Net-Positive Water Control System

ME 450: Design and Manufacturing III
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Executive Summary

Our team was tasked to work in conjunction with the BLUElab Living Building Challenge Team to design and manufacture a prototype controller for a net-positive water system to be installed in a residential Ann Arbor home. Net-positive water encompasses the movement towards a decentralized water supply where rainwater is collected and treated on-site for use as potable water, and where wastewater is treated on site before re-entering the water table. “Net-positive” is an improvement on net-zero that promotes the idea of the water re-entering the environment in better condition than it left.

After our initial meeting with our sponsors, conducting background research, and administering a collaborative ideation process, our team utilized functional decomposition and engineering analysis to better understand the flow of energy, materials, and information throughout the individual processes involved in the system.

We started our process by determining specific design requirements and translating them into the engineering specifications that our design should embody to satisfy our stakeholders. Our system is required to measure the water level in the cistern tank, alternate between the rainwater supply and an alternative water supply, have an emergency shut-off switch in case the water purification system is compromised, and have a comprehensible user interface. Additionally, we identified our major design drivers, which include an easy assembly and a list of specific unusable materials.

Our final design starts with a pressure sensor at the pump intake to monitor the water level in the cistern tank. The sensor is connected to the Arduino, inside an enclosure that also contains an LCD screen and a rotary encoder knob. These act as the user interface inside then. The controller will connect to a two-way solenoid valve that will allow the system to switch between the two water sources automatically based on the pressure sensor reading. We created multiple display screens, which can be toggled between by turning the knob, that display system parameters in various forms. It also gives the option to manually switch the valve. We performed basic engineering analysis on our system before moving ahead with prototyping and testing. This analysis included an energy evaluation of the solenoid valve as well as examining the physics behind the water monitoring pressure sensor.

As of the Design Expo, we have connected our LCD screen, pressure sensor, and valve to the Arduino to demonstrate the system’s functionality. We programmed the LCD screen to respond to the sensor readings and to show the status of the valve. Since we were able to achieve functionality of all of the basic components, we created a calibration curve for the water level in the tank against the voltage output of the pressure sensor. We also estimated the annual energy usage of system. We believe our biggest challenge in implementing the control system will be finding an accurate and reliable water level sensing method due to the complex nature of rainwater collection. This report serves to further describe our progress in the design process.

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Project Description and Background

The International Living Future Institute is an organization that promotes a certification program known as the Living Building Challenge (LBC). The idea behind the challenge is to "lead and support the transformation toward communities that are socially just, culturally rich and ecologically restorative by providing a framework for design, construction and the symbiotic relationship between people and all aspects of the built environment" [1]. As a step-by-step process toward the Living Building Challenge, several Petals must be completed in order to receive full accreditation. One important Petal under the Living Building Challenge is the water petal, which certifies a home for its net-zero sustainable and regenerative water usage.

Many homes and buildings around the United States have implemented net-zero water supply systems. The Bullitt Center is an office building in Seattle that is designed for both net-zero energy and water [2]. Although the system is designed, it is currently not in use due to Seattle city codes. However, once the legal issues have been resolved, the plan is to completely disconnect from the municipal water supply and function solely on collected water. Similarly, there is a home under construction in Oregon called the Desert Rain home that is also being designed for net-zero water [3]. Although construction is not yet complete, the plan for the home is to be completely self-sufficient. The Bertschi Living Building Science Wing in Seattle is another building that has implemented net-zero water. This building is an elementary school science building, which has completed all Petal certification.

The University of Michigan's BLUElab Living Building Challenge Team is currently working on a 110-year old historical house in residential Ann Arbor, the home to the Grocoff family. The house already functions on a net-positive energy budget, so the current project is converting the home to net-positive water, an improvement on net-zero water. The LBC team has already designed subsystems including rainwater catchment, storage, and purification. However, they have not yet begun on their plans to include an automated control system for monitoring and adjusting the water supply to the house.

Although the LBC requires that the certified home use only water collected on site, the team feels that it is necessary to incorporate an intermediate step to include a backup water supply. The goal of the system is to supply all the home's water needs from collected rainwater, but in the event of water shortage or a failure of the purification system, it is important that the family's home still have running potable water.

Figure 1. Photograph of the Grocoff family's historic Ann Arbor home. Note the solar panels on the roof that contribute to the net-positive energy usage.

Our team has been tasked with the design and prototype of an automated control system for a backup water supply. For the time being, the secondary supply will be the municipal water supply but in the future, secondary supplies may include neighboring homes or neighborhood watersheds. One of our design goal is to design a system robust enough to connect any two water supplies.

Since the other buildings in our case studies do not intend to be connected to municipal water for a backup supply, our team does not have any examples or benchmarks to work towards. We instead hope to develop a system that others look towards for their water conservation plans. Our goal is to create a design that can be repeated and emulated in more conservative rainwater supply systems.

During our research, we found two pieces of literature that will help our design process. A paper published by the 2012 IEEE Conference outlines a conceptual design for a water monitoring and distribution system [4]. The system includes a tank with one intake and several outtakes to various users. The quantity of water in the tank is measured and accounted for in a control box. Water is then distributed to the users while being monitored and tracked. The control system disables water use if a user has gone over the daily limit. Users can request more water for the day, but that is dependent on the control system monitoring the water level in the communal tank. A second piece of literature is a patent [US4709427] for a plumbing system disabler [5]. The patent incorporates water level monitoring to a remote control unit. A plunger associated with the water level sensor will connect or disconnect the water supply line depending on water levels. This will be important to us because we need to be able to connect and disconnect two different water supply lines in the house.

User Requirements and Engineering Specifications

We interviewed several stakeholders in our project, including the end user, i.e. the owner of the home where our project will eventually be installed, and other members of the BLUElab team working on different components of the system. Based on these discussions, we generated a list of user requirements, mainly determined by the desires of the end user.

First and foremost, the system needs to primarily use purified rainwater from the filtration system as a water source. Our system needs to continuously monitor the water level in the cistern and switch to an alternate water supply, in this case the municipal water line, when the rainwater reserve runs low. In addition to this, there were several other requirements important in the development of this project:

- Create a user interface that displays system information simple enough for a 5 year old or an 80 year old to comprehend, and optionally gives more advanced water consumption data, projections, and tips to reduce waste
- Include emergency override in case the filtration system fails
- Minimize power consumption, as the house also has implemented net-zero energy practices
- Comply with relevant city code regulations

After reviewing these requirements and discussing them with the LBC team, we translated them into engineering specifications.

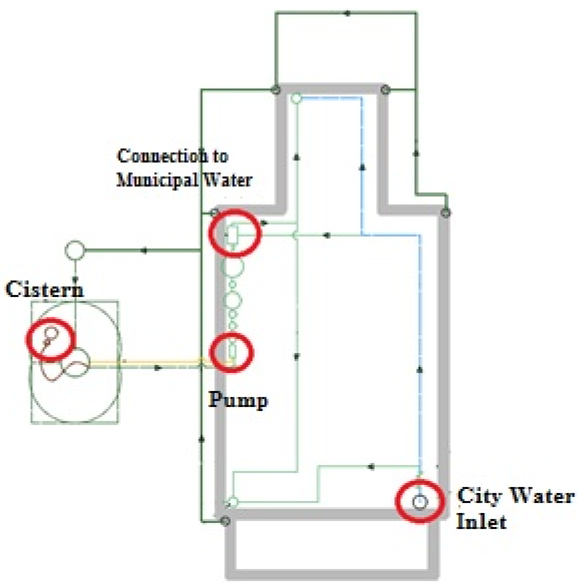

Figure 2. The LBC team has drawn a schematic of the home with pertinent components. Our control system will have to function in four main areas of the net-positive system: monitoring the water level in the cistern; switching the pump on/off; actuating a valve to change the water source; directing water flow from the inlet of municipal water.

The user interface has a readout that displays the current volume of water in the tank, a projection of how many days of water are remaining based on average water usage, a graphical display of the volume, and a screen that gives the option to switch water sources by pressing a button. If we have the opportunity, we will add other readouts for information about average water usage and some tips to reduce consumption. Mr. Grocoff suggested a statement such as "Your water will last ___ days longer if you shorten your showers by 2 minutes a day." However, this would require a lot more complicated coding and possibly extra sensors to monitor water flow in various fixtures, which we were unable to complete in the time period available. As a complete fail safe, we will have the option of a manual override to connect the municipal water supply to the home by having a manual valve in parallel with the valve we chose, thus giving the option to restore flow in the event o fa full power system failure.

We learned that there is no set energy budget for the entire net-positive water system, however we must report to our stakeholders the estimated annual power consumption, and we aim to keep it around 500 kWh per year.

We researched the Ann Arbor residential city code and the Living Building Challenge rules to determine factors that apply to our design. The two main factors are to ensure that no rainwater flows back into the city water system and to limit our material selection to materials not included on the Materials Red List. The most notable material we need to avoid is PVC.

One specification that is yet to be determined is the exact water level necessary to activate the shutoff valve and switch to city water. The rainwater collection pump uses an intake at a fixed position to collect water from the cistern and pump it through the filtration system. This is because silt in the rainwater eventually settles out and develops layers of sediment on the bottom of the cistern, as well as floating on top of the water. The pump will be damaged if too much of this silt enters it, so we need to determine the maximum thickness of these layers in and work out the minimum allowable water level.

Concept Generation

Our project is unique in that it is focused more on developing a control system composed of off-the-shelf components rather than manufacturing many parts of our own design. Therefore, concept generation mainly consisted of researching sensors, switches, and other control elements. The major categories of concepts were derived from each function in the functional decomposition we created. For example, the function “Select Water Source” required us to research several types of solenoid valves to decide how to connect the two water sources.

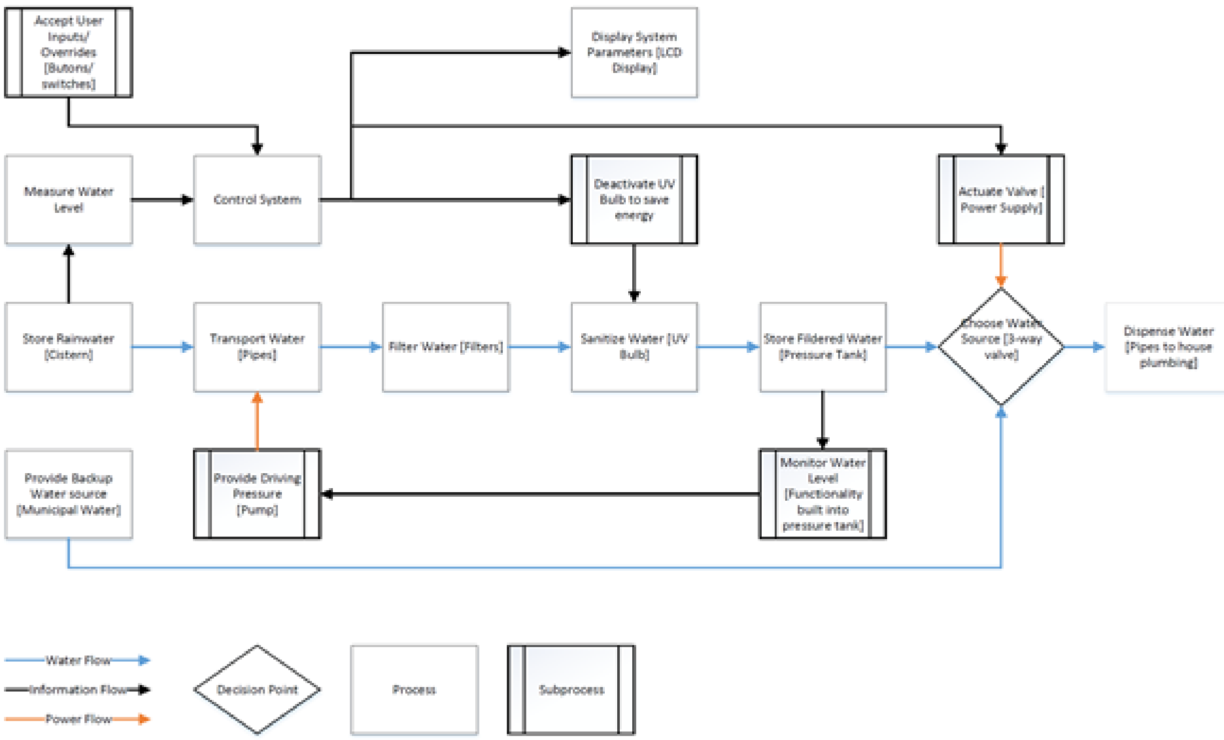

Figure 3. Our functional decomposition includes the flow of water (blue lines), the flow of power (orange lines), and the flow of information (black lines). Each block represents a specific function that our control system should be able to complete.

Most of the concept generation surrounding pre-existing components being utilized in our control system was conducted by researching part suppliers we were familiar with from previous experience in ME250/350 classes. Using this research, a list of possible parts for each concept was generated (see Appendix A).

One significant design decision was between two ways of piping the water. The original assumption was the use of a single three-way valve to actuate and select between the two water sources. This would not require us to monitor the water level in the pressure tank, as we would simply cut off flow from the pressure tank by default when the back-up water source is in use. We also came up with a second idea, which was to use a single two-way valve connected to the backup water supply. In this concept, the city water would be piped into the pressure tank, preventing it from emptying and pumping in more rainwater. The 3-way valve was determined to be ideal, but due to the difficulty of finding a 3-way valve sized for our application, we went with a 2-way valve. This also eliminates the need to control the pump, as the backup water replenishing the pressure tank will prevent the pump from ever turning on when the rainwater supply is low.

Another concept generation discussion was centered on the type of sensor to use to detect the water level. The BLUElab team initially suggested an ultrasonic sensor to measure the water height, but we also explored other options that used pressure to monitor the height. One solution was to place a pressure transducer at the intake of the pump inside the house, rather than place a sensor inside the tank and run conduit from the house to the cistern. The principle is that the pressure in the pump suction is directly proportional to the height of the tank and can be mapped accordingly. This was a challenge at first because the LBC team planned on using a floating intake for transporting water from the cistern to the purification system. However, we did some research on our own and determined that a fixed intake would work well and allow us to use a pressure transducer. So, we convinced the LBC team to change their original plans to better mesh with our design needs.

One concern in selecting concepts was compatibility. The different control boards accept different inputs. Some types, such as Arduino, accept simple wire inputs to pins on the board, while others, such as some BeagleBoard models or the Intel Galileo, are designed to use USB and/or Ethernet connections. We had to be sure to research sensors and other peripherals that were compatible with all types of control boards. Furthermore, we later learned that concept generation should have been guided by the voltage and currents of sensors and other devices.

Concept Selection

To select a complete concept, our team first researched several components and generated unique assemblies for our project. After researching these different components such as the sensors, valves, and control boards, we separated the components into categorical lists. Each categorical list consists of multiple products. For example, the control unit list includes: Arduino, Raspberry Pi 2, BeagleBoard by TI, BeagleBone Black, and Intel Galileo. From these lists, each team member individually selected the components for a possible system while considering feasibility, manufacturability, and energy consumption.

From the selected components, we determined the final concepts using the project's engineering specifications to evaluate the best valves, sensors, display and user interface, control board, and enclosure. These specifications include minimum energy usage, replicability, simplicity, robustness, and cost. We constructed a Pugh chart for each component using these engineering specifications.

The selected concepts feature an Arduino Uno control board inside an aluminum enclosure connected to a dot matrix LCD displaying information from a pressure sensor, which then controls a two-way solenoid valve to switch water sources.

Final Design

After completing the engineering analysis, the selected components are an Arduino Uno control board inside a plastic enclosure connected to a SainSmart LCD displaying information from a OMEGA pressure transducer, which then controls a Baco Engineering ¾" DC 12V Electric Solenoid valve to switch water sources for the net-positive water home control system. Figure 4 shows a mockup of the control system along with the sensor and magnetic latching valve that was determined from our engineering analysis. The figure also details the process of switching water sources as mentioned previously. This is an improvement from the functional decomposition, because the figure gives us a view into which components are placed in relation to the whole system.

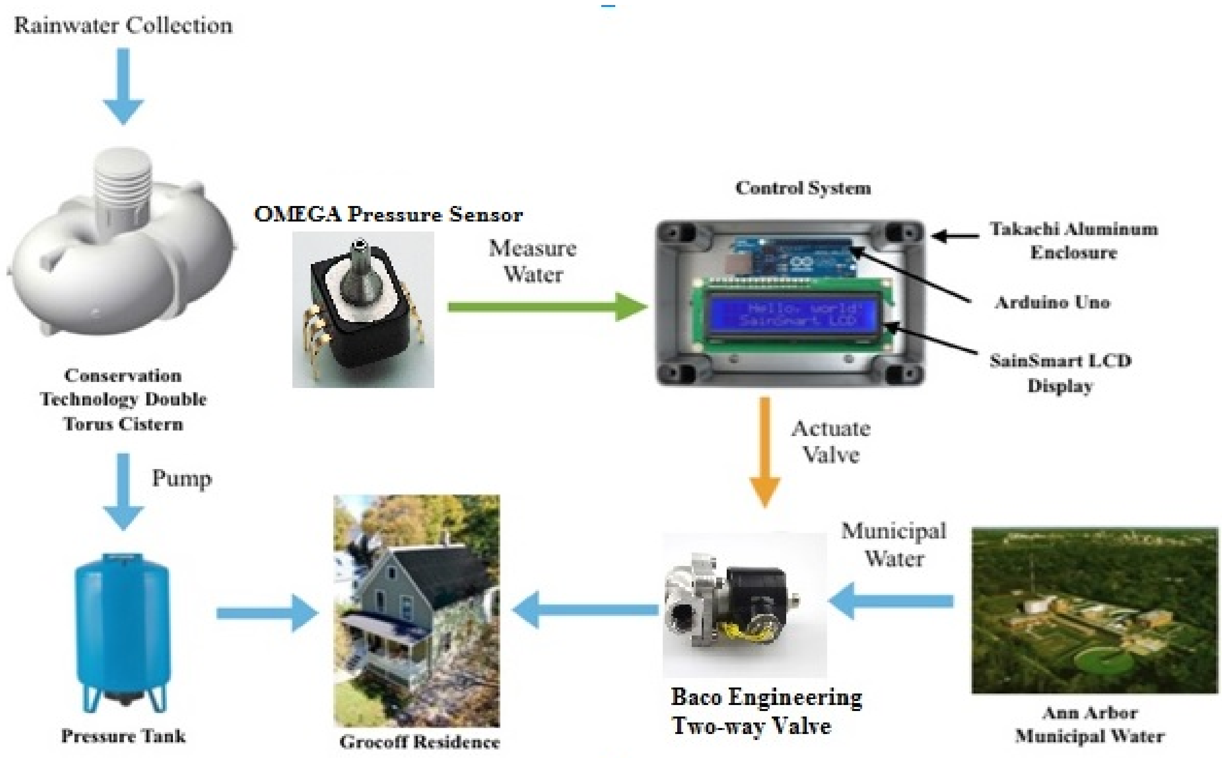

Figure 4. Final concept mock-up detailing sensor, control system, and valve components and function of each component to switch water sources.

The Arduino Uno has a processing speed of 16 MHz and an operating voltage of 5V. With this operating voltage, the control board uses very little power, which helps us stay within our energy budget. The Takachi enclosure is a premade, readily available part. It was designed specifically for use with the Arduino, our size of LCD, and the rotary encoder knob, which made it very easy for us to set up. It also will help with replicability; if this project is continued and installed in multiple homes, as assembling pre-made parts is both cheaper and easier than manufacturing a housing. The SainSmart LCD features a small, low energy usage, and cheap alternative for our display. Our current sensor selection, the OMEGA pressure transducer, is compatible with the Arduino and requires no additional circuitry. It has a pressure range from 0 to 50 kPa with a maximum typical operation voltage of 12 V. We originally purchased the Motorola MPX2053GP sensor which we realized was not ideal for use with the rest of our system.

The Baco Engineering two-way solenoid valve features two solenoids that can control the flow and normally closed. When the water level falls below a certain value the Arduino will send a signal to open the valve, allowing the city water to flow through. The valve has a working pressure of 145 psi, is made of stainless steel, has an operating temperature of 0 F to 176 F, and is three-quarter inch in diameter, suitable for our uses. From the detailed engineering analysis of our design drivers, we were able to find a better and more efficient valve that helps us to better accomplish our goals. A magnetic latching valve would be more energy-efficient as it only consumes power when the valve switches from one position to the other. However, due to the high cost and long lead time, we have decided to use a solenoid valve for proof-of-concept, and in the long run the BLUElab team will order a custom magnetic latching valve that better suits the design needs.

In addition to the components outlined above, we have designed a circuit to better calibrate the signal from the pressure transducer. The circuit is relatively simple due to our careful selection of inputs and outputs that run at the same 5V supply as the Arduino, and can interface with the Arduino pins without needing filtering, amplifying or dividing. We are using an H-Bridge to control the valve, due to its ease of use and our familiarity working with it from previous courses. We will also be using an independent 12 V power supply, since the solenoid valve runs on 12 V.

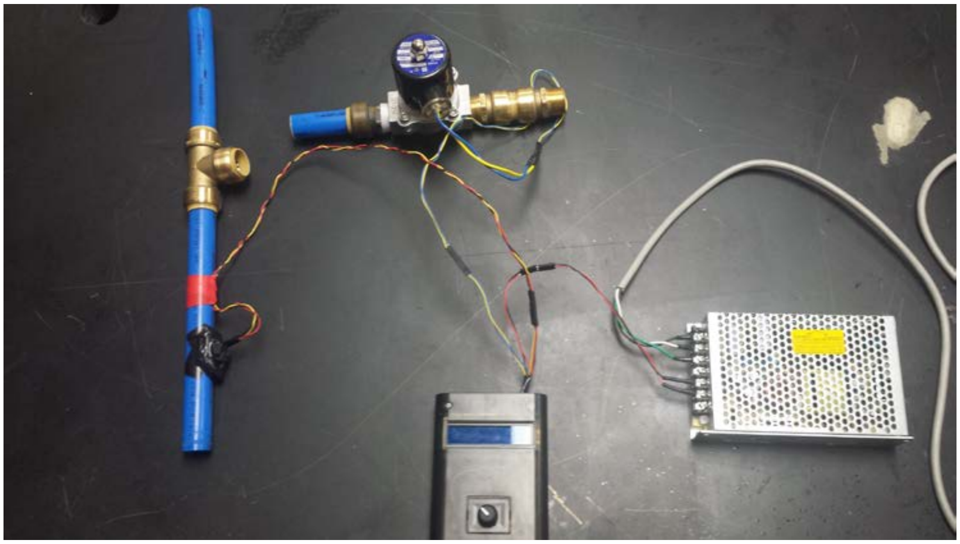

Figure 5. A photograph of our final prototype. The Arduino, LCD, H-Bridge, and Rotary Encoder are all in the enclosure. The pressure sensor is attached to a length of pipe for testing. Additional pictures can be found in appendix E.

Engineering Analysis

Our most important engineering analysis involves the power consumption of various components. We know that we will need to minimize our energy consumption as much as possible. Our main focus in this area has been selecting a valve that will use the least energy and therefore design the entire system to run on less than 500 kWh annually. Originally, we planned to use a solenoid valve because it is the easiest to control. It is either on (fully open) or off (fully closed), so there is very little room for error in the control. However, after analyzing the energy consumption, we found that this may not be the best solution, and so we carried out calculations to determine the annual energy usage for the solenoid valve, as well as special low-power solenoid valves, motorized valves, and magnetic latching solenoid valves.

For normal solenoid valves, the valve is either energized or not energized. We are able to customize which positions are on and off. Because the homeowner intends on never using the backup water supply, we could set the default, non-powered setting of the valve to be the rainwater, in which case it would not draw power except in the event that the city water backup is used. Originally we considered having the off position be city water, so that if there were a power failure it would automatically revert to the city water supply. However, it would be relatively trivial to install a manual bypass valve that would cover this failure mode. To estimate annual energy consumption of these types of valves, we simply multiplied the wattages according to the spec sheets by the number of hours in a year to obtain the theoretical maximum power per year. These values varied widely for different valves and are summarized in Table 1.

Table 1. Summary of maximum annual power consumption for various solenoid valves

Valve	Power Rating (W)	Annual Energy Consumption (kWh)
ASCO Potable Water Grade Solenoid Valve	6.30	55.19
Two-Way Pilot Operated Solenoid Valve	9.00	78.84
ASCO Low Power Valve 1	0.55	4.82
ASCO Low Power Valve 2	1.40	12.26

Another type of valve we researched was a motorized valve. In this case, a motor controls the position of the valve, so we thought that it would only use a substantial amount of energy when changing valve positions. We reviewed the documentation for these valves and calculated the annual energy usage, which is broken down by three settings: opening valve, closing valve, and holding valve (Eq. 1-3).

$$120\,V\ *\ 2.10\,A * 9\ seconds = 0.63\,Wh\ per\ opening\ operation \qquad \text{(Eq. 1)}$$
$$120\,V\ *\ 5.60\,A\ *\ 1\ second\ =\ 0.19\,Wh\ per\ closing\ operation \qquad \text{(Eq. 2)}$$
$$120\,V\ *\ 0.09\,A\ *\ 8760\ hours\ =\ 94.61\,kWh\ to\ hold\ valve\ in\ position \qquad \text{(Eq. 3)}$$

The current, voltage, and time duration are drawn from the valve documentation descriptions, e.g. the valve draws 2.1 amperes of current while opening, which takes 9 seconds. We were surprised to see that although the valve draws very little energy when holding position, it still contributes to a lot of energy over the year, nearly 100 kWh as a minimum.

The final valve type that we looked at was a new type of valve we discovered based on recommendations from our second design review: magnetic latching solenoid valves. These combine the benefits of the motorized and solenoid valves. They use solenoids to actuate to a fully on or off position in a smooth operation, but they are able to shut off power when not in use in order to save energy. They manage this by using a permanent magnet to hold the valve in position after it is opened or closed. One such valve draws 10 W when it is actuating, but since it uses no energy in the resting state, it only pulls that power for a few seconds per year, resulting in a total energy consumption on the order of 1 kWh. Unfortunately, we soon realized that magnetic latching valves are somewhat hard to come by. They are generally custom made, and the lead time is several months. Therefore we reverted to our original plan of a normal solenoid valve in order to have a working prototype, and will recommend a magnetic latching valve for future purchase to better meet the design requirements.

A second engineering analysis relates to our selection of a sensor. Originally, we selected an ultrasonic sensor to monitor the water level. Based on feedback from previous presentations, we know that it would be ideal for us to use a pressure transducer at the intake of the pump to measure the water level based on the pressure. However, the LBC team's use of a floating intake would make this impossible. After the last design review, we discussed this concern with them and suggested using a fixed level intake instead. They agreed that a pressure sensor would be convenient, however they questioned the structural integrity of the cistern should we drill a hole into the side wall in order to mount a fixed level intake pipe. We reviewed the product documentation [2] and found that it actually specifies that there are "Large flat surfaces on the dome, the top of the tank, and the ends of the tank [to] facilitate connection to 4" or 6" pipes." We called the manufacturer to confirm and found that those large flat surfaces are specially reinforced to make sure that the cistern remains stable if holes are drilled to attach pipes. Based on that information, the LBC team made the switch to a fixed intake and we therefore selected a pressure transducer.

We are using an OMEGA pressure sensor. This measures gauge pressure over a range of 50 kPa. We were able to use a mockup drawing (Figure 5) with the knowledge that the pressure at the intake of the pump is governed by the concept of manometry. This allowed us to determine the governing equation of the pressure sensor (Eq. 4).

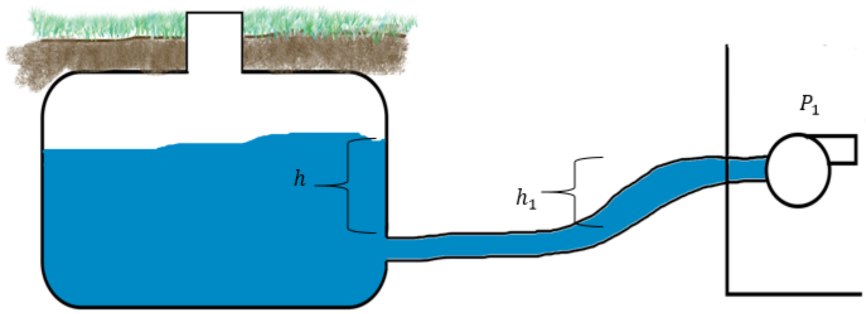

Figure 6. Figure showing the fluid flow from cistern to pump used to determine the governing equation of the pressure sensor.

$$P_1 = P_0 + \rho g(h - h_1) \quad \text{(Eq. 4)}$$

Here, P_1 is the pressure at the intake of the pump, P_0 is atmospheric pressure, ρ is the density of water, g is the gravitational acceleration, h is the height of the water above the intake, and h_1 is the height difference between the intake in the cistern and the level at which the pressure is measured in the house basement. Based on the height of the cistern being 5 feet, we know that the pressure transducer needs to measure pressures up to 15 kPa. The OMEGA pressure sensor has a much higher range than this, but the next step down in pressure range was only 10 kPa. Despite this excessive range, we felt this would be an easy to use sensor due to available documentation on using this sensor with an Arduino that we found while researching the sensor.

While we waited on our final sensor to be shipped, we used a temporary force sensor to begin programming the Arduino. One issue we confronted while testing with our temporary force sensor was the amount of noise in the signal. The readout on the LCD screen is constantly changing due to noise in the signal. As a result, we calculated the amount of noise in gallons based on known data about the sensor and cistern for our actual chosen sensor, to make sure that this will not be an issue with the real prototype [16]. We know that the cistern we expect to use has a capacity of 2500 gal (9.464 cubic meters), and a height of 5 feet (1.524 m). Dividing the two gives an average cross sectional area of 6.20 m^2, though this will require more detailed geometric analysis for the final calibration due to the complex shape of the cistern. Additionally, the PX40-100G5V data sheet reports a sensitivity of 0.267 V/PSI, or 0.03872 V/kPa, a full scale voltage reading range of 4V (0.5V-4.5V span), and a margin of error of 0.22V (±0.11V). These values were used to calculate the volume noise based on this hysteresis (Eq. 5-Eq. 7)

$$0.22\,V * \frac{0.03872\,kPa}{1V} = 0.0085\,kPa\,noise \quad \text{(Eq. 5)}$$

$$\frac{0.0085\,kPa}{1000\,kg/m^3 * 9.8\,m/s^2} = 0.00087m\,noise \quad \text{(Eq. 6)}$$

$$0.00087\,m * 6.20\,m^2 = 0.0054\,m^3 = 1.43\,gallons \quad \text{(Eq. 7)}$$

1.4 gallons is only 0.06% of the tank capacity so this error is acceptable, though we will have to take it into account when programming the display.

Failure Modes and Effects Analysis

One significant risk we have identified is the possibility that our control system does not shut off in the case of the purification failure. In this case, the system should be capable of being manually turned off or simply unplugged. We also have electrical components, including the pressure sensor and solenoid valve, working near water. These products are already built to function in the proximity of liquids, so there should not be issues in terms of electrical parts being affected by water. Additionally, we want our system components to be easy to access in the case of emergency maintenance.

Table 2. Failure modes and effects analysis matrix detailing high-risk components

Item	Function	Failure Modes	Sev.	Failure Case	Prob.	Risk Number
OMEGA Pressure Sensor	Reads water level	Failure to read water level	5	Faulty wiring	4	20
Baco Engineering Two-Way Valve	Switch water supply	Failure to switch	5	Mechanical failure	1	5
SainSmart LCD Display	Displays water level	Failure to display	2	Faulty wiring	3	6
Arduino Uno	Provides electrical signal to valve	Fails to operate	5	Faulty wiring	2	10
Takachi Enclosure	Encloses control system	Breaks	3	Structural failure	1	3

After completing the FMEA matrix above, we determined that the highest risk of failure is the sensor. The OMEGA sensor should properly read the water level in the cistern, but there could be cases where the sensor could not read the water level. The consequence of the sensor not being able to read the water level in the cistern is very high which we gave a five on a scale from one to five for the severity column. This is due to the fact that if the sensor could not perform its function, the entire control system will not work. One of the potential causes of this failure could be a fault in wiring. Although assembling the control system should mitigate this failure, in the environment the sensor is exposed to, the wiring may get tampered with. The probability of this occurring is relatively high with a score of four out of five as shown above. After completing the analysis, we multiplied the severity by the probability giving us a risk priority number. The sensor scored had the highest score of 20 making the sensor the highest risk component in the control system. As of right now, we are still currently looking into different sensors, because of the engineering analysis mentioned above, which will most likely change the score of the FMEA based on how the sensor will be placed in the control system.

Challenges

Due to the complex process of rainwater collection, including silt accumulation, a large challenge we foresee in implementing the system is calibrating the pressure transducer to translate the voltage it provides into a water quantity reading.

With our original Motorola pressure transducer, we attempted to connect it to the Arduino through a differential amplifier. Although our circuitry is wired correctly, the pressure transducer does not give the appropriate reading. Regardless of the pressure experienced by the sensor, it always reads 5V on a multimeter. This is because the Arduino could not register the small changes in voltages in the range of 40 mV. After learning from this challenge, we spent time carefully selecting a sensor that was more optimal for the Arduino interface.

Another general challenge is writing out all of the code. We have located open source drivers for many of the components we plan to use, but having never created an entire Arduino program from scratch, it was a challenge to put all of the different elements together in a way that follows the logic we need without unexpected glitches.

We are concerned with testing the full system in the house. We needed to construct a scaled down water system in the LBC lab to test our project. They have many extra water containers and pipes available, as well as the fully operational filtration/purification module. Essentially, we are unsure of what to expect and that uncertainty is somewhat of a challenge. The tank we performed calibrations on is much smaller than the 2500-gallon tank the Grocoffs plan to implement in their home.

Manufacturing Plan

Most of our project is comprised of connecting off-the-shelf components and therefore does not require manufacturing. The LBC team has already designed the purification system as shown in Figure 6. We have connected the Arduino Uno, two-way solenoid valve, H-bridge, LCD screen, a pressure transducer, and a rotary encoder knob. After our original difficulties building a circuit to connect all of these components, we selected new components that are much easier to set up. Every component simply plugs directly into power/ground, and into the Arduino inputs or outputs.

Figure 7. The purification system was designed by the LBC team before the semester. It contains a pump, three cartridge filters, a UV bulb, and an activated carbon tank. The control system will have to interface and communicate with the pump at the front end of the system in order to prevent the purification system from running dry.

Validation Protocol

We want to be able to accurately monitor the water level in the cistern with the pressure sensor. To validate this, we measured the reading for several known quantities of water to determine the accuracy of the setup. We connected a 10-gallon tank to our sensor via a pipe. We then filled the tank with water at one-gallon intervals and recorded the voltage measurement given by the system. In order to understand how reliable our data is, we performed these tests three times. We created a calibration plot of actual volume vs. measured volume. We used this to analyze the amount of error in the system and report on it. We are filtering voltage data from the pressure sensor and converting it to a volume, so a consistent offset in this data could give us the opportunity to recalibrate the sensor. The results are shown in the calibration curve (Figure 7).

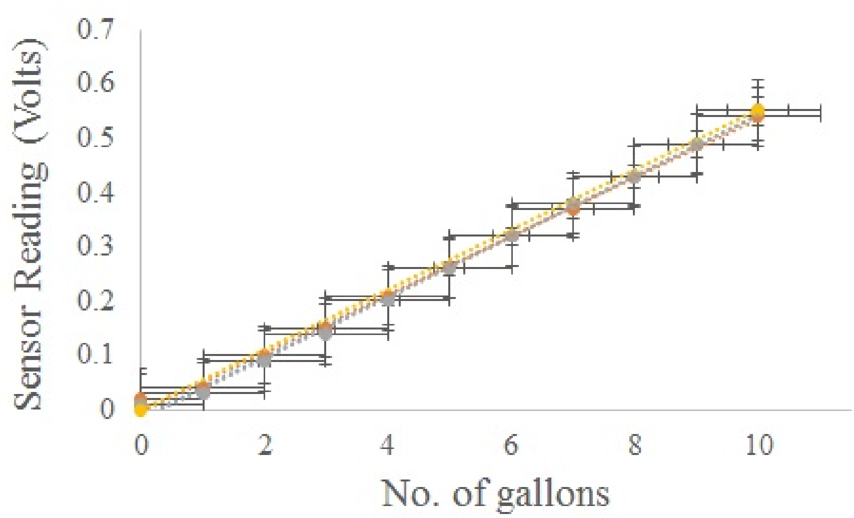

Figure 8. The calibration curve for the 10-gallon water tank resulted in 55.2 mV per gallon.

We also need to measure the amount of energy our system uses and provide an estimate for the system's annual energy consumption. In order to do this, we measured the voltage and current of each of the components individually with a multimeter. The measurements of the Arduino, LCD screen, valve, pressure sensor, and power supply are recorded in Table 3.

Table 3. Voltage and current measurements of each component used to calculate the power consumption

Component	Voltage (V)	Current (A)	Power (W)
Arduino Uno	5	0.050	0.250
LCD Display	5	0.017	0.085
Two-way Solenoid Valve (when on)	12	2.710	35.52
OMEGA Pressure Sensor	5	0.005	0.025
Power Supply	12	2.190	26.28

Since the valve we selected for the prototype will consume the most energy of the entire system, we calculated estimates assuming it would be on 25, 50, and 75% of the time (Table 4).

Table 4. Total energy consumption of system (in kWh per year)

Amount of Time with Valve On (%)	Power consumption (kWh per year)
25%	305
50%	376
75%	447

Discussion and Design Critique

We were originally urged to use a simple ultrasonic sensor, but decided to go with a pressure sensor. This was because of the concerns in the implementation of the ultrasonic sensor. It would have to be placed within the cistern approximately 50 feet from the house. We looked into hard-wiring and wireless communication between the sensor and the Arduino and both had their challenges. Hard-wiring would create a lot of noise that we would then have to filter and clean up in order to be useful. Wireless communication would be expensive and seemed much more complicated with our limited time and knowledge of the subject. The senor would also have to be waterproof which was an expensive option. The pressure sensor seemed like a more elegant solution given out restrictions.

We had a suggestion brought to us at Design Expo that was an even more elegant solution to our design problem. It was comprised of a biased valve, similar to a piston, that would open or close based on the pressure of the rainwater tank. As the rainwater runs low, the pressure decreases and the valve piston moves towards a closed position, which can be adjusted. At a certain level it would shut off flow from the rainwaters and allow the backup supply to flow in. This would reduce the amount of electronics involved in the system and resultantly be a majorly mechanical system.

Our final design could also be improved. The pressure sensor is currently attached to the pipe by hot glue which doesn't allow the sensor to work to its highest capabilities. We would have to create some sort of harness to the pipe to ensure a proper attachment. The valve we showed at Design Expo was also a stand-in for the actual valve we wanted. We used a simple two-way solenoid in place of a magnetic latching solenoid which would use on the order of 1 kWh per year instead of 300-450 kWh per year our current design will use. The magnetic latching solenoid was very expensive and had a very long lead time so we were unable to implement it this semester.

A final overarching critique is simply the amount of time spent choosing and installing parts vs. coding and testing. Due to our inexperience with this type of project, we ran into a lot of unexpected road bumps when trying to install components. The biggest one was that our first pressure sensor only fluctuated over a range of 40 mV for its entire span, which is barely perceived by Arduino. We spent a lot of time trying to build a circuit to amplify and filter the signal from this sensor before we gave up and selected a sensor that had a span from 0.5-4.5V, which required absolutely no circuitry. We also switched LCDs, and did not realize that there are several different formats for Arduino LCD, so we accidentally bought a different type and had to spend a lot of time getting our new LCD working. If we had known more about these types of things from the start, we could have selected components much more carefully from the beginning and spent a lot more time writing the code and testing the project.

Future Recommendations

When we pass the project on to the LBC team, we will provide a few suggestions to both improve the design and finalize it for the full scale home. The sensor code needs to be recalibrated for the full size tank, taking into account the layers of silt that will be in the actual cistern which were not present during our testing. When the actual piping is installed, we have suggested that a manual bypass valve be placed in parallel with the solenoid valve so that the flow of city water can be restored if there is a power failure. A backflow preventer is also needed in the final installation. We also would like for the LBC team to purchase the magnetic latching valve we wanted to implement this semester, the Peter Paul series 80 Model 828 Magnetic Latching Valve. As discussed, this valve uses orders of magnitude less energy and is ideal for the vision of this project.

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Appendix A: Concept Generation List

Sensors
ExOsense Non-Intrusive Liquid Level Sensor
UCL-510 Ultrasonic Water Level Sensor
CT-1000 Potentiometric Sensor
163000 Series Visual Level Indicators
Sparkfun Ultrasonic Sensors (various)
Wireless Ultrasonic Sensor
Radio Sensor
AquaTrak Absolute Liquid Level

Valves
A Series Solenoid Valve
B Series Solenoid Valve
G Series Solenoid Valve
Potable water-grade ASCO Valves
Low Power consumption series ASCO Valves
2-way valves from McMaster-Carr (Various)

Displays
LED Display - Digital clock style
LED Display - Dot Matrix style
LCD Displays from Arduino
Loose LED indicator lights (various)

Control units
Arduino
Raspberry Pi 2
BeagleBoard by TI
BeagleBone Black
Intel Galileo

Control Transmission from board to outdoor sensors
Run conduit in ground
Use Zigbee wireless communication

Housings
Various sketches

Appendix B: Authors

Rachel Goubert
Rachel is from the small town of Armada, MI, and is currently a senior working towards a minor in the Multidisciplinary Design Program and a concentration in the Program for Sustainable Engineering. She has been a member of the BLUElab Living Building Challenge Team for over a year. She works at the Wilson Student Team Project Center as the head of Basic II training. Recently, she began working with Professor Dasgupta in his lab on organic nanostructures as part of the RISE program. Additionally, Rachel volunteers as a mentor for FIRST robotics Team 1076, the Ann Arbor Pioneer High School team. She is an active member of Pi Tau Sigma, and in her rare free time enjoys baking, playing sports, and traveling.

Moji Igun
Moji is from Farmington Hills, MI and is currently a senior working towards a Mechanical Engineering degree with the International Minor for Engineers and a concentration in the Program for Sustainable Engineering. She is a member of the executive board for the Synchronized Skating team which is competitive at the national level. She is also a member of the Phi Sigma Rho engineering sorority and is a past executive board member. Last summer, she studied abroad in Troyes, France through an IPE program and visited several other European cities. She plans to eventually travel to every continent. To relax, she thoroughly enjoys cooking, watching the Tonight Show with Jimmy Fallon, and playing euchre.

Joe Oliver
Joe was born and raised in Redford, Michigan - a suburb of Detroit. He is currently a senior Mechanical Engineer with a concentration in Energy. Last winter he co-oped in DTE Energy's Energy Optimization program and interned at CD-adapco during the summer. He has a strong interest in sustainability and hopes to work with water and/or energy engineering in some capacity. His hobbies include tv/movies, cooking, and woodworking. He is also a member of Triangle Fraternity, and served as the president during 2014. During the school year, he works at CAEN as a lab inspector, and was awarded student of the month last September.

Jiawei Zhou
Jiawei is a senior studying Mechanical Engineering with an Energy Concentration. Last summer, he interned at PPG Industries in Barberton, Ohio where he worked on projects involving Teslin© synthetic paper. These projects include finding solutions to steam flow causing manufacturing defects, developing control-engineering solutions for Teslin© Security Grade, as well as creating measures to eliminate TCE exposure. Jiawei also worked in the ME X50 machine shop helping students find necessary equipment for project manufacturing. In ME 250, his team won runner-up in the design expo competition for overall robot design and manufacturing. Jiawei was involved in the MHybrid racing team, in which he worked in the Front Wheel Drive team to manufactured specific components. Outside of school, Jiawei is involved Triangle Fraternity, where he held various chair positions each semester.

Appendix C: Ethics Statements

Rachel Goubert

Although our team did not explicitly consult the Code of Ethics for Mechanical Engineers, many of our personal and project specific drivers were developed on an ethical standard. Our project stems from the first canon of the code of ethics: Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties. We are creating this automated back-up system so that the homeowner and his family will never have to go without water, the most basic and necessary resource.

We also had a strong focus on environmental ethics. Within the code of ethics, canon 8 states: Engineers shall consider environmental impact and sustainable development in the performance of their professional duties. Most importantly, we have been focusing on the idea of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Additionally, our project focus is "sustainable development," by "meeting basic human needs while conserving and protecting environmental quality and natural resource base." These points in the engineering code of ethics were the driving factors for the creation of our project.

The ultimate goal of the project is to design a system that can be replicated for multiple uses, whether it is keeping a municipal water supply as a back-up or encouraging connections to neighborhood watersheds. Our design will be lasting, and will have the ability to be implemented in ever-evolving systems, which makes our project design sustainable.

More quantitative impacts were the design drivers of low energy and material selection. By reducing the amount of energy we use, we are reducing the amount of electricity that may need to be generated from fossil fuels, an unsustainable resource. By limiting certain materials, we prevent further harm to the environment from manufacturing and harmful waste disposal. For example, the manufacturing of PVC releases significant amounts of toxins, so we did not use PVC in any components of our design. Additionally, we attempted to purchase components from local sources so as to reduce transportation emissions. Although it was part of our design requirements that we use certain sustainable materials, it only served to reinforce what our team was already set on doing: creating a device to function in a sustainable environment to enhance the ability of generating clean water.

Moji Igun

The Code of Ethics for Mechanical Engineers has definitely been applied to our design process. Our product is mostly electrical components that control the routing of water through PEX piping. The proximity of water to electricity is a known concern. We have designed our prototype so we have the minimal possible chance of incidents involving electric shock. This includes placing the power source far away from the piping, choosing a solenoid valve that is designed to work with water, and containing the Arduino and circuitry in a case. We are aware that there will be people of all ages interacting with the system, so it must be completely fool-proof in regards to electric shock.

We have also struggled slightly with the details of the electrical components. We always make sure to consult with Toby, Professor Gillespie, or our peers before acting in order to ensure the safety of ourselves and others. We are working with mid-range voltage power supplies so we need to ensure we do not cause harm to ourselves by performing safe electrical practices.

Aside from the safety concerns of the users, the city of Ann Arbor requires a backflow preventer on our system so that in the case the rainwater is purified. The contaminated water may not flow back into the city supply. Although our prototype does not include this feature because the appropriate valve would be too costly, we have identified this as a very important part of the final design.

<u>Jiawei Zhou</u>
The Code of Ethics under the American Society of Mechanical Engineers is separated into two fundamental categories: principles and canons. The first canon is “Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.” This canon is definitely the most important as the engineering profession, although it may not seem like it, can be responsible for many lives. Although our project is a proof of concept, we definitely considered not only the first canon, but also several others in the code of ethics to apply to our design process.

Due to the fact that our project is purely electrical, we designed a control system that would use safe wiring and no exposure of any materials that can conduct electricity. During our design process, we decided to include an enclosure for the microprocessor and display so that the user would be safe using the control system. Our project is a water control system, which makes concealing any electrical components the utmost priority. By doing this, I feel be exemplified the first canon respectfully.

Canons number two and six also apply to our project significantly. With only minor circuit building experience, we needed a lot of help in building a proper circuit and being safe about it while building it. We did not complete any electrical engineering that we were uncomfortable with and consulted reputable people such as Professor Gillespie and Toby Donajkowski. With their help, we were able to achieve a sustainable design. Because our project is a part of the Living Building Challenge, we had to consider the environmental impact. With this, we used materials that were eco-friendly such as PEX piping, which can be easily recyclable. We stayed away from harmful materials on the Living Building Challenge Materials Red List, which include neoprene, PVC, and PVDC. For sustainability, we needed to reduce the energy usage of each component, because Mr. Grocoff’s home is already sustainable in the sense of energy usage, so when designing our project, we needed to consider each component very carefully as to not make Mr. Grocoff’s home unsustainable.

<u>Joe Oliver</u>
We didn’t look at the code of ethics before we began our design process, so it wasn’t explicitly considered throughout the process. However, much of the content in the code of ethics is covered by the user requirements we took from the Living Building Challenge rules, as well as what the ethics we have been taught as Michigan Engineers.

Canons 1, 6, 8 and 9 were covered by the LBC rules. We are required to use products and materials that are made from environmentally friendly materials, based on life-cycle analysis. The overarching goal of our project was to be not only sustainable, as mentioned in the code, but regenerative. And at the end of the day, as Professor Skerlos said, sustainability is about people - protecting the world so that it can be used by generations to come.

One ethic that, in retrospect, it seems we were frequently close to breaking is “Engineers shall perform services only in the areas of their competence.” Due to the controls-heavy nature of this project, and the amount of signal processing and circuit building we have had to do, if often felt like we were in over our heads with Electrical Engineering jargon - certainly not the area of our combined competence. However, we collaborated with more knowledgeable people and gained the skills necessary to complete the tasks in front of us.

Appendix D: Environmental Impact

Rachel Goubert

Our team was lucky in that we received guidance from the Living Building Challenge Handbook in order to make appropriate decisions on our materials and components. We knew that some materials were more harmful to the environment than others. Specifically, in terms of water flow and piping, PVC is a poor material to use for environmental impact. It has chlorine in it, and the manufacturing process of PVC creates a lot of sludge and toxins that pollute the environment.

We also stressed the importance of energy conservation in our design. Although we did not look into how much energy was used to create our components, we chose components that would operate on the lowest energy usage. This was actually one of our main design drivers.

We worked on our design with long term usage in mind. We tried to choose durable parts that would last for many years in order to increase the lifetime of the system. The most probable failure of the system, barring any unexpected mechanical failure, would be the corrosion of the solenoid valve. Since we have a brass valve, this is not likely to occur for multiple years. By increasing the lifetime of our product, we decrease the amount of waste from disposal and replacement of parts.

One area where we could improve would be in the sourcing of materials. Our goal was to use only components that were distributed in the United States. However, we have purchased a solenoid valve that was originally sourced from China. We chose this because it would be delivered quickly and we were under a time crunch. As a future improvement, I would strongly recommend doing more research into a local source for a solenoid valve, in order to reduce transportation impacts and to stimulate the local economy.

Moji Igun

This project's focus is on environmental sustainability. All aspects of Matt Grocoff's household are designed to have a positive aspect on the environment. The net-positive water system utilized filtered and purified rainwater collected in a cistern next to his house to provide potable water for his family. The control system that we have designed must comply with the Materials Red List set by the Living Building Challenge. We are not permitted to use any chemicals or materials that may have a harmful impact on the environment. We have designed our prototype to use as little materials as possible and those materials that we have used are sustainable and/or eco-friendly. By implementing our design, we hope Matt will be able to completely eliminate his connection to the Ann Arbor municipal water supply and depend solely on rainwater collected and purified on site.

In terms of energy, the Grocoff household obtains its energy from solar panels and actually operates with net-positive energy. This means that after the regular usage of the power produced by the panels, there is still energy left over. Therefore, we aim to minimize the amount of energy used by the control system and are aiming for approximately 500 kWh annually. At the end of our product's life, most of the components can be recycled since they are mostly PEX piping and copper wiring.

Jiawei Zhou

With the net-positive water home control system, our project emulates the very definition of environmentally sustainable. The addition of our control system to the overall Living Building Challenge certification program made our group consider the environment very highly while design and building our project. In an attempt to solve the water infrastructure issue, where several system in place today are crumbling and need constant repair, this project uses rainwater that is collected naturally as the main source of water usage. Our project is a stepping stone to a truly sustainable water usage program, where a water usage does not harm the environment, but instead try to fix it.

From the Living Building Challenge, there is a list of materials that are deemed hazardous or harmful to the environment, known as the Materials Red List. These materials include, neoprene, PVC, PVDC, lead, mercury, etc. Our project uses PEX piping instead of PVC to regulate water flow, as well as circuitry that does not contain any lead or mercury. Our solenoid valve is made from stainless steel, which can be recycled, making the entire system very environmentally friendly. Since Mr. Grocoff's home generates its own electricity, our control system must reduce the amount of energy usage to fit within the requirements of the home. The components selected all were weighted highly on the amount of energy usage each component used, therefore the entire home can aim to become more sustainable.

Joe Oliver

Environmental considerations were the number one design driver for our project. It was essential from the beginning that we consider the environmental impact of our project, not only for the user requirements based on the client's desires, but for the rules of the Living Building Challenge. The LBC has a specific set of rules, most notably a materials red list. Materials are banned from use in LBC facilities based not only on hazardous materials in the use stage of their life-cycle, but also for their production and disposal. The rules also require all materials to be locally sourced, in order to stimulate local business and reduce the negative impact of transportation and long supply chains. We were able to meet this for the most part, but there are some temporary elements in our prototype that we had to use non-local sources for. This is mainly due to the unavailability of suppliers of specialty parts, such as solenoid valves, who can produce the parts in a timely manner, if they can even produce it at all.

Outside of the LBC regulations, we also had to consider energy continuously, as we know that energy is an even more scarce resource for our project in particular due to the Grocoff family's net-positive energy system. Nearly every component selection was heavily influenced by the need to use as little energy as possible, without sacrificing other design drivers of course. At the end, the entire goal of our project is to reduce the harm to the environment done by large scale municipal water systems, so it is our hope that the net impact on the environment from our project will be a positive one.

Appendix E: Pictures of Final Prototype