Team 8: Electro-Wave
PROJECT PROPOSAL & FEASIBILITY STUDY

Austin Juza
Matt Ramaker
Ryan Rhodes
Ed Smit

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Executive Summary

Wave energy is a renewable power source, and one that Team Electro-Wave wants to explore to see if the technology can be implemented in the Great Lakes. Thus far, wave energy has not been determined to be commercially viable in the Great Lakes region by Consumers Energy. This is a result of high initial costs and low energy generation. Comparing wave energy to solar and wind generation, Electro-Wave has a vision to use the energy in waves in order to produce useful electricity. Great Lakes wave spectrum data is used to calculate potential power output and return on investment for a wave energy plant. Eight miles off the coast of Houghton, MI in Lake Superior resides the optimal location for power output. The location averages a power output of 7.18 kW/m. Using the optimal Wave Energy Converter (WEC), 2.93 kW/m of power can be extracted. Team Electro-Wave’s goal is to determine the economic feasibility of WECs in the Great Lakes. A secondary purpose will be to develop a small scale WEC.
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1 Introduction

1.1 Team Members

Figure 1. Team Electro-Wave: Austin Juza [ME], Ed Smit [ME], Ryan Rhodes [ME], and Matt Ramaker [ME]

Austin Juza grew up in southwest Michigan, in the city of St. Joseph where he graduated from Lake Michigan Catholic High School. In college, Austin has had several internships. Following freshman year, Austin worked for Whirlpool Corporation in their Cooking Technician Lab. After his sophomore and junior year, Austin worked at Donald Cook Nuclear Power Plant where he spent time in the Nuclear Steam Supply Systems Department and the Production Engineering Department. Austin hopes to work in the renewable energy industry with no specific area of concentration.

Ed Smit grew up in northern New Jersey, in the town of Stockholm. He attended Veritas Christian Academy in Sparta, New Jersey, where he graduated Valedictorian. After graduation from Calvin College with a Bachelors of Science in Engineering, Ed hopes to find an engineering position in the renewable energy field.

Ryan Rhodes grew up in western Michigan in the city of Zeeland, Michigan where he attended Zeeland East High School. In high school, he gained manufacturing work experience by working for Innotec and JR Automation. During his junior year of college, Ryan started his first internship at Nucraft Furniture. He worked in the Engineering Change Request Department where gained experience in both AutoCAD and Autodesk Inventor. Ryan hopes to work in the oil industry following graduation.

Matt Ramaker grew up in Grandville, Michigan and graduated from Calvin Christian High School. He then went on to Calvin College in Grand Rapids, Michigan. In college, Matt worked several internships where he obtained valuable work experience. Matt worked for the Kent County Road Commission at the end of
his sophomore year where he learned about designing systems, specifically for road signs. After his junior
year in college, Matt worked for Brawn Mixer, a growing company in the fluid mixer design business. Here, Matt learned about engineering design and ethics as he worked with quoting for and assisting customers with their mixing needs. Matt hopes to continue to work in new and exciting fields as he continues his engineering career.

1.2 Team Duties

Each team member’s duties were very similar. Much of the semester required extensive and thorough research, as wave energy was a subject that no member of the team was familiar with. Further research will be required throughout the fall semester and into the spring semester to develop a well-rounded and accurate economic study of WECs. This research will include material properties, power outputs, and other aspects towards the building of a WEC.

On top of research, individual team roles were handed out in the fall semester. Austin was designated to be Team Electro-Wave’s webmaster, which means he is the owner of the website and has official access to it through Calvin IT. Austin was deemed most technologically inclined in the group. His passion for technology and his creativity lead to an exceptional website design and aesthetically pleasing user interface. Ryan was chosen to be the team member who throughout the year will communicate with potential companies/clients to provide the economic feasibility report, as well as communicate with Team Electro-Wave’s consultant, Professor Wikus Van Niekerk. Ryan was appointed to be the team liaison due to his strong interpersonal skills. With his desire to move into technical sales as a profession, this role was determined to be the most suitable. Ed and Matt, will help out with the website, provide communication between contacts, as well as continue to do extensive research and important calculations, in areas such as wave energy potential, material strengths, alternative designs, and the business plan. Both Ed and Matt are the most technically inclined in the group. Matt possess skills in coding along with a passion for mathematics. Both these skills proved beneficial to the group. Lastly, Ed’s attention to detail along with his strong writing skills proved extremely beneficial in the construction of the PPFS.
1.3 Team Organization

Meetings are conducted normally twice a week with research topics given to be completed at a certain time. Electro-Wave agreed to hold everyone accountable to show up on time for meetings and therefore all four members are in charge for keeping up to date with the schedule. A group schedule, found in Figure 3, was created to show what times are available for the team to meet. Each week, team members were assigned duties to complete by the next meeting time. This information was compiled onto a Google Presentation document to present to the other group members. This was deemed the most beneficial for keeping up to date on all aspects of the project along with being held accountable by other team members.
Before any meetings were conducted, Team Electro-Wave agreed upon rules to govern team interactions. As Christian engineers, the team agreed that the most important rule to abide by was respect and caring. Prior to the senior design project, each member had limited interactions with one another. It was deemed appropriate to follow this rule in order to maintain a safe, healthy working environment. The second rule Team Electro-Wave implemented was to entertain any and all ideas towards the project objective. This is important to preserve creativity. With these two rules implemented, Team Electro-Wave was able to perform satisfactory throughout the project.

1.4 Class Description and Purpose

Engineering 339/340, called Senior Design, is a class designed to give students the opportunity to use engineering knowledge gained through classes and experience to engineer a solution to a complex problem through involved design and prototyping. Senior Design is meant to show students how to design a solution through design criteria such as the design norms and how to develop the proper solution for a problem.
1.5 Project Definition

1.5.1 Need for Renewable Energy

Fossil fuels have a much higher energy return on investment (EROI) than most renewable alternatives. EROI is the amount of energy that has to be expended in order to produce a certain amount of energy. However, due to the depletion of resources, the EROI for fossil fuels are declining. As a result of the depletion of fossil fuels and the increasing difficulty of inexpensive extraction, renewable energies are becoming a viable option for energy production [1].

As seen in Figure 4, energy consumption has been on a general rise over the years, recessions being the only factor for reducing consumption. With the continuing modernization of countries world-wide, energy consumption is believed to follow this trend. However, fossil fuels are a non-renewable source of energy and has the potential to one day be depleted. This brings in the need for renewable energy ventures to match the continuing consumption trend.

![United States Energy Consumption](image)

Regardless of the state of oil supply, CO₂ emissions are also a growing issue. Since the Industrial Revolution, CO₂ emissions have been on a general upward trend. It can be seen below in Figure 5 that the world has drastically increased its CO₂ emissions over the past century.
This increase correlates perfectly to the amount of energy consumption as seen in Figure 4. According to the *Trends in Global CO₂ Emissions 2013 Report* [4], the United States is responsible for emitting the second most amount of CO₂. The United States emits 15% of the World’s total emissions, behind China at 29%.

While global warming has been debated for several years with no definite answer, global climate change (GCC) is the more serious issue at hand. There has been a scientific consensus that GCC is in fact occurring. Amongst other factors, CO₂ emissions plays a large part in the GCC. Figure 6 depicts the change in vegetation growth over a 16 year time span.
The vegetation zoning has shifted significantly north while the higher-level hardiness zones have decreased in size. Due to the changing seasons which occur because of GCC, “our planet is now in the midst of its sixth mass extinction of plants and animals — the sixth wave of extinctions in the past half-billion years. We are currently experiencing the worst spate of species die-offs since the loss of the dinosaurs 65 million years ago” [6]. This extinction is greatly reducing the amount of biodiversity in several regions of the world. This lack of biodiversity can have drastic effects on the environment, thus humans.

Unless steps are taken to reduce the usage of fossil fuels, resources will continue to deplete and GCC will continue to worsen. This brings up the need for more sustainable energy, such as wave energy. Harnessing energy from waves would greatly reduce the need for fossil fuels, and in turn, CO₂ emissions.

1.5.2 Method of Analysis

1.5.2.1 Feasibility Study

Team Electro-Wave is looking at wave energy differently than most WEC companies. The main goal is to determine whether or not wave energy in the Great Lakes will be economically feasible. To fulfill this goal, standard energy production systems will be analyzed on an economic basis. Fossil fuels such as coal, oil, and natural gas are the standard for energy production worldwide, due to their relatively cheap costs. For various locations in the Great Lakes, wave height and frequency will be used to calculate the average power output for locations within the Great Lakes, then a WEC design will be chosen and optimized for power output. The desired WEC and all its components will be optimized to produce the greatest amount of electricity for the lowest price. Following the optimization, return on investment (ROI) calculations will be conducted in accordance to the ROI section. Lastly, an electricity production cost can be calculated on a dollar per kilowatt hour basis. This cost will then be compared to the costs of electricity generated by fossil fuel to determine the feasibility of the WEC.

1.5.2.2 WEC Design

The WEC that will be used for the feasibility study and small scale construction will be chosen from the design options section. Following Team Electro-Wave’s industrial consultant meeting, the team will be able to determine which WEC is best suited for the Great Lakes region. Subsequently, in-depth power generation calculations will be conducted. Further analysis will take place in the form of finite element analysis (FEA) using Autodesk Inventor along with stress and strain calculations. These calculations will provide Team Electro-Wave with the required strengths necessary to construct the WEC. Materials will then be chosen to meet the required strengths for the lowest cost. Current WEC patents will highly influence the design and construction of this WEC.

1.5.3 Benefit of Wave Energy as a Solution

One of the main benefits of using wave power to produce energy, as opposed to using other renewable energy sources, is the predictability. Waves are just as predictable as cloud cover and wind speed/direction, as it is already done by the National Oceanic and Atmospheric Association (NOAA). Yet another benefit
of the wave energy is the area of potential area of use. Water covers approximately 71% of the Earth’s surface, most of it being the oceans. This area could be used to harness energy from waves, and while it could be argued that wind energy is currently being utilized offshore, the costs associated with the construction of wind farms offshore can be extremely high.
2 Design Goals

The goals that Team Electro-Wave have in mind are to provide a well-detailed study that will be provided to the customer, and will show whether or not wave energy is an economically viable source of renewable energy generation. Secondly, Team Electro-Wave will construct a WEC that transfers the energy from the waves of Lake Michigan into useful electrical energy that can be stored to power an object during the final senior design presentation. The choice of the specific WEC which will be constructed will be driven by the design norms found in Section 3 of the report.
3 Design Norms

As Christian engineers, Team Electro-Wave should be designing with a Christian mindset. Throughout this process of planning and designing WEC technology, design norms need to be implemented.

3.1 Stewardship

The first and most important is the idea of stewardship. Renewable resources like solar, wind, and waves will help man to become less dependent on the non-renewable resources which will inevitably get scarcer as time continues. Using more renewable resources results in reusing the resources God has given to man, therefore using them more responsibly and creating less pollution.

3.2 Trust

Team Electro-Wave wants the person or group using these WECs to be able to trust in the product and the engineering of it. It should produce power reliably and be strong enough to operate consistently, even in the stormiest conditions. The WEC being utilized will be placed in the Great Lakes, which is an ecosystem. The design will avoid any conflicts of interest, such as harmful elements to any organisms or any issues of aesthetics which is mention below in Section 3.3.

3.3 Delightful Harmony

The concept of delightful harmony needs to be factored into the design. The WEC should do the job it was designed for, as well as being aesthetically pleasing and creating a harmony between form and function. These WECs are going to be placed in locations where people will be viewing them from their homes as well as public places such as beaches. These should not be displeasing to those trying to take in the beauty that is the Great Lakes. The form of the WECs used should mirror this beauty and be acceptable by all people viewing it.
**Figure 7. Gantt Chart of Work Breakdown**
4.2 Project Schedule

An exhaustive list of all tasks completed for the PPFS by Team Electro-Wave can be seen below in Table 1. The list consists of the main tasks that contributed to the feasibility study. A recordation of collective team hours spent is compared to the estimated time. On average, Team Electro-Wave under scheduled each task by roughly 35 percent. Some of the notable events that contributed to this discrepancy were the design options, power calculations, team website and the PPFS.

The design options section took much longer than expected due to the amount of different WEC designs. Since wave energy is not a prominent source of alternate energy, there was no industry standard to base the research off of. A vast amount of research had to be conducted to gain a base knowledge of each WEC. After this knowledge had been acquired, the design options could be narrowed down.

The power calculations also proved to be troublesome. A modest estimate of 3 hours was determined to be long enough to complete a power density spread of the Great Lakes. Since there was such a large amount of data for each buoy, roughly 300 points of time when data was collected, data calculations took much longer than expected. A plethora of calculations had to be implemented to filter out bad data along with calculating wave power itself. A total of 38 buoys were used to calculate power density for a variety of locations along the coasts of Lake Michigan and Lake Superior.

The team website also took longer than expected due to the lack of knowledge of Dreamweaver. A self-tutorial had to commence before construction of the website began. Team Electro-Wave also decided to switch templates several times to obtain an aesthetically pleasing website.

Lastly, The PPFS rough draft was underestimated greatly. After a complete read-through of the grading rubric, it was discovered that key material was missing.

Team Electro-Wave adjusted the schedule several times throughout the semester. A set of contingency plans were built in order to reduce risks. Of these plans, implementing a time buffer of tasks that were brand new to the team were implemented due to the pattern of extra hours spent for these tasks in the past. It can be seen in Table 1 that the difference column contains much more negative numbers (tasks completed before allotted time) towards the end of the semester. This proves that Team Electro-Wave has learned to work well ahead of time in case of any expected roadblocks.
Table 1. Work Schedule

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|                | Average             | 389                  | 137                 | 35.2                |
4.3 Budget

Table 2. Budget for Constructing an Oscillating Wave Column

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<td>Isolation Valve</td>
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<td>Fast Acting Valve</td>
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<td><strong>Total</strong></td>
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Ryan Rhodes is the primary budget coordinator. Looking at the budget, Team Electro-Wave has found cost estimates for the components that comprises an Oscillating Water Column. Any increases to this budget will be made with team consensus, along with the input and approval of the team advisor. The budget was made with a contingency which will allow the team to stay under budget with any unforeseen costs.
5 Background and Research

5.1 History of Wave Energy

“The first generation of ocean energy technologies were developed over 100 years ago: the initial patents for wave-powered devices were issued in the 19th century” [8]. By the year 1980, more than one thousand patents had been registered. It was not until the oil crisis of the 1970’s that ocean wave energy really took off. [9]

5.2 Current Usage

To date, there are 140 wave power companies in the world. Pelamis is one of the world’s largest wave energy companies and also the most advanced. It was the first company to produce electricity to the grid and to be used commercially. There is currently a large 2.25 MW farm of Generation 1 Pelamis Wave Generators off the coast of Portugal. Pelamis is currently developing a Pelamis 2 generator which will compose a 25 MW wave energy farm. The Pelamis WEC is a semi-submerged cylindrical device linked together by hinged joints. This type of WEC was not considered for one of Team Electro-Wave’s designs due to the size of the converter, 100 or more meters long. [10]
6 Federal and State Regulations and Codes

There are numeral state and federal regulations that need to be followed in order to install anything in any of the Great Lakes, due to the fact that the Great Lake’s lakebeds are owned by the State of Michigan. The specific set of regulations required is different when considering near-shore construction or offshore construction, but the list of potential legal conditions, and a synopsis of each, are presented below.

6.1 The Great Lakes Submerged Lands Permit

This permit, which is required when constructing anything past the ordinary high water mark of the Great Lakes, is submitted through the Water Resource Division (WRD) of the Michigan Department of Environmental Quality (MDEQ). In addition to the permit application, detailed drawings and plans must be presented of the project, showing that the private or public use of the lands are not substantially affected. It must not affect the general public’s use of lands in areas such as fishing, swimming, hunting, navigation or pleasure boating, as determined by the State and the above departments. Lastly, an application fee is required, which must be paid at the time of submitting the application. The only other stipulation is, if the installation is near shore, to secure conveyances from the riparian owners with a separate “Application of Conveyance,” also provided by the MDEQ. These are persons who own property up to the ordinary high water mark of a Great Lake. Permission from these property owners, as well as from the adjacent landowners needs to be acquired using the Application of Conveyance. [11] [12]

6.2 Clean Water Act of 1972

Following this government regulation properly is to make sure that the units do not pollute the waters of the Great Lakes with harmful substances, such as oil. The water quality must meet specific criteria, as governed by the U.S. Environmental Protection Agency (EPA), in areas of impact on the aquatic/biological life and human health. There are numerous chemicals, bacteria, and pathogens listed in Section 304 of the Clean Water Act which fall under the category of pollutants. For the Great Lakes, all of these could be potentially deadly for not only aquatic life, but also for humans as the Great Lakes are a source of drinking water. For WECs possible pollutants are paint, oil, and other lubricants. [13]

6.3 Rivers and Harbors Appropriations Act of 1899 Section 10

This federal act states that the construction of any obstruction within any navigable waters of the United States must be authorized by Congress. Additionally, the plans must be recommended by the Chief of Engineers (U.S. Army Corp of Engineers) and authorized by the Secretary of War. [14]

6.4 Michigan Underwater Preserves

The State of Michigan contains thirteen underwater preserves, where the shipwrecks and other diving attractions, such as undersea caves, are protected for diving tourism. The waters above the sites are not affected by federal regulations, but constructing on the lakebed would have to be very carefully planned so as not to disrupt divers or the shipwrecks. Although legislation does not specifically restrict construction in these areas, permits for lakebed use (moorings) would be extremely difficult if not impossible to obtain.
The areas and depths of these sites vary among the different underwater preserves, but overall the underwater preserves span an area of 2,300 mi², about 2.4% of the area of the Great Lakes. The geographical locations of the thirteen underwater preserves and the rough areas of each are pictured below in Figure 8. [15]

![Figure 8. Michigan Underwater Preserve Areas](image)

6.5 Water-Based Renewable Energy Generation Pilot Project

This permit pertains to pilot projects, defined as “an experimental project where the renewable energy generation units will be monitored to collect information on their performance and environmental effects.” These pilot projects must be a water-based renewable energy generation system, either wind-based or hydrokinetic-based. Also, no more than 10 generation units are permitted during the pilot project. A dredge limit during construction/implementation may not exceed ½-acre of water and may not be placed in areas established by the U.S Coast Guard as “danger zones,” such as shipping areas or Federal navigation channels. As this is deemed “an experimental project,” the generation units, structures, and transmission lines must be deconstructed and removed by a date of expiration identified by the Federal Energy Regulatory Commission, unless authorized by the Department of the Army. [16]
7 Customer Selection

Team Electro-Wave, at this point, is working toward proving that this technology is viable in smaller-scale applications such as in Lake Michigan. The customer then, would be a major electricity production/distribution company such as Consumers Energy. Team Electro-Wave could also look to focus this project to shoreline property holders as their customer if the size and power output is found to be sufficient.

7.1 Requirements for Consumers Energy

Upon contacting John O. Broschak, vice president of major projects and construction for Consumers Energy, we were educated on the matters of Consumer’s new energy trends.

Consumers Energy conducts significant research on new energy trends and pursues those ideas that are in the best interest of customers. Since we are a mostly regulated utility, we must obtain Michigan Public Service Commission (MPSC) approval to add an initiative into the rate base before we know we will receive a return on our investments. Up to this point, wave power generation has not been determined to be commercially viable in the Great Lakes Region. We are implementing large wind turbine parks since that technology has become cost-competitive with coal-fired plants. We are also pursuing solar developments in a variety of settings although we have not yet executed a large-scale project to date. Solar is currently not cost-competitive with other base load power generation sources but it has become increasingly popular with the public, and as a consequence, the MPSC… In the absence of government subsidies and incentives, economics drive the viability of technologies in the energy market… The way the energy markets work these days, power generation is bid into the market and contracts executed based on the lowest bidder up to the projected market capacity needed for any given day. [17]

In short, for Consumers Energy to even consider implementing or investing in WECs for the Great Lakes, an in-depth report would be needed to show that it is cost competitive with other renewable sources. If WECs are deemed cost inefficient in comparison to current alternatives for the time being, a report will be constructed with the proper requirements to make it a viable option.
8 Location

Finding the optimal places for WEC systems are based on a few crucial factors. The first is where these WECs can be constructed from a legal standpoint, following the state and federal regulations as stated in section 6. Secondly, the optimum location will depend upon the type of WEC chosen, and whether it is an onshore, near-shore, or offshore device. Most important, however, is the wave spectrum of the Great Lakes. The areas that will have the highest power potential will have very similar characteristics. Firstly, the ideal location will have a lakebed consisting of a higher rock to sand ratio. Having rocks instead of sand will greatly lessen the friction forces opposing the waves, allowing for a higher wave velocity and height. In determining the optimum locations, maps of substrates such as the one in Figure 9 will tell where the lakebed is comprised of the material well-suited for WECs.

Second, the location with greatest wave height will be in deep water, which will be in the middle of the lake. The largest wave swells generally occur in deep water. Ideally, the location will have a formation that causes a natural funnel, such as a bay or inlet. This will decrease the area, resulting in higher waves. Lastly, the location will also have a very large fetch of lake, the length along which the wind has blown over a body of water. A larger fetch allows for larger wind speeds, which produces larger waves. These factors will be the main determinant of locations for which detailed calculations for wave power potential will be done. These calculations can be found in the section 13, later in this report.
9 Scale

Typically, WECs are only built at a very large scale in the form of wave energy farms. Team Electro-Wave has put an emphasis on research at a smaller scale for the purposes of this project. The objective of this project is to determine the feasibility of putting a WEC into the great lakes to produce a reasonable amount of electricity that it could potentially have a payback period within the lifetime of the device.
10 Design to Resist Ice Damage

After researching icing and the damage that may occur, Team Electro-Wave has determined that it will not be possible to retrieve energy from waves via any method when the lakes are frozen. This leaves Team Electro-Wave with two options regarding ice damage. Team Electro-Wave can design the structure to be left in the water using material selection or different design geometries. To withstand the expansion of the water as it forms ice, it could also be designed to be easily removed from the water during the months that the lake will be frozen. The ideal situation would be to leave the device in, so as to not risk damage to the WEC, keep costs down, and have a potential production when it is not frozen over.
11 Energy Storage

The purpose of building a small-scale WEC is to acquire actual power readings, in terms of kW output, in the Great Lakes. For this purpose, it would not be reasonable to wire the model WEC into the power grid, but rather a battery will be required for proper data readings and energy storage. For simple data recordings and energy storage, a car battery will suffice. A 12-Volt lead-acid base would be the ideal battery in terms of cost and ease of implementation. This would not be used in the final design, but strictly for testing of the prototype WEC.

Storing the electrical energy produced from the prototype WEC would be beneficial for several reasons. First, a steady electrical output will not be needed. The battery will be able to charge for a given amount of time to accumulate a charge. The time and charge readings will be able to produce a kWh reading, which is the desired piece of information for the feasibility study.

For the feasibility calculations of a large-scale WEC plant, battery storage will be neglected. It has been deemed ideal to have the WEC plant wired directly into the grid. This decision is appropriate due to the amount of WEC plants active today that operate in the same manner. Furthermore, the cold weather in the Great Lakes region during the winter months would have an impact on battery storage performance, as seen in Figure 10.

![Battery Performance vs. Temperature](image)

**Figure 10. Effects of Cold Weather on Battery Performance [19]**
12 Design Options (Alternatives)

To construct a WEC, realistic models efficient enough to perform a feasibility study needed to be found. There are hundreds of different designs currently being used to draw energy from waves. As Electro-Wave selects a design, some important characteristics are power output, location, size, reliability, durability, and simplicity of design. Taking into account these criteria, a design matrix has been constructed weighing the strengths and weaknesses of each design. These criteria are important in order to hold to the design norms that fit the design of the team’s WEC. Durability and reliability are important so that the user can trust it to work and remain working for a significant period. Simplicity and size are important for delightful harmony; Electro-Wave wants the design to be efficient in its use of space and minimize its impact on the environment. A simple design will help the user maintain the WEC. It is important to Electro-Wave that the final design accounts for each of these criteria.

12.1 WEC Design Options

Table 3. Design Matrix

<table>
<thead>
<tr>
<th>Design Options</th>
<th>Location</th>
<th>Size</th>
<th>Cost</th>
<th>Power</th>
<th>Noise/Visual Pollution</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overtopping</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>4</td>
<td>16.9</td>
</tr>
<tr>
<td>Oscillating Wave Surge</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>2</td>
<td>19.8</td>
</tr>
<tr>
<td>Eco Wave: Wave Clapper</td>
<td>5</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>9</td>
<td>24.8</td>
</tr>
<tr>
<td>Point Absorber</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>9</td>
<td>24.2</td>
</tr>
<tr>
<td>Oscillating Water Column</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>4</td>
<td>8</td>
<td>27.6</td>
</tr>
<tr>
<td>Attenuator</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>21.9</td>
</tr>
<tr>
<td>Submerged Pressure Differential</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>9</td>
<td>19.8</td>
</tr>
<tr>
<td>Bulge Wave</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Rotating Mass</td>
<td>7</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>21.6</td>
</tr>
</tbody>
</table>

The most important design options in this table, were the cost followed by location, size, and noise/visual pollution. These were our most important criteria because the fit the scope of the project best and fit within the design norms Electro-Wave is focusing on. The Wave Clapper by Eco-Wave and the oscillating water column were the two highest scoring options because of their small size and minimal pollution by noise and sight as well as being relatively inexpensive to build. This design matrix confirmed what Electro-Wave had been thinking throughout the design and research process.

12.1.1 Wave Dragon/Overtopping Device

This specific device is known as an overtopping WEC. Waves are driven over the top of this offshore platform into a reservoir above the water level, as seen in Figure 11. These waves are then released through turbines, creating electrical energy. Positive aspects for a WEC of this nature are the robustness of the device, that it uses lower powered waves, and that it is a rather simple design. Negative aspects for this WEC design is the size and high costs. It also adds the complication of water moving through the moving
parts, the turbine, which adds potential for problems when ice becomes an issue in the winter months. With this device being an off-shore device, there will have to be a system of subsea cables to transmit the power produced. Since size and cost will be a major challenge, the Wave Dragon was not deemed feasible for this project within the Great Lakes.

![Figure 11. Overtopping Device](image1)

**12.1.2 Oyster 800/Oscillating Wave Surge Device**

The Oyster 800 is another large WEC. This device measures 26 meters wide, and is usually placed in depths around 13 meters so that it is not fully submerged. Using this partially submerged technique means that the top of the Oyster 800 will be using the force from the crest of the wave, or the area of greatest impact with the WEC. The Oyster 800 works by means of a wave-powered pump that pushes high pressured water to an onshore turbine approximately 500 meters away as seen in Figure 12.

Advantages of this device would be that electricity is kept out of water and there are minimal underwater moving parts.

Negatives for this type of WEC would be the size, high installation costs, and the location where the device needs to be implemented (500 meters from shore). Due to the design and reliance on hydraulics and pressure, the parts and connection to shore cause the prices to rise out of the range of feasibility for Electro-Wave’s intended scale.

![Figure 12. Oscillating Wave Surge Device](image2)
12.1.3 Point Absorber

A Point Absorber is a floating device that absorbs energy through the movements at water level. This device converts the rise and fall of the buoy relative to the base into useful electrical energy. This device, as it is an offshore device, uses subsea cables to transmit power, as seen in Figure 13. This could be considered the most popular type of WEC, as it is simple, easy to implement, does not take a great amount of space, and has the potential to generate large amounts of energy from an array of point absorbers. [22] This device was going to be implemented off the coast of Oregon until problems with regulations arose. [23]

Advantages of this device include its ability to be implemented anywhere in a body of water that can be connected to the grid. As long as a subsea cable can be run, this device can be implemented in the center of Lake Michigan or Lake Superior where it is less likely to run into problems with ice.

Disadvantages occur with the design because the required components are quite expensive and the cost of connection via subsea cables also increases the farther from shore the WEC is placed. Electro-Wave is not sure how the inner components will hold during the possibility of ice around the device. The device is not easily removed, so the design will need to be built to withstand ice which will drive up the cost.

Due to cost, this design is not feasible to be built as a prototype, but as the full scale version, it may be financially feasible if it were to produce enough energy.

![Figure 13. Point Absorber](image)

12.1.4 Eco-Wave/Wave Clapper

A company called Eco Wave has developed a device called the Wave Clapper. This device has been tested on a smaller scale with waves no more than 2 feet high, as seen on their website. The Eco Wave is designed to be attached to a structure directly offshore. This design converts energy by “riding” the waves as they rise and fall, while being connected to a given structure with a robust hydraulic arm pictured in Figure 14.
component 2. Currently, the Eco Wave claims to be “cost competitive not only with the prices of other ocean energy devices, but also with wind, solar, hydro and even traditional methods for electricity production such as: oil, coal, gas and others”. [25]

Figure 14. Eco Wave Component Schematic [26]

The positive aspects for the Eco Wave device are the size, cost, accessibility, and the long life of the device. This device is also preferable for its simplistic mechanism for removing the buoy from the water, as seen in Figure 15, during extreme storms or icy conditions, which can be seen in. This is extremely beneficial for ice is a major issue for WEC in the Great Lakes. The Wave Clapper has been proven to produce energy on scales similar to the scale of the waves in the Great Lakes. It can also be built out of cheaper materials since the design rides the waves rather than using the force/impact of the waves like the oscillating water column (OWC). Some of the main mechanical components can be seen in Appendix A.

Figure 15. Wave Clapper Storm-Protection Mechanism [25]
Disadvantages to this device include the small scale that is currently implemented. They are designed to work on a small scale, so scaling them up may not provide as much gain as Electro-Wave hopes. This design also costs a significant amount between the hydraulic arms and the generator, making it over budget for the prototype that Electro-Wave will be constructing, as seen in the Budget Section, 4.3. Electro-Wave plans to look further into the possibility of using this design for large scale.

![Wave Clapper](image1)

Figure 16. Wave Clapper [25]

### 12.1.5 Oscillating Water Column (OWC)

An OWC is a device that is often fixed to the shore and uses the rise and fall of the waves to create pressure in an enclosed column of air as seen in Figure 18 below. This pressure drives the air through a turbine system, creating power, then draws air back through the turbine as the water falls. Both directions of air flow will drive the turbine the same way due to the design of the turbine blades, which can be seen in Figure 17. The actual Wells Turbine can be seen in Appendix B.

![Wells Turbine Blade Design](image2)

Figure 17. Wells Turbine Blade Design [27]

An advantage to this type of system is that the major components do not ordinarily come into contact with the water, extending the life of the WEC. The design is also very simple, containing very few moving parts.
Because of this, it can be built to be very durable and reliable keeping maintenance costs fairly low for this design. This design also gives the added benefit of being easily designed to withstand damage from ice. Since this is essentially an enclosed container in the water with a turbine at the end, the design can be optimized to reduce stress from the water and ice, as well as to promote the air flow that is required to produce energy.

One negative aspect is that the system is large and will likely need to be onshore. Building this off-shore would require a very large structure and a significantly higher cost.

The energy generated by this device will be dependent on the air flow through the turbine which will be driven by the volume change of the air which will pressurize it as it is forced through the turbine. The power output from this device can be described by the equation,

\[ P = \frac{\rho g^2 T H^2}{32 \pi} \]

Equation 1 shows that the power is based on the density, \( \rho \), the period, \( T \), and the height, \( H \) [28]. Power in this equation is given in units of power per length. This means that Electro-Wave can determine the size of OWC required to reach their target production range. Based on wave data collected from Buoys as seen in Section 13, Power Calculations.

Due to simplicity of design, fewer parts, and cheaper construction compared to other designs, this is the design that Electro-Wave will continue to pursue. Electro-Wave believes that this design fits with the design norms. It is a stable, durable design making it trustworthy and reliable. It is not a loud or bothersome device and does not have a large impact on the environment around it, promoting delightful harmony and integrity. It is also contributing to stewardship due to no emissions or pollution in the collection of energy through this device.

Figure 18. Oscillating Water Column (OWC) [26]
12.2 Material Selection Options

In the design of the WEC, the material selected to construct is extremely important. The material must be able to deal with the weather conditions of Michigan as well as the temperature range. The device will be beaten by waves constantly during its lifetime in the lake. The material will need to be durable through extended periods of time under water since this is a water application. Another huge factor in the material selection process is the price of the material. Electro-Wave is working hard to keep costs down so that the WEC can be as financially reasonable as possible. Table 4 below gives properties and costs for several materials that Electro-Wave has looked into.

Table 4. Material Data and Costs Sheet

<table>
<thead>
<tr>
<th>Material Data Sheet</th>
<th>Material</th>
<th>E (ksi)</th>
<th>Yield Strength (ksi)</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Density (lb/in³)</th>
<th>Cost ($/lb)</th>
<th>Cost ($/in³)</th>
<th>Cost ($/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel 316 [29]</td>
<td>30000</td>
<td>30</td>
<td>75</td>
<td>0.29</td>
<td>0.4 [30]</td>
<td>0.116</td>
<td>200.45</td>
<td></td>
</tr>
<tr>
<td>Fiberglass and Polyester [31]</td>
<td>72000</td>
<td>30</td>
<td>67.5 [32]</td>
<td>0.055</td>
<td>1.8</td>
<td>0.099</td>
<td>171.07</td>
<td></td>
</tr>
<tr>
<td>Wood (Douglas Fir)</td>
<td>1566</td>
<td>2.4</td>
<td>7.25</td>
<td>0.02</td>
<td>0.75</td>
<td>0.015</td>
<td>25.92</td>
<td></td>
</tr>
<tr>
<td>Aluminum 6061 T-6 [33]</td>
<td>10000</td>
<td>35-40</td>
<td>45</td>
<td>0.1</td>
<td>3</td>
<td>0.300</td>
<td>518.40</td>
<td></td>
</tr>
<tr>
<td>Carbon Steel</td>
<td>30000</td>
<td>60</td>
<td>122</td>
<td>0.3</td>
<td>0.5</td>
<td>0.150</td>
<td>259.20</td>
<td></td>
</tr>
<tr>
<td>Polyamide Nylon 6,6 [34]</td>
<td>522</td>
<td>6.5</td>
<td>10.9</td>
<td>0.04119</td>
<td>1.65 - 1.80 [35]</td>
<td>0.071</td>
<td>122.78</td>
<td></td>
</tr>
<tr>
<td>ABS [36]</td>
<td>319</td>
<td>6.03</td>
<td>5.8</td>
<td>0.0376</td>
<td>2.42</td>
<td>0.091</td>
<td>157.23</td>
<td></td>
</tr>
<tr>
<td>Concrete [37]</td>
<td>2000-6000</td>
<td>3-6</td>
<td>0.3-0.7</td>
<td>0.081-0.087</td>
<td>0.299 [38]</td>
<td>0.0098</td>
<td>16.98</td>
<td></td>
</tr>
</tbody>
</table>

From the data in Table 4 above, concrete is the cheapest material available. It has a fairly weak structure, but is extremely cheap compared to the other alternatives. Concrete is used a lot in stationary in water structures, so concrete seems like it could be a great option for a design such as the OWC. Concrete is already used in many OWC designs because of its adequate strength and very low cost.

It can be seen that by volume the next cheapest option would be to build the device out of wood. However, wood has a very low yield strength compared to other materials. Wood also does not do well sitting in water for long periods of time, a main component of WECs. Wood also is damaged fairly easily, making it a much less durable option.

The next materials analyzed were plastics, being the next cheapest. Looking at cost and strength, Polyamide Nylon 6,6 will be the plastic Electro-Wave will look further into. These plastics have the advantage of being...
much cheaper than the next cheapest option, fiberglass and polyester. Fiberglass and polyester also has a fairly low yield strength compared to stainless steel and the other materials. Electro-Wave will be looking further into the possibility of using these materials.

Stainless steel and carbon steel are the next options. Stainless steel is most commonly used in wetted parts applications, both corrosive and non-corrosive. Stainless steel is also the strongest of the options analyzed. The disadvantage is its increased cost per volume over the other options. For high quality design, stainless steel would likely be the best option because of its high strength.

Aluminum is the most expensive option Electro-Wave has considered. It costs almost double the next most expensive option. Aluminum has the advantage of being very strong like stainless steel as well as being fairly light.

In choosing a material for the final design, Electro-Wave will prioritize adequate strength and the cost. The density will likely not be a factor in the material selection but will be a necessary consideration when designing the WEC from the material.

Electro-Wave feels confident that stainless steel will be sufficient for the application. However, a large part of this project is trying to make this as financially feasible as possible. This requires Electro-Wave to look into cheaper materials. Electro-Wave is looking is continuing to look into Polyamide Nylon 6,6 and Fiberglass if the wave clapper should be selected.

Nylon 6,6 is the preferred option due to its low cost but it may not be durable enough to last as long as Electro-Wave requires. Fiberglass will be the next best option, still slightly cheaper than stainless steel, yet almost as strong as aluminum.

For the OWC design, concrete is by far preferred due to its low cost, and acceptable strength.

Estimates have been done based on history that suggest that fiberglass and stainless steel will be sufficient, but Electro-Wave must still do the calculations to prove it.
13 Power Calculations

\[ P = \frac{\rho g H^2}{8} \left( \frac{1}{2} \right) \left[ 1 + \frac{4\pi d/L}{\sinh(4\pi d/L)} \right] \frac{gT}{2\pi} \tanh(2\pi d/L) \quad \text{Equation 2} \]

The wave power potential for specific locations in the Great Lakes was calculated using Equation 2 which calculates the energy flux per meter of wave [39]. The main parameters in this equation that will change from location to location are the wavelength, \( L \), wave period, \( T \), significant wave height, \( H \), and the depth, \( d \). The wavelength is defined as the horizontal distance between two crests, wave period is the time required for one wavelength to pass a defined point, depth is defined as the distance from the lakebed to the stationary water level, and the wave height is the vertical distance between the trough and crest of a wave. Significant wave height used in the calculation is the average height of the highest 1/3 waves, historically. The significant wave height is the most important factor in analyzing the wave power potential, as it is raised to the second power.

Data used for these calculations came from the U.S. Army Corp. of Engineers “Wave Information Studies” (WIS) Program. The U.S. Army Corp. or Engineers (USACE) has 1,949 buoys throughout the Great Lakes to obtain wave data, such as significant wave height, depth of location, and wave period [40]. The USACE has been taking and archiving this data since 1979, which the team felt was more than enough data to use for analysis. The buoy locations range between 2 to 8 miles offshore were placed approximately 2 miles apart stretching the length of the coasts. Wave power potential was calculated using these buoys for the 38 locations around the Great Lakes and ranged from 1.77 to 7.18 kW/m. This data was mapped for a visual representation of where the optimum wave power is and where the best place would be for implementing WEC technology, and can be seen in Figure 19.

![Figure 19. Wave Power Potential in the Great Lakes](image)
There are many key aspects that can be interpreted from the map in Figure 19. The data shows that the northern locations on the map have a much higher potential than those on the southern portion. The map also confirms the fetch of each lake has a major impact, as the larger fetch of Lake Superior has a higher average wave power potential than the Lake Michigan locations.

Although the wave power equation is the same for all the different devices, each device will harness the energy in a different way.

For an overtopping device, the energy produced from the turbine is based on the gravitational energy on the water that is in the system. The equation is based on the mass of the water flowing through the system and the height it falls before reaching the turbine. In order to collect more water, the device should be lower so that more of the wave is captured; the higher it is, the greater distance water has to fall, so it is more effective. There is an optimization involved here that can be calculated based on a string of equations that deal with the energy output and the decreasing water volume towards the top of the wave. Extensive equations are used to determine how much water gets is collected by the device at each height.

For a point absorber WEC and the Eco wave device, the WEC tries to harness the energy in every direction of the wave as it follows the flow of the water up, forward, down, and back. These types of WECs are dependent mostly on the height of the wave because of the way that they rely on the wave energy equation.

For an OWC, Equation 1 from section 12.1.5 gives the power generated by a WEC of this type. Based on the data from the buoys as seen earlier in this section, the range of power generated by this device in the Great Lakes spans from 720 W/m in South Manitou, MI to 2930 W/m in Houghton, MI on the south side of Lake Superior where the red dot is in Figure 19. Using the wave potential energy as calculated with Equation 2, Electro-Wave has calculated an approximate 41% efficiency of the OWC.

14 Testing & Integration

Team Electro-Wave focused on the feasibility of implementing WECs in the Great Lakes region for the duration of the project proposal and feasibility study. At this point, Team Electro-Wave has deemed harnessing energy from the Great Lakes feasible so the commencement of the design work and testing can begin in February of 2015.

14.1 Research

The majority of the work conducted thus far has been research. The findings of this research can be found in the Background and Research, Federal and State Regulations and Codes, Location, Design to Resist Ice Damage, Energy Storage, Design Options (Alternatives) and the Power Calculations Sections. The research can be found in its entirety in the Works Cited section. Since wave energy is an emerging field in the alternative energy sector, there are no set standards of energy extraction like there is for solar and wind power. From the extensive research already conducted, an optimum design for Team Electro-Wave has been determined. Due to reasons stated in the Oscillating Wave Column (OWC) section on page 27, team Electro-Wave will pursue for the small scale design.
14.2 Design

The first step for the design of the OWC will be the completion of the wave power potential map seen in Figure 19. This will allow for the optimum location to be established and help to determine the dimensions for the OWC. As seen in Figure 18, the OWC is composed of the wells turbine and generator along with a cement casing. A small scale wells turbine will be purchased due to the complexity of the system. This leaves room for the complete optimization of the capture chamber. Several models will be conducted in accordance to maximum airflow, maximum wave height, minimum costs and maximum lifespan among other optimizations.

Material selection will be the next item to optimize. OWCs in industry are almost all constructed of concrete due to the inexpensive cost and high strength, properties that can be seen in Table 4. The correct cement composition will be chosen and tested for the required OWC. Once several preliminary designs are completed, design analysis will be conducted.

14.3 Design Analysis

Each of the capture chambers will be model in Autodesk Inventor to allow for Fine Element Analysis (FEA) to be conducted. This will be the most simplistic method for testing the strength of our design.

Within Inventor, Computation Fluid Dynamics (CFD) will be utilized for visualization of the air flow within the capture chamber and into the wells turbine. Optimizations will be conducted to minimize drag and maximize air flow through the turbine.

14.4 Testing

After the design analysis mentioned in Section 14.3 is completed, actual testing of the OWC can commence. Cement tests such as the slump test, depending on material used, can be conducted to acquire the desired properties. Several prototypes will be constructed for field testing. Each OWC will be placed either in a wave pool or Lake Michigan itself. The prototype will be placed in the waves for a specified amount of time to test the strength and durability of the device. Subsequently, a multimeter will be attached to the generator to acquire a power reading. From these tests, a final design will be chosen and perfected.

14.5 Hazard Analysis

The last step in the testing and integration section is the hazard analysis. This analysis will be conducted in accordance to the Federal and State Regulations and Codes Section. Team Electro-Wave will fully keep in mind the design norms set forth in the Design Norms Section, especially the item of trust. Team Electro-Wave will ensure that no harmful chemicals or materials will pollute the surrounding environment. The goal of this analysis is to identify any potential safety issues and address them by design. If any issues cannot be addressed, then instructional literature and product specific warning labels will be implemented. [41]
Return on investment calculations will be done considering the energy return of the system with the current rate of electricity, which is about $0.12/kWh. This will be the value of the system as it is evaluated for how many kW it can produce over its lifetime. The group is fairly optimistic about this because it will run non-stop throughout the lifetime of the generator so if the initial cost is fairly low, the WEC could have a reasonable ROI.

The product is a design to last at least 10 years. The WEC will have constant production over that time since waves do not stop. For an average location, the WEC can be assumed to generate at least 3 kW of power since the design is planning on a 2m length and based on equation 1, the equation for power from an OWC. This means that over 10 years there will be 150,000 kW-hr of production. At 0.12 $/kW-hr, this leads to a financial gain of approximately $18,000. The estimated cost of the device is $8,800. This leads to a huge gain from the system for customers on the coast. This gain will be offset a bit by the cost to connect to the grid and to wire it up to the grid. These assumptions are based on conservative estimates of production and effective useful time over the course of a year. Ice was assumed to prevent all production for 40% of the year to account for harsh winter months. 3 kW production was based on an approximate 4-5 kW from the design and scaled down to provide a conservative estimate that would cover more than the average location. This results in a payback period of 4.65 years.

This ROI calculation is based solely on theoretical equations. Electro-Wave plans to do testing to confirm and adjust these numbers in the future, but the design team is confident in these equations.
16 Great Lake Weather Conditions

16.1 Icy Conditions

Ice is a significant problem with using WECs in the Great Lakes, and something that needs to be taken into consideration. Depending on the WEC design chosen by the group, Team Electro-Wave believes there are a few different options available. If the design chosen is an offshore design, then it could be placed in the middle of the lake where ice does not usually occur. The problem with this option is that the farther out the WEC is from the shore, the more costly it will be to connect to the grid. Aside from just ice, the device needs to be designed to deal with cold temperatures in the Great Lakes Region that can get as low as -30°F. As Frost forms and temperatures get low, the components and materials need to hold their strength.

16.2 Wear

The structure will experience wear due to battering from waves as well as from weather. The structure must be able to withstand being battered around both by impact from waves and from being thrown around against the range of its anchoring due to wind and waves. The materials selected will be strong enough to withstand these forces.

16.3 Wind

Wind combined with wave movement could also be a problem in terms of dislodging the structure. While large waves are desirable for large power outputs, off-design dynamic overloads are not beneficial for energy capture. [25] Proper moorings must be chosen to anchor the part in place while still producing power adequately.
17 Conclusion

To conclude the project feasibility study, Team Electro-Wave has deemed that there is enough energy potential in the Great Lakes for an OWC to produce useful energy. As the project moves forward, Team Electro Wave will be conducting research and performing calculations to see what it would take to make wave energy an economically viable option compared to other forms energy sources. FEA and CFD analysis will be utilized in order to refine the OWC. With the current wave power potential ranging from 2 to 7 kW/m, our second goal of constructing a functional OWC on a small scale is achievable. The team will purchase all necessary material for the prototype where extensive testing will then take place in order to refine and optimize the prototype as needed.
18 Acknowledgments

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19 Works Cited


The accumulator is used to store the energy captured by the waves. This type of energy storage is preferable as it converts short surges of energy into a continuous power source. The accumulator has a smoothing effect to the electric power output. [43]
The hydraulic cylinders allow for the cyclical movement of the buoy. They allow the buoy to operate freely up and down while holding it in place in the horizontal direction. The cylinders can also control the buoy location in case of a storm or ice; they can be contracted to raise the buoy out of the water for an extended period of time.

The design of the actual buoy will play a pivotal role in the percentage of power that can be harnessed. The shape of the buoy will be optimized for the given location. The material for the buoy will be chosen from Table 2. This will affect the buoyancy and therefore the possible power output.
Appendix B: Oscillating Water Column (OWC) Components

Figure 23. Wells Turbine [45]

The key to the success of the OWC is the wells turbine. Without, it would not be able to harness continuous energy. The turbine will also result in the largest cost of the entire system. The only other components of the WEC will be mostly cement which is relatively cheap and very durable.