Algae Building Technology

Bass Connections in Energy: Design and Innovation 2020-2021

Sophia Simms, *Mechanical Engineering ‘23*
Vanessa Chen, *Computer Science ‘23*
Kyra Cooperman, *Environmental Science and Policy* ‘23
Annika Allado, *Mechanical Engineering ‘23*
Natasha von Seelen, *Electrical & Computer Engineering, Computer Science ‘21*
Will Hess, *Mechanical Engineering, Political Science ‘23*

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Introduction

Motivation

It is now a well accepted fact by scientists that major reductions in greenhouse gas emissions must be made in order to prevent the world from climate disaster.[1] The United States is the second largest GHG emitter in the entire world. The electricity sector makes up ~25% of these emissions annually[2]. Our bass connections team chose to tackle this area in order to make a significant difference in emissions reductions efforts.

In narrowing in on our goal, we focused on the different sectors that contribute to electricity usage. The building sector accounts for 76% of total electricity usage in the US, which makes it a great target for reduction efforts[3]. WIthin this sector, 44% of commercial building's energy consumption is attributed to HVAC systems. A major area of heat loss in buildings is through windows. Our hope is that our algae window can help reduce this critical component of energy consumption by regulating light and temperature.

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[1] IPCC. (2020, April). The IPCC and the Sixth Assessment cycle. Retrieved from https://www.ipcc.ch/site/assets/uploads/2020/05/2020-AC6_en.pdf

[2] Sources of Greenhouse Gas Emissions. (2021, April 14). Retrieved from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[3] U.S. Department of Energy. (2015, September). AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH ... Retrieved from https://www.energy.gov/sites/default/files/2017/03/f34/qtr-2015-chapter5.pdf

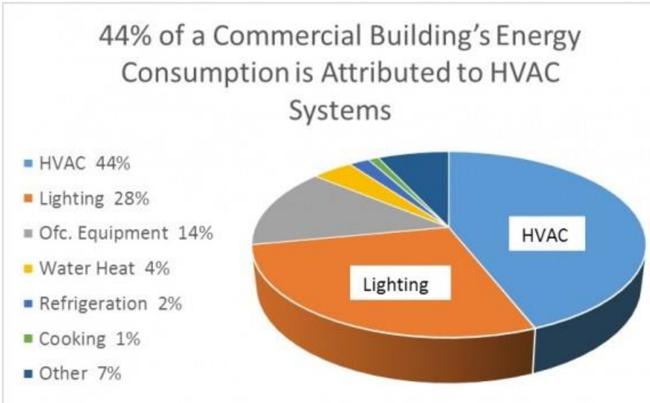

Figure 1.1: Breakdown of commercial building energy consumption[4]

Algae windows are currently being developed throughout the world and are recognized to have an enormous potential, yet they are not currently sold commercially. A full-scale pilot project was built in 2013 at the BIQ house of the International Building Exhibition in Hamburg, Germany[5]. This project, known as "SolarLeaf," provides a proof-of-concept for how algae windows can be implemented at a large scale. Our team wanted to improve upon the already existing window designs and potentially develop an option that is entirely automated through the use of sensors. The uncertainty that comes with such a new technology provides us with the perfect opportunity to engage our academic curiosity. As a group of STEM students, we constantly aim to find better, more innovative ways to design and build.

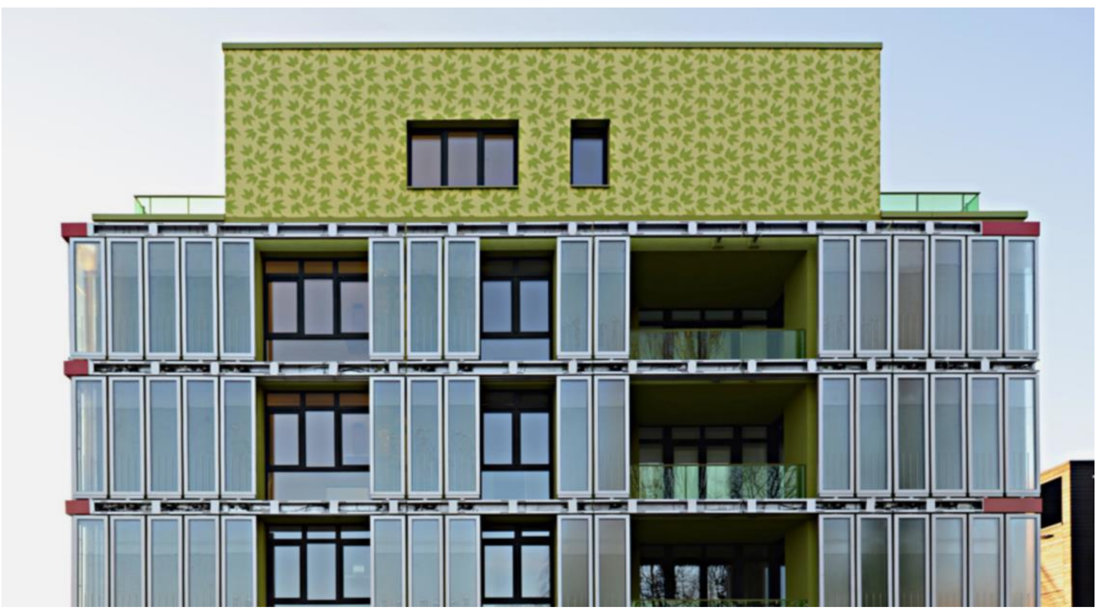

Figure 1.2: The SolarLeaf façade served as an inspiration for the team[6]

[4] Save $ on the Biggest use of Power in your Building. (2021, April 16). Retrieved from https://bluehatmechanical.com/save-on-the-biggest-use-of-power-in-your-building/
[5] Wurm, J. (n.d.). SolarLeaf. Retrieved from https://www.arup.com/projects/solar-leaf
[6] *Ibid*

Another major driver for our project choice was the opportunities for algae once it is harvested from the window. We selected spirulina as our primary algae source for its ease of growth and high nutritional value. Currently, algae is being developed for use as a food source, fertilizer, and biofuel. All of these possibilities would further aid in a reduction of emissions from other sectors (ie: agriculture and transportation), which would increase the positive impact of our project.

Technical Design

Summary of Design Approach

The team gained inspiration for our initial design from the SolarLeaf façade. This algae window implementation utilizes flat panel glass bioreactors and a closed loop system to generate heat and biomass and contribute to the energy needs of a residential building. A heat exchanger is used to recover heat from the water-algae solution. After harvesting through floatation, the algal biomass is taken off site to be converted to biogas. The biogas is then returned to the building and used as an input for a combined heat and power micro-turbine, generating more heat and electricity.

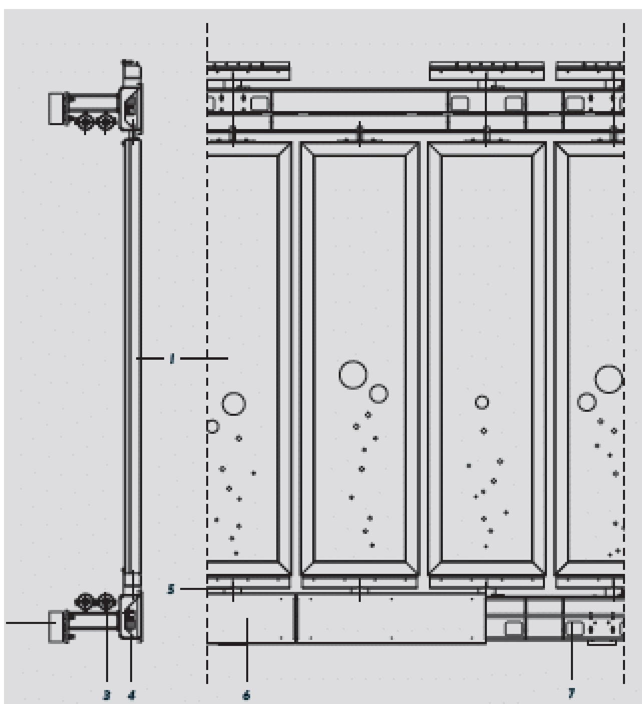

Figure 2.1: SolarLeaf technical design

Each panel consists of four glass layers and is held together by steel U-section frames. Tubing runs along the bottom of the structure to pump the growing medium into the panel and tubing at the top is used for the outflow. Magnetic valves along the bottom of the system allow for the introduction of compressed air that circulates the algae at set intervals.[7]

The team determined that our goal would be to build a small-scale system that is user-friendly, low-maintenance, and provides quantifiable benefits. A focus for our prototype would be consistent monitoring and automation, accomplished through the use of sensors. We would also collect data to determine the efficacy of the system and further the understanding of this innovative technology.

Design Decisions

Algae Type

A decision matrix (see Table 3.1 below) was used to determine which type of algae should be used in the system. The team considered several different design criteria and used a weighted system to rank candidates that were established through research. The most important considerations were decided to be the ease of growth and time taken to grow, as these factors would determine the amount of algae that could be harvested through the system and the benefits it would provide to users. The availability of the algae and the ease of the extraction process were also designated as important considerations. Through this process, spirulina was chosen as the algae that would be most aligned with the team's objectives.

Table 3.1: Decision matrix evaluation of different algae types

Design Criteria	**Weight**	**Chlorella**	**Spirulina**	**Azolla Anabaena**	**Cyclotella**	**Dunaliella**
Ease of growth (environment, requirements)	0.4	4	5	2	1	3
Ease of extraction process for byproduct	0.1	5	4	1	3	2
Availability (cost, sourcing mechanisms)	0.2	4	5	2	3	1
Time taken to grow	0.3	4	3	5	1	2
Totals:	1	4.1	**4.3**	2.8	1.6	2.2

[7] Wilkinson, S., Stoller, P., Ralph, P., Hamdorf, B., Catana, L. N., & Kuzava, G. S. (2017). Exploring the Feasibility of Algae Building Technology in NSW. *Procedia Engineering,180*, 1121-1130. doi:10.1016/j.proeng.2017.04.272

End Product

There are several uses for harvested algal biomass, as is further discussed in the environmental benefit analysis section. The team decided to move forward with using our harvested algae as fertilizer. For our small-scale system, we determined that we would likely not generate enough biomass for effective conversion to biofuel or use in carbon sequestration or wastewater treatment. Our choice of algae also contributed to this decision, as there is significant research demonstrating that spirulina is well-suited for use as fertilizer. Additionally, as the prototype is situated on Duke's campus, the team was able to connect with the Duke Campus Farm and discuss a potential partnership with the organization.

Structure

The team settled upon building the main tank using a 0.5" thick acrylic sheet as it can be easily manufactured for prototyping purposes with the available machines on campus (e.g. laser cutters) whilst being safe for the algae byproduct to grow in. The 0.5" thickness was decided in order to create a stable base for the volumetric dimensions of the tank (2 ft x 3 ft x 4") which was scaled up in order to best emulate future larger scale production (see *Appendix A.* for further calculations.) The carrying trolley was built using wooden scraps and caster wheels to decrease the cost of manufacturing.

The electronics components were wired to a Photon board to allow for bluetooth access. The sensor components and solenoid valves (that were used to control water flow) are wired to a breadboard to allow for easy manipulation during the prototyping process.

Assembly Procedure

To assemble the base, the acrylic was laser cut into 5 pieces (for the 4 sides and base) and glued together using acrylic cement. To ensure a water-tight fit, a thick layer of water-resistant silicon was smeared on the inner edges and the bottom crevasses. Once the base was assembled and tested for a water-tight fit, the tank was lowered onto the wooden trolley (which was manufactured by screwing bolts into 4 thick pieces of scrap wood and attaching 4 caster wheels to the edges) and supported by exterior aluminum L-bracket frames. The tubing for the water was snaked into the holes on the sides of the tank and connected to PVC pipe fittings to ensure tight connections.

Growing the Algae

At the beginning of the semester a Spirulina Algae Starter Kit was ordered from Algae Research Supply (algaeresearchsupply.com). The kit included a Spirulina filter, nutrients and media salts, as well as one liter of Spirulina. Over the course of the semester, the algae was grown and maintained by adding 1-2 gallons of nutrient-filled, purified water to the growing tank until the algae desired quantity and concentration were achieved. By the end of the semester, approximately 15 gallons of algae at a secchi depth of 20 mm (roughly maximum concentration for Spirulina) were grown.

Figure 4.1: The Spirulina growing process

Prototypes

Low Fidelity Prototype

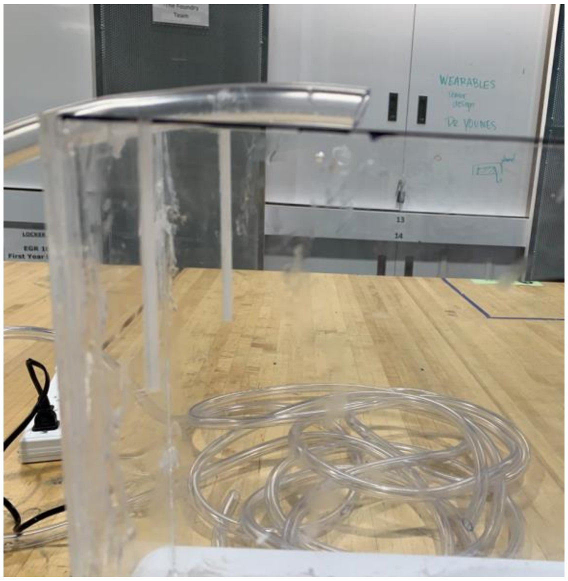

Figure 5.1: Clean water dispenser

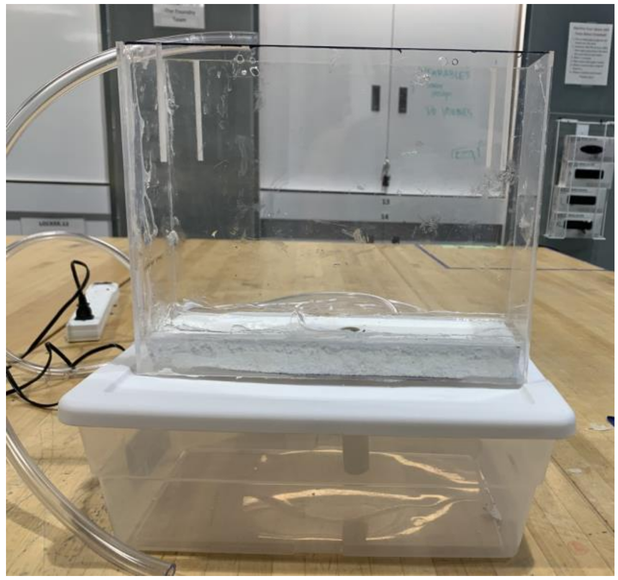

Figure 5.2: Overview of prototype structure

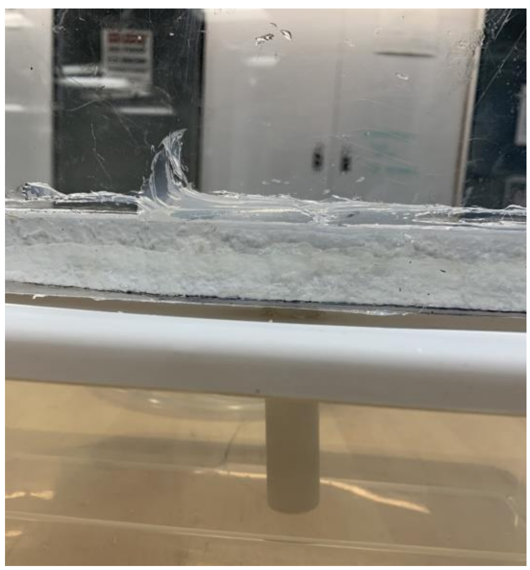

Figure 5.3: Grey water tank

High Fidelity Prototype

Figure 5.4: Front view of prototype

Figure 5.5: Prototype Details

Sensors

pH Sensor

The pH sensor, shown in the graphic below, is used to consistently measure the pH level of the algae, ensuring it stays within 8.2 - 8.7 pH, the ideal growing conditions for algae.

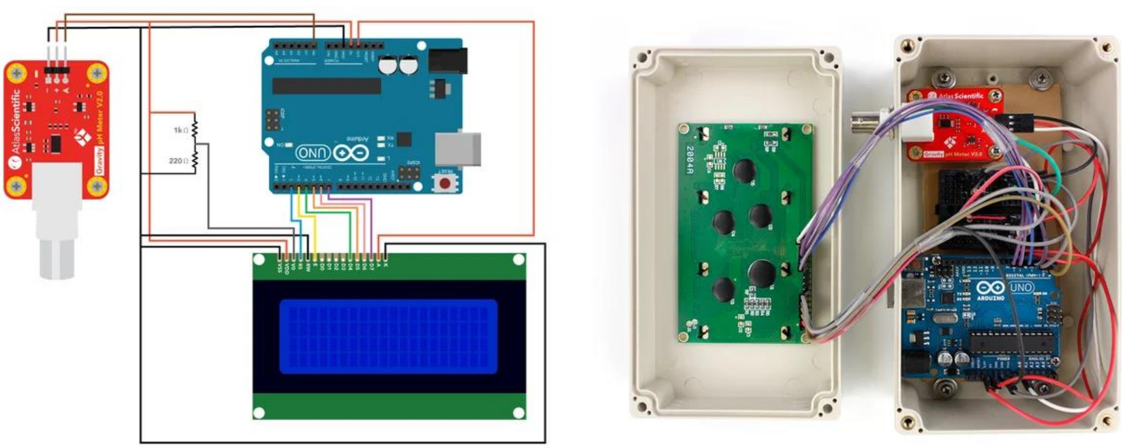

Figure 6.1: pH Sensor circuit schematics

pH Sensor Code Description

As shown in the pH Sensor sample code, the code snippet will be run repeatedly (in a loop) to ensure data has been read from the sensor and output pH reading to the serial monitor as well as the lcd (liquid crystal display). This will allow the group to easily monitor if algae pH conditions are not ideal and address them. Future features would be to incorporate SMS or email notification of extreme algae pH movement.

Turbidity Sensor

The turbidity sensor, shown in figure 6.2 below, is used to consistently monitor the turbidity of the algae water to easily identify when the average turbidity levels spike or decrease suddenly. This would allow our team to efficiently address the issue when notified by the sensor.

The sensor detects water quality by measuring level of turbidity by converting the current signal into the voltage output through the circuit. Its detection range is 0%-3.5% (0-4550NTU) *Nephelometric Turbidity Units (NTU)*, with an error range of ±05%F*S. See the graph below for the calculations from percentage (%) to voltage and NTU.

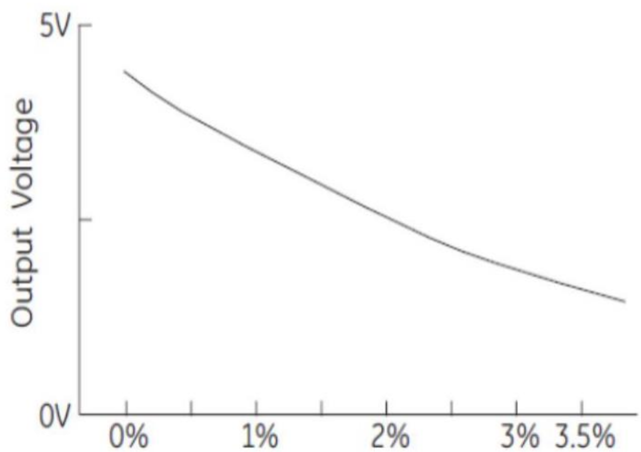

Figure 6.2: Turbidity sensor output voltage to %, representing NTU

As shown in the figure above, the graph of output voltage and concentration shows that the higher the turbidity value is, the lower the output voltage is.

Important conversion formula to convert between % and NTU:
10-6 (PPM)=1ppm=1mg/L=0.13NTU (empirical formula)
As an example, 3.5%=35000ppm=35000mg/L=4550NTU

The sample code to read data from the sensor (continuously) to collect data on water turbidity is shown in the appendix.

Expected Result:
The sensor displays an analog value of 0 - 1023 which corresponds to a voltage of 0 - 5V.

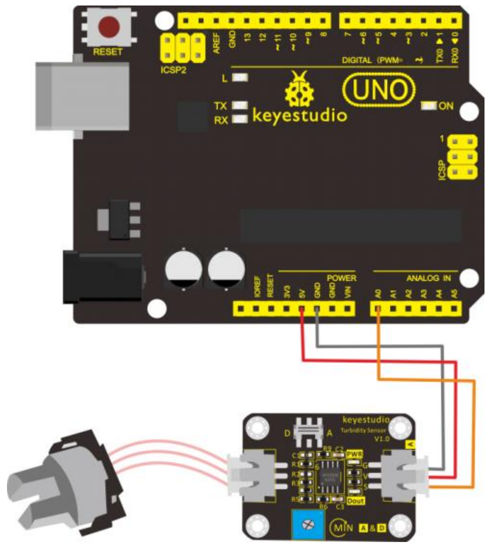

Figure 6.3: Turbidity sensor circuit

Testing

Testing Method

In order to test the effectiveness of the algae window at reducing solar heat transfer, a test was set up using a halogen lamp to simulate intense, direct sunlight. The tank built for this project was found to have leaks during testing, so a smaller but similar tank was used to hold the algae. The tank used was built with ¼ in acrylic, and contained a 1 ft high and 1.5 in thick column of algae water at a secchi depth of 20 mm. These dimensions are shorter and thinner than the tank built for this project, but the results still provide valuable information regarding the effectiveness of algae at keeping buildings cool.

The halogen lamp was placed 8 inches away from the face of the window tank, and a jar of water with a thermometer was placed immediately behind the window. The temperature of the window tank and jar were taken at 10 minute intervals for 30 minutes to see if the heat from the halogen lamp was passing through the window tank and heating the jar or if the window tank was effectively reducing the heat transfer. The test was then repeated with an empty window tank.

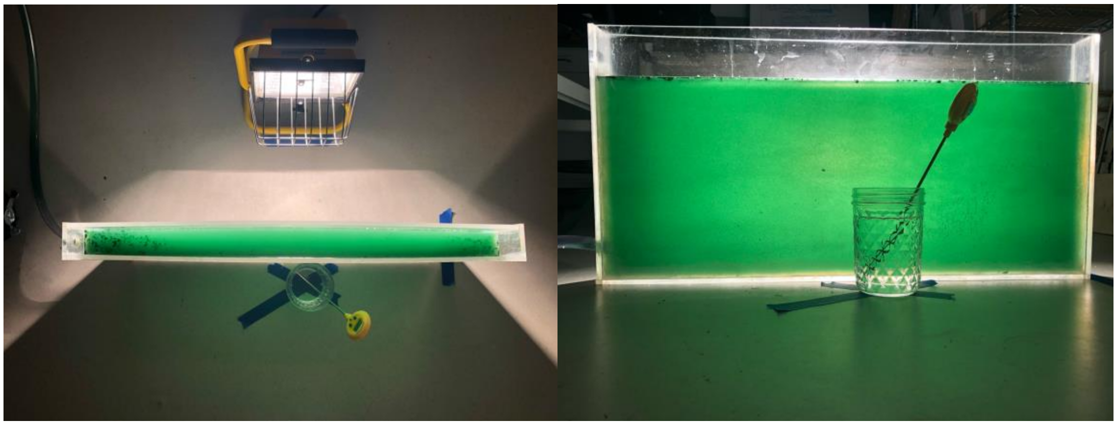

Figure 7.1: Testing setup

Testing Results

The testing results are shown below. The results indicate that the algae window was very effective at limiting the heat transfer from the halogen lamp. In the algae water test, the temperature of the water in the window increased by 7.6°C while the temperature of the jar behind the window remained constant, indicating that the algae water absorbed the heat and prevented it from being transferred through the window. Conversely, in the test with an empty tank, the temperature of both the air in the window and the water in the jar behind the window increased significantly. This shows that the results from the algae water test are in fact because of the algae, and not a result of the distance of the jar from the lamp.

Window Medium	**Measured**	**Start**	**10 min**	**20 min**	**30 min**
Algae Water	**Window (°C)**	21.7	24.6	26.1	29.3
	Jar (°C)	23.1*	22.2	22.2	22.2
Air	**Window (°C)**	22.4	29.5	35	38
	Jar (°C)	20.3	21	22	23

*Measurement was taken of a different jar of water that was filled at the same time because we forgot to take the starting measurement

Figure 7.2: Testing results

Environmental Benefit Analysis

Energy Savings

To first analyze energy savings, we will explore the SolarLeaf implementation of an algae window system (see Figure 8.1 below).

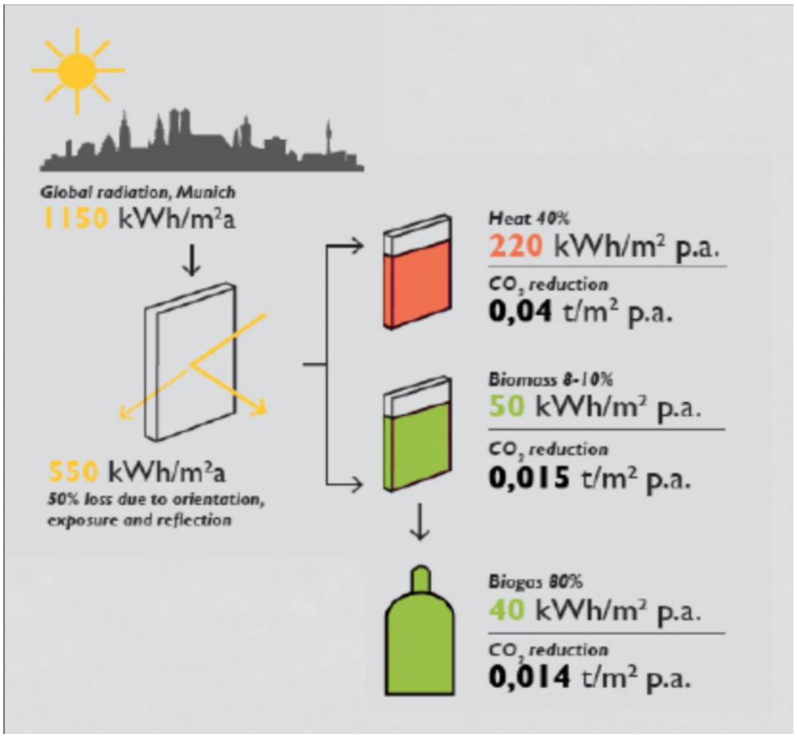

Figure 8.1: Energy Savings of Algae Window Design in Germany[8]

Incident radiation energy on a window is lost due to reflection, exposure and orientation of the algae panel. 40% is produced as heat energy which is distributed for use in the building, via hydronic heating systems. The biomass component is 10%, which is converted to biogas. Each component results in significant carbon dioxide reductions.

Given that the total energy conversion of algae windows is notably lower than that of more conventional systems, they aim to provide additional energy benefits through summertime shading, and by providing a biomass stock for additional use.

Building Efficiency

Currently, buildings account for 40 percent of all energy use in the United States. This sector overtook the industrial sector for greatest energy usage in 1998, and has continued to rise in percentage each year.[9]

[8] Wilkinson, S., Stoller, P., Ralph, P., Hamdorf, B., Catana, L. N., & Kuzava, G. S. (2017). Exploring the Feasibility of Algae Building Technology in NSW. Procedia Engineering,180, 1121-1130. doi:10.1016/j.proeng.2017.04.272

[9] U.S. Department of Energy. (2008, October). Energy Efficiency Trends in Residential and Commercial ...

Benefit analysis

Table 9.1: Corresponding environmental and social benefits of system

Environmental	Social
energy savings	savings on heating & cooling costs
CO_2 absorption, O_2 release	improved air quality
organic fertilizer	quality food supply

The primary objective of our algae window system is energy savings as well as light and temperature regulation. We also hope to offset the negative environmental impacts of fertilizer production by using our harvested algae as organic fertilizer, rather than biogas. Fertilizer production consumes approximately 1.2% of the world's total energy on an annual basis and emits about 1.1 metric tons of CO_2 / nutrient ton of fertilizer produced. Measuring the mass of algae we produce, as well as other indicators, will allow us to evaluate the total benefits of our completed system.

Fertilizer Potential

The agricultural sector emits 11% of global anthropogenic GHG emissions.[10] Much of these emissions come from the production and usage of synthetic nitrogen fertilizer. While this fertilizer has allowed the world's agricultural systems to increase tremendously, it does come at a high cost. Runoff from fields can pollute groundwater and kill off marine life. In the atmosphere, nitrous oxide is mixed into the stratosphere and destroyed ozone.[11]

Replacing a percentage of nitrogen fertilizer with algae would have a major impact on the emissions associated with agriculture. A total of 61% of GHG emissions from corn production come from nitrous oxides and the production of fertilizer[12]. Within fertilizer plants themselves, the annual methane emissions are 28 gigagrams. This value is over 100x greater than what was previously reported by the fertilizer industry.[13] With this new data coming to light, there is a great opportunity to provide a natural fertilizer alternative. If algae from an algae

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Retrieved from https://www1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf

[10] Chai, R., Ye, X., Ma, C., Wang, Q., Tu, R., Zhang, L., & Gao, H. (2019, December 30). Greenhouse gas emissions from synthetic nitrogen manufacture and fertilization for main upland crops in China. Retrieved from https://cbmjournal.biomedcentral.com/articles/10.1186/s13021-019-0133-9

[11] The downside of nitrogen fertilizer. (2015, June 03). Retrieved from https://www.caryinstitute.org/news-insights/podcast/downside-nitrogen-fertilizer

[12] Woodbury, P., & Wightman, J. (n.d.). Nitrogen Fertilizer Management & Greenhouse Gas Mitigation Opportunities. Retrieved from http://climatesmartfarming.org/wp-content/uploads/2019/02/Nitrogen-Fertilizer-Management.pdf

[13] Cornell University. (2019). Fertilizer plants emit 100 times more methane than reported. *ScienceDaily*.

window is used to offset some synthetic fertilizer the emissions footprint associated with agriculture would decline significantly.

According to a study done in Singapore, spirulina performed comparably to most chemical based fertilizers for a variety of plants[14]. For some crops, such as arugula, the yield actually increased when the fertilizers were shifted to spirulina. This study is extremely promising for the future of incorporating spirulina as a widely used fertilizer option. Not only was the net yield of crops increased, but the dry weight of the seedlings grew. This change bodes well for the future of growing, as it is an investment in the long-term plant health. Beyond the benefits for vegetable growth, rice crops also showed an increase in yield of 15-20%.[15]

Other studies have investigated a more integrative approach towards using spirulina as a fertilizer. A study conducted by the National Botanical Research Institute of India found that using fly-ash, blue green algae (spirulina), and nitrogen fertilizer had the best results for legumes and rice plants. Using all three fertilizers led to improved growth, yield, and mineral composition.[16] The reasoning for these results is that blue green algae raises the functioning of photosynthesis. It is able to help plants absorb more atmospheric nitrogen, which reduces the need for synthetic, nitrogen fertilizers. By organically enhancing natural processes, the plants had better levels of essential micronutrients without increased levels of toxic metals.[17]

Biofuel Potential

Biodiesel is one of the main sources of alternative fuels that has been fully integrated into US habits. Emissions from diesel, such as CO2 and sulfur, have major negative impacts on the environment. Current EPA fuel standards require reductions in the sulfur content of diesel, which reduces particulate emissions by up to 90%. CO2 emissions remain a major issue with diesel usage. In 2019, the U.S. Energy Information Administration estimated that 456 million metric tons of CO2 were released into the atmosphere due to diesel consumption.[18] This value is 9% of the total U.S. energy-related CO2 emissions for 2019. Implementing biodiesel as an alternative is a straightforward strategy to reduce this percentage.

There are currently many different types of biofuels that are used as substitutes for petroleum. While most are implemented no higher than B80 (80% biofuel), using B100 has the potential to lower carbon emissions by 74% compared to petroleum diesel.[19]

Using algae, specifically algae that is grown in the space of an algae window, reduces any competition over land between biofuel crops and food crops. Land use for biofuel sources, such as corn and soybeans, are a major limiting factor in its effectiveness. The energy that goes into growing and harvesting these crops takes away from the net energy balance of creating

[14] Wuang, S. C., Khin, M. C., Chua, P. Q., & Luo, Y. D. (2016). Use of Spirulina biomass produced from treatment of aquaculture wastewater as agricultural fertilizers. *Algal Research,15*, 59-64. doi:10.1016/j.algal.2016.02.009
[15] *Ibid*
[16] Tripathi, R., Dwivedi, S., Shukla, M., Mishra, S., Srivastava, S., Singh, R., . . . Gupta, D. (2008). Role of blue green algae biofertilizer in ameliorating the nitrogen demand and fly-ash stress to the growth and yield of rice (Oryza sativa L.) plants. *Chemosphere,70*(10), 1919-1929. doi:10.1016/j.chemosphere.2007.07.038
[17] *Ibid*
[18] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (2020, December 2). Retrieved from https://www.eia.gov/energyexplained/diesel-fuel/diesel-and-the-environment.php
[19] Biodiesel Vehicle Emissions. (n.d.). Retrieved from https://afdc.energy.gov/vehicles/diesels_emissions.html

these alternative fuel sources. For biofuel from soybeans, there is a 93% net energy balance. Corn is much less efficient with a positive energy balance of only 25%.[20]

A current limitation on the effectiveness of algae as a biofuel is that the energy consumed exceeds the energy available to be extracted on a daily basis.[21] There are potential solutions to this issue that are in the process of being developed. Increasing the biomass productivity and lipid contents of the algae could make the net energy balance positive. Additionally, nutrient supply through wastewater treatment and use of leftover biofuel for methane production could bring the energy balance to a 13.2% surplus.[22]

Food Source Potential

The meat industry is one of the greatest polluters throughout the world. The UN estimates that this industry alone generates 18% of total global greenhouse gas emissions.[23] The land use required to sustain industrial meat is a major reason why these emissions are so high. The area of global farmland could be reduced by as much as 75% if humans did not consume meat and dairy.[24] Land is required for animals to graze as well as for crops to grow and be processed as animal feed. With all of these factors combined, livestock takes up 27% of the world's land.[25] With increasing populations and less available arable land, this change might become necessary in the future.

The downsides of the meat industry go far beyond just land use. The impacts of cows on total greenhouse gas emissions are enormous.

Spirulina has recently become known as a "superfood" in health markets. However, its usage goes back much farther. The Aztecs used spirulina to treat various diseases and as an endurance-booster.[26] Modern research supports that spirulina is extremely beneficial, but has not yet confirmed its effectiveness for actively combating disease. It has the benefits of supporting metabolism and boosting immunity due to a high content of B vitamins.[27] Additionally, only a small amount of spirulina contains enough beta-carotene to help skin and eye health.

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[20] Hill, J., Nelson, E., Tilman, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences,103*(30), 11206-11210. doi:10.1073/pnas.0604600103

[21] Dassey, A. J., Hall, S. G., & Theegala, C. S. (2014). An analysis of energy consumption for algal biodiesel production: Comparing the literature with current estimates. *Algal Research,4,* 89-95. doi:10.1016/j.algal.2013.12.006

[22] ***Ibid***

[23] Clean Air Council. (n.d.). Meat Industry. Retrieved from https://cleanair.org/public-health/meat-industry/

[24] Carrington, D. (2018, May 31). Avoiding meat and dairy is 'single biggest way' to reduce your impact on Earth. Retrieved from https://www.theguardian.com/environment/2018/may/31/avoiding-meat-and-dairy-is-single-biggest-way-to-reduce-your-impact-on-earth

[25] Our World in Data. (n.d.). How the world's land is used: Total area size by type of use & land cover. Retrieved from https://ourworldindata.org/uploads/2013/10/World-Map-by-Land-Use-01.png

[26] Brennan, D. (2020, October 06). Spirulina: Are There Health Benefits? Pros and Cons, Nutrition, and More. Retrieved from https://www.webmd.com/diet/spirulina-health-benefits#1

[27] Team, W. (2020, September 16). Is Spirulina Good for You? Retrieved from https://health.clevelandclinic.org/spirulina-superfood-youve-never-heard/

While most spirulina is currently sold as a nutritional supplement, it also has high potential as a more substantial meat substitute. Spirulina has a very high protein content at 60%.[28] This value is significantly higher than that of beef, which is only 26-27%.[29] While taste is an important factor to consider when developing meat alternatives, nutritional value is also necessary. With current production of pea protein or soy meat alternatives, there is potential for spirulina to be incorporated into new products.

In fact, major food producers have already begun working with algae for project development. As of July 2020, Unilever partnered with the biotechnology company Algenuity to research nutritional potential for microalgae. This partnership is a major step towards bringing algae into typical diets. A similar partnership was developed with Nestlé and biochemical company, Corbion, in 2019.[30] These initiatives with such influential companies in the food production space indicate a willingness for cultural change in the industry.

Other Potential Uses

Algae also has the potential for other innovative uses, including focused carbon sequestration and wastewater treatment. The wide array of benefits that algae can provide allows for the technology to be customized based on the circumstances of each implementation.

Social Benefit Analysis

The main social benefits of the algae window are the educational offerings and potential green advertising by environmentally conscious companies. The innovative technology behind algae windows provides an opportunity for people passing by to engage with green alternatives. By providing information about the benefits of the window near the location it is installed a greater population of people can become informed about the issues of energy usage in buildings. Broader awareness has the potential to influence many more individuals indirectly by word of mouth. Given the unique look of the algae window, its presence on any given building is an effective way of signaling care for the environment. While current systems such as energy efficiency rankings and LEED certifications exist to help show the steps certain companies have taken to benefit the environment, those badges of honor are not exactly obvious to the average passerby. Algae windows on a building are an obvious display of environmental concern.

[28] Publishing, H. H. (2019, April 11). By the way, doctor: Is spirulina good for you? Retrieved from https://www.health.harvard.edu/staying-healthy/by_the_way_doctor_is_spirulina_good_for_you

[29] Arnarson, A. (2019, April 4). Beef 101: Nutrition Facts and Health Effects. Retrieved from https://www.healthline.com/nutrition/foods/beef#nutrition

[30] Meat from algae: The next plant-based contribution to sustainable food production? (2020, August 31). Retrieved from https://geneticliteracyproject.org/2020/09/01/meat-from-algae-the-next-plant-based-contribution-to-sustainable-food-production/

Business Plan

Target Market Analysis

While reducing energy emissions from buildings is the main intention of the algae window, the many other benefits it can offer will be valuable in finding and securing a market for the product.

Given the newness of our product, it is necessary that we are able to identify an interested market. The benefits of the window can only be felt if people are willing to take a chance on the new technology and install algae windows in their buildings. The prime target market will be commercial buildings. This could include office buildings, warehouses, or service centers. All of these buildings must remain relatively stable temperatures, which the algae window will help promote. Data centers themselves make up 1% of the world's total energy usage[31]. Despite increasing demand for these buildings, the amount of total energy usage is not increasing because of improved efficiency. Algae windows could be an important component in continuing this trend as the demand for centers rises.

Although the cost of algae windows will exceed that of less efficient alternatives, incorporating them into new buildings is a great way for businesses to invest in the environment. Many companies are beginning to focus on a triple bottom line (profit, social, and environmental concerns). Reducing the carbon footprint is a major step towards achieving this goal. Using algae windows will help businesses in this process, which is why this product can be targeted towards environmentally conscious companies for them to use in their office buildings.[32]

Algae is most likely to thrive in conditions where there is a lot of sunlight and moderate temperatures. These conditions could include over 200 days of sunshine per year and average temperatures around 75ºF. Areas such as Hawaii are particularly conducive to Spirulina growth and can be an effective target region. Other areas with high numbers of sunny days and moderate temperatures include Santa Barbara, CA, Costa Rica, and parts of South Africa. These areas also provide strong target markets because they foster liberal cultures where sustainability is highly valued.

Another target market for this algae window is corporations that would want to use the algae for one of its many end use opportunities. For example, a food production company interested in using spirulina as an alternative meat source would be able to use algae windows to meet their production demands. Incorporating algae windows into a company's overall demand for algae will help with cost reductions.

Lastly, universities and other research institutions have great potential as markets for the algae window. These groups are always seeking new, innovative technologies, and have a societal obligation to care for the environment. Many universities have goals for emissions reductions over the next few decades and sizable endowments to make large scale

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[31] 27, Y. S. (2020, March 13). Study: Data Centers Responsible for 1 Percent of All Electricity Consumed Worldwide. Retrieved from https://www.datacenterknowledge.com/energy/study-data-centers-responsible-1-percent-all-electricity-consumed-worldwide

[32] Wilkinson, S., Stoller, P., Ralph, P., Hamdorf, B., Catana, L. N., & Kuzava, G. S. (2017). Exploring the Feasibility of Algae Building Technology in NSW. *Procedia Engineering,180*, 1121-1130. doi:10.1016/j.proeng.2017.04.272

improvements. Incorporating algae windows can help schools reach these goals while providing a lesson in innovative technologies.

Financial Breakdown

Budget

Table 10.1: Cost breakdown of system components

Part	Description	Cost
Acrylic	.5” thick acrylic for algae windows	$450
Sealant	To seal acrylic window pieces together	$30
Sensor Systems	To automate process of algae filtration and ensure quality of algae nutrients are ideal	$33
Algae	Algae will grow within the windows to make the buildings more efficient	$144

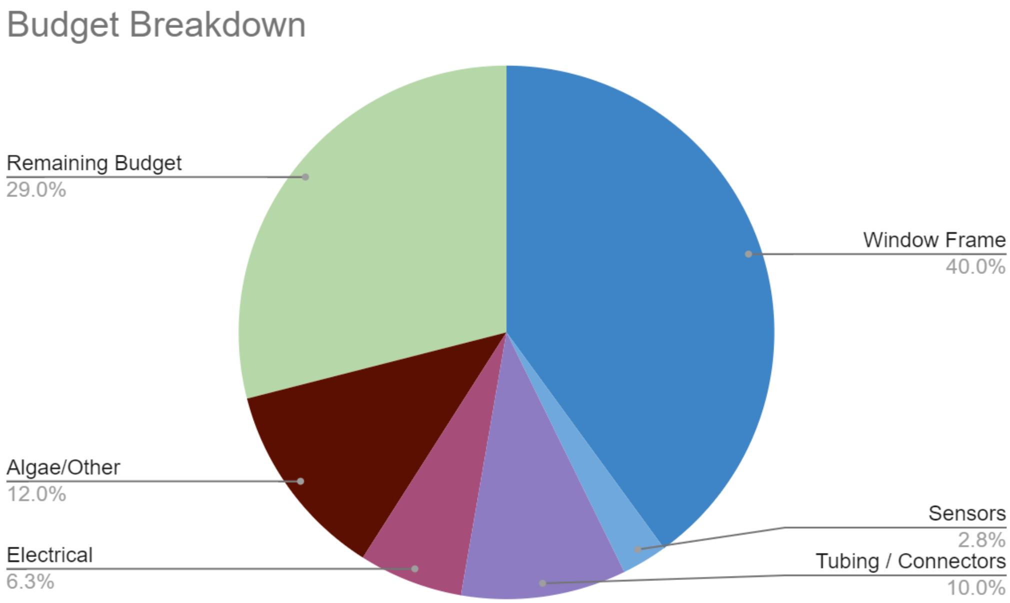

Figure 10.2: Budget breakdown after purchasing all materials

Basic Business Plan

The basic business plan analysis will discuss the algae window costs, government incentives for adopting this alternative design, possible economies of scale, projected savings and cost benefit analysis. Overall, the primary costs for the algae window would be the material cost of the window pane. One square foot of our double-sided window would cost ($24.66*2) = $49.32. Given our costs of $852 for a 2 foot by 3 foot algae window, a conservative estimate for each square foot would be $142, given that some of the costs went to prototypes / extra parts. However, if ordering in bulk, this amount could be reduced by approximately 30%, resulting in approximately $100 per square foot given the decreasing costs of acrylic in bulk and the reduced need for extra parts. In comparison, the average cost is $25 to $40 per square foot of a standard window, fully installed.[33]

Given that the algae window will be more expensive by a factor of approximately three, it is crucial to analyze possible government incentives and cost savings to identify how beneficial it might be to make the change to algae windows. Our target market of corporate buildings do have tax incentives to adopt a more energy efficient building design. Specifically, there is a tax deduction of up to $1.80/ft^2 for buildings that save at least 50% of the heating and cooling energy of a system.[34] Our testing data indicated a 14.8% increase in the temperature of the water jar with just a window with no algae compared to an approximately 0% change in temperature of the water jar within 30 minutes for the algae window. The results suggest that our window, if expanded, could have considerable success to meet the 50% heating and cooling threshold. However, the tax benefits alone clearly do not offset the costs of the initial investment, so it is important to analyze the possible heating and cooling costs saved by the algae window.

A 1 degree fahrenheit difference costs approximately 3% of building costs on average, corresponding to an approximately 5.4% difference for each degree celsius.[35] On average, office buildings using two-pipe HVAC systems will cost $15 to $23 per square foot, while large office buildings using a four-pipe configuration will cost $23 to $28 per square foot. We can calculate based on $22 to take the median of the two ranges. Given our testing data, if we are able to save approximately 50% of the building's heating/cooling costs, that would be $11 per square foot. Even though our window costs about $66 more per square foot, it seems reasonable for a building to have at least 6x less window square footage compared to building square footage, so based on these calculations, the estimate would be approximately a break-even or better. Thus, it would be helpful to perform additional tests to pinpoint how much energy

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[33] B. (n.d.). House Window Prices. Retrieved from http://www.housewindowsprices.com/window-costs-per-square-foot.html#:~:text=the window itself.-,Installation typically runs $150 to $350 per opening.,foot between per square foot.

[34] Tax Deductions for Commercial Buildings. (n.d.). Retrieved from https://www.energystar.gov/about/federal_tax_credits/federal_tax_credit_archive/tax_credits_commercial_buildings

[35] Department of Energy & Environment. (n.d.). Energy Tips for Commercial Buildings. Retrieved from https://doee.dc.gov/service/energy-tips-commercial-buildings

the algae window could save past just 30 minutes to determine how beneficial it could be to use algae windows for commercial buildings.

Conclusion

Overall, this is a technology that is still in development. Based on our data and data from other implementations, it will likely not be as cost-effective or efficient as more established methods, such as solar thermal systems, for some time. However, we feel that it is worthwhile to continue to research because the end use opportunities for the algae provide a lot of potential for energy savings. Additionally, the system can allow businesses to display their commitment to the environment and can help bring attention to innovative energy technologies.

Future Plans

Due to COVID-19 restrictions, the timeline of the project was severely impacted and unfortunately, the team was unable to meet their goals to connect the Photon board sensors to the tank prototype. During the summer, the team plans to continue the project and work on further prototyping the mechatronic systems to allow for an automated water dispensation and collection from turbidity/light readings from the sensor board. The team also plans to install an automated system to introduce nutrients into the tank to manipulate the amount of algae and prototype a filtration system to collect the byproduct and harvest the algae for fertilizer purposes.

Most importantly, while the initial data collection seemed promising, the team also plans to further test the prototype with varying algae concentrations and different environmental temperatures. Since the testing environment consisted of an artificial lamp source, data collection in external outdoor settings (e.g. set next to a window and tested at different points of the day) would also help in evaluating the potential of the window in an environment where it may be placed.

Appendix

A: Acrylic Thickness Calculations

H	***Enter Height of Tank [in]***	***24***
L	***Enter Length of Tank [in]***	***36***
	Is the top closed ? (yes or no)	***yes***
q	Maximum Water Pressure [psi]	0.8664
L/H	L/H	1.5
a	Maximum Allowable Stress for Acrylite cast in Aquarium [psi]	750
b	b	0.521006 25
Tc	**Thickness of Sheet required with top [in]**	**0.589**

B: pH Sensor

pH Sensor Sample Code

```
void loop() {
 if (input_string_complete == true) {                  //check if data received
   inputstring.toCharArray(inputstring_array, 30);   //convert the string to a
char array
   parse_cmd(inputstring_array);                       //send data to pars_cmd
function
   input_string_complete = false;                      //reset the flag used to
tell if we have received a completed string from the PC
   inputstring = "";                                   //clear the string
 }
 Serial.println(pH.read_ph());                         //output pH reading to
serial monitor
 pH_lcd.setCursor(8, 2);                               //place cursor on screen
at column 9, row 3
 pH_lcd.print(pH.read_ph());                           //output pH to lcd
 delay(1000);
}
```

pH Sensor Specs

Range: 0.1 – 14.0

Resolution: 0.1
Accuracy: +/– 0.2
Response Time: Continuous analog output
Supported probes: Any type & brand
Calibration: Optional
Temp Compensation: No (unnecessary)

Data Protocol: Analog 2.7 – 0.2V

Dimensions: 56.2mm x 32mm (2.2″ x 1.2″)
Weight: 15 grams

Turbidity Sensor

Turbidity Sensor Sample Code

```
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
}

// the loop routine runs over and over again forever:
void loop() {
  // read the input on analog pin 0:
  int sensorValue = analogRead(A0);
  // print out the value you read:
  Serial.println(sensorValue);
  delay(100);        // delay in between reads for stability
}
```

Turbidity Sensor Specs

Operating Voltage: DC 5V
Operating Current: about 11mA

Detection Range: 0%--3.5% → this maps directly to （0-4550NTU）

Operating Temperature: -30℃~80℃

Storage Temperature： -10℃~80℃

Error Range: ±0.5%F*S
Weight: 18g