric pressure, most RWIS have been designed using multiple sensors with information collected and transmitted through a central remote processing unit (RPU). While reliability and the need for information from multiple weather-related parameters has been a factor in this type of RWIS design, the integration of numerous sensors has resulted in much higher power budgets than would otherwise be necessary. The higher power budgets imposed by multiple sensors has created a especially difficult power supply problem in remote RWIS.

2.3.1.2 All-in-One Weather Sensor Packages

Low-power (2 to 6 W) all-in-one weather sensor packages are available, with new technologies currently under development and testing, as robust alternatives to the use of multiple separate weather sensor packages. All-in-one weather sensor packages offer the lower power budgets that would allow remote RWIS sites to operate using the alternative power sources discussed in Sections 2.2.2 through 2.2.6. Basic all-in-one weather sensor packages are designed to measure up to six weather parameters, including air pressure, temperature, humidity, rainfall, wind speed, and wind direction, while also offering analog input options for solar irradiance and external temperature sensors. However, separate additional sensor packages would still be required for snowfall and road surface temperature measurements.

2.3.2 Cameras and Associated Communications Equipment

Cameras and associated communications equipment used for remote RWIS and their power budgets are listed in Tables 4 and 5, respectively, with representative photos of an RWIS-based wireless communications interface, including a satellite dish and cellular antenna, shown in Figures 6b and 6c.

Table 4. Remote RWIS cameras and power budget

Camera	Power Budget (W)
Single-View	
Fixed with low POE	3 – 13 W; 12 – 27 W (w/ heater)
Fixed with high POE	20 – 30 W; 50 – 150 W (w/ heater)
Point-Tilt-Zoom (PTZ)	
PTZ with low POE	12 – 25 W; 12 – 27 W (w/ heater)
PTZ with high POE	25 – 60 W; 100 – 150 W (w/ heater)

Table 5. Remote RWIS communication equipment and power budget

Communications Equipment	Power Budget (W)
Security Firewall	Typical: 20 W; Max: 96 W
Switch	Typical: 3 W; Max: 9 W
Communications interface and Ku-band transmitter	Typical: 25 W; Max: 100 W
4G LTE Cellular Modem	Transmit/Receive (Typical/Max) 3.0-3.6/3.6-4.5 W; Idle 0.9-3 W; Dormant 0.05-0.1 W
CDMA Cellular Modem	Transmit/Receive (Typical/Max) 1.44/3.0 W; Idle 0.6 W
Multiband 3G and 4G LTE Cellular Antennas	Typical: 25-50 W; Max: 100 W
Yagi Antenna	Typical: 25 W; Max: 50 W
FreeWave Radios	Transmit/Receive (Typical/Max) 4.2-4.5/0.51-0.78 W; Idle 0.114-0.24 W
ClearRF Amplifiers	Typical: 4 W; Max: 12 W; Idle: 3.3 W

Cameras at remote RWIS sites include both single-view and pan-tilt-zoom (PTZ) varieties, while communication equipment includes both wired (dial-up modem and fiber optics) and wireless (4G cellular modem with antennas) technologies.

2.3.2.1 Cameras

Both high- and low-power-budget single-view and PTZ and low-power and power-over-ethernet (POE) cameras are used at remote RWIS sites, as listed in Table 4 with estimated power budgets. The highest percentage of the remote RWIS power budget (over 1/3 in some cases) is not only consumed by the operation of the cameras (more than one at many RWIS sites), but also the heater required to keep the lens clear of ice, snow, and condensation in winter and transitional months. Modern POE cameras and improved lenses and anti-fog coatings offer a significantly lower power budget, allowing remote RWIS sites to operate using alternative power sources.

2.3.2.2 Communications Equipment

Wireless communications technologies, including cellular modems, antennas, and transmitters, as listed in Table 5 with estimated power budgets, are generally used at remote RWIS sites.

At some remote RWIS sites near fiber optic lines or standard phone lines, a wired communications interface is employed, but those same signals can also be transmitted back to the central server using a microwave satellite modem and transmitter. The 4G LTE cellular modems combined with a lower power transmitter and antenna offer a communications interface for remote RWIS sites with a much lower power budget than microwave (Ku band) satellite-based transmitters.

2.4 State-of-the-Art and Cutting-Edge Weather Information Systems

State-of-the-art weather information systems (WIS) have been developed for a variety of remote transportation applications, including road, air, and sea. The FAA has developed WIS modules for remote airport locations. More recent cutting-edge developments have included very low-power (< 10 W) all-in-one RWIS packages that incorporate on-board battery power with currently available mobile GPS, weather sensors, and smart phone-style camera technology.

2.4.1 FAA Off-Grid Meteorological Module

The FAA has designed a complete off-grid power module (see Figure 7) for weather monitoring that employs a 54 W TEG fueled by propane (Figure 4), a 500 W thin-film tube CIGS solar PV array (Figure 7a), and a 400 W APRS World military-grade wind turbine generator (Figure 7c) to supply the power to charge eight Odyssey 12 V DC, 200 Amp-hr AGM batteries. These modules offer the reliability of operating throughout the winter season and in harsh climates and have been deployed at a number of remote airport sites in Alaska.

Figure 7. FAA remote WIS module, from left to right: thin-film solar PV tube array, control cabinet and satellite dish, and wind turbine and weather sensors

2.4.2 All-in-One RWIS System

A new all-in-one low-power weather sensor package that can be powered by a single 12 V DC battery is being developed and tested for remote RWIS applications. The system is designed to be a self-contained pole-mountable unit with an onboard battery that can be recharged using a small solar PV module or wind generator. The system is controlled from a remote terminal and can provide weather-related information that is transmitted wirelessly to a central server for access via computer or mobile devices (WeatherCloud/Fathym 2017).

A prototype system (see Figure 8) using less than 10 W has been in the testing phase and has been collecting data at a grid-connected RWIS site in Fairbanks, Alaska, since July 2016.

Billy Connor, UAF AUTC

Figure 8. Prototype all-in-one low-power RWIS system (circled in red) installed at grid-connected site in Fairbanks, Alaska

Other tests are being planned for the prototype system at off-grid RWIS sites in Alaska to verify continuous operation and reliability. The test system was designed to monitor the basic weather parameters for RWIS applications, including ambient air and road surface temperature, humidity, wind speed, precipitation, and solar irradiance (see the data interface screen capture in Figure 9). The developer plans to integrate a smart phone-style camera into the package in early 2017, increasing the overall power budget to 15 to 20 W, which includes a small heating element for the camera lens. Future integration with GPS and weather sensor technology used in modern vehicles is also planned. These types of all-in-one low-power RWIS devices are expected to be the future of remote meteorological monitoring for transportation information systems.

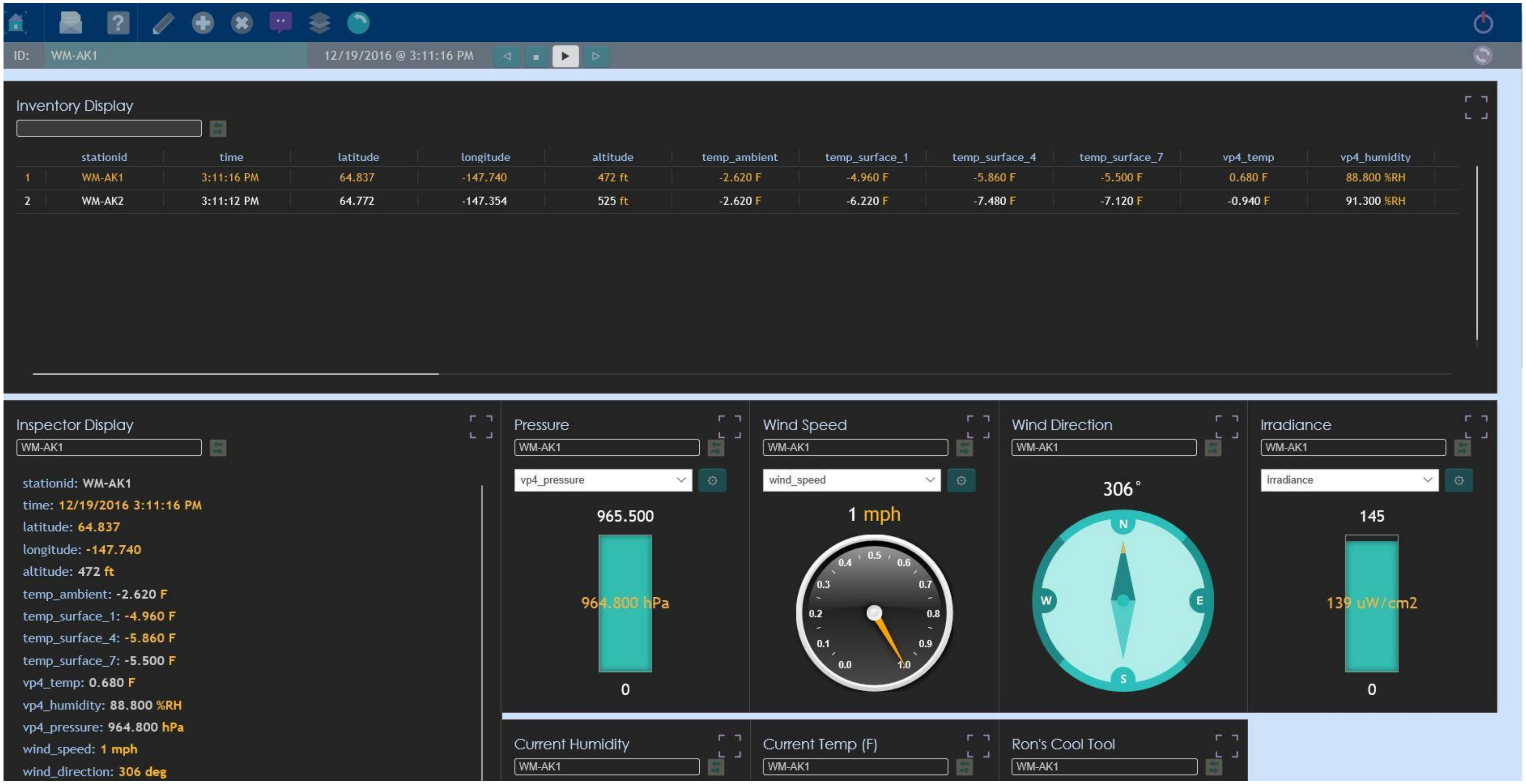

Figure 9. Partial data interface screen capture for prototype all-in-one low-power RWIS system (Fairbanks, Alaska, December 12, 2016 at 3:11:16 p.m.)

CHAPTER 3 – SURVEY RESULTS AND ANALYSIS

A review, analysis, and summary of the results of an eight-question Aurora survey, RWIS Alternative Power Sources, Sensors, Equipment, and Power Budget (see Appendix A), conducted during the summer of 2016 is presented in this chapter. The chapter is divided according to the survey questions, which concern alternative power sources, sensors, associated equipment, and power budgets for remote RWIS applications. A comparative power source and power budget analysis for the integration of alternative power sources and low-power sensors and associated equipment into existing RWIS sites is presented in the last section of this chapter.

3.1 Alternative Power Sources

Alternative power sources and configurations used for remote RWIS in the Aurora Program states were documented based on responses to Questions 1 through 3 of the survey, which were as follows:

1. What alternative power sources, including manufacturer and model, do you currently use at your remote (i.e., off-grid) RWIS sites (e.g., solar PV, wind turbines, fuel cells, TEGs)?
2. If there is more than one power source, what is the power configuration? (e.g., Is there more than one TEG? Or one TEG and two solar PV modules? Or wind turbines?)
3. What types of batteries, if any, are used in conjunction with alternative power supplies at your remote RWIS sites?

Based on the eight responses to Question 1, solar PV was the most frequently used alternative power source at remote RWIS sites (see Figure 10).

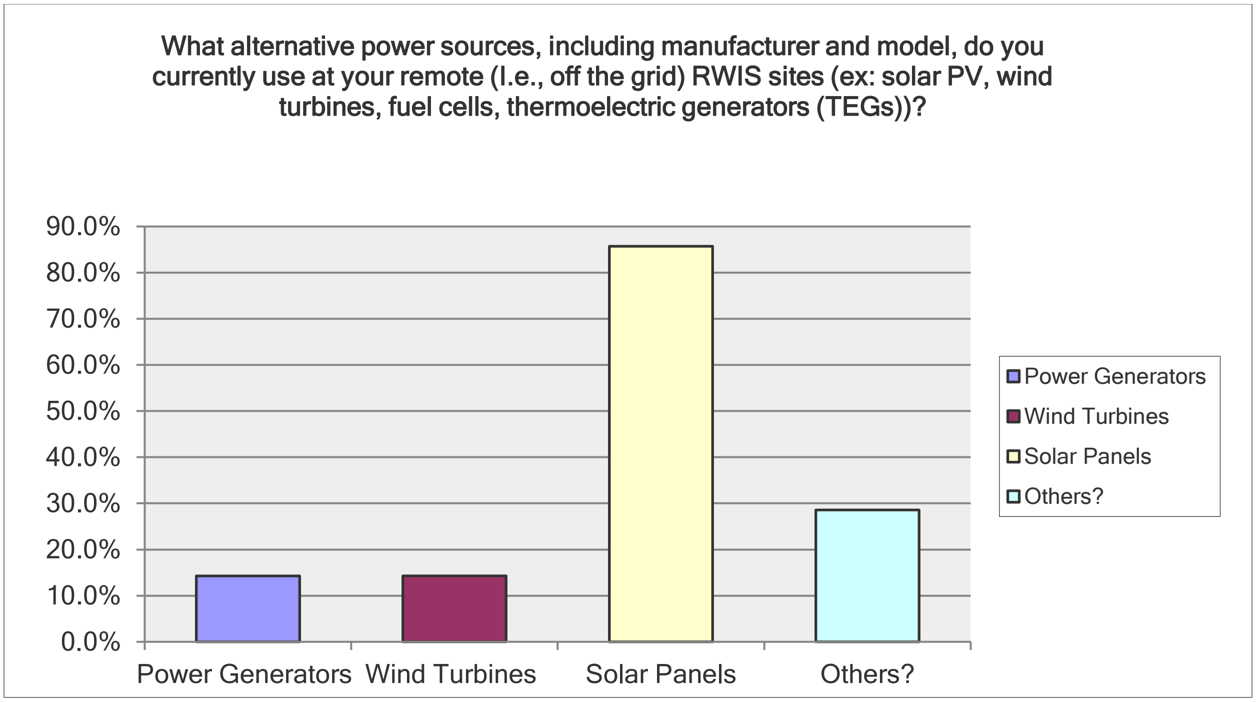

Figure 10. Alternative power sources at remote RWIS sites by percentage of respondents

Solar PV was followed by other sources, including fuel cells and TEGs; power generators, including propane- and natural gas-fired IC engine generators; and wind turbine generators. It was also noted based on the responses that wind turbine generators are not generally used at remote RWIS sites. This could be a result of the lack of a consistent wind resource and reliability in extreme weather conditions.

In response to Question 2, four of the six respondents indicated that only one source of power is used at their remote RWIS sites. One of these respondents indicated that different combinations of alternative power sources, including solar PV, fuel cells, and TEGs, are used in conjunction with IC engine generators to charge deep-cycle lead-acid batteries. Two respondents indicated that all of their RWIS sites were grid-connected or used no alternative sources.

Six out of seven responses to Question 3 indicated that 12 V DC, 100 to 130 Amp-hr lead-acid batteries, including absorbent glass mat (AGM) and gel cell deep-cycle formats, are used at their remote RWIS sites. One of those six respondents also indicated that lithium-ion batteries will be tested in the future.

3.2 Weather Sensors and Associated Equipment

Weather sensors and associated equipment used for remote RWIS in the Aurora Program states were documented based on responses to Questions 4 through 6 of the survey, which were as follows.

4. What types of weather sensors, including manufacturer and model, are employed at your remote RWIS sites (e.g., air temperature, humidity, road surface temperature, precipitation)?
5. What types of cameras, including manufacturer and model, are used at your remote RWIS sites?
6. What types of communication and associated equipment are used at your remote RWIS sites?

All eight respondents to Question 4 indicated that air temperature, humidity, wind, and pavement temperature sensors are used at their remote RWIS sites (see Figure 11).

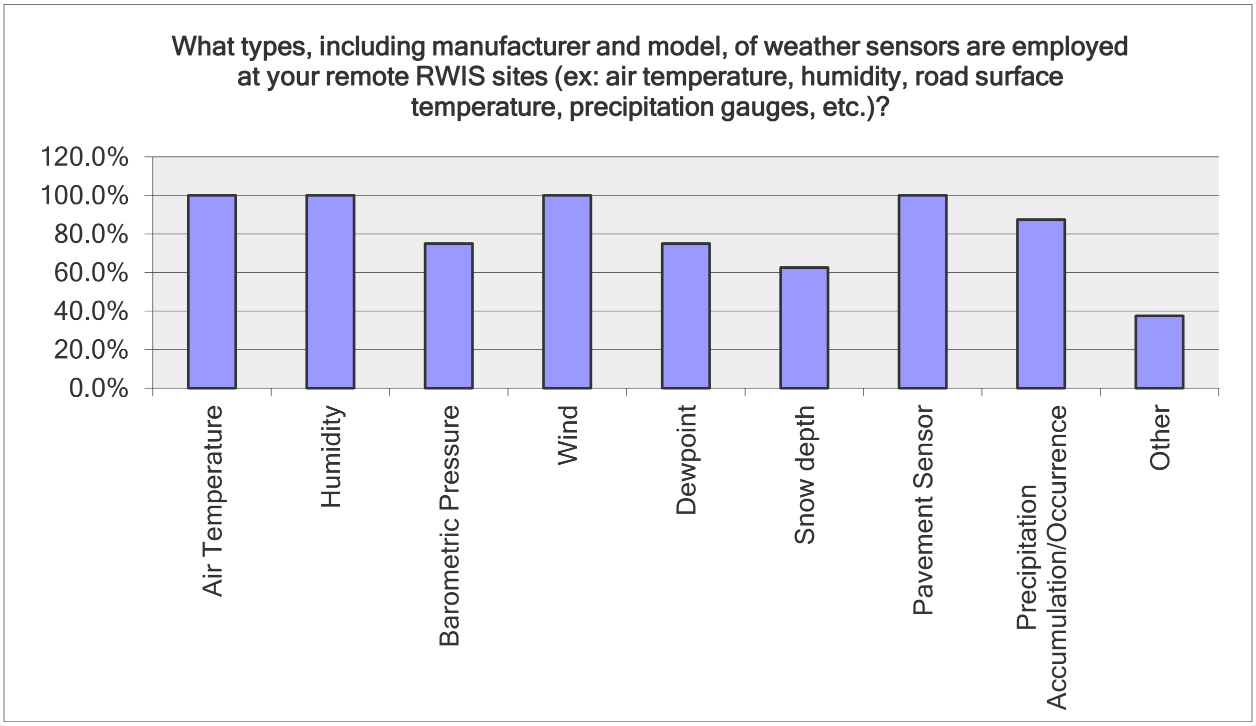

Figure 11. Weather sensor types used at remote RWIS sites by percentage of respondents

Out of the eight named sensors, fewer respondents reported that they deployed sensors for barometric pressure, dewpoint, and snow depth, in that order. The lowest percentage of respondents indicated the use of other sensors, including pyranometers (solar irradiance), tipping rain gauges, and sensors to measure subsurface temperature and soil moisture. Common individual weather sensors used for remote RWIS are listed in Table 3 in Section 2.3.1.

In response to Question 5, six out of the eight respondents indicated that cameras are used at their remote RWIS sites. These cameras included high- and low-power-budget single-view and PTZ varieties, including many with POE, as listed in Table 4 in Section 2.3.2.

In response to Question 6, all eight respondents indicated that some type of wired or wireless communication technology is used at their remote RWIS sites. Wired communication technologies include dial-up modem and fiber-optics, while wireless communication technologies include cellular modems and wireless systems along with transmitters and antenna hardware, as listed in Table 5 in Section 2.3.2.

3.3 Power Budget and Other Power Configuration Considerations

Power budgets and other power configuration considerations for remote RWIS were documented based on responses to Questions 7 and 8 of the survey, which were as follows.

7. What is the typical range of power usage for your remote RWIS sites?
8. Is there anything not covered in the previous questions about your remote RWIS site power configuration that would be helpful to know?

Six out of the eight respondents to Question 7 indicated an approximate range of either power (W) or energy (kWh) consumption at their remote RWIS sites. Power consumption ranged from about 25 W to 150 W, with indications from two respondents that the type of cameras and sensors used, and more so the heaters added to cameras and precipitation sensors, considerably increased the power consumption.

In four of the responses to Question 7, respondents provided additional notes. Two respondents indicated problems with using alternative power sources at remote RWIS sites due to the high power consumption of cameras and infrared illumination. In one case, no alternative power sources were used, and in the other case additional solar PV and batteries were added to overcome the additional power consumption that resulted when cameras were added to the site. Another respondent reported that lithium ion batteries would be tested in the near future as a replacement for deep-cycle lead-acid AGM batteries. The last respondent reported that a new ultra-low-power all-in-one RWIS package is currently being developed and tested for use in remote and harsh weather applications.

This survey and prior investigations (Weis 2014) identify the limitations of using alternative power sources in remote RWIS due to the high power consumption of cameras and precipitation gauges, particularly the heaters required to defog lenses and melt snow.

3.4 Power Budget, Power Supply Capacity, and Energy Demand Analysis

An example comparative analysis of a high-power versus a low-power remote RWIS configuration like those found among the surveyed Aurora Program states was conducted.

3.4.1 Power Budget Analysis

The power budgets for a high-power (see Table 6) and a low-power (see Table 7) remote RWIS were estimated based on manufacturers' specifications for the power consumption of installed weather sensors, cameras, and associated communications equipment.

Table 6. Power budget for high-power RWIS site

Sensors, Camera, and Communications Equipment	Power Budget (W)
Air Temperature/Humidity Sensor	0.10 W
Wind Monitor (Anemometer w/ Vane)	0.48 W
Pavement Temp Sensor	0.01 W
Temperature Data Probe	0.01 W
Optical Infrared Y/N Precipitation Sensor	0.78 W
Ultrasonic Snow Depth Sensor	0.60 W
PTZ Camera	27 W; 104 W (w/ heaters & PTZ)
Microwave (Ku-band) Satellite Modem and Transmitter	Typical: 25 W; Max: 100 W
Total Demand	**54 W; 131 W (w/heater)**

Table 7. Power budget for low-power RWIS site

Sensors, Camera, and Communications Equipment	Power Budget (W)
Air Temperature/Humidity Sensor	0.10 W
Wind Monitor (Anemometer w/ Vane)	0.48 W
Pavement Temp Sensor	0.01 W
Temperature Data Probe	0.01 W
Optical Infrared Y/N Precipitation Sensor	0.78 W
Ultrasonic Snow Depth Sensor	0.60 W
Single-View Fixed Low POE Cameras (X2)	6 W; 12 W (w/ heaters) includes two cameras
4G LTE Cellular Modem	Transmit/Receive (Typical/Max) 3.0/3.6 W; Idle 0.9 W; Dormant 0.053 W
Total Demand	**11 W; 17 W (w/heater)**

The power budgets were based on continuous operation and assumed to be relatively constant at two levels (with and without heaters on cameras). Camera heaters were activated using a 32°F set point based on temperature data at a representative remote RWIS site (see Table 8). The overall power budget would be lower if cameras were cycled on for a few seconds at 10- to 20-minute intervals.

Table 8. Average monthly temperatures (°F) for remote RWIS site

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Remote RWIS Site	22.8	24.4	30.9	41.5	45.9	54.3	57.4	55.3	50.5	43.0	17.5	28.7

3.4.2 Power Supply Capacity and Energy Demand Analysis

The estimated power budgets were then used to determine the required type, capacity, and configuration of power sources required to continuously operate the RWIS. All available power generation was used to charge the batteries, while the batteries were used to meet the power budget of the system. Any solar PV and wind generation in excess of the power budget was stored in the battery bank if the batteries were not fully charged. Any remaining portion of the power budget was assumed to be picked up using fuel cells or TEGs.

First, the estimated power generation capacity from solar PV and wind was determined for the representative remote RWIS site using solar and wind data available from the Alaska DOT&PF, the FAA, and NASA Langley Atmospheric Sciences Data Center (ASDC) archives.

3.4.2.1 Solar PV Resource

The available solar energy at the representative remote RWIS site was estimated based on the average daily insolation and the specifications of the current solar PV modules. The dimensions, surface area, and efficiency of one Kyocera 120 W solar PV module (Kyocera n.d.) were used with the average daily insolation at the site (NASA 2016) to determine the available daily solar energy as follows:

$$\text{Available Daily Solar Energy} = \text{Average Daily Insolation} \times \text{Module Efficiency} \times \text{Module Surface Area} \times \text{Number of Modules} \tag{1}$$

The solar module specifications from the manufacturer's data sheet (Kyocera n.d.) were as follows:

- Dimensions: (1425 x 653 x 59 mm)
- Surface Area: 1.425 m x 0.653 m = 0.9305 m^2
- Solar Module Efficiency: 14%

The average daily solar insolation values provided by 22-year monthly averages (NASA 2016), as shown in Table 9 for the site location, were used to calculate the available average daily solar energy for each month, as shown in Table 10.

Table 9. Average daily solar insolation (kWh/m2/day) for remote RWIS site

22-Year Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Avg.
Remote RWIS Site	0.41	1.01	2.24	3.73	4.88	5.43	4.8	3.86	2.54	1.37	0.59	0.23	2.59

Table 10. Available daily solar energy (kWh/day) for remote RWIS site

22-Year Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Avg.
Remote RWIS Site	0.32	0.79	1.75	2.92	3.81	4.24	3.75	3.02	1.99	1.07	0.46	0.18	2.03

3.4.2.2 Wind Turbine Generator Resource

The available wind energy at the remote RWIS site was estimated based on archived wind speed data (NASA 2016) and the specifications for the WT10 wind turbine (APRS World n.d.). The average monthly wind speeds for the site (see Table 11) and the power versus wind speed curve for the WT10 turbine in Figure 12 were used to calculate the available average daily wind energy for each month.

Table 11. Average monthly wind speeds (mph) for remote RWIS site

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Avg.
Remote RWIS Site	4.3	5.1	4.6	5.4	4.5	4.6	8.7	4.3	4.4	5.7	5.1	4.1	5.1

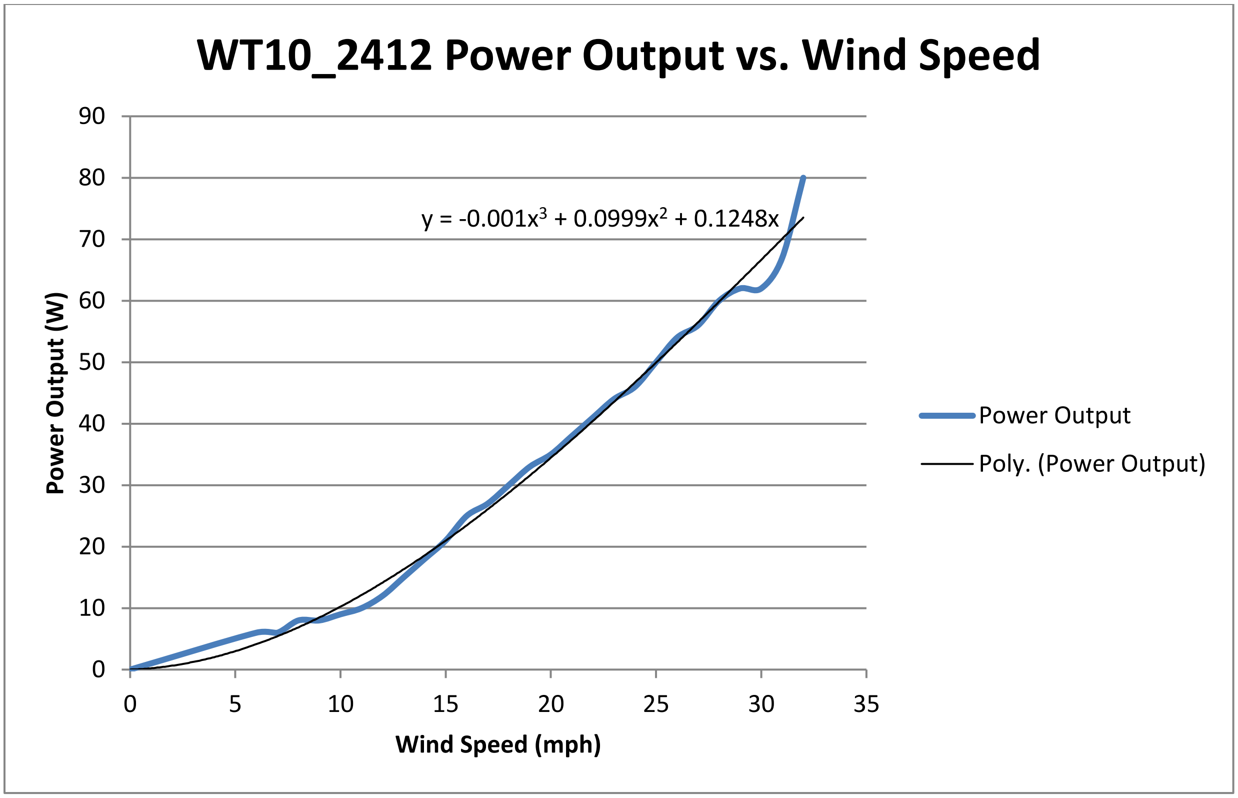

Figure 12. Power versus wind speed curve for WT10 24 V turbine charging a 12 V DC system

The available average daily wind energy for each month was calculated by taking wind speed data sampled at 30-minute intervals and then determining the power output from the curve fit in Figure 12. The daily average wind energy shown in Table 12 was then calculated by adding the calculated average power of two 30-minute intervals and multiplying each value by 24 hours.

Table 12. Available average daily wind energy (kWh/day) for remote RWIS site

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Avg.
Remote RWIS Site	1.63	4.35	1.92	6.67	1.73	2.06	2.38	1.60	2.29	2.86	3.32	3.22	2.84

3.4.2.3 Energy Demand Analysis

A maximum power capacity of 720 W for the representative remote RWIS site was determined using the six 120 W solar PV modules in place and information provided in Table 1 in Section 2.2. The surface area and efficiency of each Kyocera 120 W solar PV module was used with the average daily insolation values in Table 9 to determine the available average daily solar energy (kWh/day) using (Weis 2014).

The high-power-budget RWIS site was estimated to require 131 W × 6 h = 786 Wh or 0.786 kWh for daylight operation in the winter months, with camera heaters activated and assuming operation only during daylight hours. With the average daily solar insolation values in Table 10, the energy budget of the system was more than the daily solar energy provided in December and January. Because the values in Table 10 were estimated based on daily averages over a month, the actual available solar energy would also likely be below the required level in late November and early February. Consequently, additional power capacity would be required to operate the site through the winter season from mid-November to mid-February.

For the low-power-budget RWIS system, if just the current high-power Cohu 3920 PTZ cameras at the representative site were replaced with two single-view low-power POE cameras, the total power budget of the site would be reduced from 54 and 131 W without and with the camera heater, respectively, to 33 and 39 W. With the new cameras and heaters, the energy required during the winter months would be reduced to 39 W × 6 h = 231 Wh or 0.231 kWh for daylight operation. However, additional power capacity would still be required in December and most of January and even parts of late November and early February.

If the current communications interface, which uses a Ku-band transmitter, was replaced with the 4G LTE cellular modem gateway with the power requirements shown in Table 5 in Section 2.3.2, the power consumption for data transmit and receive functions would be reduced from 25 W to about 3 W. However, if the modem was polled to transmit data at 10-minute intervals, the modem would not draw 3 W continuously, but only during times when data are transmitted and received. In this analysis, a demand of 3 W for 1 minute every 10 minutes and 1.25 W for the remaining idle time as the minimum was used based on information from Vaisala field service engineers. The total power budget of the site with the new POE cameras and 4G LTE cellular modem, based on the manufacturers' power specifications provided in Tables 4 and 5 in Section 2.3, would be reduced to 11 W and 17 W without and with the camera heater, respectively. The energy required during the winter months with the low-power-budget RWIS system would be further reduced to 17 W × 6 h = 102 Wh or 0.102 kWh for daylight operation, but additional power capacity would still be required in December and January.

Average monthly energy analyses were conducted using the representative RWIS site for continuous and daylight operation with high and low power budgets and different supply configurations, as shown in Tables 13 through 16, which provide the following:

1. Table 13 shows energy demand for continuous operation with solar PV alone and either of the two fuel cells or TEG.
2. Table 14 shows energy demand for continuous operation combining solar PV and wind and either of the two fuel cells or TEG.
3. Table 15 shows energy demand for daylight operation plus an hour before sunrise and after sunset with solar PV alone and either of the two fuel cells or TEG.
4. Table 16 shows energy demand for daylight operation plus an hour before sunrise and after sunset with combinations of solar PV and wind and either of the two fuel cells or TEG.

Table 13. Energy analysis for continuous operation of remote RWIS site (solar PV + fuels cells or TEG)

Month	Current Energy Budget (kWh)	Energy Budget After Replacing Cameras and Communications Equipment (kWh)	Energy Demand After Incorporating Solar (kWh)	Energy Demand: Solar and Acumentrics Fuel Cell (kWh)	Energy Demand: Solar and EFOY Fuel Cell (kWh)	Energy Demand: Solar and Thermoelectric Generator (kWh)
January	109.7	22.6	12.7	-359.3	-20.8	-27.5
February	93.5	20.0	-2.1	-338.1	-32.4	-38.4
March	98.6	21.7	-32.5	-404.5	-66.0	-72.7
April	56.2	18.0	-69.5	-429.5	-101.9	-108.4
May	52.4	18.1	-100.1	-472.1	-133.6	-140.3
June	50.7	17.6	-109.8	-469.8	-142.2	-148.6
July	52.4	18.1	-98.2	-470.2	-131.6	-138.3
August	52.4	18.1	-75.4	-447.4	-108.9	-115.6
September	50.7	17.6	-42.0	-402.0	-74.4	-80.9
October	59.8	18.7	-14.5	-386.5	-48.0	-54.6
November	106.1	21.9	8.0	-352.0	-24.4	-30.8
December	109.7	22.6	17.0	-355.0	-16.4	-23.1

Table 14. Energy analysis for continuous operation of remote RWIS site (solar PV + wind + fuel cells or TEG)

Month	Current Energy Budget (kWh)	Energy Budget After Replacing Cameras and Communications Equipment (kWh)	Energy Demand After Incorporating Solar and Wind (kWh)	Energy Demand: Solar, Wind, and Acumentrics Fuel Cell (kWh)	Energy Demand: Solar, Wind, and EFOY Fuel Cell (kWh)	Energy Demand: Solar, Wind, and Thermoelectric Generator (kWh)
January	109.7	22.6	12.6	-359.3	-20.8	-27.5
February	93.5	20.0	-2.2	-338.1	-32.4	-38.4
March	98.6	21.7	-32.6	-404.5	-66.0	-72.7
April	56.2	18.0	-69.7	-429.5	-101.9	-108.4
May	52.4	18.1	-100.1	-472.1	-133.6	-140.3
June	50.7	17.6	-109.8	-469.8	-142.2	-148.6
July	52.4	18.1	-98.2	-470.2	-131.6	-138.3
August	52.4	18.1	-75.4	-447.4	-108.9	-115.6
September	50.7	17.6	-42.1	-402.0	-74.4	-80.9
October	59.8	18.7	-14.6	-386.5	-48.0	-54.6
November	106.1	21.9	7.9	-352.0	-24.4	-30.8
December	109.7	22.6	16.9	-355.0	-16.4	-23.1

Table 15. Energy analysis for daylight operation of remote RWIS site (solar PV + fuels cells or TEG)

Month	Current Energy Budget (kWh)	Energy Budget After Replacing Cameras and Communications Equipment (kWh)	Energy Demand After Incorporating Solar (kWh)	Energy Demand: Solar and Acumentrics Fuel Cell (kWh)	Energy Demand: Solar and EFOY Fuel Cell (kWh)	Energy Demand: Solar and Thermoelectric Generator (kWh)
January	42.0	8.7	-1.3	-373.3	-34.7	-41.4
February	44.9	9.6	-12.5	-348.5	-42.8	-48.8
March	57.5	12.7	-41.6	-413.6	-75.1	-81.8
April	42.6	13.6	-73.8	-433.8	-106.2	-112.7
May	42.6	14.8	-103.5	-475.5	-137.0	-143.7
June	44.3	15.3	-112.0	-472.0	-144.4	-150.9
July	42.7	14.8	-101.5	-473.5	-135.0	-141.7
August	38.4	13.3	-80.2	-452.2	-113.7	-120.4
September	33.2	11.5	-48.1	-408.1	-80.5	-86.9
October	31.9	10.0	-23.2	-395.2	-56.7	-63.4
November	47.5	9.8	-4.0	-364.0	-36.4	-42.9
December	42.0	8.7	3.1	-368.9	-30.4	-37.1

Table 16. Energy analysis for daylight operation of remote RWIS site (solar PV + wind + fuel cells or TEG)

Month	Current Energy Budget (kWh)	Energy Budget After Replacing Cameras and Communications Equipment (kWh)	Energy Demand After Incorporating Solar and Wind (kWh)	Energy Demand: Solar,Wind, and Acumentrics Fuel Cell (kWh)	Energy Demand: Solar, Wind, and EFOY Fuel Cell (kWh)	Energy Demand: Solar, Wind, and Thermoelectric Generator (kWh)
January	42.0	8.7	-1.3	-373.3	-34.7	-41.4
February	44.9	9.6	-12.6	-348.5	-42.8	-48.8
March	57.5	12.7	-41.6	-413.6	-75.1	-81.8
April	42.6	13.6	-74.0	-433.8	-106.2	-112.7
May	42.6	14.8	-103.5	-475.5	-137.0	-143.7
June	44.3	15.3	-112.0	-472.0	-144.4	-150.9
July	42.7	14.8	-101.6	-473.5	-135.0	-141.7
August	38.4	13.3	-80.3	-452.2	-113.7	-120.4
September	33.2	11.5	-48.1	-408.1	-80.5	-86.9
October	31.9	10.0	-23.3	-395.2	-56.7	-63.4
November	47.5	9.8	-4.1	-364.0	-36.4	-42.9
December	42.0	8.7	3.0	-368.9	-30.4	-37.1

In many cases, even with just solar PV and batteries, negative values for energy demand (kWh) indicated that surplus energy was available from the power sources. The energy demand in these cases would therefore be met, with excess energy available to keep the batteries charged so they can provide energy when the available solar energy is low due to cloudiness. However, another power source was clearly required for this site to operate continuously or for strict daylight operation through the winter months, even after the reduction in the power budget through replacement of the existing camera with two POE cameras and the Ku-band transmitter with a 4G LTE cellular modem. Because the wind resource at this site was insufficient to supply the additional energy required during the winter months, other alternative energy sources, such as the Acumentrics or EFOY fuel cell or the Gentherm 5060 TEG, would be required.

CHAPTER 4 – RECOMMENDATIONS AND CONCLUSIONS

4.1 General Recommendations

The following sections offer recommendations based on previous investigations and the results of a survey of the Aurora Program states. Recommendations are grouped into three topic areas:

- Assessment of alternative power supplies
- Determination of the power budget of weather sensors, cameras, and associated equipment for remote (off-grid) RWIS
- Development of operating scenarios to save energy

4.1.1 Alternative Power Supplies

Based on previous investigations, discussions with DOT personnel, and the results of the survey concerning alternative power supplies for remote RWIS, it is recommended that DOTs in the Aurora Program states consider the use of alternative power sources in addition to or as replacements for existing power sources such as IC engine generators and solar PV. While the survey results indicated that solar PV was the most widely used alternative power source for remote RWIS, wind turbine generators were not reported as a power source among Aurora Program states. The successful deployment of other alternative power sources, such as TEGs in Alaska, has shown them to be viable options for remote RWIS.

In considering the use of alternative power supplies for remote RWIS, the following steps are recommended:

1. In the case of solar PV or wind, a resource assessment should be conducted at the remote RWIS site under consideration.

2. The current power budget for the remote RWIS configuration should be determined.

3. If the site is determined to have a high power budget (> 100 W), possible scenarios for lowering the overall power budget should be explored.

4. The alternative power source should be selected based on the available capacity and the power budget required for the RWIS site to operate continuously and reliably throughout the year.

Recommendations for assessing and potentially reducing the power budget of a remote RWIS site are provided in the following section.

4.1.2 Power Budget of Weather Sensors, Cameras, and Associated Equipment

Based on previous investigations and the results of the survey concerning the current weather sensors, cameras, and associated equipment used for remote RWIS and the overall power budget, it is recommended that DOTs in the Aurora Program states consider replacing high-power weather sensors and cameras with low-power equivalents to lower the overall power budget.

As an example, the comparative analysis conducted in Section 3.4 for a high- and low-power remote RWIS configuration replaced high-power Cohu PTZ cameras with two low-power POE Mobotix M24 cameras, which yielded a reduction in the power budget of over 90 W. This reduction in the overall power budget allowed the example system to operate continuously by using solar PV and/or wind power to charge a battery bank for the majority of the year, except for late November through early February, at the representative location. The addition of a propane- or natural gas-fired fuel cell or TEG allowed for continuous operation throughout the year.

The majority of the power budget for remote RWIS was determined to result from the use of resistive heaters for defogging cameras and melting snow for certain types of precipitation gauges in the winter and transitional months. However, the POE cameras required significantly less power for heating to keep the lens clear, and precipitation gauge technology has improved to use infrared and beam-type technology to measure snowfall amounts. Therefore, it is recommended that cameras and weather sensor packages that require less power for heating be considered. It is also recommended that RWIS systems with individual weather sensor/transmitter packages be evaluated for replacement with an all-in-one weather sensor/transmitter package to reduce system complexity and the overall power budget of the system.

Steps to reduce the overall power budget for remote RWIS, as discussed above, combined with the energy saving operating scenarios discussed in the next section, facilitate the use of alternative power sources with a lower power capacity.

4.1.3 Operating Scenarios

This study determined that both the RWIS configuration and the operating scenarios play significant roles in the ability of the system to operate without the need for an IC engine generator. The two operating scenarios analyzed in this research, i.e., (1) continuous operation and (2) daylight operation, with different combinations of power supplies, including current and revised system configurations, showed that using existing solar PV technologies and either a fuel cell or TEG provided enough power to maintain operation for continuous or daylight operation.

In addition to moving to low-power weather sensors, cameras, and associated equipment, it is recommended that devices be turned off or placed in a low-power standby mode while not in use. This operating strategy could be applied to cameras, except for the lens heater. Images could be polled from the site at 10-minute intervals, significantly reducing the daily energy required to operate the site. This same operating procedure could also be followed for communications equipment, including modems and transmitters. Although the communication link must stay connected to the central server in order to poll data, the system could be operated in standby mode for much of the time.

Daytime versus nighttime operation must also be considered. While 24-hour meteorological data are often desired at critical RWIS locations, camera images may not be necessary during the nighttime hours. If nighttime images are necessary, an infrared camera must be installed, significantly increasing the power budget. Therefore, it is recommended that these and other operating scenarios that can reduce the overall energy requirements for remote RWIS sites be considered to facilitate the deployment of alternative power sources.

4.2 Overall Recommendations

Based on previous investigations, discussions with DOT personnel, and the results of the survey concerning alternative power supplies and power budgets for RWIS, the following overall recommendations are provided:

- IC engine generators at some remote RWIS sites could be replaced by combinations of solar PV, wind turbine generators, and propane- or natural gas-fired fuel cells and TEGs. Furthermore, fuel cells and TEGS could be used to supplement existing solar PV systems for continuous or daylight operation through the winter months.

- Low-power POE cameras, all-in-one weather sensors/transmitters, and communications equipment could be used to reduce the overall power budget, increase the available stored energy in batteries, and decrease the fuel used by fossil fuel-based power supplies.

- Operating scenarios such as strict daytime camera use and the polling of camera images and the cycling of equipment at 10-minute intervals could be employed to reduce daily energy consumption and facilitate the use of alternative power sources by decreasing the required power capacity of the system.

4.3 Conclusions

This report documented the findings of a review of alternative power supplies and power budgets for weather sensors, cameras, and associated equipment for remote (off-grid) RWIS applications based on previous investigations, experiences of DOT personnel, and the results of a survey of the Aurora Program states.

Three distinct conclusions regarding alternative power supplies, power budgets, and operating scenarios for remote RWIS were drawn from the findings:

- Combinations of alternative power sources, such as solar PV, wind generation, fuel cells and TEGs, are required in combination with a battery bank (energy storage) at remote RWIS sites for continuous or daylight operation throughout the year.

- The use of low-power all-in-one weather sensors/transmitters, POE cameras, and associated communications equipment was determined to significantly reduce the overall power budget for remote RWIS.

- The operating scenario used at the site is critical to energy savings and is largely dependent on continuous versus daylight operation and the duty cycles of the cameras, heaters, and communications equipment.

In summary, this investigation concluded that reducing the overall power budget for remote RWIS sites is critical not only for selecting and using alternative power sources, but also for continuous and reliable operation throughout the year.

4.4 Future Research and Development

The results of this investigation point to future research and development of remote RWIS in the areas of alternative power supplies and all-in-one RWIS packages, including in the following areas:

- Evaluation of alternative power supplies such as wind turbine generators, fuel cells, and TEGs through deployment and testing at remote RWIS sites.

- Further and more detailed analysis of the energy generation, energy storage, and power budgets at remote RWIS sites through data logging by operation and maintenance contractors.

- Development and harsh/cold weather testing of a self-contained low-power all-in-one RWIS package.

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APPENDIX A – RWIS ALTERNATIVE POWER SOURCES AND POWER BUDGET SURVEY

AURORA Survey

RWIS Alternative Power Sources, Sensors, Equipment, and Power Budget

The following survey is being conducted as part of an Aurora pooled fund project, Review Synthesis of Alternative Power Supply, to review alternative power sources, sensors, equipment, and power budgets for remote (off-grid) RWIS in the Aurora states. Information received from this survey will be used as part of a comprehensive report to review the current state of remote RWIS and provide general recommendations on alternative systems, technologies, and operation.

1. What alternative power sources, including manufacturer and model, do you currently use at your remote (i.e., off the grid) RWIS sites (ex: solar PV, wind turbines, fuel cells, thermoelectric generators (TEGs))?
2. If there is more than one power source, what is the power configuration? (i.e., is there more than one TEG? Or one TEG and 2 solar PV panels, wind turbine? etc.)
3. What types of batteries, if any, are used in conjunction with alternative power supplies at your remote RWIS sites?
4. What types, including manufacturer and model, of weather sensors are employed at your remote RWIS sites (ex: air temperature, humidity, road surface temperature, precipitation gauges, etc.)?
5. What types of cameras, including manufacturer and model, are used at your remote RWIS sites?
6. What types of communication and associated equipment are used at your remote RWIS sites?
7. What is the typical range of power usage for your remote RWIS sites?
8. Is there anything not covered in the previous questions about your remote RWIS site power configuration that would be helpful to know?