WIRELESS METEOROLOGICAL SENSOR NETWORK

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Chairperson

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Acronyms

ABS	Acrylonitrile Butadiene Styrene
ADC	Analog to Digital
API	Application Programming Interface
AT	Attention Mode
BTU	British Thermal Units
DoD	Department of Defense
DSSS	Direct Sequence Spread Spectrum
ESCO	Energy Services Company
ESPC	Energy Saving Performance Contracts
HVAC	Heating, Ventilation and Air-Conditioning
LEED	Leadership Energy and Environmental Design
LiPo	Lithium Polymer battery
MPPT	Maximum Power Point Tracking
NZEI	Net Zero Energy Installations
PCB	Printed Circuit Board
PLA	Polylactic Acid

PWM	Pulse Width Modulation
TOM	Thing-O-Matic
REC	Renewable Energy Certificates
REIS	Renewable Energy and Island Sustainability
WPAN	Wireless Personal Area Network

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Chapter 1

Introduction

1.1 History and motivation of the project

In the spring of 2012, I was brought on the Wireless Meteorological Sensor Project as a research assistant under Dr. Anthony Kuh. My task was to be project manager for a team of undergraduates and continue the work of previous students, John Hirano and Trevor Wilkey. Our team consisted of students from both the electrical engineering department and the computer science department including Adam Oberbeck, Jimmy Cumming, and Monica Umeda. Our goal was to bring a proof of concept circuit design to a field deployable prototype sensor module. This module would measure various meteorological parameters such as barometric pressure, temperature, relative humidity, solar irradiance, and eventually wind speed and direction. These modules would potentially number 100+ modules wirelessly connected in a ZigBee mesh network. The purpose of the sensor network is to monitor in real time and data log the aforementioned parameters for weather modelling and prediction. Predicting weather parameters would assist in dealing with hurdles associated with the future installation of a multi MW solar array on University of Hawaii campus. Due to the intermittent nature of solar energy, it is important to assist our local utility, Hawaiian Electric Company (HECO) and UH campus facilities with the unpredictable fluctuation of power production from solar. By predicting weather conditions, it may be possible to anticipate the reduction and subsequent return of power production from the solar array. With this knowledge, electricity consumption could potentially be reduced in concert with the reduced local electricity production. These data would be useful in helping to solve many of the hurdles involved in the transition of the existing electrical grid to smart grid characteristics.

Solar Technology and Current Hurdles

1.2 Solar power

Solar panels are an array of solar cells that are electrically connected and produce electricity from incident light. Multiple panels can be put into an array to produce a higher total power to an electrical system. Many applications include: residential homes, commercial building, industrial complexes, third world environments, and orbital installations. A single solar cell produces a particular voltage and current depending on its specific construction. To increase the voltage supplied to a system, multiple cells can be electrically connected in series. To increase current output, multiple cells can be connected in parallel. Solar panels generate DC electricity, but the electricity from the outlet is AC. Inverters convert the DC into AC for general use [1] [2]. Photovoltaic panels come in three basic categories: Thick film silicon, thin films, and third generation technologies.

1.3 Design issues

Many criteria need to be met before an array is setup on a site. Shadowing from nearby objects needs to be minimized. The location of nearby objects like trees and neighboring buildings needs to be taken into account when selecting an array's position. The mounting angle of the panels in the array needs to be appropriate for the latitude of the site. The angle of incidence of light needs to be as close to normal to the plane of the cell as possible for as much of the day as possible [3].

1.4 **Motivation to adopt Solar Energy**

As prices of oil continue to rise, the price of fossil fuel based electricity increases in concert. In Hawaii, as of 2010, 75% of electricity production is from oil [4]. This oil is 100% imported from off island. This causes the price of oil based electricity to be 3 times higher than the national average. As of August 2013, average electricity cost for residents in the United States is $0.12/kWh. Washington state has the lowest cost at $0.08/kWh and the second highest is Alaska at $0.19/kWh. Due to a full dependence on imported oil, Hawaii has the highest electricity cost at $0.37/kWh [5]. If prices of electricity from carbon sources increase, while the cost to manufacture solar panels continues to decrease, the return on investment for solar will continue to improve. If supply routes to Hawaii were cut off for any reason, the impact would be disastrous. [6] Electricity generated from solar has increased from 0.8% in 2007 to 8.1% in 2011, generating 35.9 MW. The levelized cost of photovoltaic systems is $0.15 to $0.35/kWh. The high end of the range is still less than the Hawaii average and is expected to decrease as technologies improve. [4]

1.5 **Hurdles of Solar Implementation**

One obvious disadvantage to solar energy is that it is an intermittent energy source. A conventional power plant can consistently produce power and adjust power output as the daily demand cycle progresses. Solar only works during daylight hours. Also, nearby structures such as trees and buildings have the potential to shadow the array. Occasional cloud cover also temporarily reduces power output from a solar array. As solar become more ubiquitous, and density on the grid increases, the effects of cloud cover becomes more problematic [7]. A conventional power plant uses turbines to generate electricity. These very large machines require time to start and bring up to speed in order to produce electricity at the correct parameters. One household generally has a solar system that produces, on average, 5kW. If a cloud covers a neighborhood on one substation, the local disruption of power could cause fluctuations in power quality. These fluctuations create problems for the utility and could potentially damage the customer's home appliances. [7] An additional problem could occur if a substation isolates a group of homes from the grid. If enough of the homes have solar systems that are over producing electricity, meaning they are producing more electricity than being consumed, the excess electricity has nowhere to go. On September 6 2013, Hawaiian Electric Company (HECO) implemented a rule that requires approval of a solar system before being connected to the grid. This policy has caused a delay in installation and worse, customers are paying for an installed system on their roof that is not generating electricity. The policy is also causing solar installation companies to have excess inventory and workers [8].

1.6 **Path to a solution**

There is not much that can be done about a substation isolating a neighborhood, but there is potential to address the issue with intermittent cloud cover. With the correct type of data monitored with enough spatial and temporal resolution, the local micro climate of an area can be monitored in real-time. This data can be stored and analyzed over time to create dynamic models of cloud behavior. Subsequently, prediction algorithms could be utilized to anticipate a reduction in power production locally. With this information, the local facility could reduce consumption concurrently with the reduced production. Also, the utility would have a better chance to prepare for fluctuations in the grid.

This project has designed a wireless sensor module that monitors temperature, barometric pressure, humidity, and solar irradiance. The module is also equipped with an electronic compass and GPS. Each module is portable, self- sustaining, and communicates wirelessly on its own dedicated network.

1.7 **Thesis overview**

Chapter 2 covers some of the other projects both domestic and around the globe. The chapter will review the progress other facilities have made towards adopting renewable energy sources. The sensor module developed by the University of Hawaiʻi at Manoa will be compared to other modules being researched and already commercialized. Chapter 3 will introduce wireless mesh networking and will go into detail about how the mesh network was established at UH. Chapter 4 will provide a description of prototype design for both the housing and the electronics hardware. Finally, Chapter 5 will discuss the initial data collected, some conclusions about the current design, and a preview of where the project is expected to go in the future.

Chapter 2

Renewable Energy Projects: University of Hawaii and Other Facilities around the Globe.

2.1 United States Universities

2.1.1 University of Texas Austin

In 1838 the Republic of Texas set aside 220,000 acres of land in West Texas for the purposes of establishing, what is now, the University of Texas Austin. Later, in 1876, the State of Texas Constitution called for the creation of the University of Texas and appropriated one million acres of land for the establishment of the Permanent University Fund. In 1883, an additional one million acres of land was added for a total of approximately 2.1 million acres locally known as University Lands [9].

University Lands, in West Texas, lease the 2.1 million acres for various purposes including oil and gas production, the installation of pipelines, a commercial winery and two large wind farms. One farm is the Woodward Mountain Wind Ranch, a 160-MW wind generation plant capable of providing power for 72,600 homes. The Indian Mesa Wind Farm is an 82.5 MW plant that can provide power for 20,500 homes.

The wind farms are operated by NextEra Energy Resources, the largest wind energy generator in America. NextEra is one of 1,300 companies in industries directly and indirectly related to renewable energy that operate in Texas. The wind farms provide funding for the University of Texas and renewable electricity to tens of thousands of West Texas homes. Ironically, as of 2013, the two wind farms generate more power than the local area requires and the transmission line infrastructure needed to get the power to metropolitan areas does not exist yet.

Texas produces 10,394 MW of wind energy and exceeds that of all but five countries. Much of Texas' dominance in the renewable energy field is a result of the Texas Renewable Portfolio Standard, enacted in 1999 and extended in 2005 to increase the minimum statewide capacity for renewable energy production. According to the report, the state's installed capacity reached the 10,000 megawatt target in early 2010 which is15 years ahead of schedule [10].

2.1.2 **University of Pennsylvania**

Over 86% of carbon produced at University of Pennsylvania is from building energy usage. The university expects total carbon emissions to double by 2050 if no action is taken. Univ. of Pennsylvania has committed to reducing campus energy usage by 17% by 2014. The university has implemented a program called the Climate Action plan. This plan will use three methods to achieve the stated goal: 1) Develop and monitor conservation programs to encourage a change in energy usage behavior of its occupants and management staff. 2) Improve and accelerate renovations processes for existing buildings. 3) Adopt higher efficiency standards for new buildings and expand research of renewable energy investments.

University of Pennsylvania has adopted many conservation initiatives. In 2001, the university committed to purchasing 20 million kilowatt-hours of wind-generated energy per year for three years. This was supplemented by a program that reduced their peak demand by 18 percent. In 2003 the university extended its wind power purchase to a 10-year commitment.

University of Pennsylvania houses a state-of-the-art central monitoring and control of utilities. This center saves more than $5 million annually in energy costs. Engineers can control campus-wide chilled water and steam utilities and air handling systems across campus. The center also provides the ability to avoid peak utility charges and conserve energy year-round. The universities buildings are cooled from a central chilled water loop. The chiller plant freezes water at night. This timing allows the unit to utilize low night energy costs and supplement cooling demand during the daylight hours.

The School of Design's TC Chan Center provides both a building-by-building campus energy model and a greenhouse gas inventory. The university also houses Aircuity's Optinet system. This system reduces excessive airflow in laboratories and vivaria. The system determines necessary fresh air requirements based on parameters such as carbon monoxide, carbon dioxide, particulates, total volatile organic compounds, temperature, and relative humidity [11].

2.1.3 **University of Oklahoma**

As of 2012 University of Oklahoma provides 85 percent of its energy from wind produced energy sources. In September 2008, the university signed an agreement with Oklahoma Gas & Electric Company (OG&E) to purchase 100% of its OG&E-supplied electricity from renewable energy sources by 2013 [12].

In 2008, University of Oklahoma and OG&E began construction of "OU Spirit." This project, completed in 2010, features 44 Siemens 2.3 MW turbines completed the University of Oklahoma's promise of 100 percent energy production from renewable sources a reality. [13]The OU Spirit project has also created the infrastructure to allow OG&E to provide renewable electricity to other customers across the state of Oklahoma. Along with energy production OU is undertaking a collection of energy efficient upgrades. The university is installing occupancy sensors for classroom lighting and developing water-efficient restroom facilities. OU launched an Advanced Metering Infrastructure program to customize and manage energy demand across campus using smart meters [14].

2.2 **Federal Agencies**

2.2.1 **Energy Savings Performance Contracts**

Energy savings performance contracts (ESPC) allow federal agencies to become more energy efficient through private investments. ESPCs were appointed by congress to help federal agencies to reduce the billions of dollars already being spent annually on energy costs. The agreement between a federal facility and an Energy Services Company (ESCO) designs a project to increase energy efficiency at the facility and the ESCO purchases and installs the necessary equipment. The federal facility does not have to pay for the equipment and instead promises to pay the company a share of the savings resulting from the energy efficiency improvements. The ESCO is responsible for the maintenance of the equipment and measuring the energy consumption and savings [15].

2.2.2 **Environmental Protection Agency**

The Environmental Protection Agency was the first major federal agency to purchase 100 percent of its energy requirements from renewable sources. All 175 of the agency's facilities utilize renewable energy certificates (REC) through the end of fiscal year 2012 and have signed for three separate green power contracts from Element Markets, 3Degrees Group and Orion Renewable Energy Trading Group in August 2011. This will cover the annual power production of 265 million kWh [16].

2.2.2.1 **Robert S. Kerr Environmental Research Center**

The Robert S. Kerr Environmental Research Center in Ada, Oklahoma uses a combination of renewable resources to be the EPA's first carbon neutral laboratory. Energy usage for atmosphere control and reheating is minimized via the utilization of ground source heat pumps by eliminating the need to use natural gas for such purposes. From 1994 to 1996 the average energy use was 21 billion BTU (6.1GWh equivalent) annually. In 2011 the energy use was approximately 12 billion BTU (3.5GWh equivalent). This was an energy drop of around 56 percent. The facility also purchases its 3 million kWh of electricity annually from wind energy. In 2005 the facility upgraded its HVAC system through an ESPC which included a complete variable air volume system for air supply and fume hood air exhaust, new and upgraded fan motors, and an integrated direct digital control system for HVAC, energy, fire, and security management [17].

2.2.2.2 **Region 8 Laboratory**

Region 8 Laboratory performs physical, chemical, biological, and microbiological analyses of water, soil, air, plant, and tissue samples. Data generated from these studies is used in environmental enforcement and remediation projects. The facility employs approximately 32 personnel and consumes about 17billion BTUs (5GWh equivalent) per year.

Along with the facility also having 100 percent of its electricity consumption powered via renewable energy sources through RECs, Region 8 Laboratory employs various energy conservation methods. The laboratories ventilation system reduces its system volume by 25 percent during after-hours. The system is divided into seven zones, each being capable of being exclusively reduced. If personnel are working late one area, only that area will receive 100 percent air exchange capacity. The HVAC system is monitored by a direct digital control system. This system alerts engineers when equipment is not operating correctly or at full capacity. The laboratory makes ample use of day-lighting and supplements exclusively using energy-efficient T-8 fluorescent bulbs. The artificial lighting is automated using motion sensors and deactivate when the room is not occupied. All windows are fitted with 1-inch thick, double paned thermal windows with solar flexing film. The roof has also been insulated to an R-value of 30 [18].

2.2.2.3 **Western Ecology Division Laboratory**

The Western Ecology Division Laboratory in Corvallis, Oregon consists of two facilities, the Western Ecology Division of the National Health and Environmental Effects Research Laboratory. These facilities collectively study the effects of chemical contaminants, land use, and global climate change on forests, crops, wetlands, lakes, and streams along the Pacific Coast. The facility houses approximately 110 personnel and consumes about 23 billion BTUs (6.7GWh equivalent) annually. Since 2002, the facility has purchased 360,000 kWh per year of delivered green power which is approximately 10 percent of its annual energy demand. In January 2005, the facility completed installation of a roof-mounted, 9.5 kW photovoltaic array. In fiscal year 2010 this array provided almost 5MWh of electricity. The rest of the electricity consumption is offset via RECs [19].

2.2.3 **Department of Defense (DoD)**

The DoD is the largest energy consumer in the federal government. The DoD's goal is to achieve 25 percent of overall energy use through renewable energy sources by 2025. The DOD as a whole has launched the Net Zero Energy Installations (NZEI) initiative. It is up to the various branches of the U.S. military to adopt implementation plans for planning, designing and construction.

2.2.3.1 **Air Force Academy**

In November, 2010 the U.S. Air Force broke ground for a 6 MW, 30 acre solar array. It was completed in summer of 2011. The array was the result of a partnership between the Air Force Academy, Colorado Springs Utilities and SunPower. The array cuts energy for the academy produced by fossil fuels by 11 percent and saves $1,000,000 annually. [20]The array produces about 12,000 MWh of energy per year and is designed to operate for 25 years. The solar array is the first major step towards the academies goal of producing 100 percent of its energy from renewable sources by 2020 [21].

2.2.3.2 **Canon Air Force Base (CAFB)**

October is CAFB Energy Awareness Month. In 2010, the CAFB Energy Team received funding for three projects providing more than $830,000 in annual energy savings. Two lighting projects in 2011 resulted in more than $70,000 in savings per year. A readiness squadron housed at the base gets 20 percent of its diesel from biomass, B20 Biodiesel, and 85 percent of its gasoline from ethanol [22].

2.2.3.3 **Nellis Air Force Base**

Houses a 140 acre, 14 MW solar array built in 2007 by SunPower. This array meets an average of 25 percent of the electricity requirements at the Air Force base. The array reaches this production capacity by utilizing a SunPower T20 Tracker single-axis solar tracking system. The system costs $100 million and is owned and operated by MMA Renewable Ventures, LLC. The company sells the electricity to Nellis Air Force Base at a guaranteed rate for 20 years, saving the base $1 million a year. With an annual energy output of 30 GWh, the array consists of 5,821 trackers, 72,416 solar panels and 5,891,328 solar cells [23].

Figure 2.1: Nellis Air Force Base Solar Array

2.3 **International Efforts**

2.3.1 **Masdar City, Abu Dhabi**

Established in 2006, Masdar City is a solar-powered, eco-friendly experiment. It is located in Abu Dhabi in the United Arab Emirates. The city will be built from the ground up on a previously vacant piece of desert land and be completely sustainable clean-technology incubator. A graduate level, sustainable-technology research university, Masdar Institute, in partnership with MIT will serve as the hub for ideas. This experiment will cost $18 billion, house 40,000 residents and will be only two square miles in size [24].

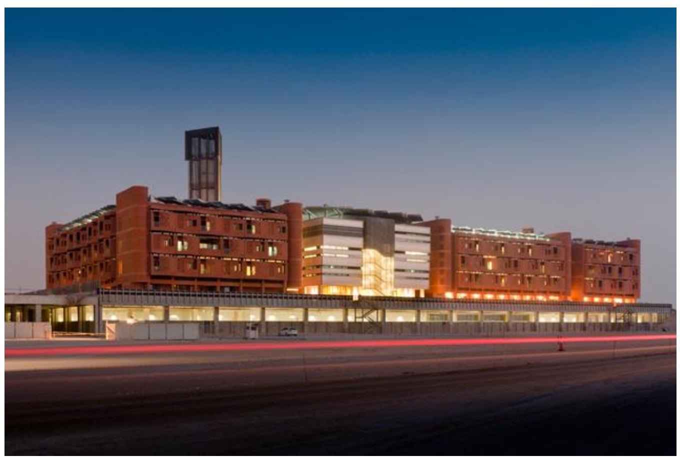

Figure 2.2: Masdar Institute Campus

2.3.1.1 **Energy Management**

The city's demand side management consists of employing the best commercially available energy-efficient techniques and stringent building efficiency guidelines. Examples include insulation, low-energy lighting specifications, window glazing, optimized natural lighting and smart meters, appliances, building management and distribution systems. The city will also include an interactive citywide energy management system that manages electrical load on the grid.

On the supply side, the city is completely powered by onsite renewable sources until it reaches a certain size. The ultimate goal is to have 20% of energy produced by onsite sources while the rest is powered by offsite renewables. As of April 2009, a 10MW photovoltaic array provides electricity and is the largest solar plant in the Middle East. The array spans 54 acres and powers the Masdar Institute, temporary Masdar administration buildings and onsite construction. Half the array consists of thin film while the other half is polycrystalline. Hot water is provided via evacuated tube solar and concentrated solar and geo-thermal heat are being tested for running absorption chillers for air-conditioning.

2.3.1.2 **Water Management**

Masdar City has a goal to reduce the usual 550 liters per person per day water usage to 180 liter per capita daily rate. This is a Phase 1 plan and ultimately the gaol is to reduce usage to 40 percent below the Phase one mark. The city uses high efficiency fittings, and appliances, smart water meters that give feedback to consumers and smart meters to identify leakage in the system. In the future, a water tariff will be implemented to promote further efficiencies.

All wastewater is treated and recycled for use in landscaping. This has resulted in a 60 percent reduction in water usage per square meter. In parallel, reduction in usage has been achieved via micro-irrigation, landscaping design that reduces plant evapotranspiration and low-water-use, indigenous plants and trees.

2.3.1.3 **Waste, Transportation and Materials**

The Phase 1 goal for waste is to divert 50 percent of waste from the landfill. The targeted waste is divided into three categories: Dry recyclables, wet recyclables and residual waste. Most private vehicles will be left at the city's edge. Transportation in the city is a combination of mass transit, self-propelled transport and walking. The Adu Dhabi light rail will pass through Masdar and connect the city to the outer metropolitan areas. The city has also initiated an electric vehicle pilot with Mitsubishi Heavy industries. The program employs point-to-point transportation within the city using Mitsubishi's EV hatchbacks. Building supplies will include 100 percent sustainable sourced timber, 90 percent recycled aluminum, concrete using recycled slag instead of cement, water-based paints with non-volatile organic compounds and reinforcing bars made of 100 percent recycled steel [25].

2.3.2 Jeju Island

Jeju island, the exclusive location of Jeju province is an island of South Korea in the Korea Strait. As of December 2011, Jeju island's population totals approximately 580,000 residents, about 1 percent of the Korean population. Comparatively, the population density of Jeju is 303 persons per square km. Korea as a whole has a density of almost 500 persons per square km. In 2006 it was reported that nearly all of Jeju Island's energy consumption was produced by petroleum sources with 27 percent for electricity production. Korea established the National Energy Basic Plan in 2008 that set a goal of a 46 percent energy efficiency increase for newly installed energy and a fivefold increase in new and renewable energy by 2030. Jeju regional energy planning is based on the Energy Basic Law established in 2006. Jeju's goal is to be sustained 20 percent by new and renewable energy sources by 2020 and 50 percent by 2050 [26] [27].

2.3.2.1 Solar power

Jeju plans on implementing large scale solar photovoltaic and solar thermal into the existing infrastructure. PV arrays can be built on the surplus property within the wind farms. By 2050, Jeju plans for 450 MW of energy generated by PV and 680,000 square meters of solar thermal. This will account for a collective 10 percent of the projected renewable energy supply for the island [27].

2.3.2.2 Wind Power

Currently, Jeju Island houses a 10MW wind farm in Haengwon, but is only 1 percent of Jeju's electricity demand. The Green Village Project includes 57 households with a collective

160 MWh annual production. This accounts for 75 percent of the project's load. Since 60 percent of Korea national wind potential is concentrated in Jeju, plans are in place to build 565 MW of wind generation by 2020 and increase it to 936 MW by 2050. This will account for 20 percent of Jeju's estimated renewable supply in 2020 and 30 percent of supply in 2050 [27].

2.3.2.3 Geothermal Power

Jeju island was formed directly from volcanic activity approximately one million years ago. A second major volcanic event created Mt. Halla in the center of the island. The origin of the island's creation has resulted in the island being a major potential source for geothermal energy production [26]. Due to difficult geological conditions and high economic costs, there are limitations to the amount of geothermal that can be utilized on Jeju Island. The plan is to focus on building geothermal plants close to industrial sites. The goal is to produce 130 MW of energy by 2050 which would be 15 percent of total renewable supply [27].

2.4 University of Hawai‘i at Manoa

2.4.1 Charter of Sustainability

In 2003 UH issued the Charter of Sustainability. Along with the charter, twelve committees were formed to address specific problems and solutions on the Manoa campus. The charter also included a mission statement: "The University of Hawai‘i will apply the principles of sustainable design and environmental stewardship to all of its activities. It will become a leader in Hawai‘i and the Pacific region in education, research, extension, and community collaboration related to sustainability."

The charter declared nine essential strategic goals including:

1) Use energy wisely

2) Practice sustainable water use

3) Minimize negative impact on the land

4) Create sustainable buildings

5) Promote alternative transportation

6) Minimize material waste

7) Adopt green purchasing policies

8) Enhance the quality of the campus experience

9) Teach the principles of sustainability

Each strategic goal includes a set of priority outcomes and action recommendations and many of these recommendations have been implemented since.

One strategic goal to highlight, as an example, is goal number 1, “Use energy wisely.” This goal is broken down into three major categories listed as: Conserving energy, using energy efficiently and generating renewable energy. The first category, conserving energy, consists of four priority outcomes:

1) Educating the members of the University of Hawaiʻi.

2) Use current technology to make conservation easier. A project currently in the works means to place grid monitoring sensors on all buildings to assess energy usage and reduction.

3) Develop an incentive program to encourage campus-wide conservation. A program since implemented is the Kukui Cup, which will be described in greater detail later.

4) Engage campus personnel in promoting sustainability goals. Many programs have been implemented such as REIS and the Manoa Sustainability Council.

The second category, using energy efficiently, has one priority outcome. Since the campus already has a well-established infrastructure, the priority outcome is to reduce energy use in existing buildings. Highlights of the action recommendations include: reducing source energy use by 20 percent and improve chiller plant efficiencies by 15 percent relative to 2003 levels by 2007. New buildings will have reduced energy usage levels of 40 percent relative to 2000 levels.

The third category, generating renewable energy, is arguably the most difficult and is the main focus of this thesis' project. The priority outcome is to use renewable resources to offset fossil-fuel dependence. Actions include generating 5% of campus electricity on-campus from renewable sources, retrofitting the Hawaiʻi Energy house to generate 100% of its own electricity and installing solar water-heating features on one building on campus [28].

2.4.2 UH Manoa Sustainability Policy Statement

In October 2006, a green building design and clean energy policy was issued at the UHM Chancellor's Energy Summit. The policy included what could be considered updates from the Charter of Sustainability. The stated goals of the policy included:

1) 30% reduction of campus-wide energy use by 2012, based on a 2003 campus energy benchmark.

2) 50% reduction of campus-wide energy use by 2015, based on a 2003 campus energy benchmark.

3) 25% of campus-wide energy use supplied by renewable sources by 2020.

4) Achieve self-sufficiency in energy and water, and treat and transform campus wastes into useable resources through actions to conserve and re-use, and through adoption of renewable energy technologies by 2050.

The policy focuses on two major categories: Green building design and clean energy. There are over twenty different guidelines issued under the green building design policy. Many include goal associated toward LEED level certifications for both existing buildings and proposed new facilities. The clean energy policy focuses on the reduction of energy from fossil fuel sources via a combination of on-campus energy production and the active seeking of purchasing electricity from renewable energy sources. The Campus Energy Management Office is primarily tasked with the planning and implementation of these guidelines [29].

2.4.3 **REIS (Renewable Energy and Island Sustainability)**

The REIS center was established in 2009 and focuses on work for cutting edge research and education problems in renewable energy and island sustainability. REIS was initially funded internally through a university sustainability grant, but is currently funded additionally by a Department of Energy grant on work force training in Strategic Training and Education in Power Systems. REIS is a collaboration of 8 colleges from the UH system including:

- College of Engineering
- College of Social Sciences
- College of Natural Sciences
- School of Architecture
- School of Ocean and Earth Science and Technology
- College of Tropical Agriculture and Human Resources
- William S. Richardson School of Law
- Schidler College of Business

The goals of REIS include developing interdisciplinary education programs, conduct multi-disciplinary research, assist the state of Hawai‘i, utilities, industry and national laboratories, develop experimental test beds and develop recruitment, retention and outreach programs all within the renewable energy, energy efficiency, smart grid and sustainability fields.

Multi-disciplinary projects include the Smart Deployable Disaster Devices ($D^{3)}$ Project. The project is a relatively small, self-sufficient renewable Energy Production, storage and distribution/delivery system for disaster type scenarios. There are two test sites for the project, one at Kahuku Farms and the other at Papakolea Community Center.

Another multi-disciplinary project is the Smart Sustainable UH Campus project. The project is focused on understanding micro-grid behaviors subject to large renewable energy sources, demand response, integration of energy control devices, and energy efficient practices. The project is particularly applied to the UH Manoa micro-grid and is the over encompassing project for the wireless meteorological device being developed for this thesis. Disciplines involved in this project include but are not limited to electrical engineering, mechanical engineering, computer science and architectural students.

Other focus projects under REIS include:

- Green Holmes Hall Initiative
- Kukui Cup
- Nanotechnology in Renewable Energy Production and Storage Devices
- Ocean Wave Energy Converter
- Solar Photovoltaic Water Pumps
- Thermo-electric Energy Harvesting
- Watt Depot

[30]

2.4.4 **Kukui Cup**

One focus project to highlight is the Kukui cup which was first conducted in 2011. The Kukui Cup puts less emphasis on the manipulation of technology and more on the dynamics of human behavior and energy usage. The project employs a combination of real-time feedback, incentives, education, and gamification techniques to support sustained, positive changes within a group of energy consumers; specifically residents of the dormitories at UH [31].

2.4.5 **Manoa Green Days**

Manoa green days is a program to help reduce energy usage which, in turn, reduces operating cost for Manoa campus. Volunteer building coordinators from more than twenty campus buildings communicate with building occupants about the initiative. Green Days usually occur on weekends, holidays and night hours for some buildings. An example of a Green Day includes turning off half of the air conditioning systems for Holmes Hall during holidays. In 2008, the annual cost of electricity for the campus was $23 million. 75% of the electricity is due to air-conditioning use. The initiative is estimated to save the campus $3 million a year. [32]

2.4.6 **Sustainable Saunders**

Saunders Hall is UH's first building with a renewable energy test. With donations and logistical assistance from Hawaii Energy Connection, Enphase Energy and the UH Manoa Sustainability Council, the rooftop of Sanders Hall houses the first project to evaluate micro-inverter technology that improves solar array efficiency. Micro-inverters convert power from DC to AC on each individual panel. This set up removes the drop in efficiency from the worst performing panel of the group. The test bed communicates real-time power production data from each solar array to a central website that archives the historical data [33].

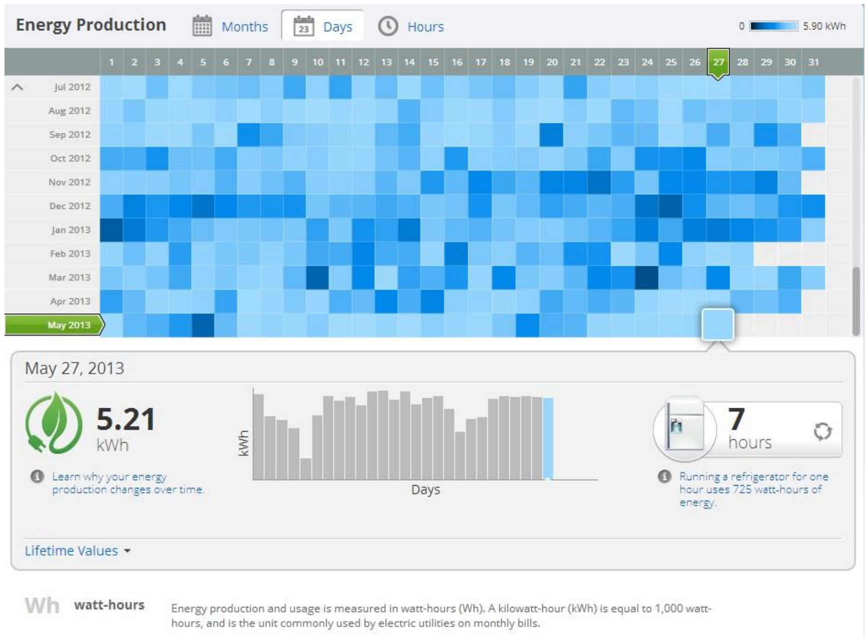

Figure 2.3: Saunders Hall energy production web page

Sensor Projects: Commercial and University Research

2.5 Commercial

2.5.1 Texas Weather Station

The Texas Weather Station is a field deployable meteorological monitoring platform. The station monitors wind speed and direction, barometric pressure, indoor and outdoor temperature, relative humidity, and rainfall. Optional sensors include solar irradiance and lightning measurement. The sensor station and a dedicated display console sells for $1202. There is no data logging with this device. Table 2-1 shows the parameters of the various sensors [34].

Function	Range	Accuracy
Temperature	-40 - +50°C	±1°C
Barometric Pressure	950 - 1150hPa	±1.0 hPa @ 25°C
Relative Humidity	0 – 100%	±3%
Wind Speed	1 – 320 km/h	±1%
Rain	182 cm^2	±1%

Table 2.1: Sensor specifications for WRL Weather Station

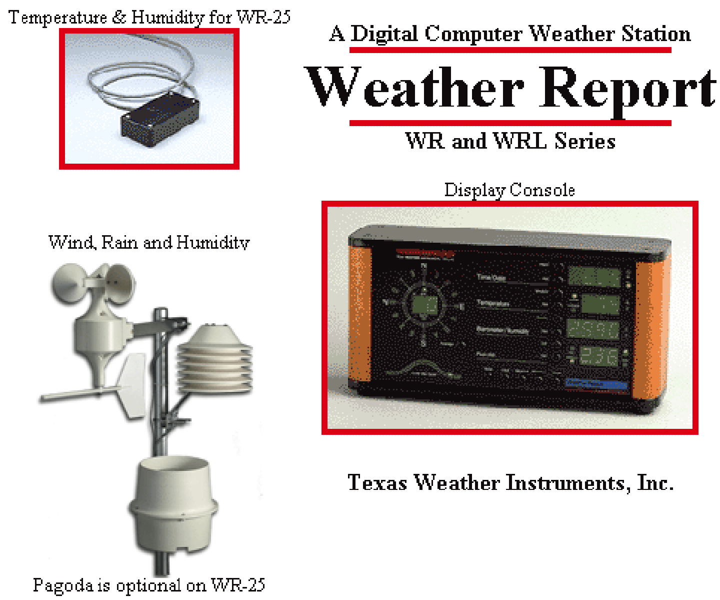

Figure 2.4: WRL weather station

2.5.2 Weather Hawk 916 wireless weather station

The Weather Hawk station uses a 916 MHz spread spectrum radio with a range of up to 0.5 miles. The Weather Hawk 916 wireless weather station monitors temperature, barometric pressure, solar irradiation, relative humidity, wind speed and direction, and rainfall. Power can be supplied via a solar panel or AC power. Data can be posted live to the internet, with updates every three second, via a program called Virtual Weather Station. The station sells for $2,388. Table 2-2 shows the parameters for the station’s various sensors [35].

Function	Range	Accuracy
Temperature	-40 - +50°C	±0.5°C
Relative Humidity	0-100%	±5% 90-100%RH, ±3% 10 – 95%RH
Barometric pressure	150 – 1150 hPa	±15hPa (0 - 85°C)
Solar Radiation	0 – 2000 W/m^2	
Rain Gauge	50cm^2	0.25mm

Table 2-2: Sensor specifications for Weather Hawk station

Figure 2.5: Weather Hawk 916 weather station

2.6 **Universities**

2.6.1 **Bucknell University**

Bucknell University utilizes a single station located in Lewisburg, PA with sensors that measure air temperature, relative humidity, wind speed, wind direction, solar irradiance, precipitation, and barometric pressure. The station provides real time monitoring once per minute with data logging. Software called BucknellBug is compatible with the station and allows user to access the data and receive local data in real time. Table 2-3 shows the parameters for the station's various sensors. [36]

Function	Component	Range	Accuracy
Temperature	HMP45C Temp/RH probe (mounting height: 2m)	-40°C to +60°C	±0.2°C at 20°C, ±0.4 at -20°C and 60°C
Relative Humidity		0-100%	at 20°C: ±2%RH (0 to 90%RH) ±3%RH (90 to 100%RH)
Precipitation	TE525WS Rain Gage	0 to 700mm/ hr	±1% up to 25 mm/hr 0 to -2.5% at 25-50mm/hr 0 to -3.5% at 50-75mm/hr
Barometric Pressure	CS105 Barometric Pressure Sensor	600-1060 hPa	0.5hPa at 20°C; ±2hPa at -20°C to +45°C
Wind Speed	Met One 034A-L Windset (mounting height: 3m)	0-49m/sec	for wind speed <10.1 m/sec = ±0.12m/sec ; >1m/sec = ±1.1%
Wind direction		0-360°	±4°; resolution 0.5°
Solar Radiation	Kipp & Zonen CNR1 Net Radiometer (mounting height: 3m)	0.3 to 3 micrometers	±10% for daily sums
Far Infrared Radiation		5 to 50 micrometers,	

Table 2-3: Bucknell university weather station sensor specifications

Figure 2.6: Bucknell University weather station

2.6.2 **Telemark University College**

The Telemark University College uses the AWS 2700 weather station manufactured by Aanderaa. The station is a self-contained sensor platform that can house up to ten sensors and a radio transmitter. The university's system monitors barometric pressure, temperature and wind speed. The station houses a data logger that can monitor up to four sensors and can transmit the data in 10 bit code via VHF or UHF radio. The logger can also send the data in engineering units via modem. Data can be accessed via the weather system website and can be viewed via PC, tablet, or smartphone [37] [38].

Function	Range	Accuracy	Resolution
Barometric Pressure	920 – 1080 hPa	±0.2hPa	0.2hPa
Temperature	-43 - +48°C	±0.1°C	0.1°C
Wind Speed	0 – 79 m/s	±2%	N/A

Table 2-4: Telemark University weather station sensor specifications

Figure 2.7: Telemark University weather station

Chapter 3

Network

3.1 Wireless Networks

Since the sensor network being utilized spans across campus to every accessible building, networking the nodes together via a hardline is not nearly practical. A wireless network is needed that could handle the specifications required. Some options of different network topologies are available. Point-to-point, ring, and tree networks are among some of the available types. For this project, a mesh network was chosen, specifically a partially connected mesh. A network of this type accommodates that fact that the campus layout is not symmetrical or consistent, therefore neither can the placement of the modules be.

The wireless hardware being used is an XBee radio frequency module. This module meets IEEE 802.15.4 standards operating at 2.4 GHz. They are low cost, low-power and compact. This also means the radios have a relatively small range. Each version of the XBee radio is pin-to-pin compatible, allowing easy interchangeability between module types.

XBee modules also use a ZigBee network protocol. This protocol provides option for different network management settings including ad hoc, many-to-one, and source routing. ZigBee brings with it a “self-healing” network capability that is being utilized in the sensor network at UH.

3.2 XBee

3.2.1 Model types

There are many parameters to take into consideration when choosing an XBee module type. There are two series types, standard and Pro models, and multiple module designs. XBee comes in series one and series two. Series one models only allow point-to-point and star network topologies. Series two allows for the multitude of network choices required for this project. The standard XBee model, as compared to the Pro model, sacrifices range for lower power consumption. The standard model has a line-of-sight range of 120m while the Pro (specifically the S2B model for this project) has a range of 3.2km. [39] Due to the remote location of each module, a Lithium Polymer (LiPo) battery is needed to provide power to each node. Radio communication is the most energy demanding function of the sensing module and the standard model XBee would be the preferred choice in this context. However flexibility for range testing is required while in the early prototyping phase. The newer Series 2B modules allow the broadcast power levels to be reduced at the cost of range. Future versions of the network will allow for a combination of standard and Pro models as monitoring locations become more solidified. Both models are compatible together on the same network. All future references to the XBee can be assumed to be referring to the XBee Pro S2B module.

Figure 3.1: XBee Series S2B module

Figure 3.2: XBee series S2 module

3.2.2 Power Consumption

As mentioned before, the transmission of data is the most demanding function for the battery to sustain. There are multiple strategies to combat this design constraint. Using a low power model is a choice already discussed. The standard model XBee uses 40 mA at peak transmission compared to the S2B Pro model at 205 mA. Another option is to reduce the broadcast power of the module when setting device parameters via the programming terminal. The terminal X-CTU is discussed in more detail in section 3.4.1. An additional feature to save power is sleep mode. This mode and its behavior can be set when programming the module and remotely when in Application Programming Interface (API) mode. While in sleep mode, the module consumes less than 3.5µA at 3.3V. Unfortunately, sleep mode can only be utilized for end devices. End devices and its counter parts are discussed in section 3.4. As of this writing, the mesh network uses only routers and coordinators for communication and therefore, the network cannot take advantage of sleep mode.

3.3 ZigBee

ZigBee is the communications protocol utilized by the XBee radios. The protocol is based on the 802.15.4 IEEE Standard. Three additional layers are provided to the native 802.15.4 standard: routing, ad hoc network creation, and self-healing mesh. ZigBee allows low-power radios to communicate over larger distances than an individual radio is capable of by routing communications through one another via a network. There are many different network configurations to choose from including star, tree, partially connected mesh, and fully connected mesh. This sensor network uses a partially connected mesh.

ZigBee can configure each XBee radio to one of three modes: coordinator, router, and end device. The coordinator is the main node through which all organization of the network is controlled and routed through. There can only be one coordinator per network. A router is capable of sending, receiving, and routing information throughout the network. There can be multiple routers and these devices must stay on all the time. End devices are less capable than routers with one advantage. End devices can go to sleep and therefore use less power. Information cannot be routed through an end device [40].

3.3.1 **Routing**

ZigBee allows for autonomous creation of routing tables to facilitate getting data to and from the coordinator to the nodes on the outer edges of the network. Most buildings on UH campus are not in line-of-sight to Holmes Hall, which is where the coordinator is located. Holmes Hall is at the South East corner of the main campus and sits geographically at the periphery of the proposed network map. A visualization of a potential mesh network configuration superimposed across the UHM campus is provided in Figure 3.3. The data logging server is located within Holmes Hall and the coordinator is on the roof hardwired directly to the server. Modules on the perimeter of the network will be out of range of the coordinator. Intermediate router nodes can, therefore, relay data through the network until the packet reaches a node within range of the final coordinator node [41].

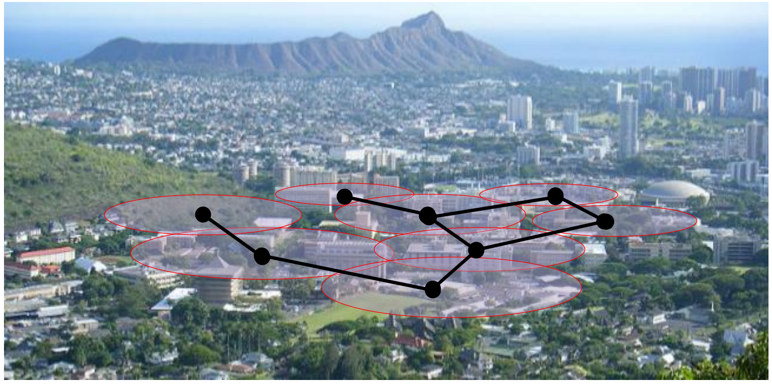

Figure 3.3: Superimposed view of a mesh network across UHM campus

3.3.2 **Ad Hoc Network**

The second feature ZigBee provides is the ability to create a network "on-the-fly". Each XBee radio is permanently assigned unique a 64-bit address. To reduce the amount of node identifying information needed to be transmitted and stored, the coordinator autonomously creates a temporary 16-bit address for each radio on the network. This allows for up to 65,536 radios on a single network.

3.3.3 **AT vs. API**

AT mode stands for "Attention mode", while API stands for Application Programming Interface. AT mode is the simpler of the two modes and has two sub-modes: transparent and command. Command mode allows for manipulation of the radios parameters. Transparent mode relays any information passed through the radio to the appropriate destination radio. AT mode is not good for large networks bigger than ten nodes.

API mode allows for the needed mesh networking. Information is sent as bytes and the bytes, in each transmission, are collectively called a packet. Each packet requires a start delimiter at the beginning and a checksum at the end. The destination address of the receiving radio and data are contained within the packet [40].

3.3.4 Self-healing Network

The last additional layer is the self-healing network. If one or more radios disconnect from the network, a dead battery for example, the network will automatically find a new route for all nodes out of line-of-sight range to the coordinator. This only works if the router that is lost was not a single point route through that part of the network. A tree network could have this problem. A self-healing network also allows for maintenance or removal of a node from the network without any significant interruption.

3.4 XBee Programming

The XBee radios require setup from their default settings to be useful for large networks. Parameters including pan ID, communication mode, and baud rate must be preprogrammed before deployment in the field. All radios must have the same pan ID and baud rate. XBees also have two modes of communication: AT and API mode. Each XBee device can be programmed in one of three categories: coordinators, routers, and end devices. Coordinators are responsible for setting up the network and managing all routing tables. The 16-bit address is issued to each device by the coordinator. Routers are modules that can send, receive, and route data within the network. If one router is removed from the network another router in range can take up the rerouting process. End devices only send and receive data. End device are incapable of routing. The advantage of this limitation is that end devices can enter a sleep mode to save power, a feature that routers and coordinators lack.

3.4.1 X-CTU

Programming the XBee radio requires a terminal program. The default program is X-CTU. All XBee radio parameters can be set and tested via the terminal. Communications can also be tested and addresses verified.

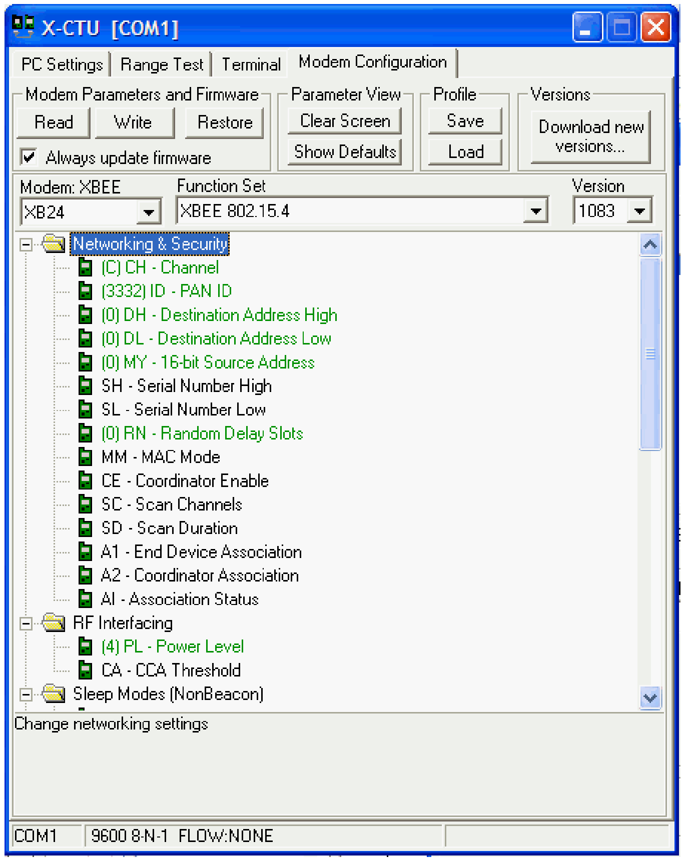

Figure 3.4: X-CTU terminal program

3.5 XBee/Arduino Interface

The various sensors in a module communicate with an Arduino microcontroller. The Arduino then sends its data to the XBee for transmission. Since a mesh network requires API mode, and API mode has a strict communications protocol, the Arduino has to send the data packet in a specific format. If communication is temporarily interrupted, data can be stored in the buffer.

3.5.1 XBee.h Library

An open-sourced Arduino library named XBee.h is available to provide packet assembly with each reading of the sensors for the respective node. The start delimiter, destination address, data, and checksum are all organized properly into the payload to be sent as a packet.

3.6 **Data Logging**

After data has been collected by a module and sent to the coordinator, that data need to be organized and logged in the server. An algorithm was developed to manage the times series of sensor readings at the server end of the system. Initially, a JSON string was employed to organize the data. The following demonstrates the time series encoded in such a way resulting in 162 bytes of information:


```
{"address": 544, "uptime_ms": 242934985, "bmp085_temp_decic": 473,
"bmp085_press_pa": 100957, "batt_mv": 3812, "panel_mv": 4750,
"apogee_mv": 46, "apogee_w_m2": 230}
```


The format has some significant practical advantages due to its ease of construction and is straight forward to parse with standard JSON deserialization functions. A big disadvantage is that it is large and the total length is variable.

In this format, each data item in the packet is not accompanied by an explicit label like in a JSON string. Instead, the data items are assigned a specific length and put in a specific pre-assigned order. An example of a data string used is shown below:

```
typedef struct {
        uint16_t schema;
        uint16_t address;
        uint32_t uptime_ms;
        int16_t bmp085_temp_decic;
        uint32_t bmp085_press_pa;
        uint16_t batt_mv;
        uint16_t panel_mv;
        uint16_t apogee_mv;
        uint16_t apogee_w_m2;
} schema_0;
```

The data packet is unpacked on the server side using a function that has foreknowledge of the different packet formats. The first two bytes indicate which data format is being used, therefore which unpacking procedure to implement. An example packet string is shown:

0000 2002 C9E47A0E D901 5D8A0100 E40E 8E12 2E00 E600

Each data item has a specific length and position in the string, separated by a space. This method has the advantage of using less memory per transmission. For example, the packet above uses 22 bytes as opposed to the previous 162 bytes.

Lowering the amount of data per packet allows for not only more information per transmission, but allows multiple time series measurements to be sent at once. Even the data from sensors read at different frequencies can be incorporated into the same transmitted string. The time stamp of each reading is provided by the server clock at the time the data packet is received, and is applied to the most recent data item. All other previous items in the time series are assigned their respective time stamps based on a multiplier associated with the time interval of gathering that sensor's data. Once on the server, the data can be access in one of three ways: command-line access directly on the server, an ssh-tunneled database connection, or through a simple website [42]. Below is an example of time series data having been unpacked correctly and displayed for analysis:

```
=> select db_time, uptime_ms, batt_mv, apogee_w_m2 from outdoor_env
        where address = 14159 order by db_time desc limit 10;
```

db_time	uptime_ms	batt_mv	apogee_w_m2
2013-06-19 19:59:32.759653-10	8700000	8700	8700
2013-06-19 19:59:31.759653-10			8699
2013-06-19 19:59:30.759653-10			8698
2013-06-19 19:59:29.759653-10			8697
2013-06-19 19:59:28.759653-10		8696	8696
2013-06-19 19:59:27.759653-10			8695
2013-06-19 19:59:26.759653-10			8694
2013-06-19 19:59:25.759653-10			8693

Chapter 4

Module Overview

The vision for the sensor module was to make a circuit and housing that was small, lightweight and easy to deploy, while still being inexpensive, self-powered and weather-proof. Most weather-proof meteorological sensing devices available are not small and consume large amounts of energy. To self-power these devices, requires a larger number of solar panels and batteries. This, in turn, significantly raises the cost of a module and makes deployment more difficult. The disadvantages are amplified when a large number of modules are needed.

Figure 4.1 Common example of a weather monitoring station

Chapter 4 will cover module housing design, internal circuit design and sensor details. In housing design, 3-D printing will be highlighted as the method used for rapid prototyping. Circuit design will cover the microcontroller used along with power production and storage methods. Sensor detail will discuss the characteristics of each sensor utilized for weather monitoring.

4.1 Box Design

The housing for the sensor box was designed around the modular nature of the prototype circuit. The various sensors, the Arduino microcontroller and the battery are all in their own exclusive compartments. This design was an attempt to organize the various parts of the module as to minimize clutter inside the housing while in the prototype phase. Approximately 90% of the housing's footprint is protected by the solar panel mounted on top. This helps to maintain the weather-proof characteristic during testing as the box's lifetime is unknown. Originally, version 1 of the housing had 4 legs that extended out to widen the base and improve the stability of the module.

Figure 4.2: Sensor module version 1 housing with version 1 circuitry

Also, the battery charging circuit was mounted directly underneath the solar panel, adjacent to the main housing. This created complications, as there were four individually exposed wires running from the charging circuit box to the main housing. Version 2 uses a smaller solar panel which does not cover the charging circuit housing. The base of version 2 also changed to accommodate a base plate used to hold a heavy object, in this case a lead diving weight, in order to prevent the module from blowing over in heavy winds.

Figure 4.3: Sensor module version 2 housing with version 1 circuitry

Figure 4.4: Sensor module version 2 deployed in field

4.2 3-D Printing

As of this writing, low cost and reasonably reliable, personal 3-D printing machines are a new technology that has been used as a critical part of this project. Unlike their commercial grade counterparts, which can cost tens of thousands of dollars, these machines cost in the range of a few thousand dollars. This technology allowed the possibility of rapid prototyping of the housing for any current iterative design. Subsequently, a new version could be redesigned and fabricated in-house as quickly as within the same day. This possibility greatly reduced any added cost of making minor changes to design. The worker hours required for fabrication was greatly reduced since the machine requires very little supervision while in operation.

4.2.1 Thing-O-Matic

The first 3-D printer utilized for prototyping was the Thing-O-Matic manufactured by Makerbot Industries. It prints primarily with acrylonitrile butadiene styrene (ABS) plastic filament. The volume of potentials print space is 96mm x 108mm x 115 mm [43].

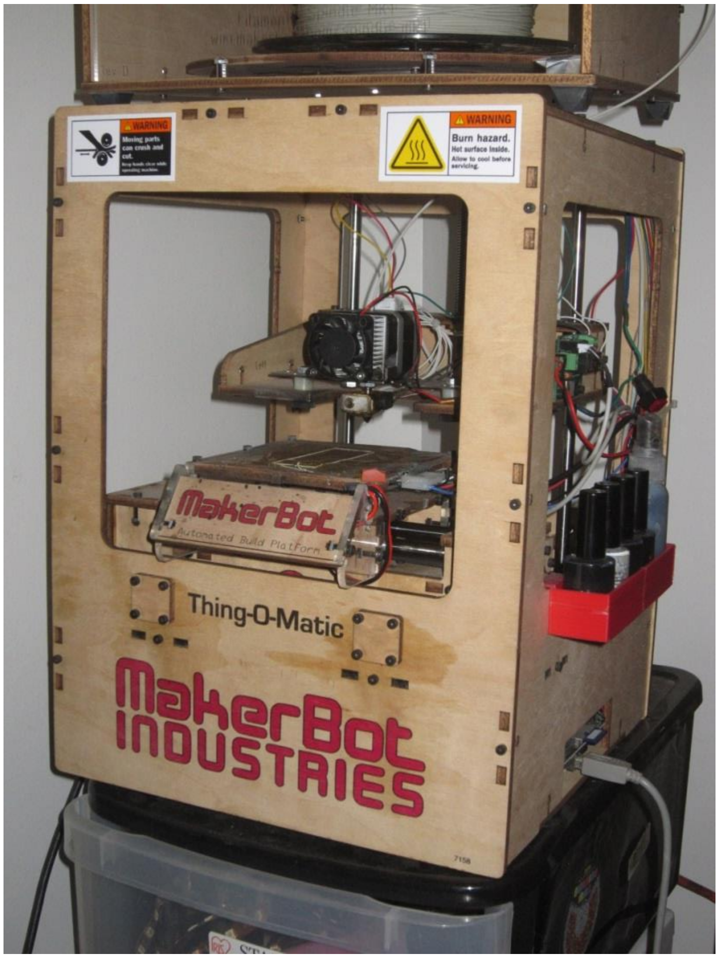

Figure 4.5: Thing-O-Matic 3D printer

This volume was not sufficient to print the entire box at once. Each compartment of the box had to be printed consecutively. Also, ABS warps easily when printing large objects and negates the precision of the 3-D printer. ABS can, however, be fused together by being temporarily dissolved with acetone. The immediate solution was to print the box in small components and "glue" the appropriate parts together post print. Total print time of the box was approximately ten hours.

Figure 4.6: Spool of plastic filament

4.2.2 **Replicator 2**

The Replicator 2, also manufactured by Makerbot Industries, is 2 generations senior to the Thing-O-Matic (TOM). Print volume is 285mm x 153mm x 155mm. It exclusively prints filament made of polylactic acid (PLA). This material is a non-toxic, biodegradable plastic made from plant based starches [44].

Figure 4.7: Replicator 2 3D printer

PLA is much less susceptible to warping than ABS. This fact, along with the larger print volume, allows for the printing of the module housing as one unit. PLA, however, does not dissolve in acetone like ABS; therefore, the fusion of parts in this manner is not possible. The total print time of all parts was approximately 7 hours. This would allow 1 box to be printed per day per machine.

4.2.3 **Printer Comparison**

The Replicator 2 has some obvious advantages over the Thing-O-Matic for prototype fabrication. Print time was significantly shorter than the TOM. Additionally, there is nearly zero post print machining required. It is possible to print with relatively reduced supervision of the machine compared to the TOM. With each unit being printed as a whole piece on the Replicator 2, there is also less total between-print down time.

The warping of ABS was a significant problem. Pieces with a large footprint would be the most susceptible to warping at the base of the object along the edges. This problem was not completely absent for PLA. However, parts that were three times as big in PLA would still not succumb to nearly as much warping as a smaller part in ABS. PLA is more rigid than ABS. This fact also means that PLA is more brittle and will snap instead of bend under too much stress. The plastic deformation of ABS seemed to be a problem with certain parts for the housing. One specific example is the housing lid. The warping of the lid lowered our confidence in the housing's weather proof capability.

Despite that these housings are prototypes; they still needed to handle being outdoor long enough to test design characteristics. This means the housing needed to be weather proofed. With ABS, it is possible to seal the parts surfaces with scraps of ABS dissolved in acetone. The acetone would quickly evaporate in a few minutes leaving behind the dissolved ABS, filling and fusing any small gaps between print layers. By comparison, PLA did not seem to need the sealing treatment. While not completely pressure tight, PLA has a more “liquid” consistency during printing. While the PLA is heated through the extrusion nozzle, it flows more as it is laid on top of the previous layer. This property helps to significantly minimize the air gap between each layer of the print. During initial testing, it appeared that no water was wicking through the PLA to the inside of the housing.

Fusing and sealing the ABS box with ABS/acetone solution did come with some consequences. The lid would warp if the sealant was applied asymmetrically on a broad surface. Fusing of the parts did not always guarantee good subunit alignment. Overall the integrity of the housing was lower using the fusing technique compared to a unit printed as one whole piece.

4.3 **Circuit Design**

The discrete module design comprises of each sensor on its own “breakout” board. Each individual PCB has its own exclusive set of components that meet specifications of their respective datasheets for using the sensor for its intended application. All sensors require 3.3V power from the Arduino to operate with the exception of the temperature sensor that requires 5V. All sensors are digital, requiring current in the µA range. The onboard 3.3V voltage regulator for the Arduino is rated for 150mA output current and is more than capable of supplying the necessary power to the sensor system (~65mA including the Arduino). The XBee radio, however, is rated for 205mA during max power. An extra 3.3V regulator is needed and is provided by the XBee shield currently being used to get full transmission range.

4.3.1 **Design Testing**

During testing, the individual breakout board’s operation was verified with its respective software library. The temperature sensor uses one-wire for communication. The luminosity and barometric pressure sensor use I^2C. The humidity sensor communicates via digital serial. Once proper understanding of the sensor had been attained, the board was consolidated with the rest of the module and appropriate modifications to the library were made.

4.3.2 **Circuit Optimization**

With the discrete design, we are able to easily test the optimal physical placement of various sensors within and around the module. It may be necessary to move the luminosity sensor to a location on a particular side of the module due to shadowing from other components like the XBee antenna. The barometric pressure sensor should be kept out of direct air flow to minimize erratic readings while not being sealed to allow real time atmospheric pressure readings. Temperature and pressure are likely to need a small amount of air flow to minimize any inaccuracy due to greenhouse effect within the compartment. The temperature and humidity sensor should also not be placed near any relatively high power components that could cause localized heating of the sensor's PCB. The initial design is shown in Figure 4.8.

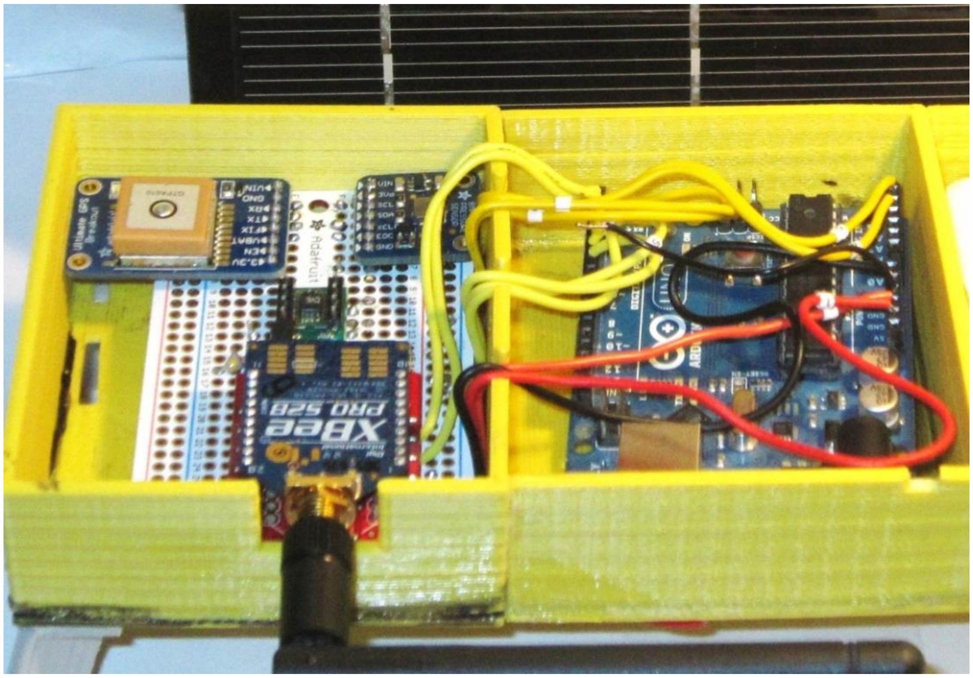

Figure 4.8: Placement of sensors in version 1 housing

4.3.3 **Module Power**

The Arduino is capable of supplying power at the necessary voltage to the sensors within the module. Due to a potential 1.2V dropout voltage on the 5V voltage regulator, the input supply voltage to the Arduino needs to be at least 6.5V in order to work reliably. Since we are using 4.2V LiPo batteries, a work around was required for our initial prototype. We placed a 5V DC step-up booster between the battery and the Arduino. We then bypassed the 5V voltage regulator by plugging the 5V booster directly into the 5V bus on the Arduino board. The XBee also requires an exclusive 3.3V with at least a 210mA rating. An additional voltage regulator could be added to the consolidated board in place of the current Arduino 3.3V regulator.

4.3.4 **Arduino Microcontroller**

The Arduino is an open-source, low-power, low-cost microcontroller platform for prototyping. Many of the libraries available were created using crowd sourced development models. The schematic design for the board is freely available and has an open source license, meaning anyone can manufacture, modify and redistribute the board design for their use. Many versions of the Arduino exist including: Arduino Uno, Arduino Mega, Netduino and Arduino Leonardo. The Arduino Uno is the board used in this project [45].

Arduino utilizes an ATmega328 8-bit microcontroller. The chip uses RISC architecture. Memory includes 32kB of in-system self-programmable flash memory, 1kB of EEPROM and 2kB of internal SRAM. Data includes 23 programmable I/O lines with 14 digital pins, 6 capable of PWM, 6 analog pins, I^2C and SPI interface and USB connectivity. The board includes a 16MHz ceramic resonator, ICSP header and 5V and 3.3V voltage regulators. Input voltage is 6.5V – 20V with an operating voltage of 5V [46].

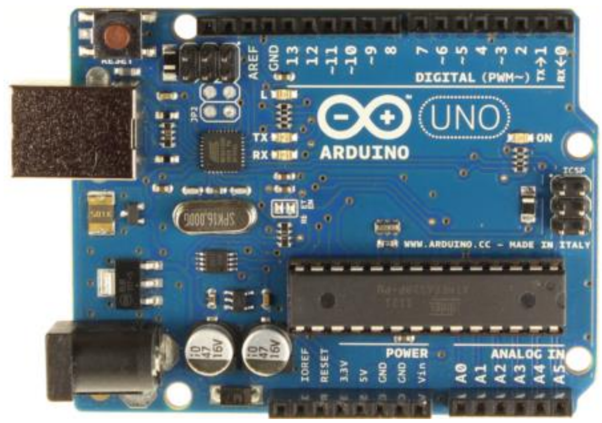

Figure 4.9: Arduino Uno

4.4 Sensors

The various sensors have been selected to measure fundamental meteorological characteristics of the local environment on the rooftop of the campus. The basis for selection was to minimize price, size and power consumption, while still maintaining good measurement accuracy and resolution. Digital sensors were selected to minimize electromagnetic noise from surrounding devices in the area.

4.4.1 Pressure

The pressure sensor uses a BMP085 sensor module made by Bosch. The breakout board was designed by Adafruit Industries. The sensor measures barometric pressure in the range of 300 – 1100 hPa with a typical accuracy of ±1.0 hPa and a resolution of 0.01 hPa. The incorporated temperature sensor has a range of -40ºC - 85ºC with an accuracy of ±1ºC. Data is transferred via I^2C interface.

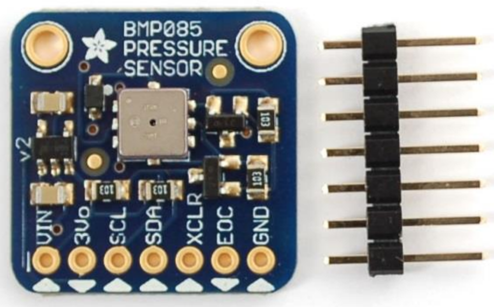

Figure 4.10: BMP085 barometric pressure sensor

Since the housing module is not pressure tight, the pressure sensor can be placed in the main compartment of the housing so that it is fully protected from outside elements [47].

4.4.2 **Luminosity**

Solar irradiance levels are monitored using the TSL2560 digital luminosity sensor designed by TAOS Inc.. The breakout board was designed by Adafruit Industries. The sensor detects infrared and visible light bandwidths with a range of 0.1 – 40,000 Lux. Data is transferred via I^2C interface [48].

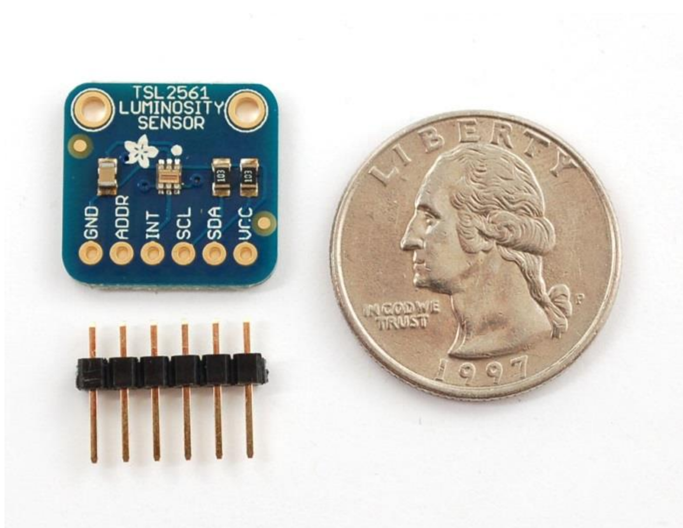

Figure 4.11: TSL2561 digital luminosity sensor

The luminosity sensor needs to be placed external to the housing preferably next to the modules solar panel.

4.4.3 **Humidity**

Air humidity is measured by a SHT11 sensor module manufactured by Sensirion. The sensor measures humidity from 0 – 100% with an accuracy of 3.5% and a resolution of 0.03%. The sensor also measures temperature with a range of -40ºC – 123.8ºC with an accuracy of 2ºC and resolution of 0.01ºC. Requires 3.3V or 5V supply voltage and consumes 550µA during measurement. The sensor is digital and communicates via 2-wire serial [49].

Figure 4.12: SHT11 Sensirion digital humidity/temperature sensor

4.4.4 **Temperature**

Temperature is measured with a DS18B20 sensor manufactured by Maxim Integrated Products Inc.. The sensor's range is -55ºC - 125ºC with an accuracy of +/-0.5ºC (at -10ºC - 85ºC) and a resolution of 0.05ºC. Communication is digital via Dallas One-wire® protocol. The sensor can be powered by either 3.3V or 5V input supply. During measurement, the sensor demands approximately 1mA [50].

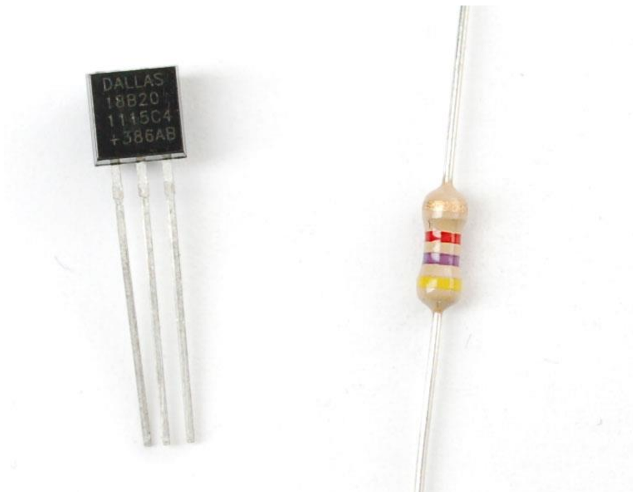

Figure 4.13: Dallas digital temperature sensor

4.4.5 **GPS**

Location and time stamping was measured with a MTK3339 GPS module manufactured by GlobalTop Technology. The breakout board was manufactured by Adafruit Industries. The module requires 3.3V – 5V power and runs at 25mA while tracking and 20mA while navigating. The GPS module can track up to 22 satellites and updates at a rate between 1Hz and 10Hz with a -165dBm sensitivity. The module communicates via 2-wire serial and can be assigned to any 2 digital pins on the microcontroller. Position accuracy is within 1.8 meters [51].

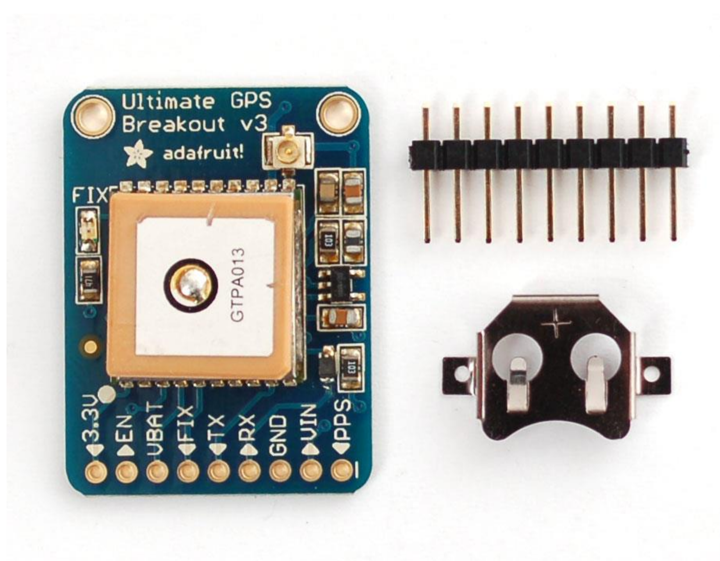

Figure 4.14: GPS module

4.4.6 **Current/Voltage**

The various current and voltage measurements are monitored by the INA219B chip manufactured by Texas Instruments. The breakout board is manufactured by Adafruit Industries. The sensor is a high-side current shunt and power monitor that monitors both the shunt drop and supply voltage. The chip communicates via I^2C. The sensor is capable of measuring a voltage of -26V – 26V with a maximum current of +/- 3.2A. The 12 bit ADC allows for a resolution of 0.8mA. The current sense resistor is a 0.1Ω 1% tolerance and rated for 2W. During operation, the chip draws a maximum of 1mA. Operating temperature is -40ºC - 125ºC [52].

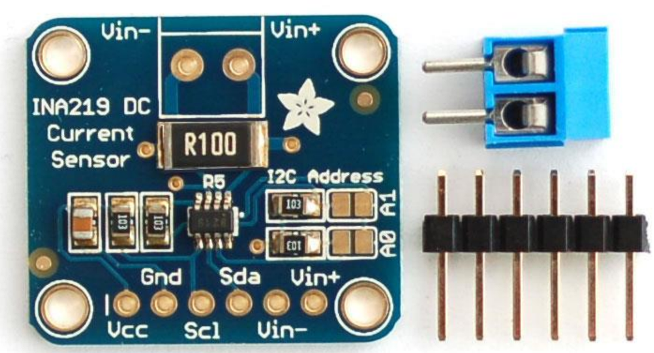

Figure 4.15: Current/Voltage Sensor INA219B

4.4.7 **Solar Panel**

The sensor module’s battery is charged via a 3.4W, 6Vsolar panel manufactured by Voltaic Systems Inc. The waterproof panel has a volume of 210mm x 113mm x 5mm. The panel has a monocrystalline cell with an efficiency rated at 18%. Open circuit voltage is 7V with peak operating voltage at 6V. The peak current rating is 566mA at 25ºC. The panel connects to its battery charging circuit via a barrel jack that is enclosed within the module’s housing [53].

Figure 4.16: 3.4W solar panel

4.4.8 Solar Lithium Ion Battery Charger

The battery is charged by the solar panel via a MCP73871 USB/solar lithium ion battery charger manufactured by Adafruit Industries. The charger is designed for use with 6V solar panels or 5-6V DC power supplies and charges 3.7V/4.2V Lithium Ion or Lithium Polymer batteries. The charger uses a linear converter, as opposed to a DC/DC converter, to mimic maximum power point tracking for the solar panel. The disadvantage is that this is not truly the most efficient method for power tracking. The advantage is that the cost of the linear converter is half what a DC/DC converter would be. With small scale applications like this project, a loss of efficiency can be compensated for by using a larger panel at lower cost [54].

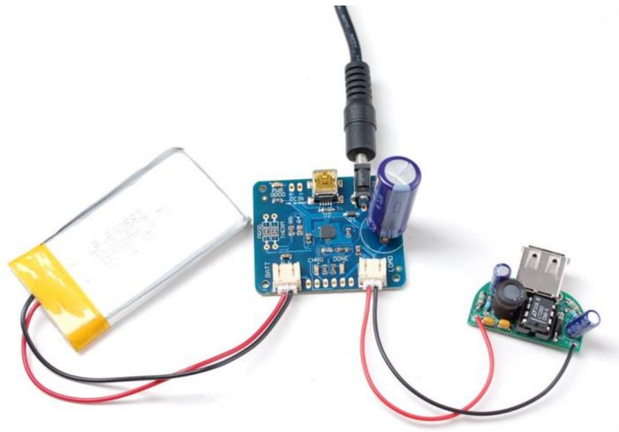

Figure 4.17: Solar Lithium Ion battery charger

4.5 Design Comparisons

4.5.1 Module Cost

Tables 4-1 and 4-2 show a collection of prices for all hardware needed for a sensor module. The prices compare the cost of buying components in low quantity (less than ten) to bulk quantity (greater than 100). The total price does not take into account the cost of manufacturing the housing.

Sensor	Pressure	Humidity	Irradiance	GPS	Temp	Current
Cost(unit)	$19.95	$35.00	$7.95	$39.95	$4.00	$9.95
Cost (bulk)	$15.96	$28.00	$6.36	$31.96	$3.20	$7.96

Table 4-1: Sensor costs per unit and in bulk

Device	Arduino	XBee	XBee Exp	Battery	Solar	Charger	5V Step-up
Cost (unit)	$29.95	$44.95	$9.95	$29.50	$34.95	$17.50	$5.95
Cost(bulk)	$25.46	$35.96	$7.96	$23.50	$27.95	$14.00	$4.76

Table 4-2: Hardware costs per unit and in bulk

Total Single: $289.55

Total Bulk: $233.02

4.5.2 Cost Comparisons

As discussed in chapter 2, there are competing designs both commercially and in research at universities. The majority of commercial designs are more expensive. By comparison, the Texas weather station and the Weather Hawk system are $1,202 and $2,388 respectively.

4.5.3 **Sensor Comparisons**

Given the significant difference in cost our sensor module has to others, it is logical to assess the quality of modules ability to fulfill its intended function as a reliable measurement device. The comparative accuracy of the sensors will be used as one metric for determination. The accuracy for the barometric pressure sensors on the other stations ranged from ±0.2 to ±1.5hPa. The accuracy of the pressure sensor on our design was ±1.0hPa. The accuracy of the temperature sensor on the other stations is ±0.1 to ±1°C as compared to ±0.5°C for our module. Finally, the accuracy of the relative humidity sensors on other modules ranged from ±2% to ±5%. Our module had an accuracy of ±3.5%. Our novel wind sensor is not field deployable yet and no accuracy data is available as of this writing. The tentative conclusion is that our device has the potential to demonstrate a significant advantage over other current weather stations by being less costly while still having a comparable performance as a meteorological sensing device.

Chapter 5

Data, Conclusion, and Future Efforts

5.1 **Field test**

The prototype module was given a one month trial to test network reliability, power self-sufficiency, sensor behavior, and weather proofing. The unit was placed on the rooftop of Holmes Hall near current installed solar systems and an already functioning weather station.

5.1.1 **Data**

Figure 5.1 shows solar irradiance from the pyranometer of another module and temperature from the prototype's pressure sensor on March 7, 2013. Figure 5.2 shows a graph of irradiance measured by the prototype's solar panel current readings and temperature measured by the dedicated DS20 temperature sensor.

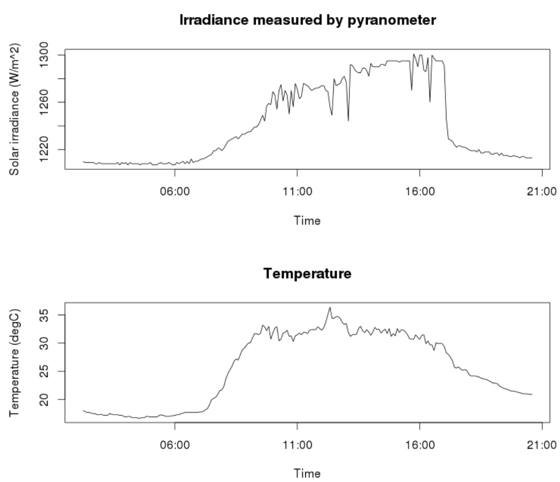

Figure 5.1: Solar irradiance and temperature as measured by solar irradiance sensor and integrated BMP085 temperature/pressure sensor (respectively)

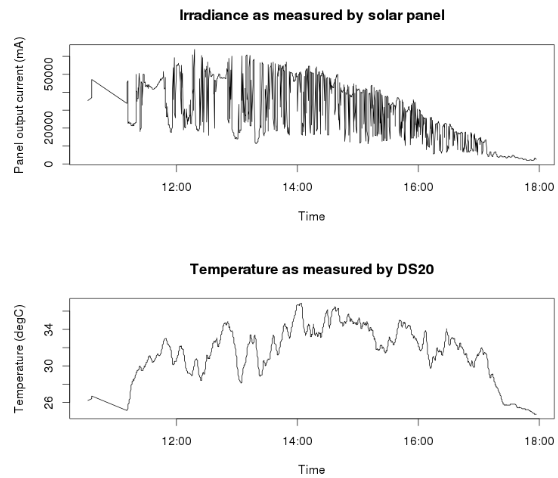

Figure 5.2: Solar irradiance and temperature measured by solar panel and specialized temperature-only DS20 sensor (respectively)

A comparison of solar irradiance shows that the solar panel produces a much noisier reading than the pyranometer. The current measurement is obviously affected by normal operating variables and the panel's non-linear characteristics and is not the preferred method of measurement. When comparing the two temperature readings, there is an obvious difference in the sensitivity of the devices. The dedicated DS20 temperature sensor exhibits higher detailed readings than the integrated temperature sensor in the BMP085 barometric pressure sensor. Although somewhat redundant, the increased detail seems an acceptable trade-off to the moderate increase in design complexity and unit cost. Further experiments will be needed to confirm the initial assessment.

The module would not remain powered throughout the night time hours. Operation would resume daily at approximately 9am. It is apparent that further research needs to be conducted on the whether the module power consumption can be reduced. The most power demanding device is the XBee module during transmission. It is possible to optimize power control via a reduction in broadcast range settings and sleep mode parameters. If self-sufficiency still cannot be achieved, a larger solar panel will have to be integrated into the design.

Exploratory analysis of correlation data demonstrates the potential that higher complexity models could provide. Figure 5.3 shows a data correlation chart for all measured parameters. All data graphs and correlation charts could be accessed via an XML-RPC client and accessed over Android remotely. This would allow administrators and researchers continual access to the status of the system and all available information [55].

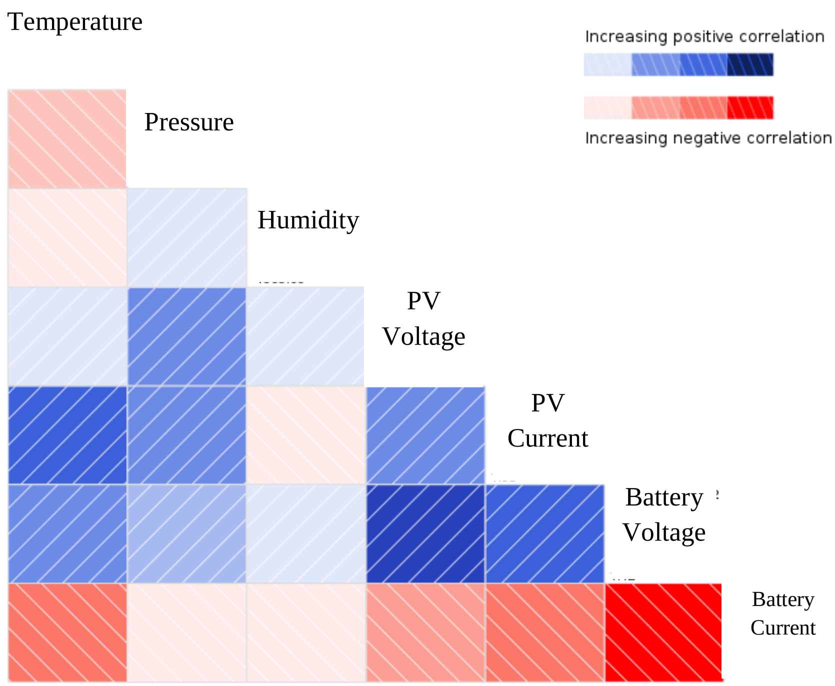

Figure 5.3: Correlation data on 3/7/2013

5.2 Future Efforts

5.2.1 Ultimate design goal

Once all characteristics of the circuit design have been optimized, the next version will physically consolidate all appropriate sensors and necessary Arduino circuitry onto one PCB. In this design, it is likely that keeping the temperature and humidity sensors together on an exclusive board would still be preferable. The two sensors could be consolidated in a wellventilated compartment to minimize anomalous readings due to potential greenhouse effects within the module. Further testing would need to be conducted to verify any significant difference in accuracy, due to internal placement, for the temperature and humidity sensors. In order to be exposed to sunlight, the luminosity sensor would also need to be placed externally and could not be sealed within the housing. This configuration would allow the rest of the sensors (barometric pressure, GPS, and current sensing) and circuitry to be more protected in their own isolated compartment. The design would allow for a smaller module, more robust circuit construction and easier mass manufacturing.

5.2.2 **Next Step**

As of this writing, a PCB design is being tested that allows a more convenient placement of the sensors while the sensors are still on exclusive breakout boards. The first prototype design, discussed in chapter 4, used solder-able breadboards and jumper wires for interconnecting the various boards. A custom circuit board has been designed that allows the various breakout boards to be soldered into through holes via headers. Wire runs along the PCB provide appropriate connection for operation. This design will be the next iterative prototype.

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