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ECE aspects of Zero Energy House

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ECE Aspects of Zero-Energy House

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Abstract

The goal of this MQP was to design and implement a photovoltaic (PV) system and Oasis; a stand-alone web-based bidirectional wattmeter to aid Team BEMANY of the Solar Decathlon China 2013 competition in meeting their goal in implementing a zero energy house. To achieve this goal, a wireless digital multimeter with an accuracy of 0.1% with a minimum wireless range of 10m was created to monitor the voltage of the individual panels of the PV array and it relayed the data to a microcontroller based server. This server would then communicate with a router to upload the data to a website. This website served as the graphic user interface for the entire system.

1. Executive Summary

This project explores the design of a photovoltaic (PV) system and implemented the Energy Management system for said PV system. The complete system's purpose was to improve Team BEMANY's odds of winning the energy-balance contest of Solar Decathlon China 2013 competition.

In an effort to promote solar energy, the Department of Energy challenged collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive through the creation of the first Solar Decathlon. This competition grew in popularity across the globe. Since then, two other competitions came to existence; namely Solar Decathlon Europe which took place in Spain and the Solar Decathlon China 2013.

The winner of the overall competition is decided based on four qualitative and six quantitative contests. Qualitatively, jurors who are experts in their respective fields such as architecture, mechanical engineering, and communications, award points for features of the house that cannot be measured numerically such as aesthetics, practicality, and design inspiration. As for the quantitative contest, each team can earn points by completing household tasks such as cooking, washing dishes, drawing hot water, doing laundry and maintaining set indoor temperature and humidity levels. Completing these tasks result in a certain level of energy consumption. This energy consumed is provided by a small village grid and ideally, Solatrium, the house designed by Team BEMANY, (the Belgium-United States team) consisting of Ghent University of Belgium, Worcester Polytechnic Institute, Polytechnic Institute of New York

University, would return to the grid as much energy as it consumed; thus satisfying the requirement the energy balance contest.

In an effort to make Solatrium a zero energy house, its photovoltaic (PV) system was designed and a complete web-based monitoring system capable of monitoring PV production and domestic consumption was created. The system was to be completed with a web-based user interface that enabled the user to remotely access information about the PV system's performance however due to time constraints, this was not implemented. Future features include but are not limited to enabling override of the home automation system which controls the lighting, and the heating, ventilation, and air conditioning (HVAC) system to ensure that the net energy used is at least zero.

1.1 PV system Design

The photovoltaic (PV) system was designed by determining the size of the array, creating distribution plan, deciding on the PV panel based on module efficiency, their tilt angle, and the invertor. To minimize cost, the smallest adequate PV array size was determined by choosing the most efficient appliances and heating, ventilation, and air conditioning (HVAC) equipment. Also, passive cooling methods were explored because the HVAC system can consume over 49% of the net energy used [1].

1.2 Energy Management

Once again, to fulfill the zero energy requirement of Solatrium, this major qualifying project also aimed to design build and implement a complete stand-alone zero-energy house monitoring system which consisted of three main subsystems: the monitoring subsystem, a website to serve as the user-friendly interface and a server that would control the monitoring subsystem and relay the information provided by it to the user interface.

The monitoring subsystem consisted of a switching network and wireless digital multimeter (DMM) with a 0.01 V resolution and a minimum wireless range of 10m. The switching network was controlled by the microcontroller which served as the heart of the DMM and would connect the DMM to a specific panel so that the DMM can measure the output voltage and then send the data to the Server. Said server would then process the data it received and upload to a website. This website would not only serve as the house's energy report card, but it would allow the customer to track the performance to the PV array through any web-enabled devices.

2. Marketing

Monitoring photovoltaic (PV) systems has been a necessity since the 1970's when solar cells were first integrated with crucial systems such as power navigation warning lights, horns on many offshore gas and oil rigs, lighthouses, and railroad crossings [1]. However, the targeted market consists of residential PV system owners, which is currently a growing percentage of the energy market due to the dramatically increasing number of solar panel installations. From 2009 to 2010, the residential solar PV market average growth rate increased from over 40% per year to 68% [2] and by the end of 2010, over 2,600 installations statewide occurred in the state of Massachusetts alone [3]. Due to this growth, the cost of installation is expected to decrease by at least 45 % by 2020[4]. In addition, according to the Department of Energy (DOE) "*The value of the energy provided by these solar systems will increase through advanced communication interfaces and controls while the reliability of electrical service, both for solar and non-solar customers, will also increase*[5]." making the monitoring system is worth the time, money and effort.

Oasis, the energy management system must meet the needs of the user, and the installation technician involved (should one be needed) in the development and building of zero-energy houses; the technicians being the students involved with the Solar Decathlon China 2013. The system must be safe, accurate and reliable; prioritized in that order. The system must also be compatible with existing systems to ease installation. To maximize accuracy, features such as individual panel monitoring and both graphical and numerical performance modeling were

[1] http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf
[2] http://eetd.lbl.gov/ea/emp/reports/lbnl-4121e.pdf
[3] http://www.masscec.com/index.cfm/cdid/11663/pid/11150
[4] http://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf
[5] http://www1.eere.energy.gov/solar/pdfs/segis_concept_paper.pdf

included. This would allow the user to easily detect issues such as unusual power consumption or production loss. For convenience, Oasis was web-based so that the user could detect the previously mentioned abnormalities from any web enabled devices, making Oasis very easy to use and integrate with the market.

2.1 Existing Monitoring System

Existing monitoring system differ in reporting and data acquisition methods. Remote systems report their data remotely through the web or Bluetooth, which is extremely convenient for the user. The data acquisition method of choice does vary depending on the desired level of information. The simplest, most inexpensive monitoring systems gathers information on the system level, meaning the total output of photovoltaic (PV) array's performance and the total energy consumed throughout the house would be reported and recorded making it least informative approach. Some production monitoring systems provide string level accuracy, where each individual panel's performance is monitored for maximum level of information. The same is true for consumption monitoring systems, where individual receptacles and individual appliances are measured. Of course the middle ground of these two levels is a hybrid system which monitors individual sets of panels and circuits inside a house.

2.1.1 Production monitoring system: Prior Art

Given that team BEMANY's goal was to balance production and consumption, monitoring each individual panel is very important, therefore this section will evaluate some of the remote PV monitoring systems that have panel level monitoring to maximize the level of information.

A. Enphase Enlighten Monitoring system

As the name implies, this type of monitoring system measures the AC voltage. Siemens' micro-inverter system comes with a panel-level monitoring system which relies on the voltmeter inside the communication gateway to collect data from the load center [6]. As shown in figure 2-1, the data is then uploaded to a web-based software via an Ethernet broadband router that plugs into any standard AC outlet. The software enables remote monitoring through web enabled devices such as smartphones, and tablets.

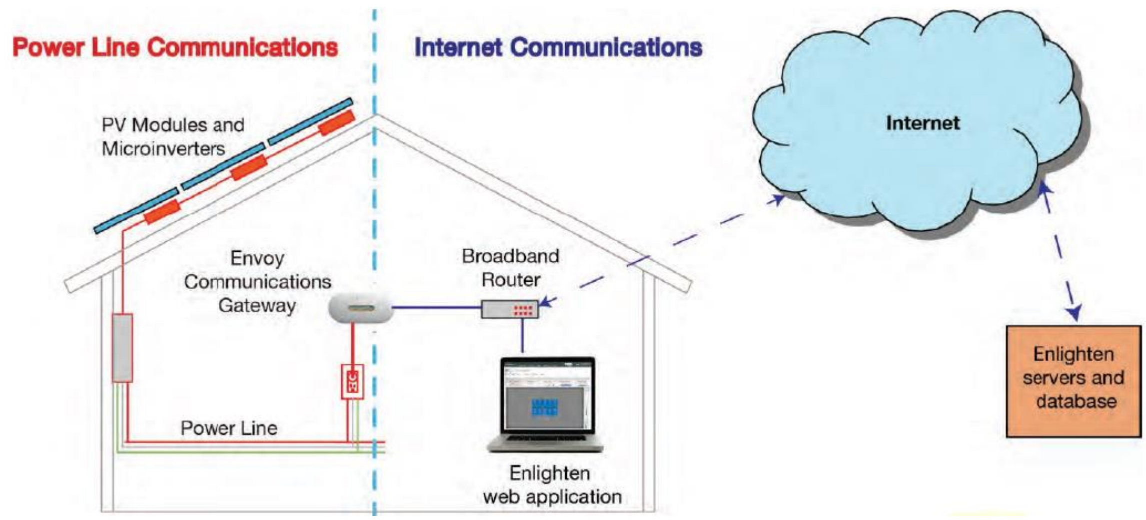

Figure 2-1: Enphase Enlighten Monitoring system

This system offers 24/7 monitoring & analysis, advanced data management & storage and auto upgrades & diagnostics of the system components. It typically consumed 2.5 VA. However this system is only compatible with PV systems that use micro-inverters.

B. Sunny BEAM

The Sunny BEAM system from SMA Solar Technology AG acquires the performance data of the PV system from the inverter's communication module (COM). This COM wirelessly communicates with other inverters and a hub shown below via 100 m range of password protected Bluetooth [7].

[6] http://w3.usa.siemens.com/us/internet-dms/btlv/residential/residential/docs_Home/SIE_BR_MicroinverterBrochure.pdf
[7] http://www.sma.de/en/products/monitoring-systems/sunny-beam-with-bluetooth-wireless-technology.html#Technical-Data-9226

Figure 2-2: Sunny Beam hub

The hub, shown in figure 2-2 is solar powered and displays the data graphically on a large screen, and can log it in CSV format for excel compatibility when it is connected to a computer via its USB interface. This is available in multiple languages, and the system has a self-diagnosis with potential solutions. The accuracy and measuring the performance of the PV system is dependent on inverter; which are the most common point of failure in PV system. This also defines the level of accuracy, making it impossible for the user to control and customize it.

C. Maximum Peak Power Tracker

The aforementioned monitoring system depends on inverter to gather data. Inside the inverter, are Maximum Power Point Trackers (MPPT) which can be considered as another type of monitoring system. MPPT automatically alter the output of the panel to maximize its power output given data it has previously acquired from said panel [8]. This data is the output current and output voltage of the panel, which is acquired via current and voltage sensors.

There are two main current sensing methods; resistive and magnetic based measurements. In a resistive set-up, a small resistor is put in the path of power flow and the voltage drop across it is measured and converted to a current value. Whereas in a magnetics based method, a coil (possibly an inductor), a current transformer or a hall-effect sensor is used to generate voltage induced by the magnetic field around a wire.

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[8] http://www.blueskyenergyinc.com/uploads/pdf/BSE_What_is_MPPT.pdf

As for voltage, there are two types of voltmeters; analog and digital. Since the data needed to be acquired at a reasonable rate and transmitted wirelessly, only digital voltmeters were reviewed. All digital voltmeters consist of an attenuator to scale the voltage down to an appropriate range, an analog-to-digital (ADC) converter and some sort of microcontroller that is programmed to interpret the signal from the ADC and output the appropriate code that is then converted into what is seen on an LCD screen. Thus, the measuring method used by a DMM relies heavily on the type of ADC.

D. Digital Multimeters (DMM)

DMMs have various different type of which is dependent on the ADC that is used [10]. Essentially, there are two types of families of ADCs; integrating and Non-integrating which can be further broken down into three approaches, or seven different implementations. The first type applies the relationship between voltage and time. This method is used by Ramp type, Dual slope Integrating type DMM which measuring the amount of time that is needed to charge a capacitor at a constant current [9]. Other integrating type DMM operate similarly but use the relationship between the input voltage and frequency as opposed to voltage and time [10]. The Non-integrating type use a voltage matching approach where the input voltage is compared to an internal reference voltage and the LCD does not read a value until the input is equal to the reference voltage [10]. This approach is broken down into the following implementations: Successive approximation registry (SAR), Continuous balance, ADC Staircase and Sigma-Delta (Σ-Δ) ADC [10].

Only the SAR and Σ-Δ were considered because continuous balance and A/D staircase are slower than other methods, undependable accuracy, susceptible to error due to noise & interference [7]. Also ADC Dual-slope integrating type though extremely fast and accurate, it is

[9] Electronic Instrumentation By H. S. Kalsi

meant for scientific-grade measuring application where high accuracy is needed and thus is an over-design for PV monitoring [10].

SAR ADC

Successive approximation register or SAR is very accurate because the registry tries to efficiently match the input voltage to its reference voltage. Instead of trying to match the input voltage starting from the lowest reference voltage value like in sequential search algorithm, the registry implements a binary search algorithm starting with the most significant bit that could represent the internal reference voltage and works its way to the least significant bit as shown in figure 2-3[10].

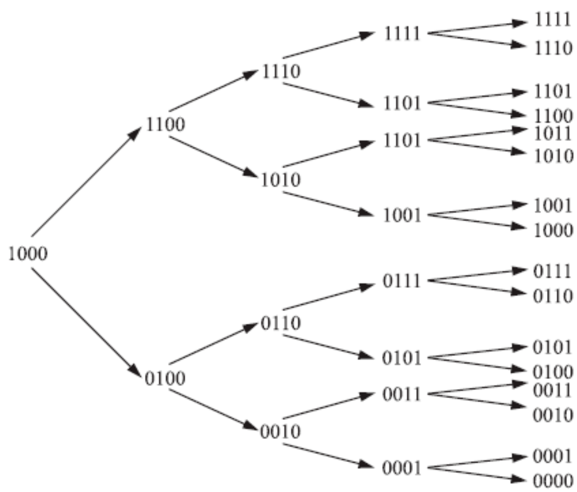

Figure 2-3: SAR ADC 4-bit decision three

Σ-Δ ADC

Σ-Δ ADCs are the most popular type of ADC in bench top DMM. They are analogous to operational amplifier configured as a current buffer in the sense that the input voltage is equal to the output given the rail to rail voltage except that the output is a digital string or bit stream whose average value is equal to the input voltage again given a certain range; negative to positive reference voltage [8].

10 http://www.analog.com/library/analogDialogue/archives/39-06/architecture.pdf

E. *Oasis summary part I*

In summary, the aforementioned design options have certain characteristics and features that make them extremely helpful in the development of Oasis, the web-based bidirectional wattmeter. In addition to being a web-based remote monitoring system, it has variable resolution levels. Due to uncertainties associated with the implementation phase of PV array, Oasis is designed to adapt and fit most residential PV system. Like Sunny Boy, the DMM has a wireless communication feature that is secure.

In the Enphase system used by Siemens, a computer acts as the server which communicates with the router. This is requires for the computer to be constantly operating which would hinder team BEMANY's chances at winning the energy balance contest. Thus, Oasis followed Sunny Boy's example in having a stand-alone server which logs the data and handles uploading said data to the webpage. Other features such as system diagnosis and battery monitoring were also implemented to assure convenience.

All the aforementioned systems depended on the inverter(s) to log the performance data of the PV array. Enphase relies on micro-invertors which is favorable. Having multiple small inverter allows the user to monitor each panel's performance and it reduces installation time and in turn installation cost. This also eliminates the risk of the entire going offline should the inverter fail however, each micro-invertor is approximately \$240 and for an array of 30 panels which is common for grid-tied domestic systems, the cost of monitoring jumps to over \$7200. In the sunny Boy system, the monitoring resolution is a bit less depending on how panels are connected per inverter but the price of the inverter and the extra equipment can cost all together up to \$3427 extra.

Inverter independence eliminates this issue. It is also a crucial feature of Oasis because team BEMANY had not yet implemented all of the PV system designs; therefore invertor dependence would stifle completion of the system given the time constraint. Without a proper monitoring system, team BEMANY would not know how much power they are producing or consuming unless someone constantly watches over the meter located outside of the house.

Thus, having a monitoring is important to team BEMANY because superfluous energy consumption is likely to be undetected which would result in losing the competition. As for residential PV system owner, this undetected unwanted behavior would delay the return on investment.

2.1.2 Consumption Monitoring

As mentioned before, the consumption monitoring systems vary in degrees of depth therefore can be broken down by this characteristic. Most systems of measure the overall power consumption of a house thus are very simple, quick to install and very reliable. Contrary to these whole-home solutions are targeted systems or devices that measure the power consumption of individual appliances or outlets. This is preferable for applications that require a more detailed outlook on the consumption characteristics of a house. Targeted systems therefore involve more hardware thus can be more expensive and difficult to install.

A. Black & Decker

This Whole-Home system has three major components that are independent of each other: the weather proof sensor that attaches to the meter, automatic light switches that detect the occupancy of a room via passive infrared sensors and a portable display, shown in figure 2-4. The sensor wirelessly communicates with the portable display panel and takes real-time measurements in kilowatt-hours (kWh) and dollars [11]. Customer reviews have reported that it was very easy to setup however, because it is a Whole-Home solution it doesn't provide enough information. According to another customer review, the measuring resolution was too high, the

[11] http://www.treehugger.com/gadgets/black-decker-launches-energy-saver-series-tools.html

update rate was too slow and the data cannot be analyzed. Also the display is battery operated but needed to be replaced every 10 weeks.

Figure 2-4: Black & Decker Energy monitoring

B. Power2Save E2, ELITE and Home Hub energy monitors

This family of Whole-Home monitoring systems also consists of a sensor that clips onto a cable, a transmitter and a display hub that is portable or can mounted to a wall. The sensor relays data to the transmitter which is located near the load center. The transmitter then sends the data wirelessly to the display shown in figure 2-5; which reports kWh, carbon foot print and cost per year. This system is attractive because it can save up to 24 months' worth of history depending on the transmission time the user sets and automatically updates the tariff [12]. For instance, this allows the user to decide when is the best time to do laundry depending on when it is least expensive to do so. The system can connect to a computer to examine trends. When the Home Hub is included, it connects to a router and uses ENGAGE web portal for extended remote monitoring from any web-enabled devices. Unfortunately the Transmitter and Display unit are battery powered and do not have a battery monitoring feature that alerts the user to change the battery, and the Hub is power using an AC Adapter.

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[12] http://www.power2save.ca/products/energy_monitors

Figure 2-5: Power2Save ELITE model

C. *Wattson Solar Plus*

This is perhaps the most popular energy management system. This version of this Whole-Home solution monitors electricity consumption and generation on the same unit. Like the Power2Save option, the sensor(s) clip onto a wire and the transmitter's transmission time is variable. It has a 1:1 ratio between transmission time and how many months the battery that power the transmitter will last. Again the wireless link between transmitter and display allows the display to show kWh, carbon foot print and cost per year in multiple currencies. This display has position sensitive display modes and glows according to the level of energy production and consumption. As illustrated in figure 2-6, it can be connected to a computer to log daily consumption data and the entire system has does not have any Hazardous materials (RoHS compliant). The housing comes apart and is recyclable and as a bidirectional system it is inverter independent, compatible with single and three phase and measures with 1W resolution [13]. This is by far the closest system to Oasis however, the transmitter is battery powered and the display must be plugged in.

[13] http://www.diykyoto.com/uk/aboutus/wattson-solar-plus

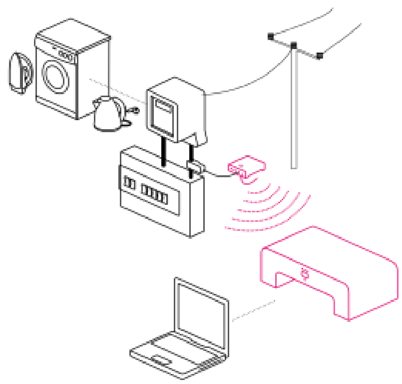


Figure 2-6: Wattson SOLAR Plus setup

D. *POWERSAVE energy monitoring*

This Whole-Home monitoring system can be considered a hybrid because it is modular. Multiple clip-on sensors and transmitters can be used to expand from single phase to three phase monitor, in addition to its plugin sensors which resemble the Kill-A-Watt. The plugin sensors and clip-on sensor's transmitters connect wirelessly to the display Hub or an internet gateway which can be connected to a web bridge. This web bridge then connects to a router to enable web-based monitoring. The display again reports kilowatt-hours (kWh), carbon foot print and cost per year but only in dollars [14].

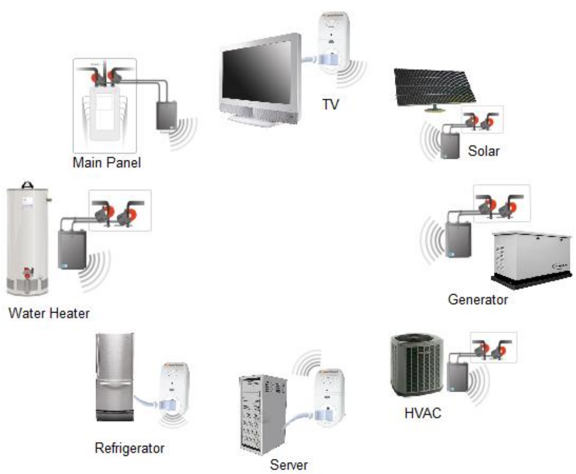


Figure 2-7: POWERSAVE energy monitoring applications

[14] http://www.currentcost.net/monitor.html

As you can see in figure 2-7, this system is very versatile however, the same deficiencies as the aforementioned systems apply. The transmitter is battery powered but it does not have battery condition alerts and the Web Bridge plugs into the wall.

2.2 Design Requirements

The design requirements for Oasis are abundant therefore the specific requirements will be addressed in their appropriate section later in this chapter. However, the system as a whole must be dependable, easy to install, as maintenance-free as possible, inexpensive, and invisible to the PV array. In other words, Oasis will need to be completely isolated from the PV array and the stand-alone to ensure that its presence does not alter the performance of Solatrium, the house built by the Solar Decathlon.

To assure dependability, Oasis will be designed to be accurate, fast, versatile and robust. Its accuracy must at least match the accuracy of a bench top digital multimeter (DMM). The measurements will be taken fast enough so that the website can display the PV array's performance in real-time. The DMM must be able to simultaneously measure each panel's output voltage and output current. Given that Solatrium would most likely come back to Massachusetts, Oasis must be "New-England-proof" or be primarily located indoors; which would also increase its reliability and life-span.

Like some existing products, Oasis will also comprise of two hardware blocks: a DMM and the Server that would process the data acquired by the DMM's sensors network and upload it to the website. These blocks will interact wirelessly as well and be battery powered to ensure that Oasis' presence does not affect the performance of Solatrium.

The DMM must have battery monitoring feature and alert the user to swap the battery of the Server with the DMM. The Server must be powered through the Ethernet port and act as a charging station for the DMM's battery. It must also comprise of a microcontroller capable of serving as the control center of Oasis and process the data received to provide information in terms of energy, cost, and carbon foot print as well as predict weekly overall consumption so that team BEMANY is aware of its odds of winning the energy balance contest. It will serve as the central controller for the entire Oasis and serve as a backup data storage space for the system. All of the data must be logged daily and stored on an SD card for long term monitoring. This would allow the user to analyze their energy spending habits without interrupting the system and increase the amount of data that can be stored.

2.2.1 Communication Block Technical Requirements

The communication circuit as mentioned earlier in this chapter was restricted to primarily wireless with a range of at least 10 m while minimizing the power required. To incorporate real time communication, the output data rate was the highest standard rate maximum rate that yielded no losses in packets.

2.2.2 Input Block Requirements

The input block conditions the incoming panel voltage so that it can be processed by the measurement block. Typically the input block of a DC voltmeter consists of a linear attenuator to reduce the incoming signal to a reasonable range. This input block must scale down 600 V to the reference voltage needed by the measurement block and have a high input resistance so that little to no current is drawn from the device being measured.

2.2.3 Measurement Block Requirements

This version of Oasis measures DC voltage only thus is not compatible with system that uses micro-inverters. However, the measurement block must measure individual panels as many times as the user desires. This is to ensure that every reported measurement is accurate and statistically significant. The same will be done for current measurements in every branch of the house. That said receptacles will be monitored by current branch as opposed to individually.

The voltage readings were constrained to 10 mV resolution and 0.1% accuracy. The PV panel's current should have 100 mA resolution and 0.1% accuracy. Like the panels' current, the current in each circuit of the house must be measured with a 100 mA resolution and 0.1% accuracy as many times as desired. Thus, the current sensors must be hall-effect to limit complexity and make installation as safe and as easy as possible. Additionally, these sensors must have high sensitivity, robust to temperature. This would result in 0.1W resolution for both production monitoring and for consumption monitoring.

2.2.4 Power Block

As mentioned earlier, Oasis needed to be a stand-alone system to ensure that team BEMANY use only the energy that they need to use per competition regulations. However, an AC adaptor must also be included to power the system in case the competition coordinator do not allow a battery with a capacity as high as what is needed, or if the battery were to malfunction. This redundancy will allow the user to plug the system into an outlet and still be able to monitor their PV array.

As a mainly battery operated system, Oasis must have small power consumption. Given the limited capacity on the battery set by the Solar Decathlon, the system needed a low-power mode where the DMM and the Server would "sleep" an hour after the last zero voltage measurement and "wakes" up six hours later the sun rises. These requirements constrained the system to have power characteristics similar to a handheld device.

The case for the DMM's battery must be insulated and sealed completely to reduce the battery's performance dependence on temperature and easily accessible. The battery itself should have a capacity high enough that can run the device for at least three months without recharging. As for the charging circuit in the Server, it will be designed so that in at most four hours, it can fully charge the battery from a 70% discharge, without overcharging the battery.

2.2.5 Oasis summary part II

Overall all the consumption monitoring systems on the market consist of three major blocks that interact wirelessly for the most part. These are sensors that measure current, a monitor to process the data gathered by the sensors and a portable display. To analyze the acquired data, the monitors or displays need to be connected to a computer. Systems like Power Save and Agilewave (not mentioned previously) have a separate block dedicated to enabling web-based monitoring and data analysis. The lacking feature in the aforementioned systems lie in the way they are powered and maintained. Dependence on an AC adapter is tolerable for customers given that the power consumed is less than 5 Watts however to ensure that this dependence will not hinder Team BEMANY's chances of winning the energy balance contest, Oasis will not depend on an AC adapter.

Oasis is a modular Whole-Home product that monitors consumption and production using two units: a DMM, and a server. The high sensitivity sensor(s) in the DMM would also clip onto a wire making it compatible with a single phase and three phase system and ensure high resolution measurements. The DMM monitors its battery and alerts the user once it needs to be recharged.

In addition to acting as a charging station for the DMM's battery, the Server processes all of the information using the data the DMM has transmitted. This Server connects to any Ethernet port and does not rely on an AC adaptor for power, though that option is available for redundancy. The majority of components that make up the system are RoHS compliant.

3. Design and Implementation

3.1 PV system Design

The goal for all Solar Decathlon competitions is to build of a Zero energy house. One of the rules regarding the photovoltaic (PV) system is that energy storage devices that have a capacity greater than 100 mWh are prohibited, thus the PV system of choice was a 7 kW grid-tied system.

As the one-line diagram in Appendix D describes, the system consist of an array of solar panel whose power will go into a combiner box, be converted to from DC to AC, passed through several safety devices (Ground Fault interrupter, AC and DC disconnect) and tied to the village grid. The purpose of the safety devices will be expanded upon further in this chapter.

To determine the size of the PV array, all the loads i.e. the appliances and mechanical loads were chosen and calculated. To determine the total minimum amount energy the PV array would need to produce during the competition period the loads' required input power were multiplied by how long each individual load would be operational given the competition schedule provided by the Solar Decathlon China 2013 competition coordinator. In an attempt to maximize energy efficiency and minimize the size and cost of the PV array, a few changes to house were recommended. By using the metrological information found through NASA, a PV array consisting of 22 monocrystalline, 327 W panels from Sunpower was designed. However due to uncertainties associated with the donor for the solar panels, a list of other potential panel was made shown in Appendix B table 8-1.

3.1.1 Load calculations

A. Mechanical Load calculations

The mechanical loads of the house primarily come from two systems: The heating, ventilation, and air conditioning (HVAC) system and the Plumbing system. The design of the HVAC system was extremely crucial because given a low Seasonal Energy Efficiency Ratio (SEER) value can consumes over 49% of the energy used for in a medium size home like Solatrium.

HVAC

The HVAC system that was designed to be as efficient as possible so given the size of the house and the building material, a mini split ductless system was necessary. Professor Van Dessel calculated that a 2.5 ton system was need and with some help from Johnson Controls, this number was confirmed. To calculate exactly how much power the system would use, a thermal analysis of the house was done through Ecotect, which is a sustainable building design tool which is capable of simulating and analyzing, a building's energy performance given its environment. Using this, it was predicted that the HVAC system would consume 235 kWh for heating and 221 kWh for cooling for the course of ten days given a coefficient of performance (COP) of 1. Thankfully, Johnson controls was able to donate a mini split ductless HVAC, with a SEER value of 23 which is equivalent to COP of 6.741. This means that this system is capable of meeting the thermal needs while using 14.84% of the power needed from a system with a COP of 1. To evenly cool the house a modules was placed in each of the bed rooms and two equidistant from the center of the Atrium.

Plumbing

The plumbing system consists of two sub-systems; the domestic water and the fire suppression system. To minimize installation times, piping and hot water wait time, a mix of a trunk and branch system and a remote manifold system was designed (see figure 3-1). To minimize installation time and how much piping was needed, cross-linked polyethylene (PEX) pipes were chosen for both subsystems because of their flexibility.

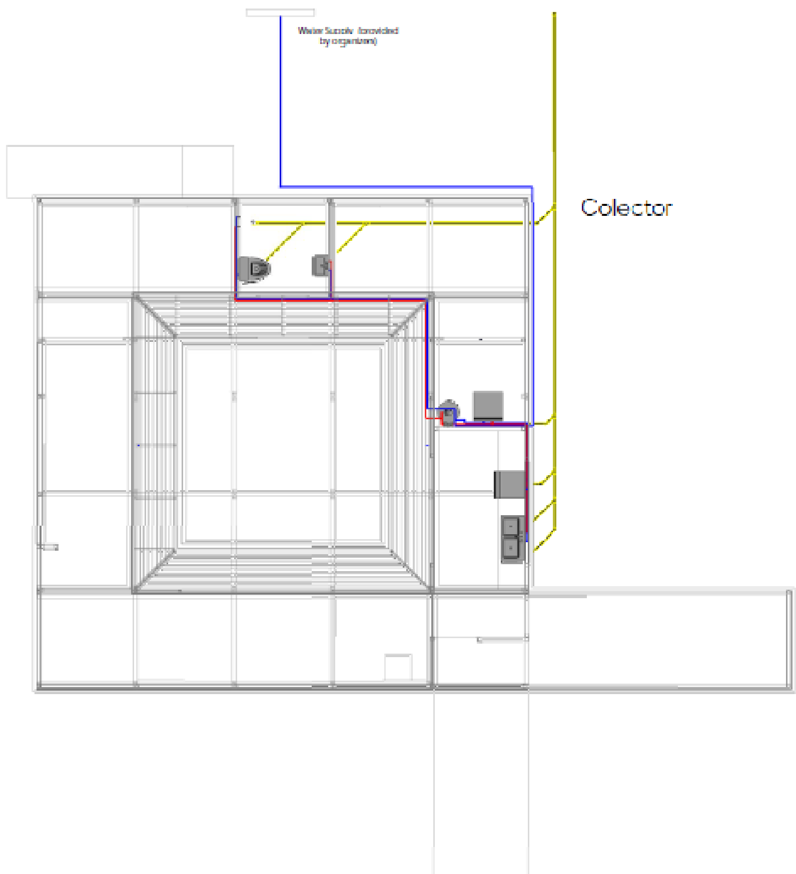


Figure 3-1: Plumbing Distribution Drawing

Strictly for the domestic water, the source of the hot water plausible for the competition given the size of the technical room (1.9 x 2.199 m), the energy used and that the water will be provided municipally include Hybrid water heater, Instant hot water dispenser (Point-of-Use Centralized hot water a.k.a. direct hot water), and solar hot water. Given that a solar hot water could become unreliable during the winter but an instant hot water dispenser would use too much energy during the winter, both approaches were included in the design.

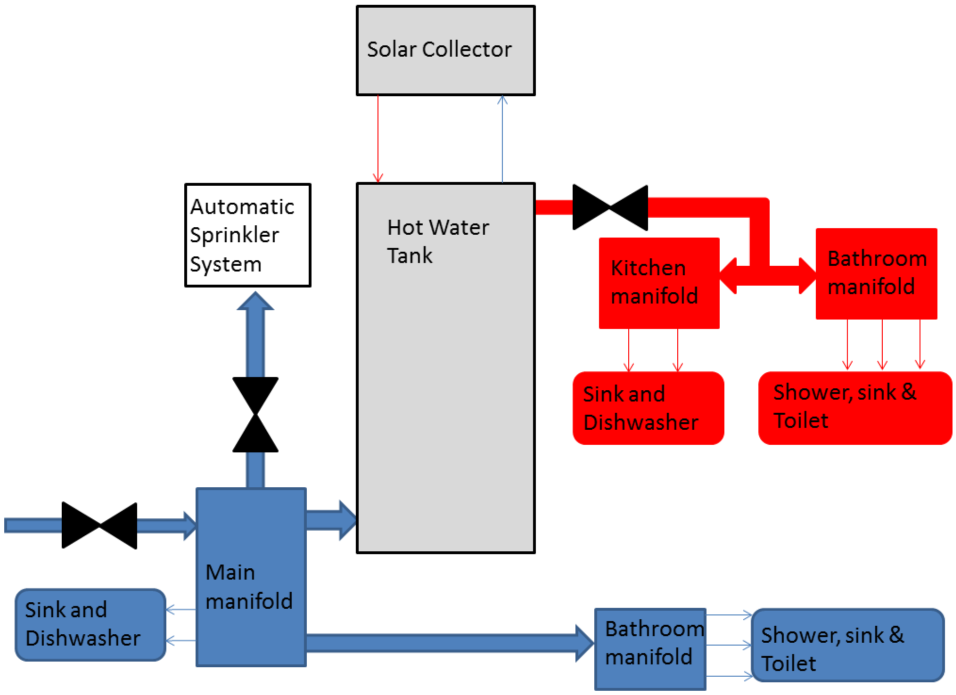


Figure 3-2: Conceptual Hot water one-line diagram

Simply put, the glycol within solar collector tubing is heated and carries the heat into a small tank. The heat then is then diffused into the water within this tank. Thus, the temperature of the water coming into the direct hot water heater is closer to the desired temperature making change in temperature if needed much smaller. The amount of energy used by the direct hot water heater is proportional to the change in temperature that it needs to provide; the change in temperature being the difference between the set temperature and the temperature of the incoming water. Should the temperature of the incoming water be higher than the set temperature, the direct hot water will simply remain inactive.

Thankfully, SECUSOL had a drain back solar hot water system that had a direct hot water unit built into it, shown in figure 3-3. Under the worst cases scenario (i.e., without the solar hot water's assistance) the total energy used by the hot water system is 3.08 kWh for the competition period.

Figure 3-3: SECUSOL Hot water appliance

B. Appliances

The appliances that were required were that of a typical American home; refrigerator, cooktop/range, microwave, dishwasher, home entertainment system (television, computer, sound system), lighting clothes washer and dryer. In general, the appliances that were considered include brands from other zero-energy houses from the past competitions and major brands such as GE, Maytag, Siemens, Samsung, kitchen aid, Bosch. Each appliance was chosen based on their respective requirements set by the competition coordinators. To determine the best appliances for the competition, the respective energy consumption per competition day (excluding standby power) of the appliances that were complaint with the Solar Decathlon 2013 restriction was calculated. For further detail, please to the specific appliance of interest.

Refrigerator

How much energy a refrigerator uses is heavily dependent on its size. Therefore, the smallest refrigerator that passed the sizing requirement set forth by the competition coordinator was chosen, that being the Sunfrost RF12 which uses 171 kWh per year; 918.53 Wh per competition day.

Cooking

When it comes to cooking appliances, there are a few options. Some homes have a range, others have a cooktop and a separate oven and some do not have an oven at all. Seeing how an oven was not needed for any of the contest during the competition period, a 30 inch induction cooktop and a microwave with convection oven feature were chosen.

An induction cooktop was chosen because it is safer, quicker and uses a lot less energy than conventional cooktops. Induction cooktop top induce a magnetic field which creates Eddy currents in the metal pot thus heating the pot directly. Conventional cooktop rely on resistive heating and heat diffusion which is altogether a slower heating process. Because induction cooktops heat the container, they operate for a less time, hence use less energy and the cooktop top does not remain hot after being used which makes it safer. The cooktop of choice was a Kitchen Aid KICU500XSS because it the better option given energy consumption and price.

In case, the occupant of the house decides to cook a dish which requires an oven, a microwave with a convection oven feature was chosen. This would eliminate the need for an oven. The convection feature was crucial because convection ovens are more efficient and cook food faster and better than conventional ovens. This is because the hot air inside of them is actively circulated by a fan making the heat transfer from the air to the food more even and faster than in a conventional oven where the hot air relies on diffusion.

Dishwasher

A dishwasher was required for one of the contest during the competition period. Contest 8-5 required team BEMANY to washer a total of 30 place settings. In the interest of minimizing the operating time of the dishwasher, the size of the dishwasher was restricted so that as many place settings as possible would be washed at once. Thus the minimum required place setting was determined to be 15 which would result in the dishwasher being active only twice. The list of the dishwashers that met this minimum place setting requirement was further narrowed down by total energy per wash and gallons of water used per wash. The dishwasher that had the minimum energy usage and water usage per wash cycle was the Asko D5894XXLFI with 891.32 Wh per wash cycle.

Home Entertainment system

As required by the competition's home entertainment contest 9, a television and a computer were required. To satisfy the occupants of the house, a sound system was also included in the list an appliances needed. However, we decided to integrate the sound system with the television. Since the television would be displaying the PV array's performance, a list of Smart LED TV with internet capabilities with a minimum size of 36 inches was made. An LED television is more efficient than plasma TVs. The list of LED smart TVs was narrowed down based on the energy used, sound level and size; prioritized in that order. Based on these requirements, a value analysis was performed and the top two television sets were Samsung SMART 6300 and 6000; which according the calculation, use 337 Wh per day.

As for the computer needed, a desktop replacement laptop was chosen because laptops use less energy than a desktop and based on the specification of the memory, hard drive motherboard, and graphics card installed, a desktop replacement laptop can be as powerful if not more powerful than a desktop for less energy used per year.

Washer and dryer

Much like the dishwasher, a washer was needed and one was chosen based on water usage and energy used per wash. The clothes washer contest required us to wash 6 loads during the entire competition period; each load consisting of 6 bath towels which resulted in a total weight of approximately 13 lbs. Since front loaders use less energy than top loaders and in the interest of minimizing the how many wash cycles is needed to win this contest, a list of front load washers with a minimum loading weight of 10 pounds was created and narrowed down to the washer that used the least amount of energy given their power and active time. Also, since condensation dryers do not need a vent and use less energy than conventional dryers, a second list of condensation type dryers with a minimum loading weight of 10 pounds was also created and narrowed down to the dryers that used the least amount of energy given their power and active time.

In the interest of using less space, since the house's technical room is small (1.9 x 2.199 m), we also explored washers with a condensation dryer function and we found that the most efficient option is a 2-in-1 washer dryer. The total energy consumption per competition day for this module was 4.48 kWh per competition day.

Lighting

All the lighting fixtures were chosen based by Briana Weisgerber from a few companies that agreed to sponsor team BEMANY. The fixtures were restricted to LEDs and of her choices total energy consumption of all the lighting fixtures, provided that they remain on for approximately 3 hours per night resulted to 0.95 kWh per competition day

C. Passive house design decision

To minimize the energy used by the HVAC system, the house was design to passively maintain a comfort level chosen by the competition coordinators. The house was insulated and heated passively through solar heat gain using double pane glass windows. As for passive cooling, the raised atrium roof was made opaque, and the atrium windows shown in figure 3-4 were suggested to be replaced by bifacial solar panel for additional shade. Furthermore, the house has a green roof for addition leak protection and cooling.

Figure 3-4: Solatrium

3.1.2 System calculations

A. Energy

To determine the size of the PV system, first we need to know exactly how much energy is needed. The total energy is the sum of all the other loads' energy usage. Each load's energy usage is the product of their rated power and the amount of time they were active.

(1) Energy = time (h) * Power (kVA) * PF

All the calculations were made under the assumption that the power factor was unity.

(2) Total energy needed = Energy HVAC + Energy Hot Water + Energy appliances

Given the energy used by the HVAC system that were estimated directly through Ecotect and the competition schedule, the HVAC will use 8.97 kWh per comp day. As for the other two loads, the detailed competition schedule was used to calculate the total amount of active time for each appliance and for the hot water system. To estimate how much energy was used by the hot water system and all the appliances, their rated power was multiplied by a ninth of their respective total operating time. The hot water system and all the appliances were calculated to use 0.34 kWh and 16.04 kWh respectively, which resulted in 25.35 kWh used total per competition day.

B. Insolation

Since goal of the energy balance contest is to have a net energy used to be zero, the energy used represents the minimum amount of energy produced. The targeted energy produced is 140% of the energy used; the extra 40% being a safety factor to account for system resistance, dust, shading and other unpredictable factors. To convert this minimum energy produced (kWh) to a system size (kW), we must use the solar irradiance or insolation. Insolation is a measure of solar energy or solar radiation on a given surface area expressed in mega joules per square meter (MJ/m2) or watt-hours per square meter (Wh/m2). As you can see in equation 3, the units do not result in kilowatts. Thus Wh/m2 needs to be converted to hours, namely sun hours.

(3) System size (AC) = Energy used*(1+safety factor)/insolation,

where the safety factor is expressed as a decimal.

Sun hour is another method of representing insolation where 1 sun hour (1 kWh/kWp) is equal to 1 kWh/m^2. Datong's average insolation is 5.26 kWh/m^2 or 5.26 Sun hours so the system needs to be 6.75 kVA. To convert this apparent power to real power, the inverter's power factor; power factor being the ratio of real power and apparent power was used in equation 4, thus resulting in a system size of 7.1 kW peak for an inverter with a power factor of 0.95.

(4) System size (DC) = System size (AC) *invertor's power factor efficiency

C. Energy and cost analysis

The average cost of PV system = $5.5 per Watt [15]. Should all the appliance had been chosen from in company, in this case GE, the size of the entire system would be 8.53 kW which would result in a system cost of $46,915 which is $9,130 more than the minimum size determine with the most energy efficient appliances.

3.1.3 Panels

The different types of solar cells on the market that were considered were monocrystalline, Polycrystalline and amorphous; Monocrystalline being the most efficient and amorphous being the cheapest but also least efficient. For these reason, the types that were considered polycrystalline and monocrystalline. Within those cell types, the one of the non-standard panel types that was considered was bi-facial solar panels. This was considered because the house has an atrium which has a raised ceiling. This raised ceiling is supported by a frame that is closed off with double pane, low E, glazed glass windows. In my design, these glass windows would be replaced by the bifacial solar panels so that some of the power used during the night would be recuperated

A. Constraints

The area reserved for the solar panels was limited to 63.96 m^2, so the panels were chosen based on efficiency. Higher the efficiency the more watts/area so panel with high efficiency won because it used less area.

(5) Module efficiency = 10 * Min power per square meter = system size/usable area

[15] http://bostonsolar.us/costs-solar-photovoltaic/

To make sure that the panels are far apart enough to ease cleaning the most efficient solar panel on the market was chosen.

Figure 3-5: PV array distribution drawing

As shown in figure 3-5, all of the panels were to be oriented completely flat on the roof per aesthetic limitations set by team BEMANY. The mounting system was donated by Unirack who had agreed to sponsor the team before the panels were chosen. The location of the panel was limited to certain area to avoid shadowing. The exact locations of the shadow were rendered through Revit Architecture, which is a building information modeling software that is capable of modeling a house and set geographic setting to anywhere on the planet for solar studies. This feature was used to determine where the shadows from the atrium’s frame would be.

3.1.4 Inverter

In the interest of maximizing efficiency, only transformer-less single phase solar invertor were considered for the design. Of this type, inverters capable of handling 4-5 kWp were chosen so that the largest PV array (12 kWp) could be split somewhat evenly. The crucial features and characteristics were efficiency, MPPT which would enable team BEMANY to change the size of the PV array should they need to without having to change the inverter; 50 Hz output. Single phase inverters were chosen because central inverter configuration is susceptible to reliability issues and the inverter could be configured for a three phase wye connection. As you can see in the table 1, the Power One PVI-5000 had the highest efficiency therefore was chosen.

Table 1: Inverter list

Inverter	Max input	Max AC out	eff.
Fronius IG Plus 55 V-1/2/3	5.26	5	95.06%
Sunny Boy 4000TL	4.2	4	95.24%
Power one PVI-5000-TL-OUTD	5.2	5	96.15%
Kaco 5002 xi/x	5.2	5	95.50%
SolarMax 4000P	4.8	4.6	95.83%

3.1.5 PV system sizing summary

To minimize the amount of energy used throughout the competition, the house was design to need minimal assistance from the HVAC system, the most efficient appliances were chosen and each mechanical systems was designed to use the least amount of energy while maintaining their practicality.

As mentioned early, the PV array will be a 7.2 kW array consisting of 22 monocrystalline panels from Sunpower's 327 E20 series. The size of the array was chosen based on how much energy is used through the contest during the competition, Datong's metrological information.

The total energy used by all the loads throughout the competition was calculated to be 170.98 kWh; of which 3.08 kWh is consumed by the plumbing system, 26.90 kWh is used by the HVAC system and the remaining 141.00 kWh is used by lighting and the appliances.

3.2 Oasis Energy Management System conceptual Design

This complete web-based monitoring system is capable of monitoring PV production monitoring and domestic consumption. The system will consist of a switching network, wireless digital multimeter with a maximum resolution of 10 mV resolution with a minimum wireless range of 10 m and a server. The DMM consist of an external ADC, a voltage attenuator to scale down the panel's voltage to the ADC's range, and a microcontroller that also acts as the controller for the switching network which connects the different panel(s) to the DMM's input. Once measured, the data is sent to the Server via a wireless module. Said Server would then upload the data to a website which allows the user to monitoring their PV system.

Oasis was design with the intention of having the DMM next to the load center which was located near the PV combiner box. The Server was to be placed behind a router or over an Ethernet port.

3.2.1 Communication block

DMM and the Server communicate wirelessly to each other. To achieve this, the communication block was crucial and the first block to function to be implemented. The methods of wireless communication considered were Bluetooth because it is robust, low power, and low cost; Wi-Fi *802.11a* and XBee RF modules. The Wi-Fi module was immediately eliminated because higher frequencies also have high power demands associated with them, despite the fact that higher frequencies are less likely to experience interference. This relationship between power and frequency explained why the power required was at least 8 times higher than Bluetooth. .. Thus, out of the remaining two options, the best modules from each family given the technical requirements were the RN-42 Bluetooth 2.1/2.0/1.2/1.1 and the XBee ZB.

<u>Technical requirements</u>

- Range: 10 -60 m which is enough to reach the modem which will upload to the web.
- Data Rate: 4800 bps – 1Mbps
- Maximum Linear Power density < 5 mW per meter
- Power < 150mW

A. Value Analysis criteria

To compare the two options, power was the only concern. That said the option with the least power density was chosen therefore the BT-PAN1720 was the better option but it was not available from any of the distributors supported by the ECE shop. That said, I ordered and used the next best option which as you can see from table 2 was the XBee ZB.

Table 2: Wireless Transceivers design options

module	Distance	MAX Power	op voltage	Power Density
XBee ZB	40	148.5	3.3	3.7125
XBee 802.15.4	30	165	3.3	5.5
XBEE Wi-Fi	30	858	3.3	28.6
BT-PAN1720	40	132	3.3	3.3
RN42	20	148.5	3.6	7.425
WT32	30	252	3.6	8.4

B. Test results

Before setting up the DMM, XBee modules were tested using the Echo test mentioned in the user manual. To do so, using X-CTU the modules were configured to have the same channel and the transmission speed by first reading the settings on one of the module, changing the baud rate to 9600 bps then uploaded the settings. After uploading was complete, the XBee modules were swapped and the settings were written again. Once complete, the first XBee module was powered and the RX and TX pins were connected to each other and then in the terminal, “hello world” was typed. The terminal tab in X-CTU is where incoming and outgoing data can be seen as ASCII characters. As the test was typed, each letter sent shown in figure 3-6 in blue was returned in red as expected. This test was repeated without a level converter which were donated by a friend, and failed. In the interest of time, the level converter was kept in the implementation of the DMM.

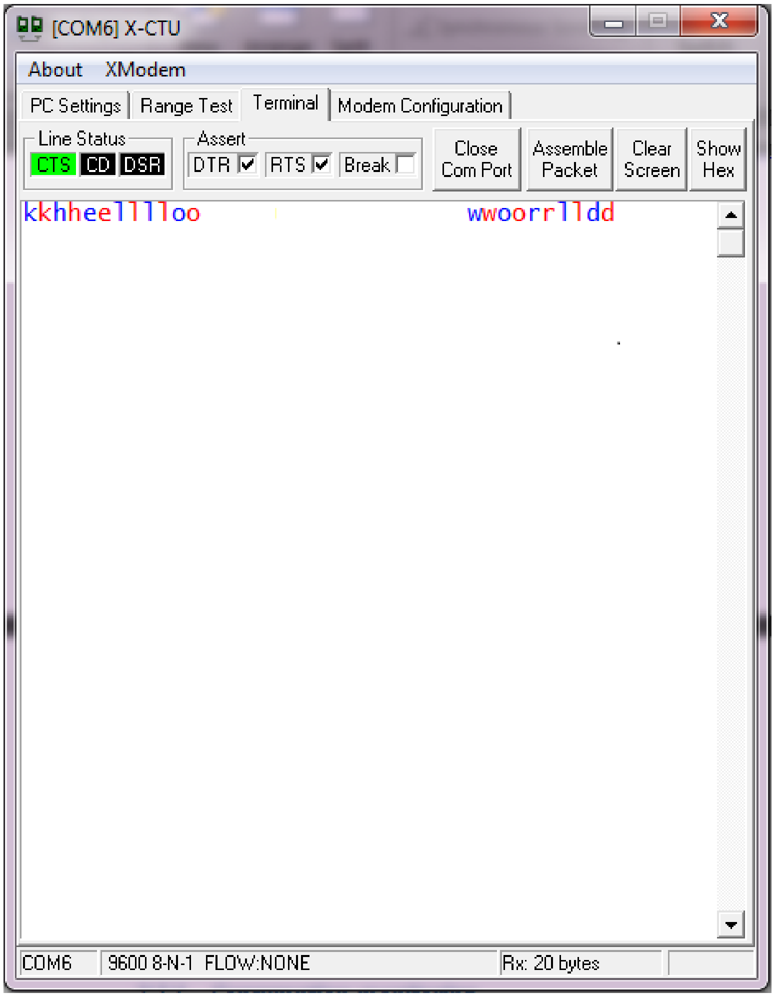


Figure 3-6: Echo test results

3.2.2 DMM

The DMM is based on four subsystems or blocks shown in figure 3-7: the previously designed Communication block, measurement block, Input block and power system. The measurement block is essentially a digital voltmeter that controls the input block's switching network which essentially connected the individual voltage sources to the meter's input. As for the Communication block, it is the bridge between the DMM and the Server which controls it while the power block system provides enough power to the measurement and the Communication system.

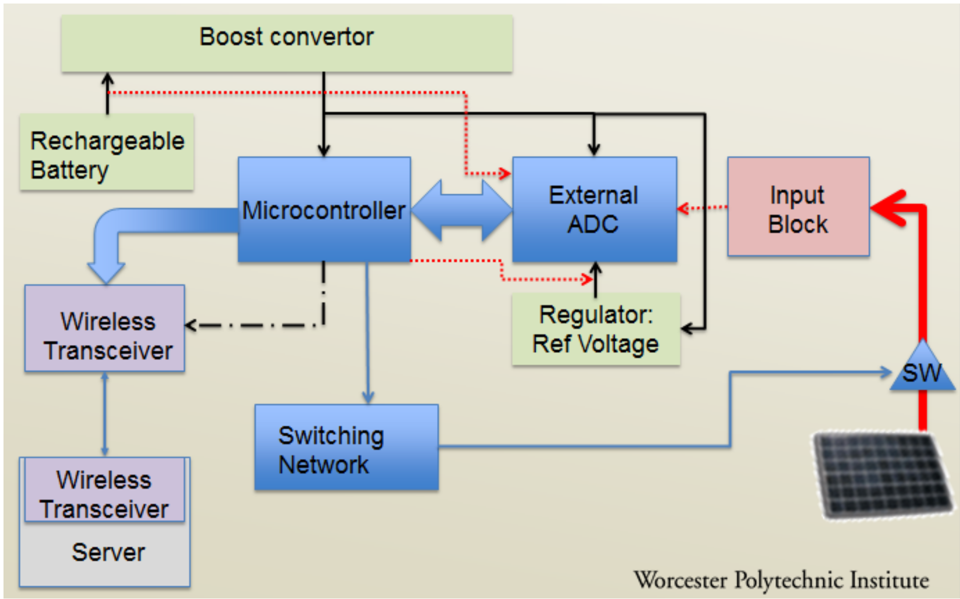


Figure 3-7: DMM Functional system diagram

The most important blocks were built first, and then other features were added through iteration starting with setting up wireless communication between the DMM and my computer. This allowed me to troubleshoot everything by printing error messages using the wireless transceivers. Then a setup function was written which the user would go through to configure their system. To be statistically significant, this initial setup would set how many times each panel, circuit branch and panel string current would be measured.

A. Measurement block

As illustrated in blue in the functional system diagram shown previously, the measurement block consists of a microcontroller, the external ADC and the switching network. The switching network consists of solid-state voltage controlled switches that connect the DMM's voltage attenuator to the solar panels. The switches are turned on by the series of Decoders controlled by the microcontroller that is acting as the DMM's processing unit.

ADC

Most microcontrollers have a built in ADC which is generally 10-bits. Unfortunately, this would not meet the level of accuracy that I want, so an external ADC is needed. Worst case scenario, the maximum voltage of the PV array would be measured and per UL regulations would be 600 V. After attenuating this range to a manageable range of 0-2.5V, a 10mV change in the original system need to be detectable thus, a 1 bits must be equal to this 10mV attenuated; which is 83.33µV per bit. **Log2 (2.5/0.000083333) = 14.87 bits**. Thus a separate 16-bit ADC will be used to meet the level of accuracy of ±0.1% error.

Value Analysis

To be able to measure voltage and current simultaneously, I needed an ADC with two channels, operated with 5V at most and with at least 16 bits. Of all the RoHS compliant multi-channel 16 bit ADC shown below in the table 3, I choose the MX7705 because it had the least power consumption and was the only one with a through-hole alternative which I choose to make prototyping easier. The next revision of product however would have the surface mounted version or the ADS1208 to cut costs.

Table 3: External ADC design options

ADC	Type	Sampling Rate	Min Power (mW)	Price	Packaging
AD7686BRMZ	SAR	500	21.5	21.85	SMD
ADS8325	SAR	100	4.5	10.013	SMD
ADS8318	SAR	500	22.5	16.45	SMD
BDGSRG4	SAR	500	22.5	19.51	SMD
ADS1208	Sigma Delta	40	65	8.55	SMD
AD7401A	Sigma Delta	20000	93.5		SMD
MX7705	Sigma Delta	38.4	1	12.87	Through-Hole or SMD

Microcontroller

When choosing a microcontroller, I focused on a few physical characteristics. I needed an easily programmable microcontroller with at the very least 3 general purpose I/O pins; two for resetting the peripherals when needed, one to monitor the battery of the DMM, for the control system and simultaneous measuring; a SPI interface to communicate with my external ADC; a 2-pin UART port to communicate with my XBee module; low current draw so that the battery's required capacity would be held at a minimum; and a few interrupts to facilitate troubleshooting, all for less than $100. The Arduino family was chosen because it has exceptionally small learning curve associated with making it very easy to program. Fortunately, an Arduino MEGA 2560 was donated.

Test results

As proof of concept, initially I used the onboard 10 bit ADC the Arduino MEGA had, and streamed the output using the XBee and X-CTU. The voltage was swept from zero to five volts and back down using a linear potentiometer and the input was read from pin A0 using Arduino's Analog read example. The readings had a 2 ½ digit resolution so I concluded that the 8-bit Atmega2560 microcontroller was not enough to parse the acquired code.

Next was the implementation of the external ADC. Following the SPI skeleton used in Arduino's Barometric Pressure Sensor example, the serial clock polarity and phase were set to 0. As for the wiring, the input and outputs were connected properly and the ADC's clock input was connected to the serial clock pin of the SPI breakout. In spite of this, the SPI transfer worked and readings using the MX7705 were displayed. From time to time, the results would be zero regardless of the input. To determine the source of this problem, a few print statements were added to see if the registers were not set properly. These print statement indicated that the registers were set properly so, I power cycled the board and everything was functioning again but the voltages were still very inaccurate. I then experimented with the reference voltage and the circuit was working once more with a reference of -0.68V.

After taking the circuit apart to take it home for Christmas and putting it back together again once I returned to the campus, the data ready pin stayed HIGH which corresponded to the ADC being occupied. During Christmas break, I added comments and changed the SPI mode to 3 so that the serial clock polarity and phase would be on the rising edge and set as the reference voltage to 2.5V instructed by the datasheet. Knowing that the wiring might have changed, I reevaluated the wiring and power cycled but this did not fix the issue and neither did resetting the ADC. I stopped using the serial clock as the clock source of the ADC though this worked before and I broke down the code into parts and ran each part on after the other adding an extra layer after each success. Many false diagnoses were made but as you can see in Appendix A figure 7-12, and measuring using the default values recommended by the datasheet only worked once as shown in Appendix A figure 7-11. I tried reverting back to older versions of my code but to no avail; once again, the data ready pin stopped indicating that the conversion was complete. So reading the data ready bit was done instead and results were acquired. I repeated the test but it became clear that soft polling by itself was not reliable because the expected 2V was measured as 0V. So I used soft polling and measured the data ready pin, but again the pin was not indicating that the data was ready to be read. The same outcome was seen with a different ADC so I then tried to manually pull the data ready pin low by connecting it to ground and the code continued to the next step. This indicated that the problem was not a wiring or a hardware problem.

Finally at a loss, I contacted Maxim Integrated and spoke with a support technician who was equally puzzled by my issue. He asked me to send him my code to revise it which I did. Still I did not stop troubleshooting and with some help from one of my friends, I was able to determine that the source of all my issues were typos and my SPI configuration. While troubleshooting, I accidently reverted back to an older version of my code where the clock polarity and the phase for the SPI clock were incorrect. This was determined by using a four channel oscilloscope to view the timing diagram. Once the SPI mode was reverted back to 3 as it should be, as you can see in figures 3-8 through 3-12 the timing diagrams resembled the ones in the ADC's datasheet but the results were still very inaccurate. Later the source of the error was confirmed to be typos in the datasheet.

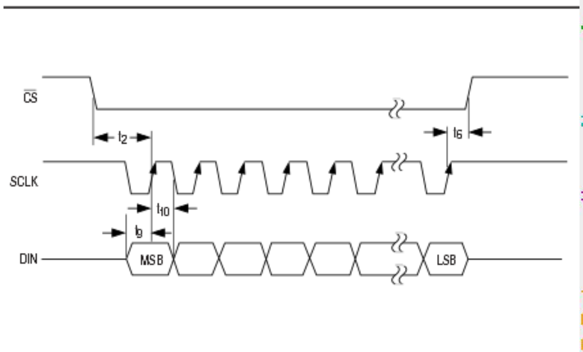


Figure 3-8: Writing timing diagram

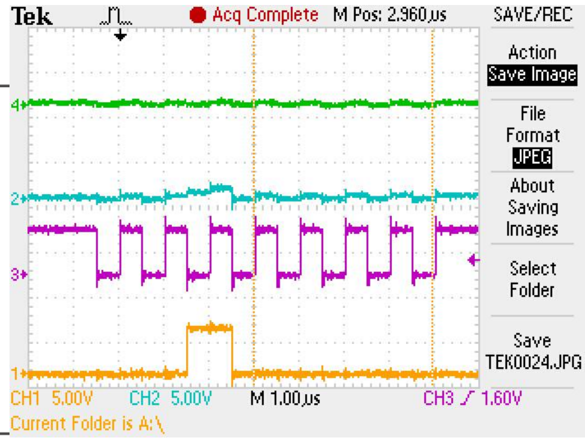


Figure 3-9: Accessing the clock register

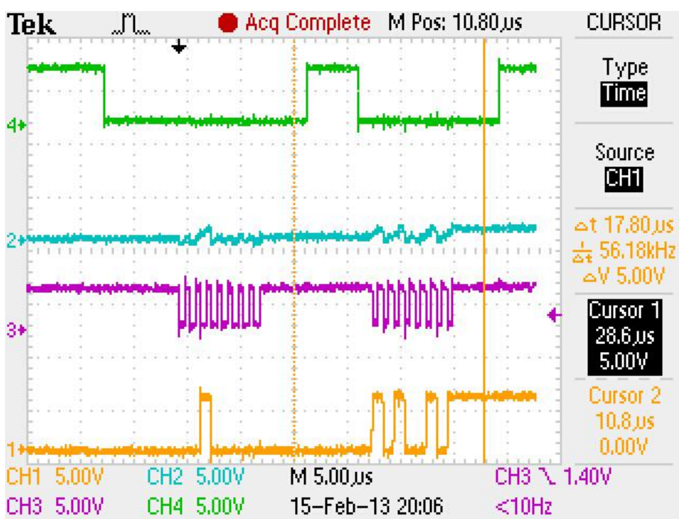
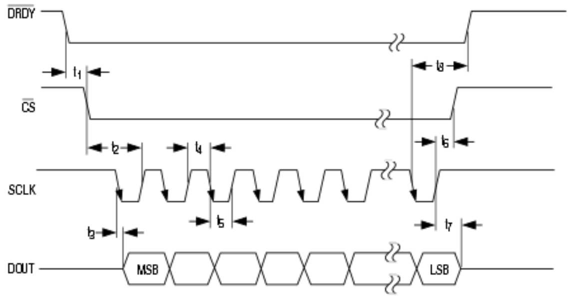


Figure 3-10: Setting the clock register to 0xA5

Where from top waveform to the bottom, channel 4 is the chip select, channel 2 is the ADC's SPI output, channel 3 is the SPI clock and channel 1 is the ADC's SPI input.



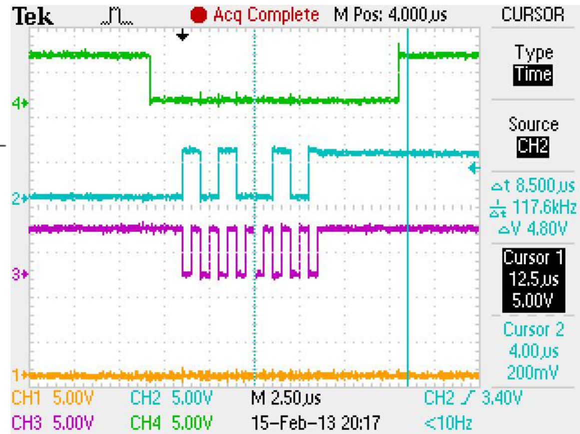


Figure 3-11: Reading timing diagram

Figure 3-12: Reading the clock register

I proceeded to measure multiple inputs parsed by the Arduino and again the resolution decreased back to 2 ½ digit. Thus I decided to leave it up to the Server to parse the data.

Furthermore, the total current draw of each component and the entire circuit when powered using a bench top power supply and a bench top DMM. The ADC drew 4 µA, XBee and microcontroller drew 0.1µA on standby and 22.8 µA when transmitting. The total current was 1.6 mA idling, and 1.7 mA receiving. For the final circuit configuration please refer to Appendix D-2: DMM.

B. Input block

The input block consists of three major components: an attenuator, a switching network and sensors to measure current. Controlling the switching network was done using output pins from the DMM's microcontroller. The command to switch to another panel was automatically administered after all the measurements for a given panel were taken. Each measurement was initiated by the Server.

Attenuator

The attenuator consisted of a voltage divider followed by a unity-gain buffer using a single supply op-amp, namely the TLV2760. This op amp was chosen because it was the least expensive op amp available that could accomplish this. A potentiometer was be used to account for the tolerances in the resistors. The unity-gain buffer is needed to supply the ADC's channel with the input current it needs without drawing any current from the PV panels.

Simulation

As you can see in the figures 3-13 through 3-15 the voltage divider can be used to achieve the linear attenuation needed at the input of the DMM.

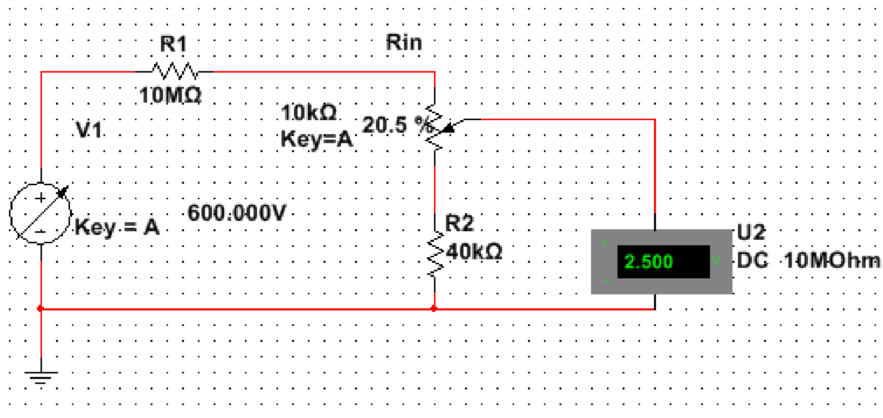


Figure 3-13: Attenuator test at maximum input

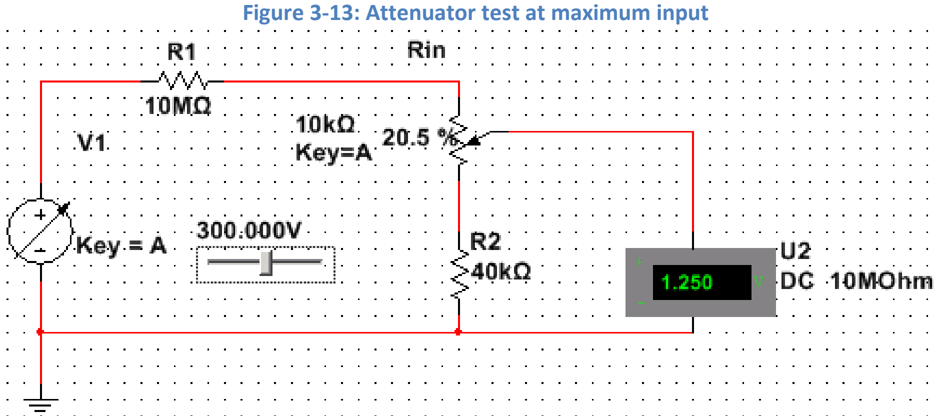


Figure 3-14: Attenuator test at 300V

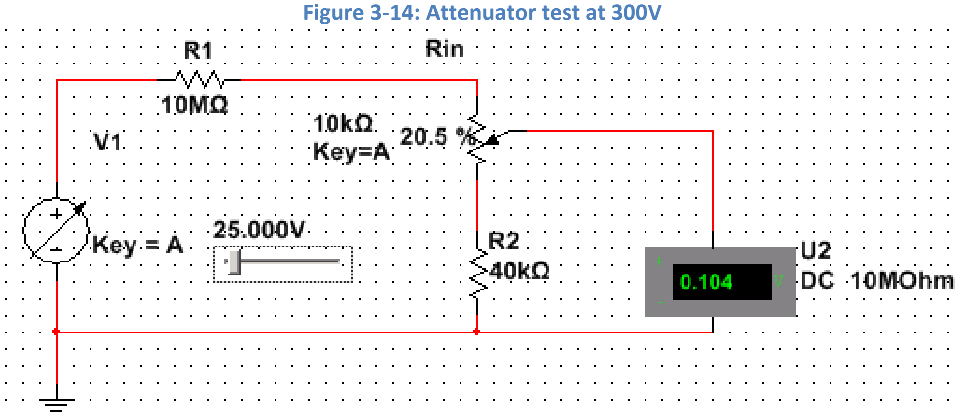


Figure 3-15: Attenuator test at 25V

Test results

This circuit was extremely simple and worked on the first attempt. It tested with 30V from a bench top power supply and ideally expected the measured the output to be 0.125V using the bench top DMM. In actuality the power supply was set to 30.001V and the potentiometer was calibrated until the bench top DMM read 125.00 mV which was as close as I could get to the expected output of 125.004 mV. The current through the resistor was measured to be 2.84 µA so assuming that he maximum measured voltage would be 600V, the resulting current would be 56.8 µA which would correspond to a power dissipation of 33.9 mW**.** Thus, given a 20% safety margin on the current draw, the resistors rated for at least 50 mW were used.

Switching network

The switching network consists of three main parts: The chip selector and the switch selectors; which were implemented using decoders, and the switches themselves. The switch selectors were all giving the same input to minimize the number of digital I/Os needed on the microcontroller development board while the chip selector would enable one of the switch selectors which would then turn on a specific switch.

The types of switches that were considered power MOSFETs, optocouplers, and IGBT. Typically, optocouplers have better isolation then MOSFETs and IGBT which also have turn-off loses and higher leakage or tail-current associated with them. Among the different types of optocouplers, only the Darlington had an output voltage of at close to 360V, which would comply with the maximum string voltage output given the 40% safety margin from the absolute maximum of 600V.Given this criteria, the only optocouplers that were fit for this application were the CPC1302 and CPC1301. This type of solid state relay had the highest output voltage of 350V and the 1302 model was chosen to minimize cost as it had the lowest price per channel.

Value Analysis

For the switch selector, Google in conjunction with mouser was used to acquire a list of decoders that met my operating voltage and output requirement so I choose the least expensive Through-hole option which was the CD4514B. As for the chip selector, I needed an active low decoder to enable the switch selectors and I already had a 3 to 8 decoder (74LS138) at my disposal so for a proof of concept, I decided to use it instead of looking for another decoder with low propagation delay.

Test results

The Arduino Mega is designed to output in binary using its digital I/Os any integer that can represented using eight bits. That said, two ports were used: the first to set the chip selector and the second to set the switch selectors.

Unfortunately, due to the delays team BEMANY experienced with the solar panels, ordering the switches was delayed and the rest of the system continued developing. As a result, the budget was exceeded and I was not able to get the switches I desired. That said, I used N-channel MOSFET within three CD4007 that I already had at my disposal. As for the remaining outputs of the switch selectors, they were connected to red LEDs to indicate which pin was active. Due to the dynamic nature of the switching network, a video of the switching network working was taken. Please refer to the link in the Appendix A-2 for the link and Appendix D-2 for the circuit diagram.

Sensors

Existing consumption monitoring systems use clip-on sensor which make it very easy and quick to install. These clips are essentially current transformer or hall-effect sensors capable of handling up to 200 Amps and 600V which is perfect for most houses, since the main input power cable goes through a 200 Amp circuit breaker. Given these technical requirements, I looked at hall-effect sensors from Allegro Microsystems that meet my technical requirements, contacted them and requested 35 A136LKTTN-T linear sensors which they provided.

Test results

The sensors were tested given their default setup indicated in the datasheet shown in figure 3-16, where the load capacitance was 10nF and filter capacitor was 1nF.

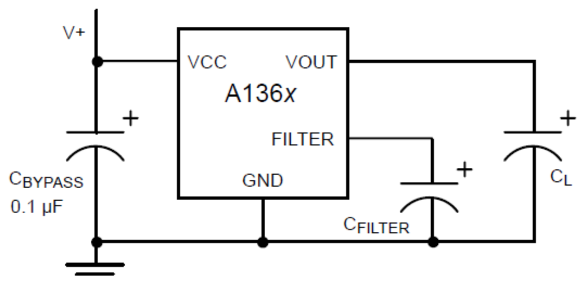


Figure 3-16: Hall-effect sensor test setup

The circuit branch was simulated using the power cable of my laptop. The output was 5V which was far from the 2V quiescent point stated in the datasheet. In addition, I was unable to acquire ring concentrators before I ran out of time. Should the concentrators had been acquired and design to expose the sensor to 7G/A, I expected 2.16758 mV at the output using my laptop cable. Given this setup, 71.42mV/A would be observed which corresponds to 534.12 µA resolution. Together with the achieved 10 mV resolution, the DMM would have had a 5.3412 µW resolution.

C. Power Block

The main components of this block were the battery and the boost converter to increase the battery's output voltage to the microcontroller's input voltage.

Battery

In the world of rechargeable batteries there are two main types; acid and alkaline. Only alkaline types were considered because acid freeze in cold climates rendering them unreliable.

Within alkaline, the batteries differ based on the chemistry and given said chemistry, characteristics such as charging method, depth of discharge (DoD), and disposal method vary. Only Lithium based chemistries were considered because nickel metal hydride (NiMH) had a n output voltage below the desired range and Nickel-Cadmium battery contain a heavy metal that is hazardous to the environment so they have a high disposal cost associated with them, and are not environmentally friendly.

Technical specifications

- Voltage: 3.3V – 5V
- Continuous use: 2190 h (three months' worth)
- Minimum Capacity: 5256 mAh

Note: the minimum capacity was calculated with a 20% surplus margin to account for voltage mismatch

Value Analysis

The comparison between lithium ion and lithium polymer based on their DoD, specific energy, specific power and normalized cost was done during my ECE 2799 which concluded that a Li-Po battery was the best choice. Since I still had a 6600 mAh Li-Po battery from my ECE 2799 project, I decided to use it. This does the maximum battery capacity of the Solar Decathlon Competition so for the competition the DMM would have to be plugged into a receptacle if the competition coordinator did not overlook it.

Using this battery, the total energy available was 17094 mWh given a restriction to 70% discharge. Given the 10 mW power required to operate the DMM, this battery will only last 2.34 months. The desired three months would be achieved with a Lithium-Polymer battery with at least 8455.6 mAh.

Boost converter

A boost convertor is a DC-DC switch mode converter that increases it input voltage by decreasing its output current. Since the battery is a 3.7V and the microcontroller operates with 5V, this convertor is mandatory. Since the development board of the microcontroller has regulated 3.3V and 5V only one is necessary.

Value Analysis

Of the boost convertor IC available on Digikey, the least expensive option which was the LT1111 was chosen. The buck-boost IC's recommended setup for a 5V output from the datasheet was used.

Test results

Initially the output voltage of the converter was 4.96V because I used the available part form the ECE shop. As additional results, the inductor dissipated a lot of heat. Later, the diode was replaced with suggested parts in the LT1111's datasheet as well as the inductor with a power inductor rated for at most 0.5A. Given this criteria, I found three inductors from mouser of which I ordered and used the least expensive option; the KMP 2700T. The output voltage using this inductor was 4.9957 V.

As it is now, the boost converter only functions properly when the battery's voltage is 3.7V. Later revisions should implement a closed-loop negative feedback feature that allows the boost converter to adjust the switching frequency so that the output stays 5V unless regardless of the output voltage of the battery.

3.2.3 DMM Summary and design changes

In short, the DMM built had a 38μV resolution which corresponded to 9.155 mV resolution from the panel voltage using a 16-bit sigma delta ADC. Controlling this ADC as well as the other peripherals is an Arduino mega 2560. This was chosen for its simplicity and favored for directly outputting integers in binary code using the digital ports. Altogether with the XBee ZB module and the level convertor, the DMM draws at most 2 mA, which given the battery used would a little over 2 months and a week.

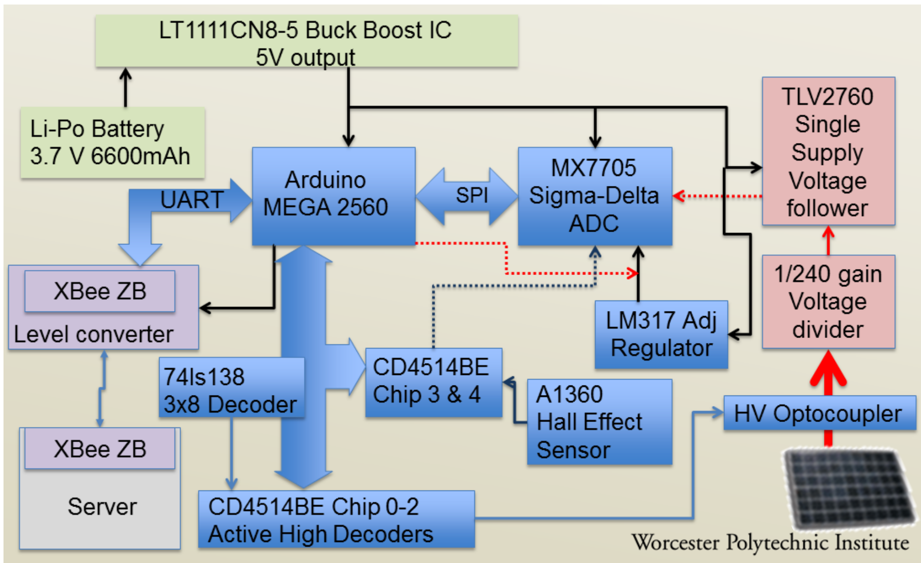


Figure 3-17: As-Built DMM revision 1

3.2.4 Server

The Server was mainly a microcontroller and a battery charger. To avoid plugging into the wall to use AC power, a Power-over-Ethernet module was also needed. That said, the microcontrollers mentioned in the following section were chosen with easy PoE integration in mind. Rapid prototyping was also crucial because only eight weeks were left until the final product was due. Thus, development boards that cost at most $200, with built-in Ethernet interface and an onboard PHYceiver to manipulate the hardware for the send and receive commands of the Ethernet frame were targeted. In addition to those restrictions, only development boards with a 32-bit processor to parse the data coming from the DMM were considered. Also size was a crucial issue because smaller development boards would be able to fit on an Ethernet port without blocking another port.

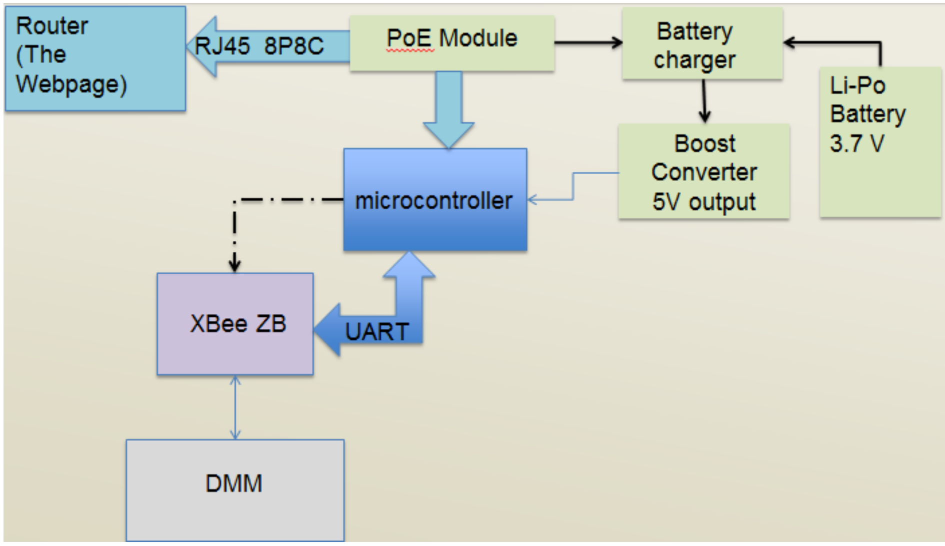


Figure 3-18: Server conceptual block diagram

A. Microcontroller

Given the aforementioned technical requirements, four development boards matched my criteria. The first was the mbed NXP LPC1768. Given the information provided on its website, it had a lot of support and examples that accomplished exactly what was desired; make a server using a microcontroller. It also had a pre-set Ethernet port but purchasing and configuring the Ethernet port in addition to setting up XBee Serial communication with the DMM, creating a webpage and programming the interactions between the mbed and the webpage were additional mandatory tasks.

From Sparkfun, I found the Ethernet Web PIC Development Board. This was slightly cheaper than the mbed but it was had little support in comparison and this option had parallel connector which was going to make it difficult to attach a PoE module. Next was the Spinneret Web Server from Parralax which had an SD card slot included and Ethernet port already setup. This option also required an additional Prop plug making it the most second most expensive option with as much support as the PIC Development Board.

The mbed was the most attractive option despite the fact that I would need to setup the RJ45 socket. By consulting with a friend of mine who had worked a lot with Ethernet, the Rascal micro was recommended to me. This option also had a built-in SD card slot and an Ethernet port. In addition this board is programmed in Python through Ethernet; it was designed to be a web server. It included a web server editor and a webpage that by default streams the input voltages of its ADCs. This was very attractive to me despite the fact that it cost three times more than the mbed. As an embedded Linux system, the Google manipulation program that was originally written to load the DMM's output into an excel file could be used here because the Rascal Micro is compatible with Python.

Value Analysis

Support

- Tutorial and examples that accomplished exactly what I intended to do: 2
- Tutorials and examples that accomplished the building block of what I intended to do: 1
- No support: 0

Weight

- SD card bonus: 5
- Price : 4
- Support: 3
- Area: 2
- Additional task: -1
- Additional component: -1

Price Score

- \$0 - \$37.5: 4
- \$38 - \$75: 3
- \$75.5 - \$112.5: 2
- \$112.5 – \$150: 1
- \$150+: 0

Area Score

- 10 cm^2 – 19.9 cm^2: 4
- 20 cm^2 – 29.9 cm^2: 3
- 30 cm^2 – 39.9 cm^2: 2
- 40 cm^2 – 49.9 cm^2: 1
- +50 cm^2: 0

Additional component

This score was equivalent to the number of additional components needed to get the microcontroller working.

Additional Task

In order to get a fully functioning server, I would need to setup Ethernet and serial communication, setup the website, and then program the interaction between the website and the microcontroller. This score was equivalent to the remaining number of tasks that I needed to do in order to get a fully functioning product.

Table 4: Server development board design options and scores

Dev. Board	area	support	price	price score	additional components	additional task	Bonus Features	Score
mbed	13.52	2	59	3	1	4	0	20.296
PIC	39	1	51	3	0	3	0	14.2
Spinneret	33.0995	1	74.98	3	1	3	1	19.3801
Rascal	50	2	175	0	0	2	2	14

As shown in table 4, the value analysis clearly shows that the mbed is the best choice. However, the HTTP library essentially broke during the design phase so the choices were re-evaluated while excluding cost as a factor. This was done by assigning a price score of 5 to every option and the Rascal was the clear winner as shown in table 5.

Table 5: Server development board design options and revisited scores

Dev. Board	area	support	price	price score	additional components	additional task	Bonus Features	Score
mbed	13.52	2	59	5	1	4	0	28.296
PIC	39	1	51	5	0	3	0	22.2
Spinneret	33.0995	1	74.98	5	1	3	1	27.3801
Rascal	50	2	175	5	0	2	2	34

Test results

The rascal had a built in testing platform to check that all the pins were functioning accordingly. This platform was used to confirm that the board was not defective. Indeed, the board was working properly.

As for the power budget of the Server, the rascal and the XBee ZB together pulled 0.21 A from the power supply when initializing. However an accident occurred which was recovered by replacing the 3.3Vsource on the board but the current draw grew 0.52 A. This explained why the 7805 linear voltage regulator on the board got very hot. This 7805 steps the 9V source to 5V. This 4V drop at 0.52 A results in 2.08 W of heat. This is a prime example of an application where a DC-DC buck converter would be much more efficient. Because the 7805 is very close to the SD card of the Rascal micro, to avoid the heat from damaging the SD card, the server was powered directly with 5V.

The initially, the Rascal micro did not have a “serialRead” function. With some advice from the creator, this function was implemented. In conjunction with that a new webpage was created to test the initialization of Oasis, starting with connecting with to DMM. This was accomplished using one of the existing test pages as a template where clicking a button would call the Server’s OasisConnect() function which mirrored the DMM’s connect2server() function for call and response. This initial step was successfully implemented however due to limited time and knowledge of JavaScript and HTML this was the only task that was accomplished.

B. Power block

The components that make up the power block are the battery, the battery charger and the PoE module. In compliance with the battery chosen for the DMM, a lithium ion battery was also used for the server. The only difference lies in capacity, where this battery is a temporary replacement for the DMM’s main battery which theoretically would last 27 days. This replacement battery’s capacity was restricted so that the user could leave the battery for multiple days at a time. That said batteries with at least 1000 mAh were considered and the cheapest option was chosen that being a 1400 mAh Li-Po.

PoE Module

Power over Ethernet is a system that allows data and power to be transmitted through the same Ethernet cable by transmitting 48V through the unused wires within said Ethernet cable.

The PoE module was restricted to have a 5V output however; this model was not available through any of the distributor supported by the department so a 9V module was ordered instead. Unfortunately, the distributor's stock was depleted before the order was put in so a 12V module was sent instead.

Thankfully, the PoE modules can be adjusted to a lower or higher output voltage so this 12V module was configured to 9V output. Since the battery charger has a 5V input, a buck converter was implemented to resolve this mismatch.

Buck converter

A buck converter is a DC-DC converter that reduces the output voltage but increases the current by storing some of the current induced by the input voltage in a magnetic field and releasing it when the input voltage is removed. Of the high efficiency converters available from Digikey, only the options with an output current of at least 1 A were considered. Given this requirement, the least expensive choice was the MCP16323.

Test results

Since the MCP16323 was a quad-flat no lead package, a printed circuit board was undeniably necessary to move forward. That said, the PCB was designed and order but did not arrive before the time limit came to pass.

Battery charger

Ideally, the battery charger would be capable of fully recharging the main battery after 4 hours from a 70% discharge while not hindering the battery's life expectancy. Given these criteria, the MCP73833 Lithium Battery charger chosen from my 2799 project was appropriate so it was also used. However, the output is that of the battery's voltage so a boost converter was mandatory. To implement said boost converter, the least expensive option capable of outputting 5V at 200 mA was chosen from Digikey which was the TPS63002.

Test results

For the same reason mentioned previously, this block was not tested or implemented.

3.3 Server Summary

Unfortunately, the power block was not implemented within the limit, and the majority of the functionality lies within the scope of a Computer Science project however, the skills acquired for designing and implementing a PCB with the conceptual blocks shown in figure 3-19 in green are invaluable.

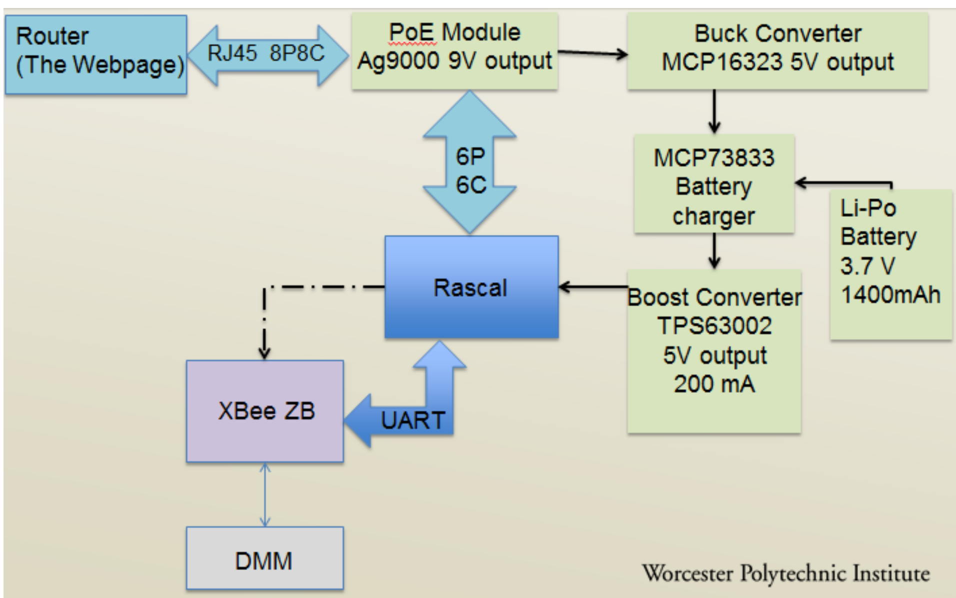


Figure 3-19: Server updated conceptual block diagram

4. PV system Design change

This chapter describes the PV system and the loads used in the house for the competition. This PV system is significantly different from than the systems originally designed and specified previously because all of the electrical loads were donated to team BEMANY.

4.1 PV system

The approach to the PV system sizing changed from using what is needed to using the worst case scenario. Thus an 11.6 kW system will be implemented in compliance with the inverter. This decision will assure that Solatrium does have a positive net energy usage however; the price of the solar panels which were 40 monocrystalline 290 W panels from 1SOLTECH's reflection series may be taken into account for the price of the house which is already over the targeted $250,000. This could be detrimental to the market appeal contest scores.

Inverter was an SMA Tripower 12000TL central three phase invertor. This was chosen among the option available for donation because the size the PV system was no longer a concern. This decision was made without any of my input and I was not notified.

4.1.1 Passive house design changes

Due to the low R value of the bifacial solar panels and construction issues that would arise from using these panels as a replacement for the glass of the Atrium frame, this suggestion was rejected. Also, the green roof was rejected due to the financial and transportation complications it would bring.

4.1.2 Load calculation

The appliances were all donated by GE which caused the minimum size of the PV array to increase from 7.10 kW to 8.04 kW. This change may seem small but it is a financial increase of $2810. The full list of appliances can be found in Appendix C-2. In summary, the total energy consumption increased by 89.34 kWh for the entirety of the competition.

A. Mechanical Loads

Overall the mechanical load increased by 7.78 kWh. This was due to the increase in the HVAC load in spite of the decrease in energy used for plumbing. The HVAC module used were four mini-split system and the module themselves were York.

As for the hot water, GE's hybrid stand-alone solution was used less energy in comparison to the solar hot water design under worst case scenario. This yielded 1.62 kWh less.

4.2 PV system design conclusion

Although, all the recommended designs were not implemented, Solatrium will have a positive net balance if at least 26 panels are installed during the building phase of the competition. This minimum would be a 7.54 kW system which would yield a net of approximately 4.43 kWh. At most, an 8.12 kW system (28 panels) is needed which would result in a net of approximately 25.97 kWh but if all of the panels are used, this 11.6 kW system will result in a net of 170.06 kWh.

5. Oasis further development

This project involved the hardware and software development of Oasis, a stand-alone energy monitoring and management system which encompassed many concentrations within the electrical and computer engineering such as wireless communication, power systems, embedded systems, as well as skills from other disciplines; namely 3D modeling, systems programming and web development through HTML and JavaScript. Oasis, though incomplete due to time constraints would have had the ability to monitor and energy produced by a photovoltaic array and the energy consumed within a medium sized home (approx. 1500 sq. ft.). Oasis was designed to have the highest level of accuracy by implementing per panel voltage reading and string level current measurements for production monitoring. For consumption monitoring, the current measurements would have been taken per circuit branch.

5.1 DMM Optimization

In the end, the DMM was capable of measuring voltage because the ring concentrators for the hall-effect sensors were not acquired due to financial constraints. As it stands now, a program could be written to automatically configure putty to read the incoming data from the DMM through a COM port and save it as an excel sheet. Following this step, said program would run a python code which was written to upload and download files from a directory into the users Google drive account (see Appendix C for details).

Many existing blocks still need to be revised for Oasis to be considered market ready. For instances, cost could be reduced by removing the level converter that was used in conjunction with the wireless transceiver which was implemented using an XBee ZB. The cost could also be reduced by implementing the DMM using an Arduino UNO which is smaller and less expensive than the Arduino Mega 2560. This would require a smaller housing than the one made in this revision. In addition, a housing would need to be made for the switching network which itself could be optimized using surface mounted decoders and a printed circuit board (PCB).

Since the input stage of the DMM is being revised, the power connector which would carry the output voltage of the selected panel to the DMM needs to be implemented using a connector rated for at least 600V and 1A. Ideally this would be a BD connector as shown below where the other wire would be earth ground.

Figure 5-1: BD connector (3.5 mm pitch)

The next block in need of optimization is the sensor network. This network consisted of the hall-effect sensors which need a housing to shield to electronic components, and well as the ring concentrator. In the design, the ring concentrators were estimated for 7 Gauss per Amp. This design would result in resolution in the order of micro amps so the gain of the concentrator could be lowered so that less material (ferrite or cold- rolled steel) is used per sensors.

As for the power blocks, the boost converters as they are can be modeled using an open-loop control diagram. This should be modified so that it is self-adjusting. Thus it would become a closed-loop system so that the 5V output could be maintained despite the fluctuation in the battery's output voltages. This could be done using the information the DMM's built-in ADC gathers about the battery by monitoring the MX7705's reference voltage however, an analog approach would be better because it would be faster to implement. As for the battery itself, the capacity of the main battery should be doubled if feasible. This would give the DMM 6 months of uninterrupted operations.

5.2 Server Optimization

Finally, the Server should be finished. Due to the time restriction and this crucial part of Oasis was not fully developed. Connection between the Server and the DMM was the only step that was completed. The remaining steps included acquiring the measurement parameters through the 4Display screen which was initially acquired to implement a display hub. Given the remaining weeks, this hub was abandoned and its directives, namely displaying information and being the charging station for the battery; were reassigned to the Server. The screen on the Server would act as the local alert medium and as the local user interface when changing the battery or initializing Oasis for the first time.

Given more time, the Server would have been programmed to automatically check the measuring parameters upon start up and connect to the DMM. Following this, it would go through the measurement settings menu using the 4Display screen to acquire the measurement parameters should they not exist. After each measurement parameter is entered, that value would be transmitted to the DMM, which in turn would send a confirmation message to move onto the next parameter. Upon completion, the Server would check for internet connection and display “Please connect me to an Ethernet port” as well as a graphical representation of the aforementioned message. Once internet connection has been established, the status of the system would be displayed. This status would include battery conditions, DMM connection, internet connection and current net energy used. The text of the net energy used would occupy as much of the screen as possible and be colored green if it is greater than 10 kWh, white if it is positive but less than 10 kWh, orange if it is negative but greater than -10 kWh or red if it is less than -10 kWh. Text message alert would be included and configurable through the webpage or the display screen. Utilizing this feature would be controlled through an interrupt of which the service routine would be sending a text message through Google and indicating the error and if it was automatically resolved and that a confirmation message needs to be sent back, as per the restriction set by Google.

On the webpage, the existing page that streams output of the Rascal's onboard ADCs would be used as a template to create multiple pages that graph the output of each individual panel and current branch. The measurements would be received by the Server through a function which would receive the incoming data, average it, subtract the previous average from it, parse it then load it in an array shown below in table 6. The entire array would then be read one row at a time and graphed. The graph would always append the new value.

Table 6: Server example array containing performance data

time	Panel 0	Panel 1	……	Panel x-1	Panel x	Circuit Branch 0	Circuit Branch 1	….	Circuit Branch x-1	Circuit Branch x
6:00:00	28.91	35.51	……	35.59	35.58	12.01	20.00	….	1.03	3.64
6:01:00	28.95	35.52	……	35.60	35.61	12.01	19.98	….	1.04	3.65
6:02:00	28.99	35.51	……	35.20	35.60	12.02	19.99	….	1.06	3.65
6:03:00	29.01	35.60	……	35.01	35.59	11.98	20.01	….	1.02	0.00
6:04:00	29.0	35.58	……	35.03	35.58	12.00	20.00	….	0.00	0.00

As for switching the battery, before the text message alert is sent, the Server would save all the present parameters and values. This would make sure that the data would not be lost and that the system would automatically reconfigure and resume normal operation without any input from the user.

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