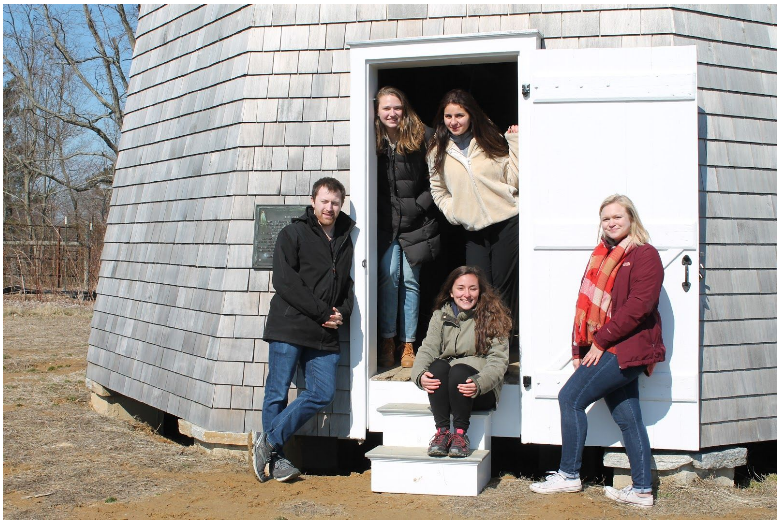
An Electro-Mechanical, Wind Energy System Design for the Historic Shelter Island Windmill

Worcester, MA 2019-2020

A Major Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science.



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Submitted To:

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Abstract

The goal of this project was to recommend design options for the implementation of an electro-mechanical system within a 210-year-old wind powered grist mill located at Sylvester Manor Educational Farm on Shelter Island, NY. Sylvester Manor Educational Farm serves its community through its dedication to historical preservation, education, and sustainability. As part of these efforts, they recently began renovating the Shelter Island Windmill so that it can produce flour as it once did back when it was built in 1810. Our team was tasked with providing design recommendations for a system that allowed the windmill to harness energy from the wind and convert it into electricity that could be used on the farm, while still allowing operation of the mechanical grist system. To determine the energy potential of the Shelter Island Windmill, we used the maxima and minima power coefficients for a four blade dutch windmill and the average wind conditions present on Shelter Island. After considering these findings, in addition to any system inefficiencies, we determined the windmill's potential energy production to be 6 kWh per day, assuming that the windmill is operational for 50% of the day. The proposed design features a three phase alternator, gearing mechanisms, power electronics, and deep cycle batteries, which allow Sylvester Manor Educational Farm to switch between operation of the mechanical grist system and the electrical system. Additionally, we built a 3 foot scale model of the windmill that included a representation of both the grist and electrical systems. This scale model will serve as an educational tool for the Sylvester Manor Educational Farm by demonstrating the history of the Shelter Island Windmill through representation of the exterior and interior grist system, as well as the concept of rotational, kinetic energy from the wind being converted to electrical energy.

Acknowledgements

Our team would like to acknowledge Sylvester Manor Educational Farm for sponsoring this project and offering their support and expertise during our visits to Shelter Island, NY. Specifically, we would like to thank Sara Gordon, Stephen Searl, Jim Kricker, and the rest of the team at Sylvester Manor Educational Farm. We would also like to thank the Shelter Island Historical Society for their help with our research and the WPI Mechanical Engineering department for financially supporting this project. Finally, our team would like to thank our advisors Harold Walker, Brian Savilonis, and James O’Rourke for the guidance they provided during the entirety of our project.

Table of Contents

List of Tables

List of Figures

Executive Summary

Over the course of this project, our team assisted Sylvester Manor Educational Farm in developing an electro-mechanical, wind energy system design for the historic Shelter Island Windmill, a 210-year-old wind-powered grist mill located on Shelter Island, NY. Specifically, our team was tasked with providing design recommendations for a system that allowed the windmill to harness energy from the wind and convert it into electricity that could be used on the farm, while still allowing operation of the mechanical grist system. In addition to the proposed system design, we calculated the energy potential of the Shelter Island Windmill at its current location on Sylvester Manor Educational Farm and built a 3 foot scale model of the windmill that included a representation of both the grist and electrical systems, which will serve as an educational tool.

Sylvester Manor Educational Farm serves its community through its dedication to historical preservation, education, and sustainability. As part of these efforts, they recently began renovating the Shelter Island Windmill located on their grounds to its original function as a grist mill. The Shelter Island Windmill, a smock style tower mill, was originally built in Southold, NY in 1810 by a team of carpenters led by the millwright Nathaniel Dominy V (Sylvester Manor, 2019). As a gristmill, it was primarily used to produce flour from grain, such as wheat, corn, rye, meslin, and provender using wind power (Hefner, n.d.). It is currently the only gristmill out of 11 built by Nathaniel Dominy to still be standing on the North Fork of Long Island (Sylvester Manor, 2019).

Our first objective was to determine the energy potential of the Shelter Island Windmill. To find this value, we used Equations 1 and 2 listed below, where Equation 1 represents the power produced and Equation 2 represents wind velocity.

$$P_m = 0.5 * \rho * A * V_w^3 * C_p * \eta_{total} \qquad \textit{Equation 1}$$

$$V_2 = V_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \qquad \textit{Equation 2}$$

Equation 2 illustrates the relationship of how wind velocity varies with height. Alpha, which varies with the terrain, was identified to equal 0.2 because the nearby terrain of the Shelter Island Windmill features low bushes with some trees, which affects the overall energy potential (Engineering Toolbox, 2008). This allowed us to find the velocity of 3.43m/s. We began the calculations for Equation 1 by finding the coefficient of performance, Cp, for the blades. We assumed that the Shelter Island Windmill was closest in structure to that of a Dutch four-arm windmill, giving us a maximum Cp of 0.2. Therefore, the sails are only catching 20% of the total wind power. Using Equation 1, the maximum potential power of the windmill without inefficiencies was calculated to be 1122 Watts. In order to increase the accuracy of our estimations, we also calculated a range of power outputs for varying coefficients of performance and blade tip speeds. The minimum power output, given a Cp of 0.01 and blade tip speed of 4.1, was 56.1 Watts and the average power output, given a Cp of 0.12 and a blade tip speed of 2, was 673.2 Watts. Additionally, we approximated the electrical system to produce between 500-1000 watts. If Sylvester Manor Educational Farm decides to integrate an electro-mechanical system into the Shelter Island Windmill during their renovation efforts, there are many different uses for the wind energy that would be harnessed and converted into electricity, such as providing electricity for the nearby greenhouse that houses various crops being grown on the farm.

Our next objective was to design an electro-mechanical, wind energy system for the historic Shelter Island Windmill. There are four possible directions for Sylvester Manor Educational Farm to move towards in regards to this windmill and wind energy projects in general; solely a mechanical system, an electrical system, an electro-mechanical system, or an additional energy source, independent of the windmill. In order to organize and assess each system design option, we created a system design analysis matrix that listed each parameter that we believed was important to Sylvester Manor Educational Farm in their decision making process. The results from the system analysis matrix showed that the electrical-mechanical system would be the best option for Sylvester Manor Educational Farm. Sylvester Manor Educational Farm already has plans to renovate the interior mechanisms and sails of the windmill. It is our recommendation that they continue to complete this process with the additional electrical system components in mind. The electrical system would be incorporated on the third floor of the windmill through connection to the windshaft. During operation, our system design allows the miller to be able to disengage either the electrical system or the mechanical system, as the inefficiencies of the existing grist system do not allow both the mechanical and electrical systems to operate at once.

Based on the design of the existing mechanical system in the Shelter Island Windmill we calculated the rotational speed, the angular velocity, and the torque for the main components of the mechanical system. Approximately 5610W of power enters the sails through the wind at an average velocity of 3.43m/s. The power generated from the sails is around 1000 W, their RPM is 10 rpm and torque is around 1000 N · m. If the system was an ideal system with no losses then the sails would transfer the equivalent values to the windshaft. The desired RPM of the brake wheel, driven by the windshaft, is around 10 rpm, and has a torque of around 1000 N · m. The wallower's RPM, driven by the brake wheel, is 20 rpm and the torque is 500 N · m. Additionally, the range for the power generated by the sails was found to be 1,000 Watts to 60 Watts, the RPM was 20 rpm to 8 rpm, and the torque was 1000 N · m to 30 N · m. The range found for the torque experienced by the brake wheel ranges from 1000 N · m to 30 N · m. The torque on the wallower ranges from 500 N · m to 20 N · m. However, the system does experience inefficiencies. Tests done on a Dutch windmill constructed in 1648 with wooden gears found that the efficiency is around 39 percent (De Decker, 2009). The power measured at the windshaft was 40 horsepower or 29,828 watts, while the power at the machines was found to be 15.6 horsepower or 11632.92 watts (De Decker, 2009). This means that two thirds of the power was lost in the system to inefficiencies (De Decker, 2009). For the windmill on Shelter Island this means the power from the wind shaft would decrease from a maximum of 1,000 Watts to 390 Watts at the lantern pinions or at the connection after the lantern pinions. Taking into account the efficiency, the torque at the lantern pinions would decrease from around 8-9 $N \cdot m$ to 3.51 $N \cdot m$ at the local maximum.

On the other hand, a general electrical design for a system that could be used at Sylvester Manor Educational Farm features an AC generator, which generates power. The power then flows through the rectifier to the charge controller. After that, electricity can either go to the load (like a refrigerator, fan, or even back to the grid) or to the batteries. If electricity goes to the batteries, then when electricity is not being generated, the load can still receive energy from what is stored in the batteries. We researched various options for these components to be able to recommend specifics in our overall electro-mechanical system design. For the electrical system design, we have provided two options. One of which is completely isolated from the grid and the other has the capability to connect to the meter. The main difference between these two designs is the featured inverter. A grid connected system will have more regulations and a higher cost of labor, however, it may allow for more versatility compared to an isolated system design. When choosing batteries for the two electrical system options there are two routes that can be taken: AGM or lithium batteries. An AGM battery bank is a little over a third the cost of a lithium battery bank, but when thinking about the cycle life of the battery banks, the lithium batteries will last 3-5 times longer. Therefore, if the farm plans to use the batteries often, then it is recommended that lithium batteries be chosen.

The efficiency of a system depends on many factors, such as the system's connection point, the RPM of the generator, and even the system's temperature, which can affect the performance of the batteries. Assuming that about 500-1000 watts of energy would enter the generator, we were able to estimate the overall efficiency and size of the system. Therefore, based on this approximation and an average efficiency of 0.71 for either system, the farm would receive about 355-710 watts of electrical power. The windmill will be producing roughly 500 watts of power when running, but will also not always be running. Here we will assume that the windmill is running about 50% of the time for a rough estimate. This means that the windmill will only be running 12 hours of the day and will, therefore, produce 6,000 watt-hours of energy per day. Over a three day period, this means the windmill will produce 18,000 watt-hours. If we use 12 volt batteries, 500 amp-hours total will be needed.

The cost savings of this new system design are projected to be about $1.4136 a day or $515.96 a year, when the windmill was estimated to only be running 50% of the time. Additionally, we determined the amount of money that would be saved by looking at Sylvester Manor Educational Farm's electricity bill for June 2019, where the cost for the 18th and 19th was $0.2356/kWh. At this rate, a payback period for the components of a battery only system using AGM batteries would be 14.7 years. For lithium batteries this period would increase to 30.9 years. With a grid connected system using AGM batteries, the payback would be 18.25 years and for lithium it would be 34.4 years. If an isolated system were implemented, less money could be spent on batteries depending on the application. If the windmill was powering something crucial than the battery bank proposed above would be more appropriate; however, if the batteries are powering something less crucial, like lights, then much fewer batteries could be used. This could be a big cost savings as the batteries are the most costly part of the system by a large margin.

Our final objective was to design and create a working scale model, including the electro-mechanical wind energy system, of the Shelter Island Windmill for Sylvester Manor Educational Farm to use for educational purposes on the farm and within the community. T Based on communication with our sponsors, we decided that the scale model that we would be constructing would have a scale of 20:1 or approximately three feet, including the height of the sails. Furthermore, it is made almost entirely of wood and demonstrates how power could be produced and harvested from the windmill without compromising its historical authenticity. Essentially, to demonstrate this one would apply a force to the sails, whether this is by hand or by a wind source. The force applied then turns the windshaft and the gears inside and the belt attached to the windshaft initiates the generator, which turns on a small light bulb. There are many ways in which Sylvester Manor Educational Farm can utilize the scale model in their efforts to educate about sustainability and the history of the Shelter Island Windmill.

As the Shelter Island Windmill is such an important symbol to Sylvester Manor Educational Farm and the rest of the Shelter Island community, it is crucial that the windmill remains a representation of the history of both the windmill itself and the surrounding community. The farm hopes to expand upon its sustainability efforts by allowing the newly restored windmill to once again produce flour for the local community and hope to explore other renewable energy projects in the future. As technology continues to adapt, society becomes more and more interested in new ways to mitigate the negative effects of climate change on our planet. Therefore, this unique project is a perfect opportunity for Sylvester Manor Educational Farm to not only renovate the existing windmill and symbol of their community to its working condition, but explore the power of renewable energy and add to their sustainability efforts.

1.0 Introduction

Over the course of this project, our team assisted Sylvester Manor Educational Farm in developing an electro-mechanical, wind energy system design for the historic Shelter Island Windmill, a 210-year-old wind-powered grist mill located on Shelter Island, NY. In the Summer of 2018, Sylvester Manor Educational Farm began renovating the foundation and exterior of the Shelter Island Windmill. In the future, the organization hopes to renovate the windmill's interior mechanisms so that it has the capability of grinding grain and producing electricity using energy harnessed by the wind. To help with this objective, our team provided design recommendations for the renovation of the interior of the Shelter Island Windmill. Our task was to provide options that supported the mill's historicity, functionality, longevity, and sustainability. The proposed design would feature a three phase alternator, gearing mechanisms, power electronics, and deep cycle batteries, which allow Sylvester Manor Educational Farm to switch between operation of the mechanical grist system and the electrical system.

During our design process we performed an analysis of the windmill's existing, historical mechanical system. Specifically, we determined wind energy potential by using the maxima and minima power coefficients and blade tip speed values for the windmill and an average wind speed of approximately 3 m/s. We found that for the windmill to be operational the rotational speed for the sails needed to range from approximately 8-20 RPM. For the sails, we found the frequency to be within 0.9-2 rad/s and the torque to be within 30-1,000 $N \cdot m$. After considering these findings, in addition to any system inefficiencies, we determined the windmill's potential energy production to be 6 kWh per day, assuming that the windmill is operational for 50% of the day. This energy could be used to power any of Sylvester Manor's facilities, such as their greenhouse or their local farm stand.

Additionally, we built a 3 foot scale model of the windmill that included a representation of both the grist and electrical systems. This scale model will serve as an educational tool for the Sylvester Manor Educational Farm to use in their museum and at events throughout the community. Specifically, it demonstrates the concept of rotational, kinetic energy caused by wind power, which is converted to electrical energy. At the same time, the history of the Shelter Island Windmill is conveyed through representation of the exterior and interior grist system originally built in 1810. As such, this unique project demonstrates how the history of wind-energy technology has evolved over the last 200 years and how outdated systems can be complemented by modern technology.

2.0 Background Research

2.1 Sylvester Manor Educational Farm

2.1.1 The Property and Its History

Sylvester Manor Educational Farm is located on Shelter Island in New York, between the North and South Forks of Long Island. Their mission is to "cultivate, preserve, and share [the] lands, buildings and stories" located on the grounds (Art & Architecture Quarterly, 2015). The location of Sylvester Manor Educational Farm on Shelter Island can be seen in Figure 2.1.1.

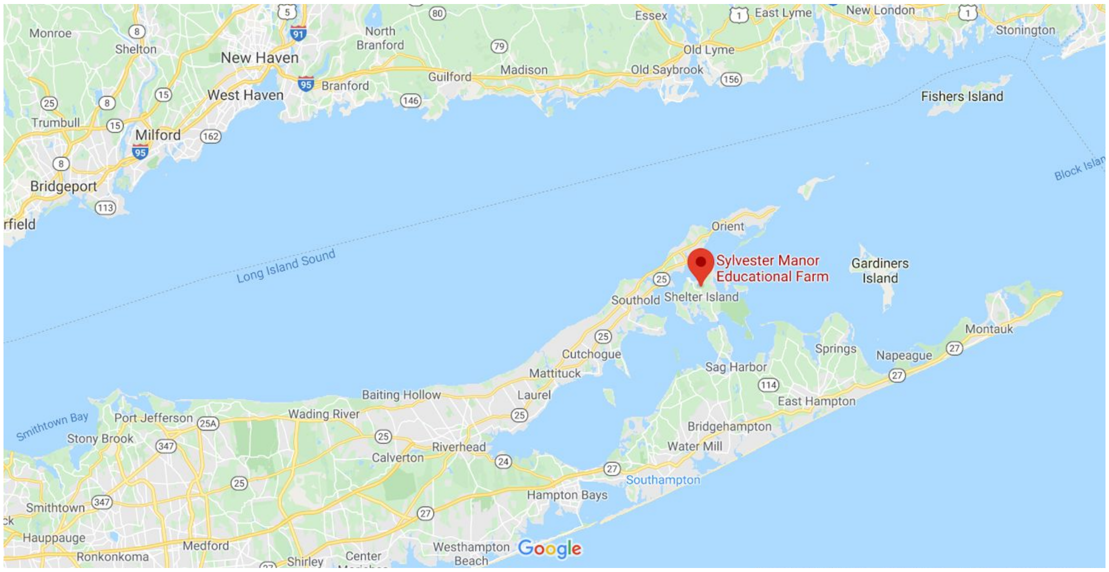


Figure 2.1.1: Map of Long Island, Featuring the Location of Sylvester Manor Educational Farm (Google Maps, n.d.)

The site of the farm was originally used as Native American hunting and fishing grounds, but became home to Sylvester Manor in 1652 where it has housed eleven different generations (Art & Architecture Quarterly, 2015). The manor began as a slaveholding plantation and has transformed throughout the eras into the farm that is located there today (Art & Architecture Quarterly, 2015). With many different inhabitants the house went through phases of change; however, it also went through many decades with no significant change, which aided in the preservation of the manor. Some of the notable changes through the eras were structural due to aesthetics and style at the time. In 1737, Brinely Sylvester constructed a new residence in which he repurposed different aspects from the original structure; however, the new structure was Georgian in style rather than the original Dutch style (Art & Architecture Quarterly, 2015). The manor was altered again around the year 1830 by Samuel Smith Gardiner and Mary Catherine L'Hommedieu (Art & Architecture Quarterly, 2015). The alterations were minor and made to fit their lifestyle. In 1908, Cornelia Horsford added to the house in colonial revival style to show her place in society and to be indicative of the time (Art & Architecture Quarterly, 2015). The last inhabitant was Andrew Fiske, who incorporated more modern touches to the manor such as a modernized kitchen (Art & Architecture Quarterly, 2015). The original sale of Shelter Island in 1651 was for over 8,000 acres, but over time, as land was distributed or sold and needs shifted, the manor property's size diminished (Art & Architecture Quarterly, 2015). A picture of the manor house located at Sylvester Manor Educational Farm is featured in Figure 2.1.2.

Figure 2.1.2: Sylvester Manor House, Shelter Island, NY (Art & Architecture, 2015)

Today the 243 acre manor maintains a variety of sites that promote its current goals of education, sustainability, and historical preservation. The land primarily consists of an open field that is filled with historical gardens, forests, and other natural landmarks that have endured since the 1600's. In addition, there are barns and sheds that have been used for storage for hundreds of years, as well as burial grounds, cultivated farmland, a greenhouse, a farmstand, a historical cannon, and of course, the Shelter Island windmill. For reference, the Shelter Island Windmill is designated as number 20 on the map featured in Appendix I, which provides a more in depth list of all the locations present on the Sylvester Manor grounds.

2.1.2 Significance and History of Windmill

The Shelter Island Windmill, a smock style tower mill currently located at Sylvester Manor Educational Farm, was originally built in Southold, NY in 1810 by a team of carpenters led by the millwright Nathaniel Dominy V (Sylvester Manor, 2019). A picture of the windmill can be seen in Figure 2.1.3. Nathaniel Dominy V, who lived from 1770 to 1852, was not only a millwright, but a cabinetmaker in a family of prominent woodworkers and clockmakers on Long Island (Hefner, 2017). The project required a team of four carpenters and local craftsmen, not including Nathaniel Dominy V, and was completed after 186 days. As a gristmill, the windmill was primarily used to produce flour from grain such as wheat, corn, rye, meslin, and provender using wind power (Hefner, n.d.). In 1840, it was purchased by Joseph Congdon and moved to the center of Shelter Island to produce flour. In 1879 Lillian Horsford, a descendant of the Sylvester family, purchased the windmill in order to preserve it and production ceased. In 1926, shortly after the windmill was put back into use during World War I, it was moved to Sylvester Manor by Cornelia Horsford (Hefner, n.d.). From then on it remained the tallest point on the property and continued to produce flour for the local community. It is currently the only gristmill out of 11 built by Nathaniel Dominy to still be standing on the North Fork (Sylvester Manor, 2019). Appendix B features the Historical American Engineering Record of the Shelter Island Windmill, which provides a more in depth look at the history of the construction of the windmill.

Figure 2.1.3: Historic Picture of Shelter Island Windmill (Sylvester Manor, 2019)

The windmill has not been in service since the 1960's; however the farm's goal is to restore it to its full functionality. The farm has stated that "The ultimate goal is to fully restore and preserve the windmill so that it can be open to the public for viewing and educational programs, and its legacy as an operational windmill revived" (Cassidy, 2018). They hope to maintain as much of its historicity as economically possible, without sacrificing its sustainability and longevity. The windmill and its long history stands as a symbol for Sylvester Manor Educational Farm and its dedication to community, education, sustainability, and history and is even featured in the organization’s logo and branding. In the future, the farm hopes to expand upon its sustainability efforts by allowing the newly restored windmill to once again produce flour for the local community. It is their vision that the flour produced could be used to make bread and other goods to be sold to the community at their farmstand on the property. Additionally, by restoring the windmill they are promoting the idea of wind as a source of energy and hope to explore and host other renewable energy projects, such as solar energy or more modern wind turbines, on their property in the future.

2.2 The History of Windmills

2.2.1 Wind Power Evolution

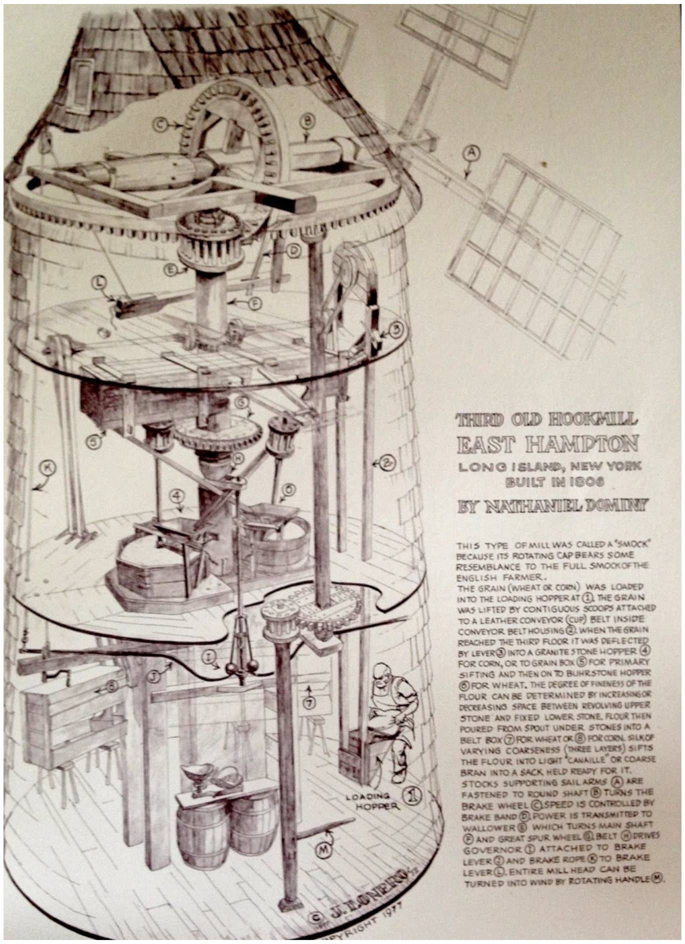
A windmill is simply defined as a machine that is powered by the wind and has been historically used for milling grain, pumping water, or generating electricity (Merriam-Webster, 2019; Shepherd, 1990). The earliest mention of wind power dates back to ancient times in places like India, Tibet, and Afghanistan, but the first established use of a windmill took place in the tenth century in Persia and is known as a vertical-axis mill (Shepherd, 1990). This idea of the vertical-axis windmill spread to other nearby countries like China. At the end of the twelfth century a new, more complex, and more efficient type of windmill emerged in Europe, known as the horizontal-axis windmill (Shepherd, 1990). The simplest type of horizontal-axis windmill is the post mill, named after the large, upright post that the mill is balanced upon (Shepherd, 1990). This invention was considered a triumph of mechanical engineering, as it was the most complex power device of medieval times (Shepherd, 1990). With a goal in mind of designing larger mills, engineers and builders were tasked with changing the design of the post mill from one where the whole body of the mill moved to face the wind to one in which only the sails, windshaft, and brake wheel moved (Shepherd, 1990). The result was a tower-mill, which was introduced in the fourteenth century. The mill was designed to be fixed to the ground, allowing it to be taller and larger in cross section (Shepherd, 1990). In England, mills made of timber were covered in white clapboarding to mimic a smock-frock and were, therefore, named smock mills. In contrast, Dutch-style mills had a brick base and a thatched body (Shepherd, 1990). Many Dutch-style tower mills still exist today in Holland (Shepherd, 1990). By the end of the nineteenth century, generating electricity through wind power became of interest and the first modern windmills or wind turbines were developed (Shepherd, 1990).

2.2.2 Restoration of Similar Windmills

There are many historic grist mills located in the United States that have been restored or preserved. The main purpose of these restorations has been to restore the functionality of the windmill, similar to the purpose behind the current restoration of the Shelter Island Windmill. However, some restorations focused more on preserving the historic authenticity of the mill, while others focused more on the functionality. The Hook Mill or the Old Hook Mill located in East Hampton, NY is an example of a similar windmill restoration project, in which both historicity and functionality were prioritized. The Hook Mill, seen in Figure 2.2.1, was built in 1806 and restored to working condition in 1939 after stopping operation in 1908. After restoration, it continued operation until the 1950's (Art & Architecture Quarterly, 2017; Hefner, 1984). Since then, the Village of East Hampton has continued to preserve the integrity and historical nature of the Hook Mill by making additional repairs in the 1980s and as recently as 2012 (Art & Architecture Quarterly, 2017). As of today, the mill seasonally remains open to the public as a museum (Hefner, 1984). Similar to the Shelter Island Windmill, the Hook Mill is also a wind-powered grist mill and smock mill built by Nathaniel Dominy V.

Figure 2.2.1: Old Hook Windmill (Marlin, 2014)

Figure 2.2.2 below provides a more in depth look at the interior mechanisms of the 1806 Hook Mill located in East Hampton. The diagram features an explanation of the journey of grain from the loading hopper (1), to the grinding stones (6), to the belts or silk meant for sifting (7,8) (Marlin, 2014). It also labels the crucial components present in the overall system such as the sails harnessing the wind (A), the brake wheel controlling the speed of the windshaft (C), and the wallower turning the main shaft (E). The mechanisms within the Hook Mill are very similar to that of the Shelter Island Windmill and, therefore, its renovation efforts can serve as a guide to the renovation of the Shelter Island Windmill.



THIRD OLD HOOKMILL
EAST HAMPTON
LONG ISLAND, NEW YORK
BUILT IN 1806
BY NATHANIEL DOMINY

THIS TYPE OF MILL WAS CALLED A "SMOCK" BECAUSE ITS ROTATING CAP BEARS SOME RESEMBLANCE TO THE FULL SMOCK OF THE ENGLISH FARMER.

THE GRAIN (WHEAT OR CORN) WAS LOADED INTO THE LOADING HOPPER AT ①. THE GRAIN WAS LIFTED BY CONTIGUOUS SCOOPS ATTACHED TO A LEATHER CONVEYOR (CUP) BELT INSIDE CONVEYOR BELT HOUSING ②. WHEN THE GRAIN REACHED THE THIRD FLOOR IT WAS DEFLECTED BY LEVER ③ INTO A GRANITE STONE HOPPER ④ FOR CORN, OR TO GRAIN BOX ⑤ FOR PRIMARY SIFTING AND THEN ON TO BUHRSTONE HOPPER ⑥ FOR WHEAT. THE DEGREE OF FINENESS OF THE FLOUR CAN BE DETERMINED BY INCREASING OR DECREASING SPACE BETWEEN REVOLVING UPPER STONE AND FIXED LOWER STONE. FLOUR THEN POURED FROM SPOUT UNDER STONES INTO A BELT BOX ⑦ FOR WHEAT OR ⑧ FOR CORN. SILK OF VARYING COARSENESS (THREE LAYERS) SIFTS THE FLOUR INTO LIGHT "CANAILLE" OR COARSE BRAN INTO A SACK HELD READY FOR IT.

STOCKS SUPPORTING SAIL ARMS Ⓐ ARE FASTENED TO ROUND SHAFT Ⓑ TURNS THE BRAKE WHEEL Ⓒ. SPEED IS CONTROLLED BY BRAKE BAND Ⓓ. POWER IS TRANSMITTED TO WALLOWER Ⓔ WHICH TURNS MAIN SHAFT Ⓕ AND GREAT SPUR WHEEL Ⓖ. BELT Ⓗ DRIVES GOVERNOR Ⓘ ATTACHED TO BRAKE LEVER Ⓙ AND BRAKE ROPE Ⓚ TO BRAKE LEVER Ⓛ. ENTIRE MILL HEAD CAN BE TURNED INTO WIND BY ROTATING HANDLE Ⓜ.

Figure 2.2.2: Hook Mill Interior Mechanisms (Marlin, 2014)

One other notable restoration was of the Jamestown Windmill in Jamestown, Rhode Island. This windmill was built in 1787 and was in operation until 1896 (Jamestown Historical Society, 2015). Figure 2.2.3 shows the Jamestown windmill during its first era of operation in 1890. The windmill is three stories tall and has an octagonal structure with a domed cap that holds the sails in place. The mill is currently operating under the ownership of the Jamestown Historical Society. Throughout the windmill's history it has survived many storms and even thieves who stole components of the windmill. Therefore, major restorations have been required every 15 to 20 years, with the final restoration occurring from 2000 to 2001. This final restoration cost over $70,000 (Jamestown Historical Society, 2014).

Figure 2.2.3: Jamestown Windmill (Campbell, 2020)

The Jamestown mill was built to function as a grist mill and can be classified as a smock mill (Jamestown Historical Society, 2014). The mill was used to grind cracked corn to produce corn meal as well as animal feed (Jamestown Historical Society, 2014). Its components, once again similar to the grist components in the Shelter Island Windmill, can be seen in Figure 2.2.4. In addition to the sails, the brake wheel, the wallower, the hopper, and the stones, as discussed with the Hook Mill, one can see that the Jamestown Windmill features a mechanism, consisting of the Y rope, Y wheel, and winding gear, for turning the cap so that the sails face the wind. Additionally, there is a mechanism for reducing the speed of the brake wheel, which consists of the brake line, brake rod, and brake band. Similar mechanisms are also present in the overall system of the Shelter Island Windmill.

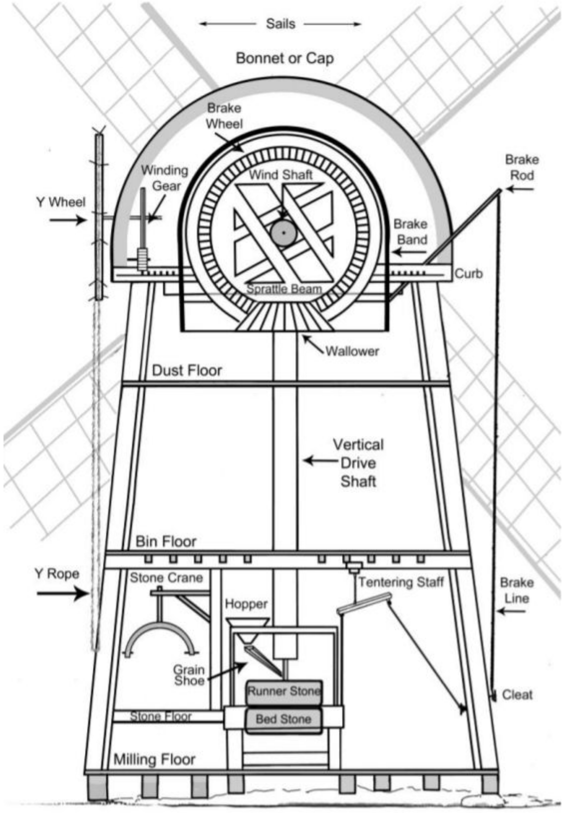


Figure 2.2.4: Jamestown Windmill Components (Jamestown Historical Society, 2014)

2.3 Components of the Shelter Island Windmill

When in operation, the Shelter Island Windmill served as a functional grist mill for many years, serving the needs of the community in which it stood. Its three stories housed the various wooden, mechanical components that allowed the windmill to produce flour from grain and other produce using wind energy. Unlike other windmills that Nathaniel Dominy built, it was constructed almost entirely of wood, including the windmill's trunnels or nails (Brennan, 2018). A picture of the Shelter Island Windmill as of 2019 can be seen in Figure 2.3.1 below.

Figure 2.3.1: The Shelter Island Windmill, 2019 (Campbell, 2019)

2.3.1. Foundation

The foundation of the Shelter Island Windmill was restored in 2018 and was raised 6 feet to allow for permanent concrete footings to be installed (Brennan, 2018; Cassidy, 2018). Traditionally, windmills rested on field stones. After renovation the mill continues to rest on field stones, but they are now anchored by the concrete footings (Brennan, 2018). Figure 2.3.2 documents the raising of the windmill's foundation during restoration.

Figure 2.3.2: Raising of the Foundation (Shelter Island Reporter, 2018)

2.3.2 Turret

The windmill also has a turret, as seen in Figure 2.3.3, which is a vertical shaft that extends from the first floor to the mill cap on the third floor. The turret's purpose is to rotate the mill cap which turns the sails so that they are facing the wind. To rotate the turret, the miller would push the bar that is attached to it on the first floor (Brennan, 2018). The turret windmill was invented in the 15th century to allow for the windmills to be larger and more efficient. Prior to this invention, post mills required the entire body to be turned when the miller desired to shift the face of the sails (Schobert, 2014). Therefore, the turret allows the structure of the windmill to be fixed, but enables the sails to be turned, allowing for a greater efficiency of the overall system because more wind energy could be harnessed, resulting in more power.

Figure 2.3.3: First Floor Turret (Campbell, 2019)

2.3.3 Grist System

When it was operational, the intended purpose of the Shelter Island grist mill was to grind grain or other produce into flour. The system components that produce the flour are split between the three floors of the Shelter Island Windmill.

The top floor of the windmill contains the components that are used to harness the power from the wind. The sails, located on the outside of the mill, but connected through the wind shaft, are to be newly renovated based upon the mill's original construction (Kricker, 2019). The largest, and most prominent feature on the third floor is the brake wheel. It is 7’ 8” in diameter, and has 60 wooden cogs. It is connected to the wind shaft, which holds the sails and is the windmill’s primary gear; it takes power from the wind and transfers it to gears below (Brennan, 2018). However, in conjunction with other components in the mill, it also allows the miller to regulate the speed of the sails and overall system (Brennan, 2018). These additional components are the jointed lever and wallower. As the miller pulls the lever, a band wraps around the outer edge of the brake wheel, causing it to slow down (Brennan, 2018). The wallower then slows down along with it, causing the rest of the gearing within the mill to also decrease in speed (Brennan, 2018). Figure 2.3.4 below shows the interaction between the brake wheel and wallower. The wallower is a lantern pinion, similar to those found in clocks, which engages with the brake wheel and is used to turn all other gears in the mill (Brennan, 2018). Lastly, there is a final gear located on the third floor that is used to transfer power to the secondary, auxiliary machinery, which rotates the bolters or sifters on the third floor (Brennan, 2018).

Figure 2.3.4 Wallower (left) and Brake Wheel (right) (Campbell, 2019)

Moving down the windmill, the second floor holds the mechanisms that cut the grain. From the third floor, the energy is transferred from the center shaft to the great spur wheel. This is the largest, centermost gear on the second floor and is supported by the mill’s main, center post. Beside the great spur wheel are two lantern pinions, one on either side. One or both of these lantern pinions can be engaged by the great spur wheel. The lantern pinions are connected to the stone nuts, also known as capstones, which spin over stationary bed stones that are encased in boxes called tuns (Brennan, 2018). Above the tuns are the hoppers which hold the grain and feed it into the enclosed case where it will be cut by the grooves in the capstones (Brennan, 2018). The cut grain falls to the first floor into the bolters. The stone crane is also located on the second floor beside the great spur wheel. This crane allowed millers to lift the stones for sharpening

(Brennan, 2018). Today the mill is missing the yoke but it would be attached to a bracket with a wooden screw and features hanging, metal bands meant to connect to and lift the stones (Brennan, 2018). The miller would then be able to turn the screw and swing the capstones to initiate sharpening. Figure 2.3.5 features the components located on the second floor.

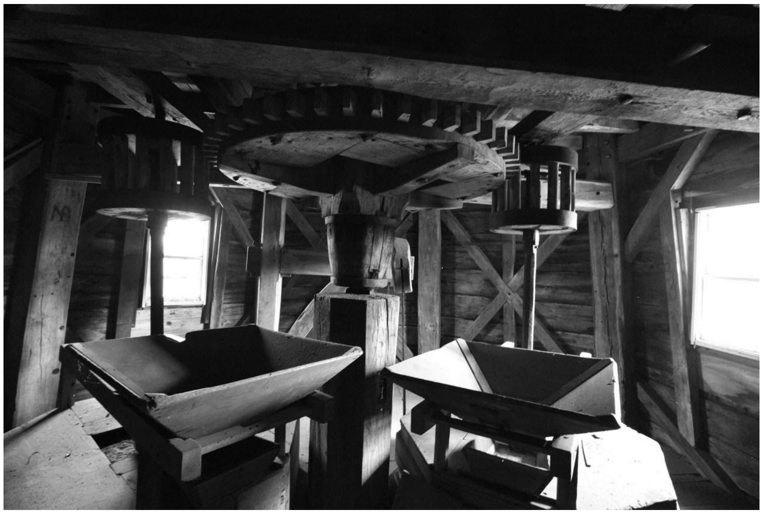


Figure 2.3.5: Shelter Island Windmill Second Floor (Walker, n.d.)

The first floor contains the centrifugal governors, which are also used to regulate the speed of the mill (Brennan, 2018). In order to prevent friction between the capstones and bed stones during high speed winds, the centrifugal governors engage in a process called 'tentering' (Llewellyn, n.d.). The three iron balls that are attached by hinges to a central axle, which is attached to the millstones, fly further outward as the speed of the mill increases (Llewellyn, n.d.). This outward movement forces a lever to lift the capstone slightly above the bedstone, so that friction is removed, along with the potential for detriment to the stones and ignition (Llewellyn, n.d.). The first floor also contains the bolters, which are very large structures that hold the grain after it has been ground into flour by the capstones. There are two bolters that take up a considerable amount of space, as they are 15 feet long (Brennan, 2018). The bolters are tilted on a downward angle from the central spindel to cause the heavier product to collect at the lower end. The bolter spins so that it can force the flour to go through a fabric shell and fall to the wooden trough (Brennan, 2018). The sifted flour can then be bagged by the miller and distributed to the community. An image of the bolters can be found below in Figure 2.3.6. Refer to Appendix C for more images of the Shelter Island Windmill taken September 28th, 2019.

Figure 2.3.6. First Floor Bolters (Campbell, 2019)

2.4 Wind Energy

2.4.1 Wind Energy Conversion

The purpose of a windmill is to take the wind's kinetic energy and convert it into power to be used for grinding grain, generating electricity, or pumping water. The wind comes in contact with the blades and creates a high pressure area on the sails which results in a force applied to the sail. This process is similar to the lift force on an airplane wing and is necessary for the functionality of both historical and modern windmills. The force applied on the sail, therefore, turns the rotor. The rotor now has rotational energy that is transferred through shafts or gears. Depending on the application, these shafts or gears will connect to some other component to then convert that rotational energy into another form. Historically, the application would be to grind grain into flour, like the Shelter Island Windmill, or pump water to be used within a community. However, if electricity is the desired output then a generator would be put in place, where the rotational energy of the rotor inside the motor is converted to electrical energy (Energy Informative, n.d.).

2.4.2 Wind Turbines

There are two common sources of wind power; windmills and wind turbines. Modern windmills are often referred to as wind turbines; however, a wind turbine is technically classified as the wheel, rotor, or blades of the overall system (Shepherd, 1990). Although both historical and modern windmill mechanisms use kinetic energy, they differ from one another in their purpose. Historical windmills, such as the Shelter Island Windmill, convert wind energy to mechanical energy in order to complete tasks like pumping water or grinding flour (Merritt, 2017). On the other hand, modern windmills or wind turbines, seen in Figure 2.4.1, produce electrical power from the wind to generate electricity. Another major difference between windmills and wind turbines is their size. Windmills are much smaller in size than wind turbines and can produce from 1 kW to 25 kW of energy, while wind turbines can produce up to 1.5 MW of energy (Kurz Industrial Solutions, 2019). This is because wind turbines are much larger in size and more efficient. Wind power is given by P= ½*density*rotor swept area*coefficient of performance*wind velocity^3*generator efficiency*gearbox bearing efficiency (Behera, 2012). Because wind turbines will have larger efficiencies, the overall wind power they produce is much larger. To generate electricity, a commercial wind turbine stands from about 30 to 100 m above the ground in order to take advantage of faster, more stable winds (Windurance, 2019). As the tip speed ratio of the blades of modern wind turbines is greater than that of a windmill, the performance coefficient also increases. Additionally, as wind energy technologies continue to adapt, companies are taking advantage of high-end blade pitch technology so that their turbines are able to stabilize and stop in dangerous or nonideal conditions. Using this advanced wind turbine blade technology maximizes cost-effectiveness and turbine life, which adds to the overall appeal of wind energy (Windurance, 2019).

Figure 2.4.1: Modern Wind Turbines (Campbell, 2018)

3.0 Methodology

3.1 Energy Potential

Our first objective was to determine the energy potential of the Shelter Island Windmill. To find this value, we used Equations 1 and 2 listed below. In Equation 1, P_m represents power produced, ρ represents the density of the air at sea level, A represents the rotor swept area, V_w represents wind velocity, C_p represents the power coefficient, and η_{total} represents the overall efficiency of the mechanical system (Sarkar & Behera, 2012). From this equation, we were able to find the amount of power produced by the wind. The average wind speed at 10 m above ground was used to estimate the average wind speed at the height of the windmill's rotor (WillyWeather, 2019). This is demonstrated in Equation 2, where V_2 is the wind velocity, V_1 is the wind velocity found from a local wind gauge, Z_1 is the height that the wind is measured at, and α is the coefficient of wind shear (Engineering Toolbox, 2008). Refer to Appendix E for the detailed calculations of the energy potential for the Shelter Island Windmill.

$$P_m = 0.5 * \rho * A * V_w^3 * C_p * \eta_{total} \qquad \textit{Equation 1}$$

$$V_2 = V_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \qquad \textit{Equation 2}$$

Conceptually, Equation 1 tells us the power that the mechanical device is receiving is from the wind flowing through a cross section of area equal to the area the sails make while spinning. C_p is the coefficient of performance of the blades. Additionally, η_{total} is the sum of the generator efficiency and the gearbox bearing efficiency (Sarkar & Behera, 2012). Equation 2 illustrates the relationship of how wind velocity varies with height. Alpha, which varies with the terrain, indicates that this is not a linear relationship. Alpha was identified to equal 0.2 because the nearby terrain of the Shelter Island Windmill features low bushes with some trees, which affects the overall energy potential (Engineering Toolbox, 2008).

We began these calculations by finding the coefficient of performance, Cp, for the blades through the graph in Figure 3.1.1. We assumed that the Shelter Island Windmill was closest in structure to that of a Dutch four-arm windmill, giving us a maximum Cp of 0.2. Therefore, the sails are only catching 20% of the total wind power. We then found data on the velocity of wind on Shelter Island through the East Hampton Airport's wind gauge. The average wind speed was 3.43m/s (WillyWeather, 2018). Using Equation 1, the maximum potential power of the windmill without inefficiencies was calculated to be 1122 Watts. For more detailed explanation behind this calculation, refer to Appendix E. The data used for wind velocity had potential to increase in accuracy, as the wind gauge was located a few miles away from the windmill. The closer the wind gauge is to the windmill, the more accurate our power estimation could be. In order to increase the accuracy of our estimations, we also calculated a range of power outputs for varying coefficients of performance and blade tip speeds. The minimum power output, given a Cp of 0.01 and blade tip speed of 4.1, was 56.1 Watts. The average power output, given a Cp of 0.12 and a blade tip speed of 2, was 673.2 Watts. For further details on these calculations, refer to Appendix H.

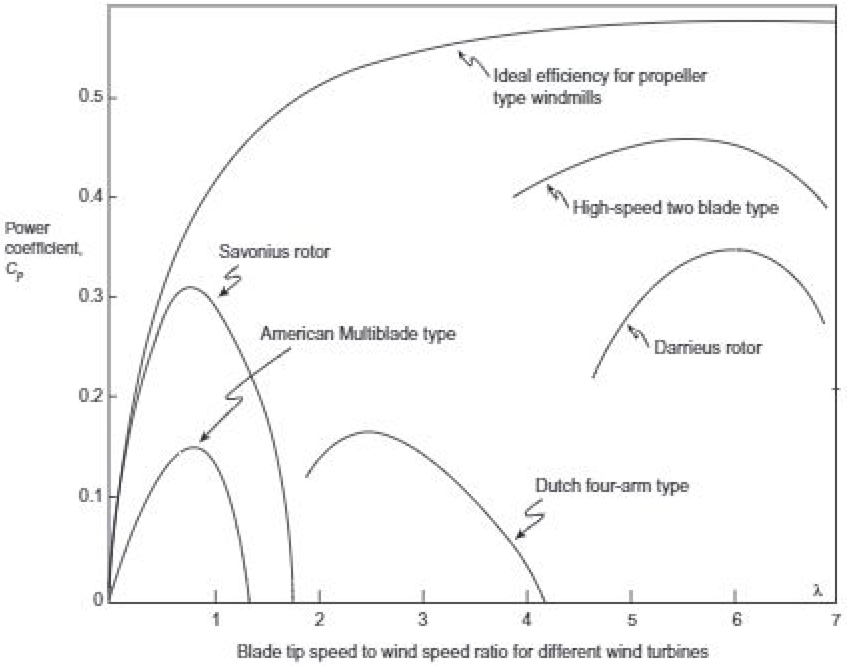


Figure 3.1.1: Coefficient of Performance vs. Blade Tip Speed Ratio for Various Blade Types (Salameh, 2014)

3.2 System Design

3.2.1 System Design Options Overview

Our next objective was to design an electro-mechanical, wind energy system for the historic Shelter Island Windmill. There are four possible directions for Sylvester Manor Educational Farm to move towards in regards to this windmill and wind energy projects in general. The first is to integrate an electricity generating system while restoring the mechanical system. The second is to simply restore the mechanical system within the windmill. A third option would be to focus solely on the electrical wind energy production, and not restore the mechanical functionality. Finally, the fourth option would be to purchase a residential wind turbine to produce energy, independent of the windmill. Sylvester Manor Educational Farm could also explore the possibility of combining option 4 with options 1, 2 or 3. Additionally, the option of adopting another form of renewable energy such as a solar power system could be explored. A discussion of the considerations of the four wind energy options can be found in the following sections. However, for the scope of this project, Sylvester Manor Educational Farm has requested an in depth exploration of the first option, which is to integrate an electrical system with the pre-existing mechanical system.

A block diagram layout of the mechanical and electrical system integration can be found in Figure 3.2.1. This is simply a labelling of each of the components that are involved in the mechanical and electrical systems. This diagram is particularly helpful for understanding the process that flows from wind energy to finished products, flour and electricity. In the following sections, the specific components and the processes will be explained in further detail.

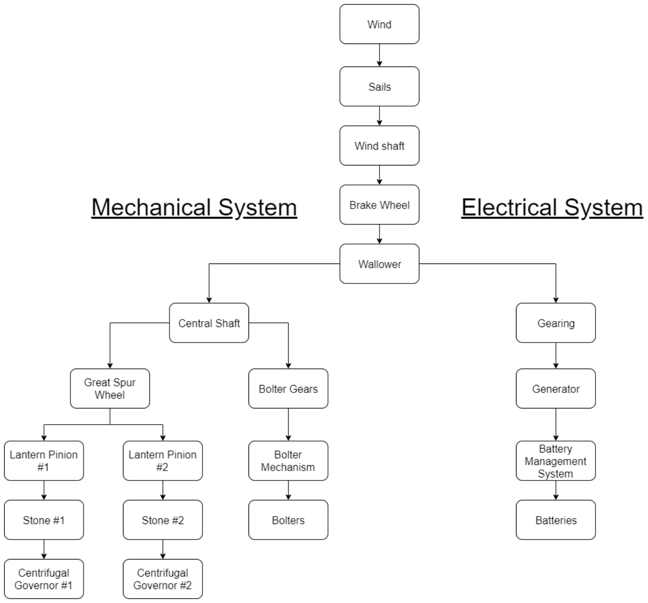


Figure 3.2.1 Block Diagram of Integrated Electro-Mechanical System

3.2.2 System Design Analysis Matrix

In order to organize and assess each system design option, we created a system design analysis matrix, shown in Figure 3.2.1. In this matrix, we listed each parameter that we believed Sylvester Manor Educational Farm considered when making decisions. Some of these parameters were size, cost, sustainability, and educational value. We then gave each parameter a weight, depending on the importance of the parameter to Sylvester Manor Educational Farm. A weight of 1 was given for those that were least important and a 10 was given to those that were most important. Each system design option was given a score in terms of how effective they were in addressing each parameter, where 1 represented a poor score and 10 represented a good score. For example, for the grist and mechanical system integration, the educational value would be the greatest, so it received a score of 10 in that category. After each system was scored for each parameter, the scores were multiplied by the weights of the parameters, and then totaled for each system to receive a final score. These values provided us with estimations for the feasibility of each system and how they aligned with the objectives of Sylvester Manor Educational Farm. Therefore, the highest score should represent the best option for addressing the objectives of Sylvester Manor Educational Farm. As our knowledge of the systems and our sponsors' priorities grew, we were able to adjust the numbers accordingly. This gave us a helpful comparison between each of the systems, and allowed us to determine the most beneficial system for our sponsor. However, it should be pointed out that these options are not mutually exclusive. The Sylvester Manor Educational Farm may choose a combination of options, such as integrate the electro-mechanical system into the windmill, as well as pursue a more modern wind turbine system.

		System Options (Ranking 1-10)			
Design Parameters	**Weight**	**Mechanical**	**Electrical**	**Electro-Mechanical**	**Wind Turbine**
Cost	5	8	6	4	2
Energy Production	5	0	7	4	10
Sustainable Materials	9	9	8	8	5
Durability of System	7	4	8	7	10
Historicity	8	10	2	7	0
Ease of Use	6	7	9	3	9
Educational Purpose	10	6	6	10	4
	Final Score:	**331**	**323**	**335**	**269**

Table 3.2.1 System Analysis Matrix

3.2.4 Electrical System Design

3.2.4.1 System Outline and Components

Figure 3.2.2 displays a diagram of a general electrical design for a system that could be used at Sylvester Manor Educational Farm. Power is generated at the alternator (also known as an AC generator) which then flows through the rectifier to the charge controller. After that, the charge controller delivers 24 Volts DC to the batteries and the load (such as a refrigerator, fan, or even back to the grid). If the batteries have been sufficiently charged, the load can still be powered even if the generator is not operating. Figure 3.2.2 conveys a more in depth explanation of what each component does and the various characteristics we looked at when selecting components.

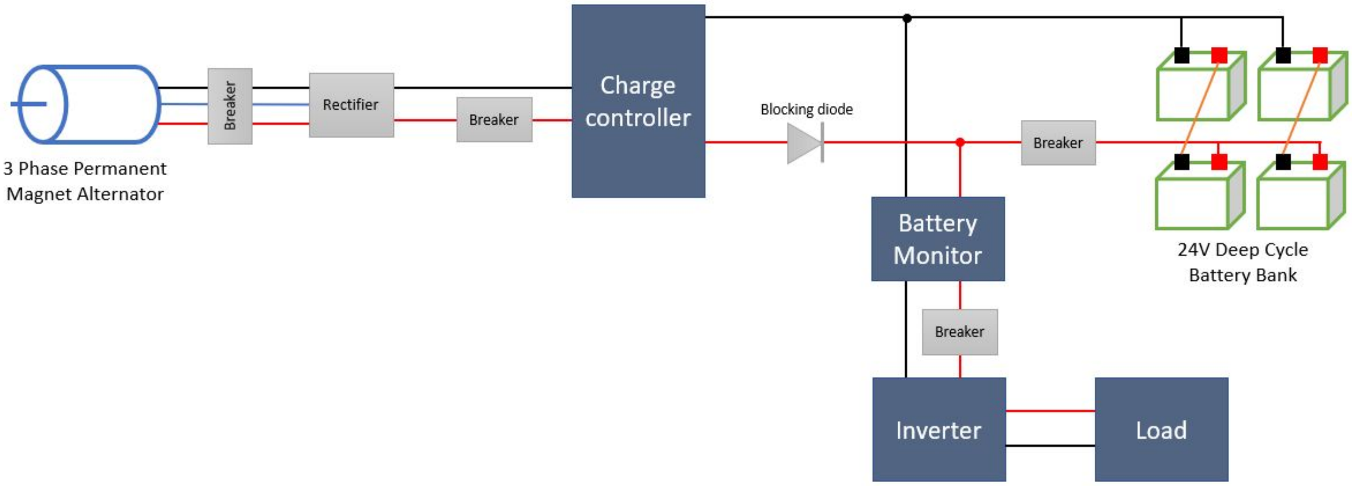


Figure 3.2.2: Diagram of Electrical Components

First, we assessed 3 phase permanent magnet alternators. The purpose of a 3 phase permanent magnet alternator (PMA) is to generate electrical power from the wind energy. There are various types of generators that could work in this system, but considering the amount of power we have estimated to be produced by the windmill, the 3 phase PMA is recommended. It is the most common and inexpensive generator used to produce electrical power in the range we are looking for. Additionally, the PMA creates 3 phase AC electrical power. However, to travel through the charge controller and into the batteries, the waveform needs to be DC. Therefore, a rectifier is required to convert the current from AC to DC.

Breakers and fuses are used to ensure safety and to protect other valuable components in the overall circuit. When the current running through a circuit is too high, the breaker or fuse will break the connection in the circuit, stopping any electricity flow. Breakers and fuses serve the same purpose, but do not operate in the same way. A fuse will burn up and need to be replaced, whereas a breaker is a switch that can connect and disconnect the circuit (Malamos, 2016). For this project, we recommend using breakers so that if they trip, the millwright can reset them.

On the other hand, charge controllers ensure that the DC output charging the batteries is at the correct voltage. In order for batteries to charge, the voltage going into the battery must be greater than the voltage of the battery itself. For example, if a battery is at 12.5 Volts, then for it to charge, you must apply more than 12.5 Volts to the battery. Charge controllers are also used to divert the power away from the batteries when they are full to help protect them (Dankoff, n.d.). For this application, there are two 12 Volt batteries in series to make a 24 Volt system.

Another component we assessed when proposing system designs, were diodes, which is an electronic device that allows current to flow in one direction. When the turbine is not running, blocking diodes protect the charge controller by stopping the flow of current from going back into the charge controller from the batteries.

Deep cycle batteries were also considered for our proposed system design. They can be used to store electrical energy in a home or farm and can be discharged and charged many times before they become ineffective (Don, n.d.). Deep cycle batteries store electricity so that there is still power even if the windmill is not turning. Depending on the application, the battery bank may need to be larger or smaller. For instance if the farm is to power something that is more essential like keeping a refrigerator running than the battery bank will need to be bigger. However, if it is just to power lights, then a much smaller battery bank may be used since it would not matter as much if the lights went out.

The most common types of deep cycle batteries on the market today are absorbed glass mat (AGM) or lithium batteries (Don, n.d.). The most important factors when determining whether to use AGM or lithium batteries were considered while finalizing a system design for the Shelter Island Windmill. In terms of capacity, AGM batteries are cheaper than lithium. For instance when looking online, a 100 ah lithium battery is generally 5 times more expensive than a 100 ah AGM battery. Therefore the initial investment for a lithium battery will be much more. Lithium batteries also have a much longer cycle life. Battle Born, a lithium ion battery brand, has lithium batteries with a cycle life of about 3000 to 5000 cycles, whereas a typical AGM battery has a cycle life of about 1000 cycles (Rushworth, 2015). AGM batteries also have a lesser depth of discharge. This means they can not be discharged as much before they need to be charged back up again. For instance, an AGM battery’s depth of discharge is generally around 50%. This means, if a battery is rated at 100 ah then only 50 ah can be used before it needs to be recharged (Rushworth, 2015). A lithium iron phosphate battery’s depth of discharge is generally about 80% to 100% (Rushworth, 2015). For charging, a Battle Born lithium battery will operate within the range of 25 to 135 degrees F, and discharge between -4 to 135 degrees F (Alternative Energy Store Inc., n.d.). A BattaMax AGM battery will operate (charge and discharge) between -4 to 113 degrees F (Windynation, n.d.). If a battery’s temperature falls outside its operating range, its performance can be significantly impacted. Lastly, The battery monitor lets the user know what capacity the batteries are at as well as other critical conditions, such as the temperature of the batteries. Some charge controllers have battery monitoring capabilities, and lithium batteries sometimes have an internal battery management system (Battle Born Batteries, n.d.). For this project we are looking at Battle Born's lithium batteries, which have a built-in battery monitor.

In addition to batteries, we also looked into inverters. The voltage that is coming from the batteries, which is 24 Volts DC, must be transformed to 120 Volts AC in order to be used for household items or be sold back to the grid. This is the job of the inverter. The inverter creates an AC voltage as either a pure sine wave or a modified AC sine wave. A graph demonstrating the difference between these two can be seen in Figure 3.2.3. The pure sine wave works with all electronics, while the modified sine wave can only be used with certain electronics. Modified sine waves are cheaper, but the electricity produced by them cannot be sold back to the grid (Beaudet, 2015). There are also two different types of inverters: regular and grid tie. The grid tie inverter takes into account the grid voltage, frequency, and phase and matches it with the signal being inverted (Rozenblat, 2017). In order to connect to the grid, the system will need a grid tie inverter instead of a standalone inverter. When deciding upon an inverter, we mainly took into account the power ratings.

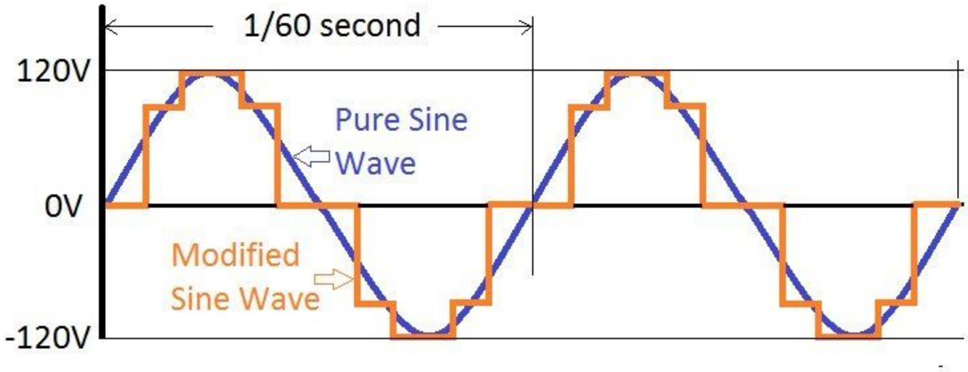


Figure 3.2.3: Difference Between Pure Sine Wave and Modified Sine Wave (Beaudet, 2015)

3.2.4.2 Batteries vs. Grid

There are two different ways that the excess energy produced can be utilized. The first is to store the energy in batteries and use them when needed and the second tie the electricity produced to the grid. For net metering, a grid tied inverter would be used which inverts the DC signal from the batteries to be the same in frequency, amplitude, and phase as the AC from the grid. The cost of labor is also greater due to the need for underground wires to be run from the windmill to where net metering occurs. This system still allows for the excess electricity produced by the windmill to be used for things that had been previously running off power from the grid.

3.2.5 Mechanical System Design

The current design of the Shelter Island Windmill is to operate as a grist mill which would grind grain into flour, if functional. The components in the windmill that produce the grain are split between the three floors. A labelled diagram of the grist system can be found in Figure 3.1.10.

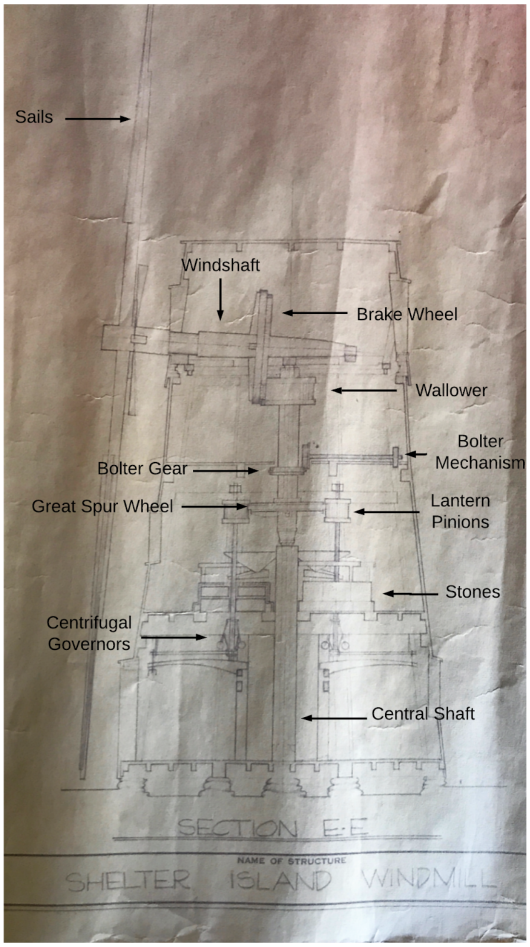


Figure 3.2.4: Labelled Diagram of Grist System

3.2.6 Mechanical Operation of the Grist Mill

The initial function of the Dominy Windmill was to act as a grist mill. This purpose is reflected in the mechanical design of the windmill. Based on the design of the existing mechanical system in the Shelter Island Windmill we calculated the rotational speed, the angular velocity, and the torque for the main components of the mechanical system. These components include the sails, windshaft, brake wheel, wallower, bolter gear 1, bolter gear 2, great spur wheel, lantern pinion 1, and lantern pinion 2. The calculations for these components are located in

Appendix H. These calculations required some assumptions. One unknown was that the sails are currently not attached to the windmill and are not functional; however, the millwright, Jim Kricker, has stated that he wants to make the sails as similar to the original ones as possible. This means that for the calculations we used the dutch windmill model for appropriate tip speed ratios and blade efficiencies. Another unknown was the wind speed on Shelter Island at the location of the windmill. The potential energy calculations were done with a wind gauge located on Shelter Island at the local airport. Detailed wind speed calculations from this data can be found in Appendix D. The wind speed for these calculations was assumed to be 3.43 m/s. We also assumed the air density to be 1.25kg/m^3.

We began our calculations with the sails and worked down to the lantern pinions. We used the equation for power which is demonstrated in our Methodology through Equation 1. The tip speed ratio and the coefficient of performance were gathered from Figure 3.1.1, which displays the coefficient of performance and the blade tip speed ratio for various blade types. For our calculations we used the minima and maxima for the tip speed ratio and the coefficient of performance. The minimum for tip speed ratio was 1, the minimum coefficient of performance was 0.01, and the maximum of the parabola from the Dutch windmill gave a tip speed ratio of 2.5 and a coefficient of performance of 0.2 (Salameh, 2014). This created a range of values for the parameters which would accurately represent and encompass the differing variables of the system. The range of numbers are reflected in Appendix H in Tables 2, 3, and 4. The calculations provided insight on the mechanics of the system and how efficiently the system could operate, which would allow for more accurate predictions of our electrical system design if it were to be added to the windmill.

The findings are outlined subsequently. Approximately 5610W of energy enters the sails through wind at an average velocity of 3.43m/s. The sails, with a performance coefficient of 0.2 which is the relative maximum for a Dutch Windmill, transfers the energy from the wind to the inside of the mill, using the wind shaft and brake wheel. The power generated from the sails is around 1000 W, their RPM is 10 rpm and torque is around 1000 N · m. If the system was an ideal system with no losses then the sails would transfer the equivalent values to the windshaft. The wind shaft has a diameter of 20 inches and drives the spinning of the brake wheel. Its desired RPM is around 10 rpm, and has a torque of around 1000 N · m. Assuming an ideal system the wind shaft would transfer the equivalent values to the brake wheel. The spinning motion of the brake wheel, which has a diameter of 90 inches and 60 teeth, spins the wallower, which has a diameter of 44 inches and 28 teeth. The wallower's RPM is 20 rpm and the torque is 500 N · m. The gear ratios can be seen in Table 1 in Appendix H. Also, it is important to take into consideration the minima and maxima of the Coefficient of Performance vs. Blade Tip Speed Ratio. The range for the power generated by the sails was found to be 1,000 Watts to 60 Watts, the RPM was 20 rpm to 8 rpm, and the torque was 1000 N · m to 30 N · m. The range found for the torque experienced by the brake wheel ranges from 1000 N · m to 30 N · m. The torque on the wallower ranges from 500 N · m to 20 N · m.

These findings are based on an ideal system that would not have any energy losses. However, the system does experience inefficiencies. Tests done on a Dutch windmill constructed in 1648 with wooden gears found that the efficiency is around 39 percent (De Decker, 2009). The power measured at the windshaft was 40 horsepower or 29,828 watts, while the power at the machines was found to be 15.6 horsepower or 11632.92 watts (De Decker, 2009). This means that two thirds of the power was lost in the system to inefficiencies (De Decker, 2009). For the windmill on Shelter Island this means the power from the wind shaft would decrease from a maximum of 1,000 Watts to 390 Watts at the lantern pinions or at the connection after the lantern pinions. Taking into account the efficiency the torque at the lantern pinions would decrease from around 8-9 $N \cdot m$ to 3.51 $N \cdot m$ at the local maximum. These results are reflected in Table 5 in Appendix H.

3.3 Scale Model

Our final objective was to design and create a working scale model, including the electro-mechanical wind energy system, of the Shelter Island Windmill for Sylvester Manor Educational Farm to use for educational purposes on the farm and within the community. The first step in completing this objective involved communication with our sponsors regarding what they wanted to accomplish with the scale model. The specifications that were communicated with us are as follows:

- The scale model must be a working model with some sort of electrical component and demonstration.
- The scale model must be interactive. In other words, the audience must be able to perform an action on the windmill in order to achieve the intended outcome.
- The scale model must achieve Sylvester Manor Educational Farm's intended educational purpose. This purpose includes representing the historicity of the actual windmill, while demonstrating basic knowledge of simple machines and wind power systems.
- The scale model must be able to be displayed on a table, while at the same time be transportable for demonstrations at locations outside of Sylvester Manor Educational Farm. In other words, the scale model cannot be too heavy or too large.
- The scale model must be large enough to demonstrate its functions to an audience.
- The scale model must have some resemblance to the actual Shelter Island Windmill.
- Ideally, the scale model would appeal to all ages and demographics to extend the intended educational objective across multiple generations.

These specifications helped us guide our decisions regarding the planning, manufacturing, and building of the scale model. Our next step involved determining the size and scale of the model. To accomplish this we first acquired the schematics of the Shelter Island Windmill during a visit to Sylvester Manor Educational Farm. These in depth schematics can be seen in Appendix A. Additionally, a Thames & Kosmos Wind Power Science Kit was purchased to identify the size of a scale model of a wind turbine also used for educational purposes (Amazon, 2019). A picture of the constructed wind turbine model can be seen below in Figure 3.3.1. The size of this particular scale model of a modern wind turbine was 3 feet tall.

Figure 3.3.1. Completed Thames & Kosmos Wind Power Science Kit (Campbell, 2019)

With knowledge of the actual size of the Shelter Island Windmill and the size of a model of a modern wind turbine, we decided that the scale model that we would be constructing would have a scale of 20:1 or approximately three feet including the height of the sails. This size was confirmed with Sylvester Manor Educational Farm during a phone call to update them on the project. After deciding on the size of our scale model and assessing all of the available options for materials and manufacturing resources we were able to determine the expenses we would need to construct the scale model, which came out to be approximately $130. With a budget provided by the Mechanical Engineering Department of $1250, we had plenty of resources to accomplish this objective. This budget, along with our expected expenses can be seen in Appendix F. This budget reflects our decisions to use plywood as our main material and laser cutting as our main manufacturing technique, rather than 3D printing, to add to the resemblance factor in relation to the actual Shelter Island Windmill. To assist in the process of laser cutting, we decided to create a Solidworks model of the scale model and convert the necessary files to scalable vector graphics. A view of this Solidworks model can be seen below in Figure 3.3.2.

Additionally, a close up view of each Solidworks component within the assembly is pictured in Appendix G.

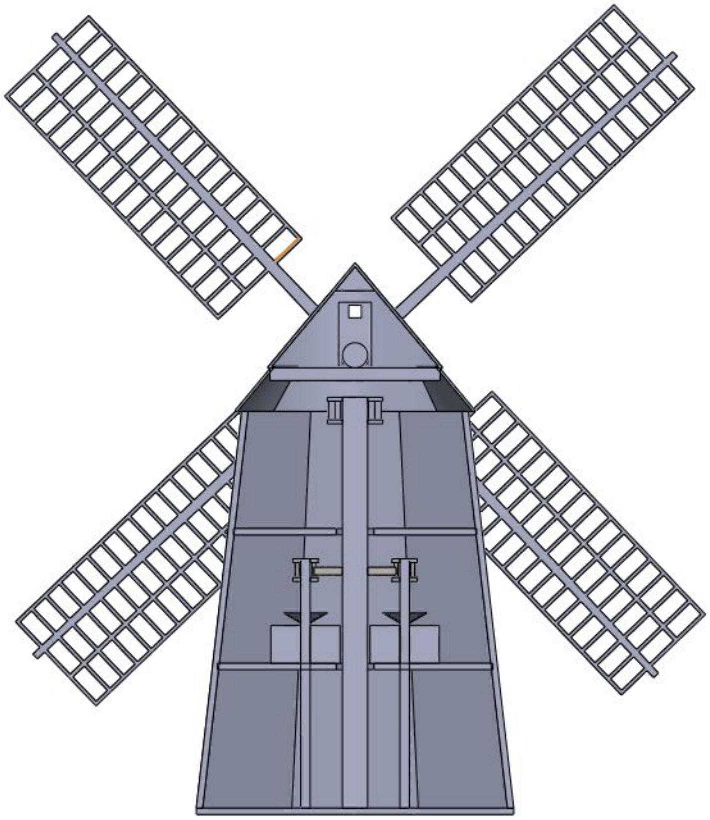


Figure 3.3.2: Solidworks Assembly of Scale Model

The electrical portion of the scale model features a similar design to the electrical portion of our electro-mechanical system design. An additional gear was added to the windshaft that rotates along with the sails, windshaft, and brake wheel. A small belt was attached to the gear and then to the generator. The generator allows the mechanical energy from the wind to be converted to electrical energy that allows a small light bulb to turn on. The stronger the wind or force on the sails, the brighter the light will be from the light bulb. Using our existing knowledge on mechanical and electrical systems and the gathered information above, we were able to construct a working scale model of the Shelter Island Windmill, while keeping the specifications and educational objective of our sponsors in mind.

4.0 Results

4.1 Energy Potential

The system that would be present in the Shelter Island Windmill is relatively small compared to the world of power generation. Therefore, the system design and component selection will be different from that of a large wind farm and resemble closer to that of a residential setup. In section 3.1 we approximated that Sylvester Manor's windmill would generate an average of 1122 Watts of power. However, this value is the maximum average because we did not take into account the inefficiencies of the gears and other system components that are involved before the generator. Thus we approximated the electrical system to produce between 355-710 watts. If Sylvester Manor Educational Farm decides to integrate an electro-mechanical system into the Shelter Island Windmill during their renovation efforts, there are many different uses for the wind energy that would be harnessed and converted into electricity. These various uses are as follows:

- To provide electricity for the nearby greenhouse that houses various crops being grown on the farm.
- To provide electricity for the nearby farm stand that provides various goods to the community.
- To power interior or exterior lights on the windmill itself that would need to be newly installed.
- To power outdoor lights used for various events held at Sylvester Manor Educational Farm.

Additionally, we recommended that Sylvester Manor Educational Farm purchase a wind gauge to assess the wind present at the location of the Shelter Island Windmill. The wind gauge that we recommended and that was purchased by the farm was the Davis 6152 Wireless Vantage Pro2 and 6510USB WeatherLink. This wind gauge transmits wireless data up to 1000 feet, stores up to 6 months of data, is solar panel or battery operated, and its electronics come housed in a weather-resistant shelter (Scientific Sales Inc., 2020). The wind gauge will provide our sponsors with a more accurate understanding of the wind present on the farm and how the wind speeds vary over the day, month, or year. If Sylvester Manor finds that there is more energy potential at the windmill than we found, the electrical system will need to be reconfigured to fit the appropriate size. This project could be given to another WPI MQP team in the future.

4.2 System Design

Our findings for the system design of the windmill are described below. The four possible options described earlier were analyzed. The options being: to restore the mechanical functionality, to adopt an electrical generating system as well as restore the mechanical system, only implement an electrical generating system, and lastly to purchase another source of renewable energy. The result from Table 3.2.1 System Analysis Matrix showed that the electrical-mechanical system would be the best option for Sylvester Manor Educational Farm. The mechanical system, electrical system, and wind turbine respectively came next. Based on the results of Table 3.2.1 an electro-mechanical system design was explored for integration into the existing Shelter Island Windmill. However, Sylvester Manor does have the option to explore integrating multiple systems, given that one alone does not satisfy their needs. They may consider implementing the electro-mechanical design as well as a more modern clean energy system. For the sake of this project, we were tasked with exploring the design for the electro-mechanical system.

4.2.1 Mechanical System

The mechanical system present in our proposed electro-mechanical system design would preserve the historical aspects of the grist system already present in the Shelter Island Windmill. Sylvester Manor Educational Farm already has plans to renovate the interior mechanisms and sails of the windmill. It is our recommendation that they continue to complete this process with the additional electrical system components in mind. The electrical system portion of the overall system design would be incorporated on the third floor of the windmill through connection to the windshaft. A figure of the overall electro-mechanical system within the Shelter Island Windmill can be seen in Appendix J. During operation, our system design allows the miller to be able to disengage either the electrical system or the mechanical system. In other words, when it is our sponsor’s desire to use the grist system rather than the electrical system they would be able to engage the interior mechanisms and have the capability of producing flour. The inefficiencies of the existing grist system do not allow both the mechanical and electrical systems to operate at once.

4.2.2 Electrical System

For the electrical system design, we have provided two options. One option is completely isolated from the grid and the other has the capability to connect to the meter. The components associated with both the isolated system and the grid connected system can be seen below in Tables 4.2.1 and 4.2.2, respectively.

Component	**Name Brand**	**Cost**
Generator	Freedom II, Missouri Wind and Solar: 24V	$582.33
Breaker 30 amp (3, one per wire)	ZOOKOTO 12-24V 30 Amp ATV Resettable Circuit Breaker Fuse holder Metal Stud Bolt 30A	$19.17
Charge Controller + Inverter	All In One Sky440 Charge Controller Board with Optional Inverter: 24V	$899.00
Battery monitor	Victron BMV-712 Battery Monitor *Not needed for lithium batteries*	$206.55
Breaker 63 amp (2 of these)	2P 250V Low-voltage DC Miniature Circuit Breaker For Solar Panels Grid System din rail mount(63A), Breaker DC Circuit Amp Solar Double Pole	$67.17
Batteries	30 AGM Batteries from Windy Nation 15 Lithium Batteries from Battle Born	$5,700 or $14,250
Miscellaneous cost	6 gauge wire Heat shrink, crimps, other	$69.99 + $100
	Total Cost (AGM batteries) **Total Cost (lithium Batteries)**	$7,644.21 $15,987.66

Table 4.2.1: Isolated System Component Options

Component	**Name Brand**	**Cost**
Generator	Freedom II, Missouri Wind and Solar: 24V	$582.33
Breaker 30 amp (3, one per wire)	ZOOKOTO 12-24V 30 Amp ATV Resettable Circuit Breaker Fuse holder Metal Stud Bolt 30A	$19.17
Charge Controller	All In One Sky440 Charge Controller Board with Optional Inverter: 24V	$849.00
Grid tied inverter	OutBack Power VFXR Hybrid Grid-Tie Inverters: 24V	$1,867.38
Battery monitor	Victron BMV-712 Battery Monitor	$206.55

	Not needed for lithium batteries	
Breaker 63 amp (3 of these)	2P 250V Low-voltage DC Miniature Circuit Breaker For Solar Panels Grid System din rail mount(63A), Breaker DC Circuit Amp Solar Double Pole	$67.17
Batteries	30 AGM Batteries from Windy Nation 15 Lithium Batteries from Battle Born	$5,700 or $14,250
Miscellaneous cost	6 gauge wire Heat shrink, crimps, other	$69.99 + $100
	Total Cost (AGM batteries) **Total Cost (lithium batteries)**	$9,461.59 $17,805.04

Table 4.2.2: Grid Connected System Component Options

The main difference between these two designs is the featured inverter. If the load is not connected to the grid then a regular inverter will be sufficient. However, if it is connected to the grid you will need a grid-tied inverter, which matches the phase of the grid frequency with the signal that the inverter is generating. In the battery isolated system design, the inverter is a modified sine wave, therefore, making it very cheap. However, the system is limited with its applications. A heater for a greenhouse, like the one located on Sylvester Manor Educational Farm, is an example of an application suitable for an isolated system design with a modified sine wave. On the other hand, a grid connected system will have more regulations and a higher cost of labor. However, it may require less batteries and allow for more versatility compared to an isolated system design.

When choosing batteries for the two electrical system options there are two routes that can be taken: AGM or lithium batteries. In section 3.2.4.1, the differences between AGM and lithium batteries are discussed along with their most important features. One thing to note is that the battery banks in the chart above are of equivalent capacity. However, an AGM battery bank is a little over a third the cost of a lithium battery bank, but when thinking about the cycle life of the battery banks the lithium batteries will last 3-5 times longer. Lastly, the lithium batteries chosen have a built-in battery management system (BMS), which means there is no need to spend money on an extra one, therefore lessening the price even more. If the farm plans to use the batteries often, then it is recommended that lithium batteries be chosen because of these reasons. Table 4.2.3 below presents a list of all the chosen components, including the batteries, featured in our proposed system design and any additional information to allow for better understanding.

Both AGM and lithium batteries have temperature constraints that may be of concern at the windmill. To protect the batteries, a BMS is used so that if it gets too hot or cold the battery will disconnect so that it can not be charged or discharged at these times. These batteries can be stored at colder temperatures than they can operate at however they will not be able to be charged or discharged. In the case of Sylvester Manor Educational Farm it is likely that the temperature will drop below the batteries operating temperature. When this happens the BMS would disconnect the battery so that it could not be charged or discharged (Real Goods, 2019). Thus if it is not imperative that they be used constantly they should be able to be stored in the windmill or the greenhouse.

Component	**Specifications**
Freedom II, Missouri Wind and Solar: 24V	● Rated up to 2000 watts ● Outputs 24 Volts at 150 RPM ● Comes with bridge rectifier
All In One Sky440 Charge Controller Board with Optional Inverter: 24V	Charge controller ● High amp rating: 440 amps, 10,000 watts ● Comes with dump resistors Optional inverter ● 2500 Watts ● Modified Sine wave ● Input: 20 to 30 volts ● Output: 120 VAC, 60 Hz ● Operating range -15C to 55C
OutBack Power VFXR Hybrid Grid-Tie Inverters: 24V	● Input: 24V ● Continuous power rating: 3500 VA\ ● Maximum output current: 50 amps AC RMS ● Rated temperature range -20 C to 50 C ● Listing and Certification: UL 1741, CSA C22.2 No. 107.1, UL 1778 Annex FF
Victron BMV-712 Battery Monitor *Not needed for lithium batteries*	● Built in Bluetooth communication ● Comes with sensor to record temperature of batteries

2P 250V Low-voltage DC Miniature Circuit Breaker For Solar Panels Grid System din rail mount(63A), Breaker DC Circuit Amp Solar Double Pole	● Rated up to 250V ● Trips at 63 amps
30 AGM Batteries from Windy Nation 15 Lithium Batteries from Battle Born	AGM ● Capacity: 100ah ● Nominal voltage: 12 volts ● Max discharge current 1200 amps (5 seconds) ● Max Charge current: 30 amps ● Weight: 67 lbs ● Discharge temperature: 5 to 122 degrees F ● Charge temperature: 32 to 104 degrees F ● Depth of discharge: 50% ● Cycle life: not specified, assumed 1000 as its an AGM battery Lithium ● Capacity: 100ah ● Nominal voltage: 12 volts ● Continuous current rating: 100 amp ● Surge current: 200 amps (30 sec) ● Weight: 31 lbs ● Operating temperature: -4 to 160 degrees F ● Discharge temperature: 25 to 135 degrees F ● Depth of Discharge: 100% ● Cycle life: 3000-5000
6 gauge wire Heat shrink, crimps, other	● 6 gauge wire 100 feet

Table 4.2.3: Chosen Components of System Design and Specifications

4.2.2.1 Efficiency

The efficiency of a system depends on many factors, such as the system's connection point, the RPM of the generator, and even the system's temperature, which can affect the performance of the batteries. Below are the estimated efficiencies present within the two electrical system options. The efficiencies of the proposed isolated system is presented in Table 4.2.4, while the efficiencies of the grid connected system is presented in Table 4.2.5. This information was discovered through extensive research on various products and communication with the companies selling those products. Assuming that about 500-1000 watts of energy would enter the generator, we were able to estimate the overall efficiency and size of the system. Therefore, based on this approximation and an average efficiency of 0.71 for either system, the farm would receive about 355-710 watts of electrical power.

Component	**Efficiency**
Generator	0.85 (Missouri Wind and Solar)
Charge Controller + Inverter	0.9 (Missouri Wind and Solar)
Battery monitor	0.99 (assumption)
Breaker 60 amp	0.99 (assumption)
Breaker	0.99 (assumption)
Batteries	0.99 (Buchmann, 2019)
Miscellaneous cost	0.99 (assumption)
Total efficiency	**0.72**

Table 4.2.4: Isolated System Component Efficiencies

Component	**Efficiency**
Generator	0.85 (Missouri Wind and Solar)
Charge Controller	0.95 (Missouri Wind and Solar)
Grid tied inverter	0.92 (from product details)
Battery monitor	0.99 (assumption)
Breaker 60amp	0.99 (assumption)

Breaker	0.99 (assumption)
Batteries	0.99 (Buchmann, 2019)
Miscellaneous cost	0.99 (assumption)
Total efficiency	**0.70**

Table 4.2.5: Grid Connected Component Efficiencies

Using this information, we were able to size the battery bank. First off, we established the days we wanted to have power without the windmill turning, also known as the days of autonomy. We assumed 3 days of autonomy because 3-5 days of autonomy is generally accepted when using solar. Although this is not a direct comparison, it is a helpful assumption that involves another form of renewable energy (Bas, 2010). The windmill will be producing roughly 500 watts of power when running, but will also not always be running. Here we will assume that the windmill is running about 50% of the time for a rough estimate. This means that the windmill will only be running 12 hours of the day and will, therefore, produce 6000 watt-hours of energy per day. Over a three day period, this means the windmill will produce 18000 watt-hours. If we use 12 volt batteries, 500 amp-hours total will be needed. Our calculations can be seen below in Equations 3, 4, and 5.

$$500\ watts\ *\ 24\ hours\ *\ 50\%\ =\ 6000\ watt-hours/day \qquad Equation\ 3$$

$$3\ days\ of\ autonomy\ *\ 6000\ watt-hours/day\ =\ 18000\ watt-hours \qquad Equation\ 4$$

$$18000\ watt-hours\ \div\ 12\ volts\ =\ 1500\ amp-hours \qquad Equation\ 5$$

For AGM batteries, the depth of discharge (DOD) is generally 50% which means it is not ideal to discharge them past 50% of their capacity. Therefore, if we have an AGM battery rated at 100 amp-hours, the usable amp-hours is only 50. Windy Nation sells 12 volt 100 amp-hour batteries for about \$190. Below, Equation 6 was used for calculating the cost of a battery bank using AGM batteries.

$$\frac{1500\ amp-hours}{(100\ amp-hours\ *\ 50\%\ DOD)} = 30\ batteries\ \rightarrow 30\ batteries * \$190\ =\ \$5700 \qquad Equation\ 6$$

Sizing for lithium batteries is more simple because their DOD is much higher. Battle Born lithium batteries have a depth of discharge of 100% (Alternative Energy Store Inc., n.d.). Therefore, you'll need 15, 12 Volt 100 amp-hour lithium batteries to have the appropriate size for this system. Equation 7 below was used for calculating the cost of a battery bank using AGM batteries.

$$\frac{1500\ amp\text{−}hours}{(100\ amp\text{−}hours * 100\%\ DOD)} = 15\ batteries\ \rightarrow 15\ batteries * \$950\ =\ \$14,250 \qquad Equation\ 7$$

These costs were estimated with the assumptions that the windmill will be running 50% of the time and that we will need 3 days of autonomy. If the windmill is running more than 50% of the time, then the battery bank will need to be bigger and if the windmill is running less than 50% then a smaller battery bank may be used. Similarly, if more or less days of autonomy are needed the battery bank should be increased in size, proportionally to the days needed.

4.2.2.2 Additional Costs, Payback Period, and Savings

There will most likely be some additional costs associated with installing the electro-mechanical system design into the Shelter Island Windmill other than the system components. To complete the rest of the isolated battery system, a carpenter will be needed to bolt down the generator at the top floor of the windmill. Additionally, a gear will need to be attached to the main wind shaft to allow for the belt to connect with both the windshaft and the generator rotor. It is estimated that this additional cost will come to approximately $500 to $1000 depending on the length of the job, as a general purpose carpenter charges about $25/hour. An electrician will also be needed to install the electrical wiring of the system and connect it to whatever purpose Sylvester Manor Educational Farm has chosen as their end goal. The electrician will need to ensure everything is safe and up to code. It is estimated that this job will also cost between $500 to $1000, as electricians are paid about $75 an hour. Lastly, if Sylvester Manor would like to connect to the grid they will need to work with renewable energy contractors to make sure that everything is up to code and that it is correctly connected to the meter. Wind turbines at this low of power are not generally connected to the grid so it is difficult to assess the price.

The cost savings of this new system design are projected to be about $1.4136 a day or $515.96 a year. However, this calculation originates from the size of the battery bank where the windmill was estimated to only be running 50% of the time. Additionally, we determined the amount of money that would be saved by looking at Sylvester Manor Educational Farm's electricity bill for June 2019, where the cost for the 18th and 19th was $0.2356/kWh. Based off of our prior calculations we believe the windmill would produce about 6 kWh a day which equates to $1.4136 per day. At this rate, a payback period for the components of a battery only system using AGM batteries would be 14.7 years. For lithium batteries this period would increase to 30.9 years. With a grid connected system using AGM batteries, the payback would be 18.25 years and for lithium it would be 34.4 years. This is all under the assumption that nothing breaks or needs to be replaced and that energy prices do not change.

One of the areas that Sylvester Manor Educational Farm can save a lot of money in the process of installing this new system would be with the batteries. If the farm decides that they would like to go with the isolated battery design, they can reduce the number of batteries that they will need. Right now the battery bank is sized for three days of autonomy, however, this could be decreased depending on what the electricity is used for and how critical it is that it be powered. For instance, if it were just supplemental heating of the greenhouse and there was a back up heater, the windmill wouldn't need many batteries at all, which would greatly reduce the expenses. Another area to save would be in regards to labor. If Sylvester Manor Educational Farm could find tradespeople willing to donate their time or businesses willing to donate materials and potentially even system components, the cost on this project would be greatly reduced.

4.2.2.3 Simulations and Waveforms.

Below is the schematic of how the electrical system will be set up. Figure 4.2.2.3.1 shows the proposed electrical components. The elements inside the blocks are not what is used commercially as that information is proprietary; however, the waveforms accurately depict how the system should work. This system was simulated for when the generator is producing 24 volts.

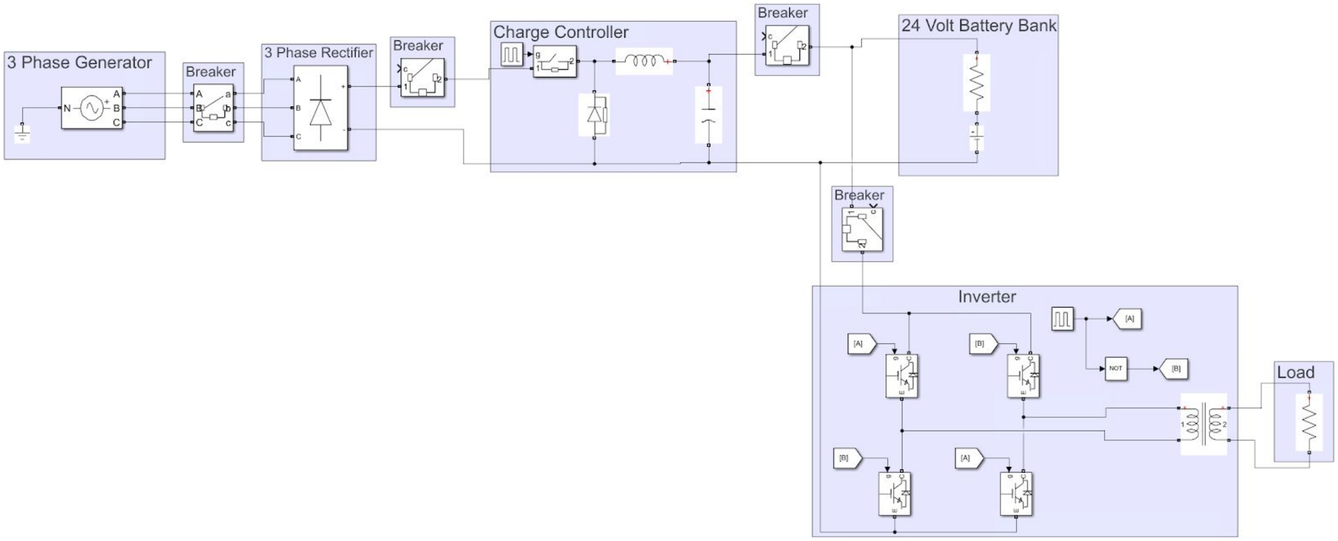


Figure 4.2.2.3.1: Electrical system layout

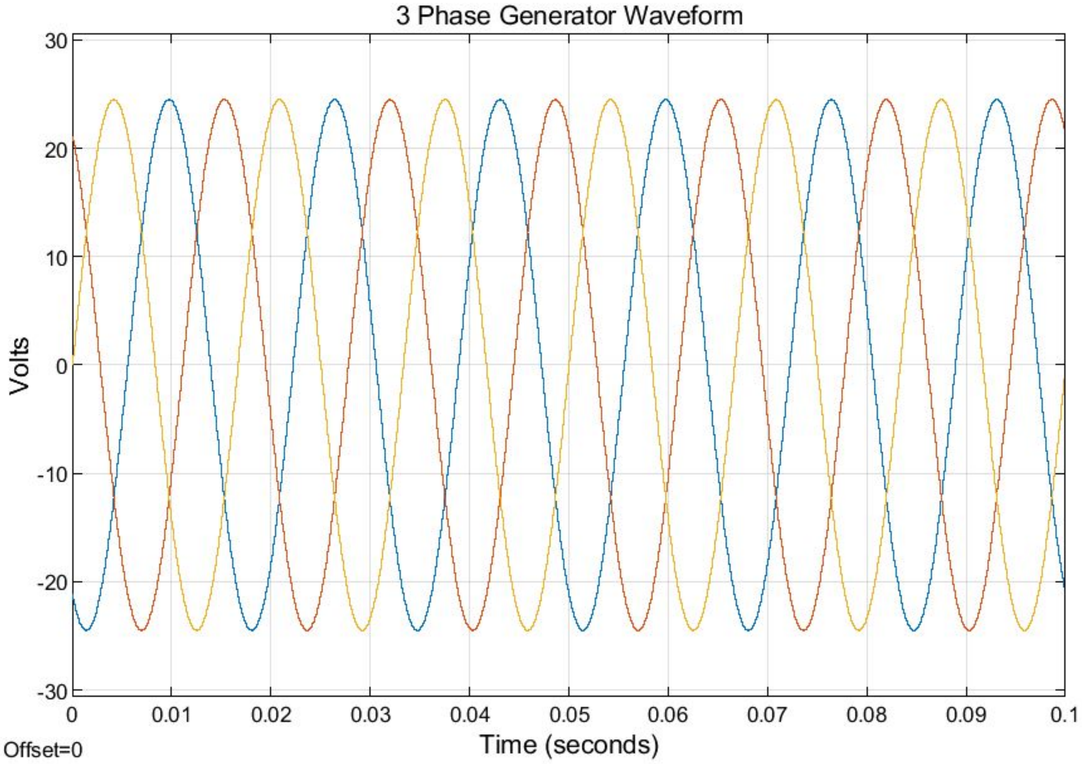


Figure 4.2.2.3.2: Three phase generator voltage waveform

The 3 phase generator will have 3 wires that output 3 different voltage waveforms with 120 degree phase shift differentiating all of them.

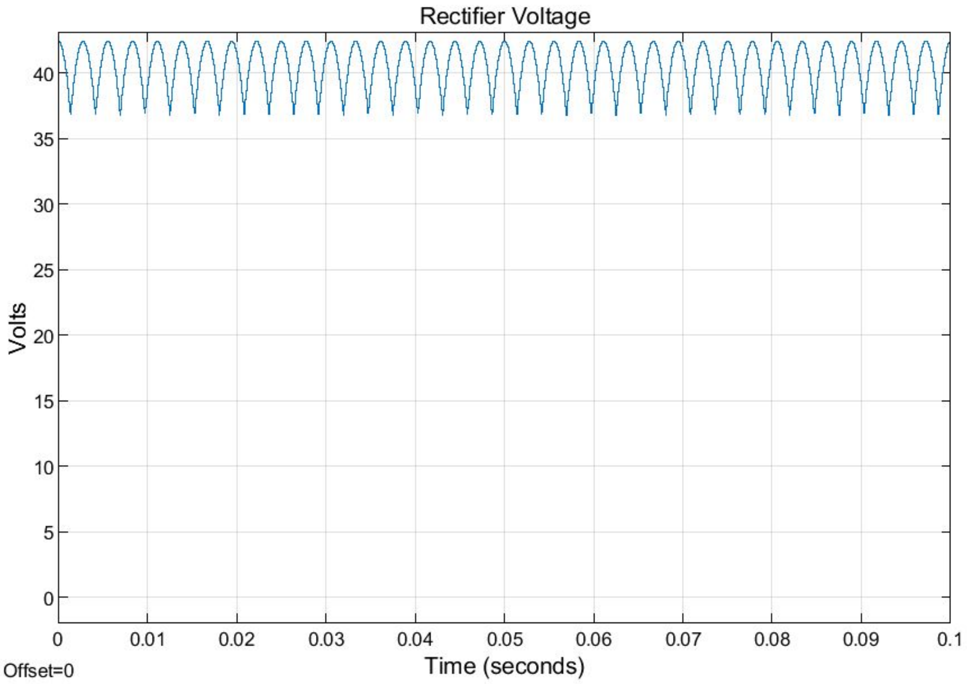


Figure 4.2.2.3.3: Rectifier Voltage

After the electrical power has transferred through the rectifier the voltage should be around 39 volts and oscillate between a few volts above and a few volts below. This system is manufactured to handle variations in wind so all of these components should be able to manage fluctuation in the system due to sensitive gears.

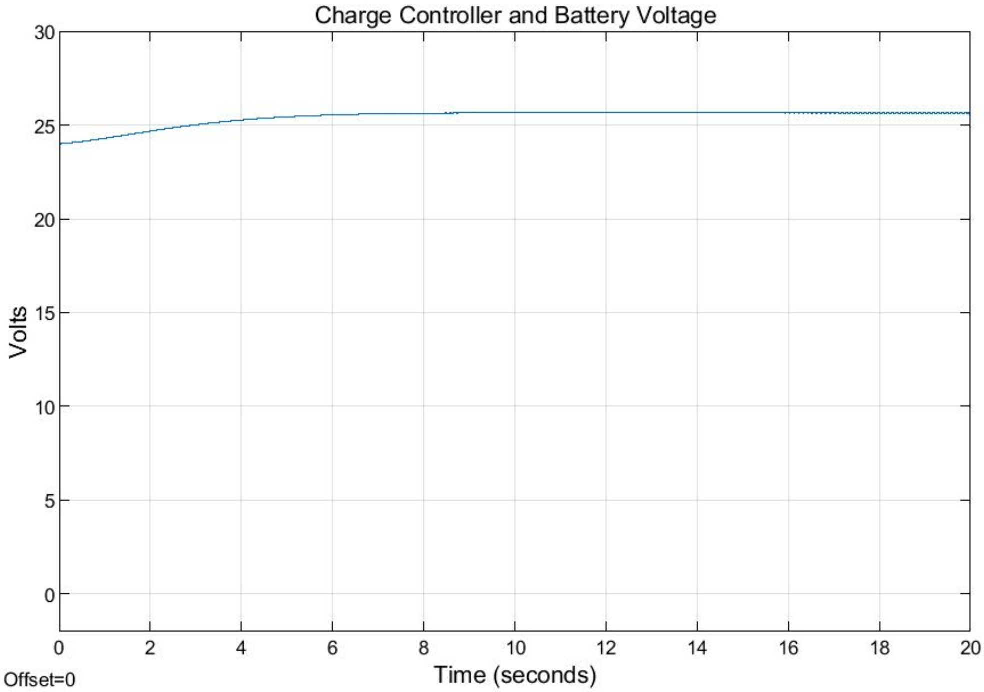


Figure 4.2.2.3.4: Charge controller and battery voltage

Once the electrical power has transferred through the charge controller, the voltage will be stepped down to around 26 volts DC, allowing the system to charge the batteries. Since the charge controller and batteries are in parallel, they will have the same voltage waveform.

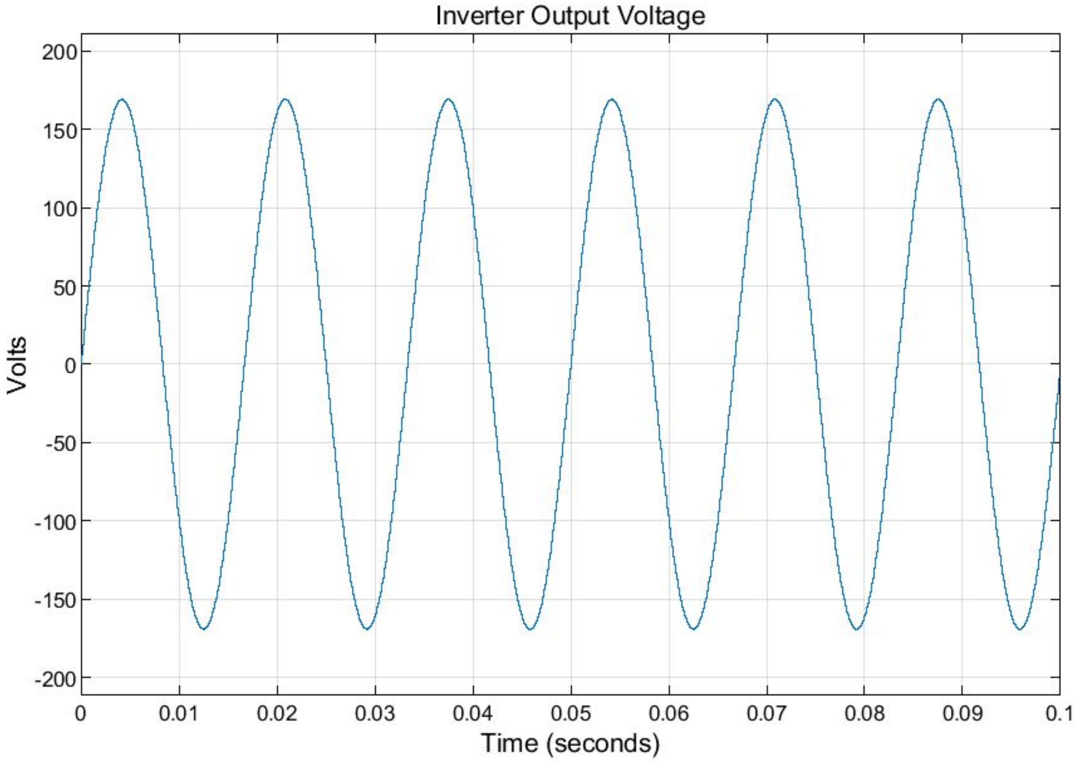


Figure 4.2.2.3.5: Output voltage of electrical system

Lastly, the inverter will output an AC voltage of 120 volts rms at a frequency of 60 hertz. Depending on the type of inverter the electrical signal will either be a pure sine wave or a modified sine wave.

4.2.2.4 Coupling the Electrical System to the Windmill

It is proposed to connect the pre-existing system to the generator via a large gear on the wind shaft with a V shaped groove cut into it. Then to have a belt that connects the large gear on the wind shaft to the generator gear, and to then anchor the generator to the floor. Missouri Wind and Solar uses this type of set up for hydro power but mentioned that it will also work for this application as well. Additionally, we ran calculations to ensure that the belt would not break under this load and found that the belt will have a factor of safety of at least 6 based on our estimates.

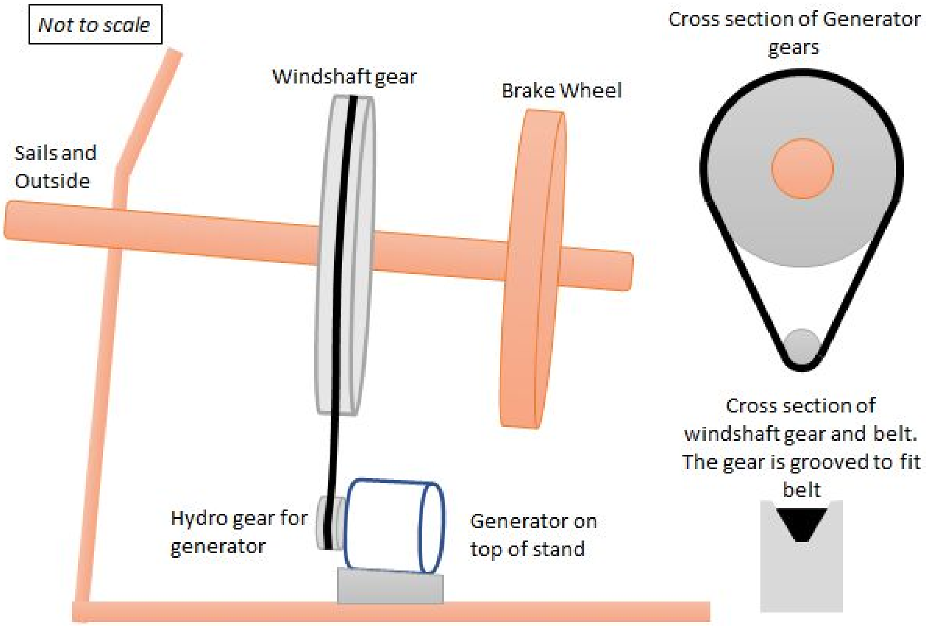


Figure 4.2.2.4.1: Electrical system connection diagram

Gear ratio

For the generator to run correctly there needs to be a gear ratio between the generator gear and the windshaft gear. The size of gearing ratio depends on the systems starting revolutions per minute and the corresponding desired revolutions per minute of the generator. In this system, we recommend that the gearing ratio is designed so that the cut in velocity corresponds to the RPM of the generator that outputs battery bank voltage (24 volts). Below are the system of equations to determine what the wind shaft gear diameter should be. R is the sail radius which is 8.5 meters and $RPM_{BatteryV}$ is the RPM of the generator to attain battery voltage as the output for this generator which is about 133 RPM. λ and $V_{cut\ in}$ are the tip speed ratio and the cut in velocity of the windmill, respectively, and these can be found experimentally using the wind gauge.

$$GR = \frac{R * RPM_{BatteryV}}{\lambda * V_{cut\ in}} \qquad Equation\ 8$$

$$Wind\ shaft\ gear\ diameter = GR * Generator\ gear\ diameter \qquad Equation\ 9$$

To determine the cut in velocity, the farm will need to use the wind gauge and determine at what wind velocity the windmill starts turning. Then to find the tip speed ratio the farm will want to record the wind velocity (V_{wind}) and the revolutions per minute of the windmill while it is running. Once that is obtained, the equation below can be used. For this equation, V_{wind} should be in meters per second.

$$\lambda = \frac{RPM*2\pi*8.5}{60*V_{wind}} \qquad Equation\ 10$$

4.2.2.5 Torque and Power

The equations below illustrate the relationship between RPM, voltage, torque, and power. PF represents the power factor of the generator and this value can range from 0.5-0.84 based on the load applied. From these equations, we found that when rotating at 133 RPM, about 50 Watts of power is produced. At 480 RPM, the power is about 940 Watts which approximates the specs given on the generator. Therefore at higher speeds the generator will produce exponentially more power than at lower speeds.

$$\tau = \frac{90}{(RPM)\pi} * 0.04 * V^2 * PF \qquad \textit{Equation } 11$$

$$P = \tau * \omega \qquad \textit{Equation } 12$$

4.2.2.6 Additional Considerations

There are several additional topics that should be addressed before and when installing the electrical generation component of the electro-mechanical system design into the Shelter Island Windmill. Firstly, we caution the use of the generator after grinding grain because the electrical sparks from the generator could cause a potential fire. Next as noted earlier, batteries generally do not like to work in below freezing weather or above 100℉. The battery management system will help protect the batteries from the effects of extreme temperatures, however, sustained temperatures above or below ambient conditions will affect the batteries cycle life and/or capacity (Real Goods, 2019). Another thing to note is that these batteries have a life cycle that causes them to deteriorate over time and will need to be replaced. Depending on the type of battery and the amount of use, the battery life will vary. Lastly, Aquion has a new battery technology where they make their batteries out of saltwater, so that it is more eco-friendly and non-harmful for the environment. We have not been able to find a price on these batteries, but they may be willing to work with Sylvester Manor Educational Farm, as they share similar missions. The downside to these batteries is that their energy density does not have a high current discharge rate. Therefore, the bank may need to be sized to accommodate the desired discharge rate rather than the capacity needs. Lastly, there will be additional electrical codes that Sylvester Manor Educational Farm will need to abide by that may alter the design slightly. The electrician and a renewable energy contractor should be up to date about these codes and regulations and how they apply to Sylvester Manor Educational Farm.

4.3 Scale Model

Using all of the knowledge gathered on the Shelter Island Windmill, we were able to successfully construct a working scale model, while keeping the specifications and educational objective of our sponsors in mind. An image of our final scale model can be seen in Figure 4.3.1 and Figure 4.3.2 below. The scale model is made almost entirely of wood and is 3 feet in height. The purpose of the scale model of the Shelter Island Windmill is to demonstrate how power could be produced and harvested from the windmill without compromising its historical authenticity. Essentially, to demonstrate this one would apply a force to the sails, whether this is by hand or by a wind source. The force applied then turns the windshaft and the gears inside and the belt attached to the windshaft initiates the generator, which turns on a small light bulb. Some of the pertinent features of the scale model to achieve our sponsor's specifications include:

- A working electrical system featuring a generator that turns on a lightbulb when the sails and windshaft rotate.
- A working brake wheel and wallower which spins the main shaft.
- Realistic representation of the interior mechanical mechanisms, including the windshaft, the brake wheel, the wallower, the lantern pinions, the stone boxes, the bolter, and the main shaft.
- Hinges to allow for the back side of the windmill to open up and show the interior of the model on all three floors.
- A removable windmill cap to show the interior of the model on the third floor.
- Removable sails to allow for easy transport of the model.
- Cloth attached to the sails to allow the sails to catch more wind.

Figure 4.3.1: The Exterior, Front View of the Scale Model

Figure 4.3.2: The Interior, Back View of the Scale Model of the Shelter Island Windmill

To accompany the scale model, we have also created an educational poster to help Sylvester Manor Educational Farm with their efforts to educate through demonstration of the scale model. The poster, which can be found in Appendix K, features a short history of the Shelter Island Windmill, an overview of wind energy and renewable energy and an explanation of how the scale model works. Additionally, a connection of the scale model to the actual windmill is made along with an overview of what the energy produced from the windmill could be used for on the farm.

There are many ways in which Sylvester Manor Educational Farm can utilize the scale model and its accompanying poster in their efforts to educate about sustainability and the history of the Shelter Island Windmill. First, they can utilize the scale model directly on their farm to educate visitors on the history of the Shelter Island Windmill as well as how they hope to renovate it. Additionally, they can speak to the importance of renewable energy and sustainability both on the farm and in the world in a time where climate change is such a controversial topic that needs to continue to be acknowledged and mitigated. The scale model can either be located in the manor house or in the windmill itself. Secondly, they can further the message and importance of the Shelter Island Windmill within the community by traveling with the scale model to local schools, libraries, or other events. The portability of the scale model will allow Sylvester Manor Educational Farm to further their mission and hopefully allow the Shelter

Island community to get more excited about their history and the potential for more local sustainability efforts. Lastly, Sylvester Manor Educational Farm could utilize the scale model in their fundraising efforts for the overall farm and the renovation of the windmill. Due to the Shelter Island Windmill having a large visual presence for the farm, the scale model could accompany our sponsors to any fundraising events in order to attract more attention and support.

Conclusion

After approximately 6 months, our team was successful in assisting Sylvester Manor Educational Farm in developing an electro-mechanical, wind energy system for the historic Shelter Island Windmill. In this report, we provided design recommendations for the renovation of the interior of the Shelter Island Windmill that supported the mill's historicity, functionality, longevity, and sustainability. The proposed design features a three phase alternator, gearing mechanisms, power electronics, and deep cycle batteries, which allow Sylvester Manor Educational Farm to switch between operation of the mechanical grist system and the electrical system. During our design process we performed an analysis of the windmill's existing historical mechanical system and determined the windmill's potential energy production to be 6 kWh per day, assuming that the windmill is operational for 50% of the day. This energy can potentially be used to power any of Sylvester Manor's utilities, such as their greenhouse or their local farm stand. Additionally, we were able to build a 3 foot scale model of the windmill that included a representation of both the grist and electrical systems. This scale model can serve as an educational tool for the Sylvester Manor Educational Farm to use in their museum and at events throughout the community and demonstrate the concept of wind power being converted to electrical energy, as well as the history of the Shelter Island Windmill.

As the Shelter Island Windmill is such an important symbol to Sylvester Manor Educational Farm and the rest of the Shelter Island community, it is crucial that the windmill remains a representation of the history of both the windmill itself and the surrounding community. Often, historical buildings like the Shelter Island Windmill have become forgotten and disregarded. On the other hand, as technology continues to adapt, society becomes more and more interested in new ways to mitigate the negative effects of climate change on our planet. Therefore, this unique project is a perfect opportunity for Sylvester Manor Educational Farm to not only renovate the existing windmill and symbol of their community to its working condition, but explore the power of renewable energy and add to their sustainability efforts. In other words, by implementing an electro-mechanical, wind energy system into the windmill during their renovation efforts, the Shelter Island Windmill will become an even more powerful symbol and educational tool within the community.

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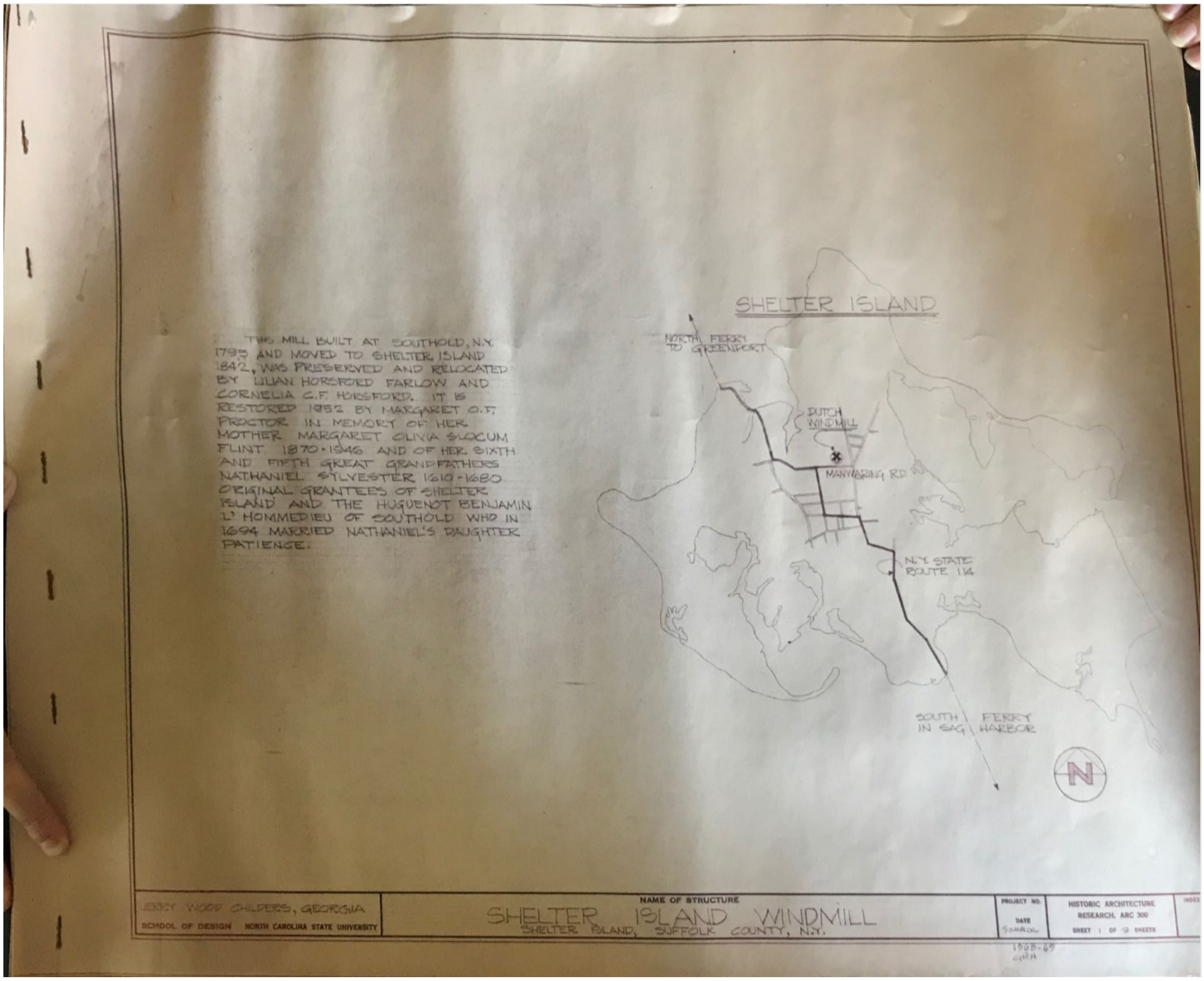
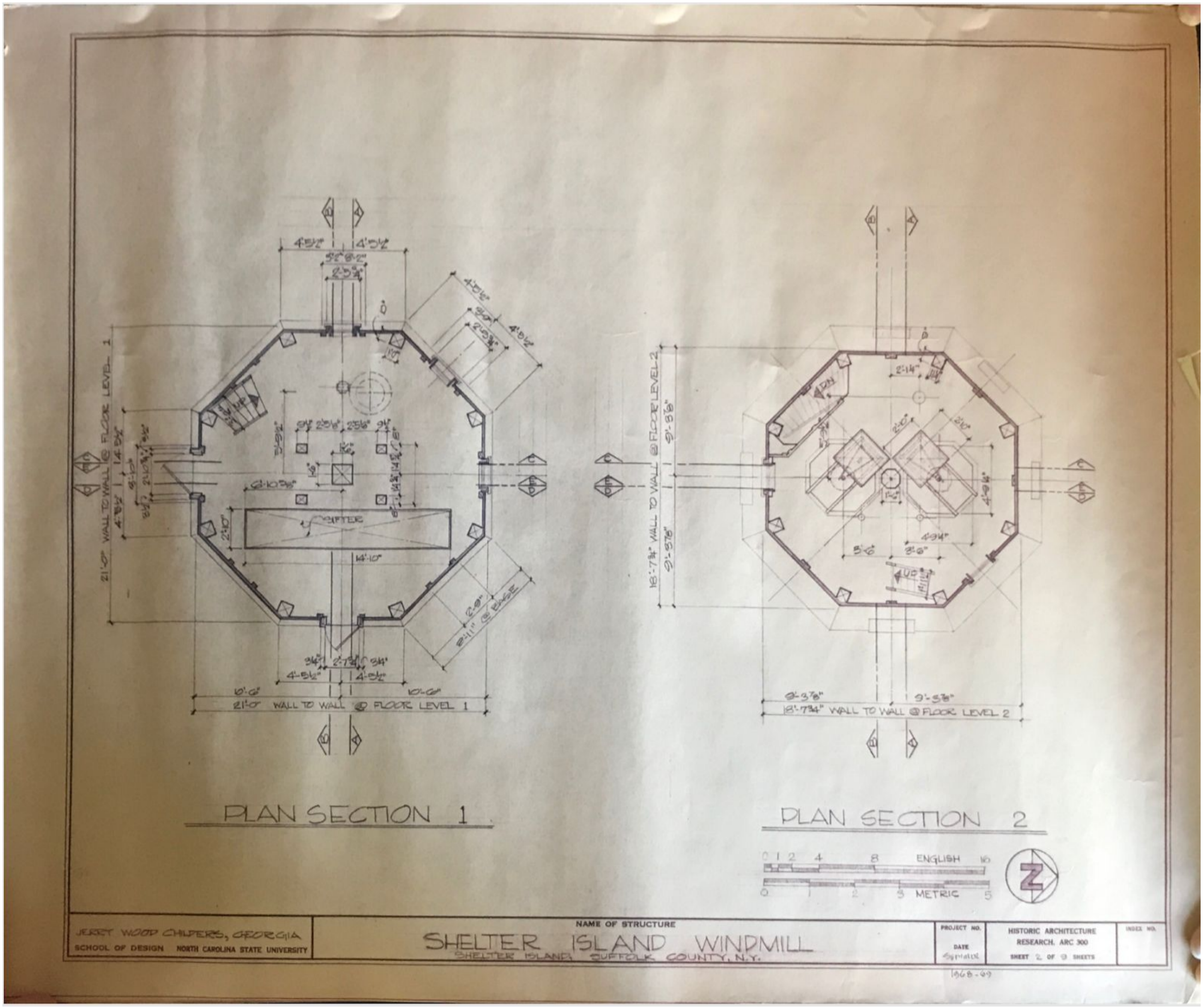
Appendix A: Schematics of Shelter Island Windmill

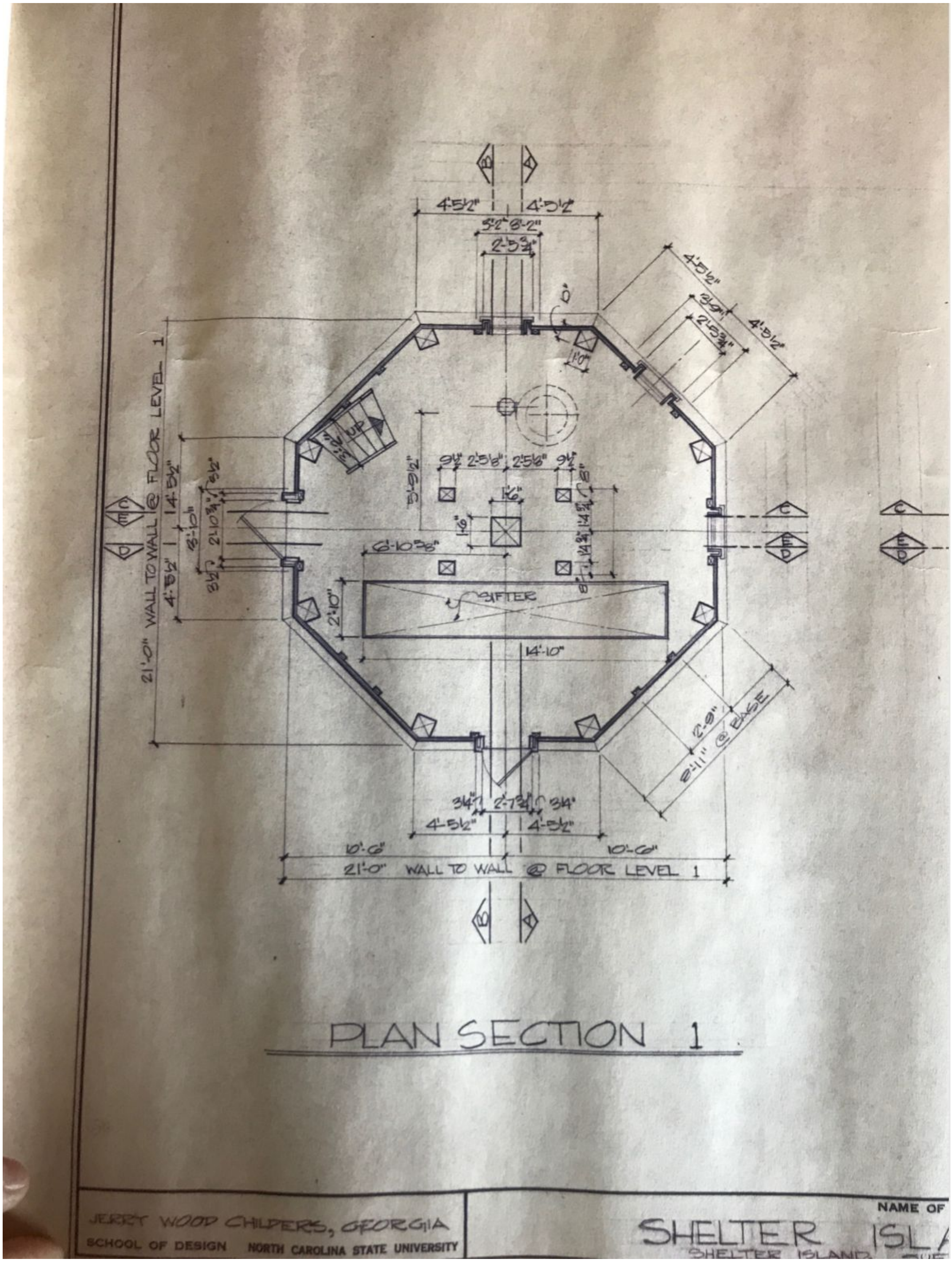
This appendix contains the schematics of the Shelter Island Windmill provided by Sylvester Manor Educational Farm. The schematics were drawn by Jerry Wood Childers in the Summer of 1968 as his senior architectural project at North Carolina State University.

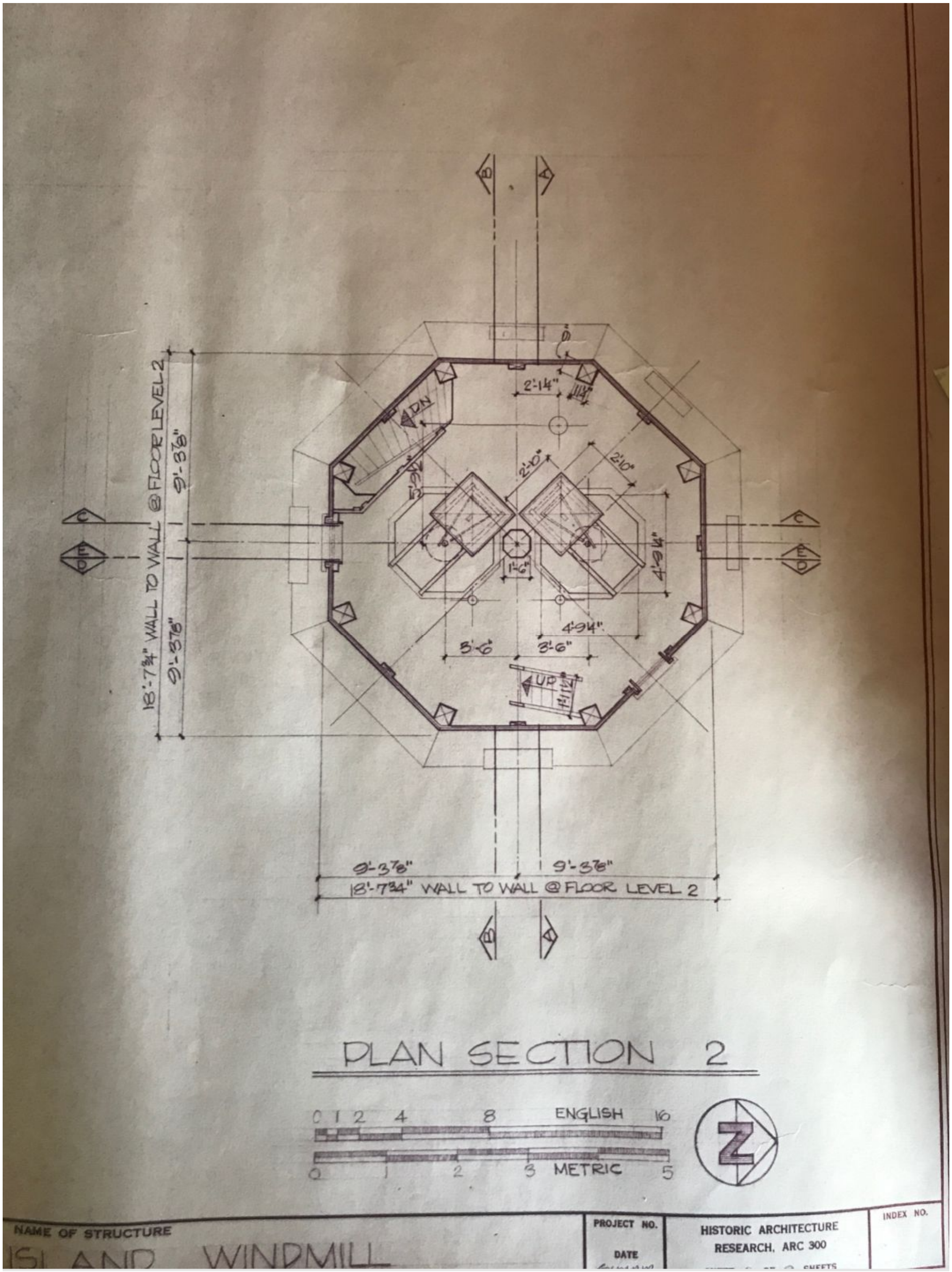


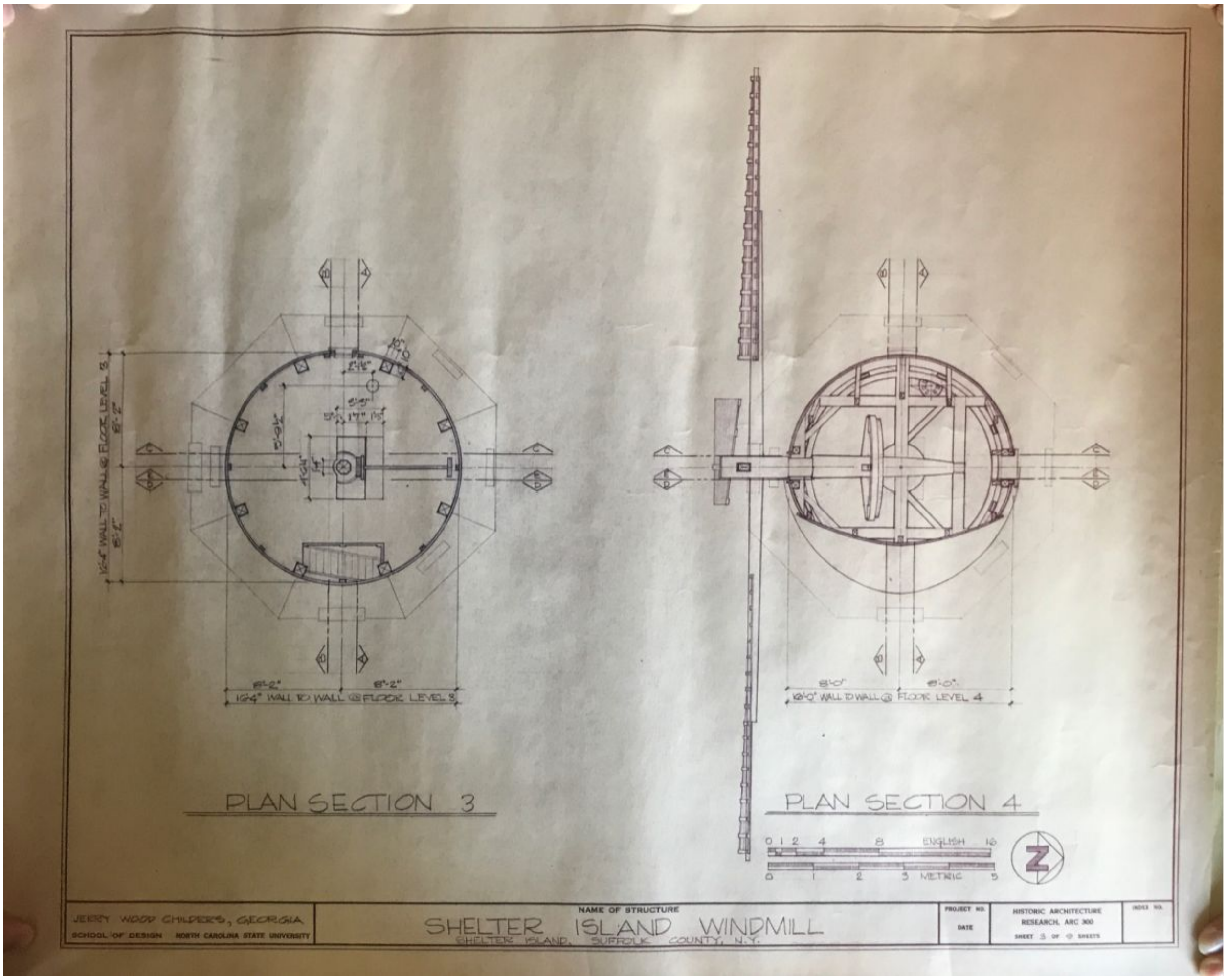
THIS MILL BUILT AT SOUTHOLD, N.Y. 1795 AND MOVED TO SHELTER ISLAND 1842, WAS PRESERVED AND RELOCATED BY LILIAN HORSFORD FARLOW AND CORNELIA C.F. HORSFORD. IT IS RESTORED 1952 BY MARGARET O.F. PROCTOR IN MEMORY OF HER MOTHER MARGARET OLIVIA SLOCUM FLINT 1870-1946 AND OF HER SIXTH AND FIFTH GREAT GRANDFATHERS NATHANIEL SYLVESTER 1610-1680 ORIGINAL GRANTEES OF SHELTER ISLAND AND THE HUGUENOT BENJAMIN L'HOMMEDIEU OF SOUTHOLD WHO IN 1694 MARRIED NATHANIEL'S DAUGHTER PATIENCE.

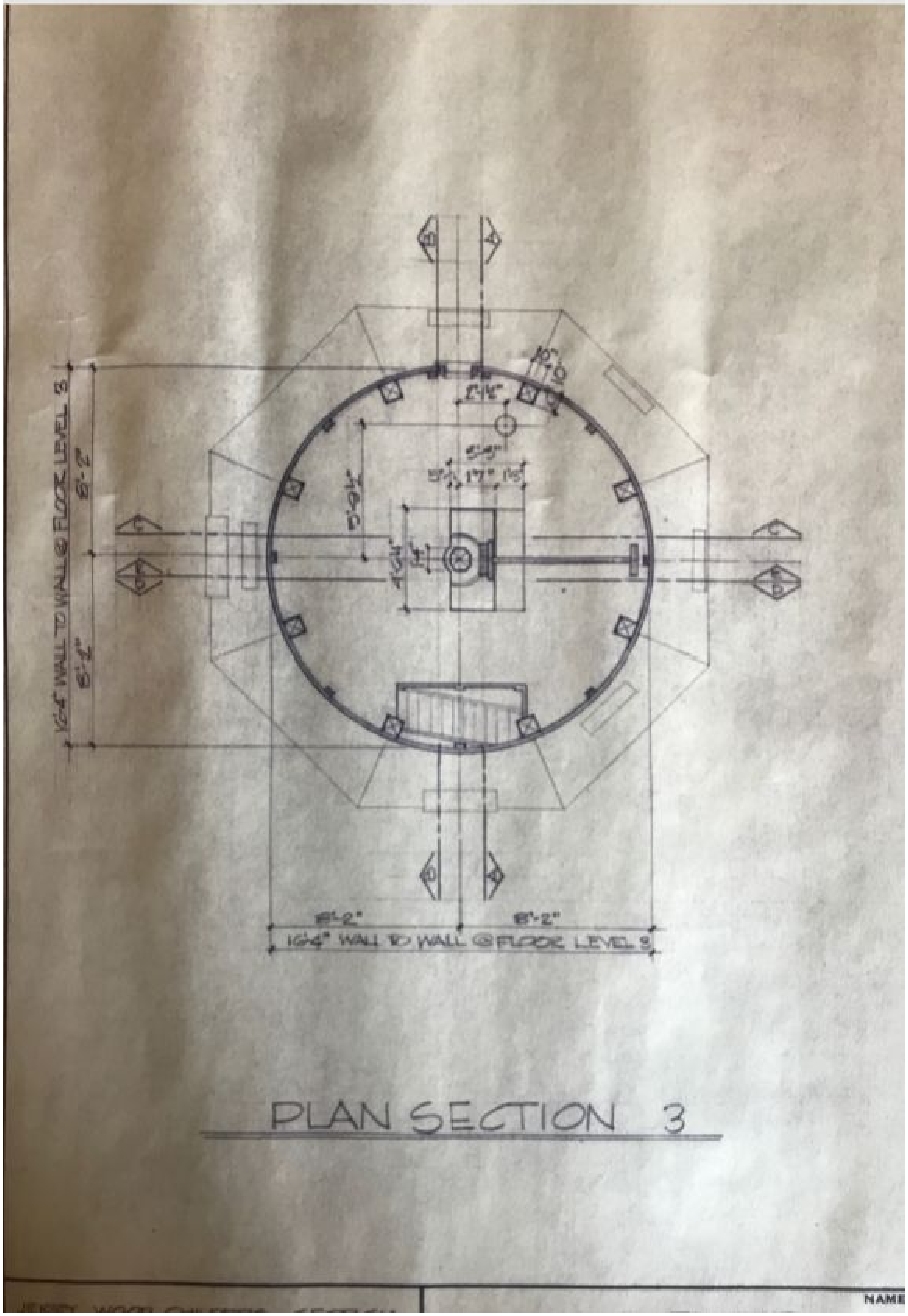
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET 1 OF 9 SHEETS
INDEX
1968-69

21'-0" WALL TO WALL @ FLOOR LEVEL 1
21'-0" WALL TO WALL @ FLOOR LEVEL 1
SIFTER
18'-7¾" WALL TO WALL @ FLOOR LEVEL 2
18'-7¾" WALL TO WALL @ FLOOR LEVEL 2
PLAN SECTION 1
PLAN SECTION 2
ENGLISH
METRIC
Z
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET 2 OF 9 SHEETS
INDEX NO.
1968-69


4'-5½"
4'-5½"
5'-2" 8'-2"
2'-5¾"
4'-5½"
3'-9"
2'-5¾"
4'-5½"
1'-0"
UP
9¼" 2'-5⅛" 2'-5⅛" 9¼"
5'-9½"
1'-6"
1'-6"
6'-10⅜"
SIFTER
2'-10"
14'-10"
2'-9"
2'-11" @ BASE
3¼" 2'-7½" 3¼"
4'-5½"
4'-5½"
10'-6"
10'-6"
21'-0" WALL TO WALL @ FLOOR LEVEL 1
21'-0" WALL TO WALL @ FLOOR LEVEL 1
4'-5½"
14'-5½"
4'-5½"
3'-10"
2'-10¾"
3½"
A
B
C
D
E
PLAN SECTION 1
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF
SHELTER ISL
SHELTER ISLAND


B
A
2'-1¼"
11¼"
DN
2'-10"
2'-10"
5'-9¾"
1'-6"
4'-9¼"
4'-9¼"
5'-6"
3'-6"
UP
1'-11½"
C
E
D
18'-7¾" WALL TO WALL @ FLOOR LEVEL 2
9'-3⅞"
9'-3⅞"
9'-3⅞"
9'-3⅞"
18'-7¾" WALL TO WALL @ FLOOR LEVEL 2
PLAN SECTION 2
0 1 2 4 8 ENGLISH 16
0 1 2 3 METRIC 5
N
NAME OF STRUCTURE
ISLAND WINDMILL
PROJECT NO.
DATE
HISTORIC ARCHITECTURE
RESEARCH, ARC 300
SHEETS
INDEX NO.


16'4" WALL TO WALL @ FLOOR LEVEL 3
8'-2"
8'-2"
2'-1⅛"
5'-5"
17"
5'-9½"
4'-2¼"
8'-2"
8'-2"
16'4" WALL TO WALL @ FLOOR LEVEL 3
PLAN SECTION 3
8'-0"
8'-0"
16'-0" WALL TO WALL @ FLOOR LEVEL 4
PLAN SECTION 4
0 1 2 4 8 ENGLISH 16
0 1 2 3 METRIC 5
N
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET 5 OF SHEETS
INDEX NO.



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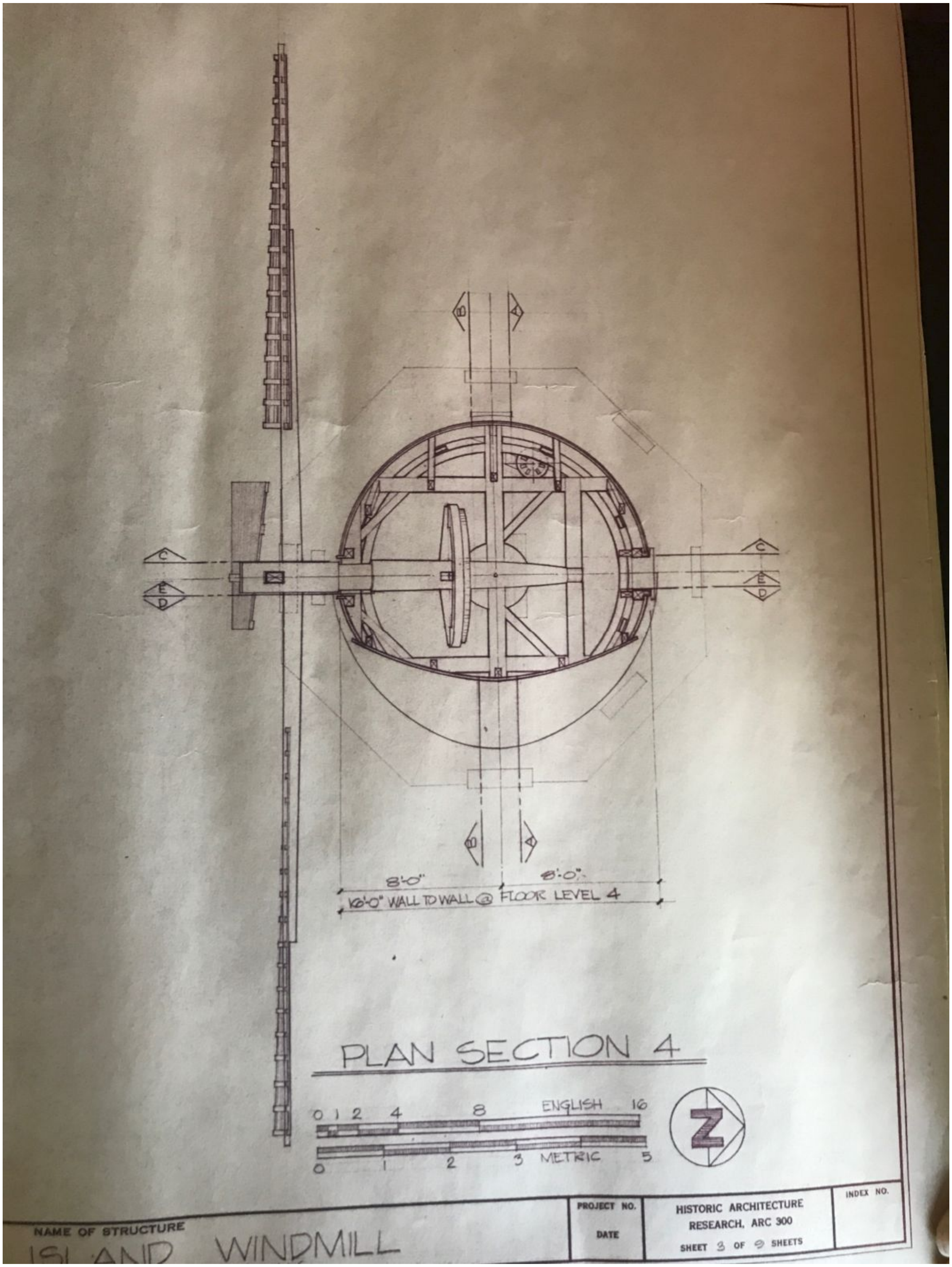
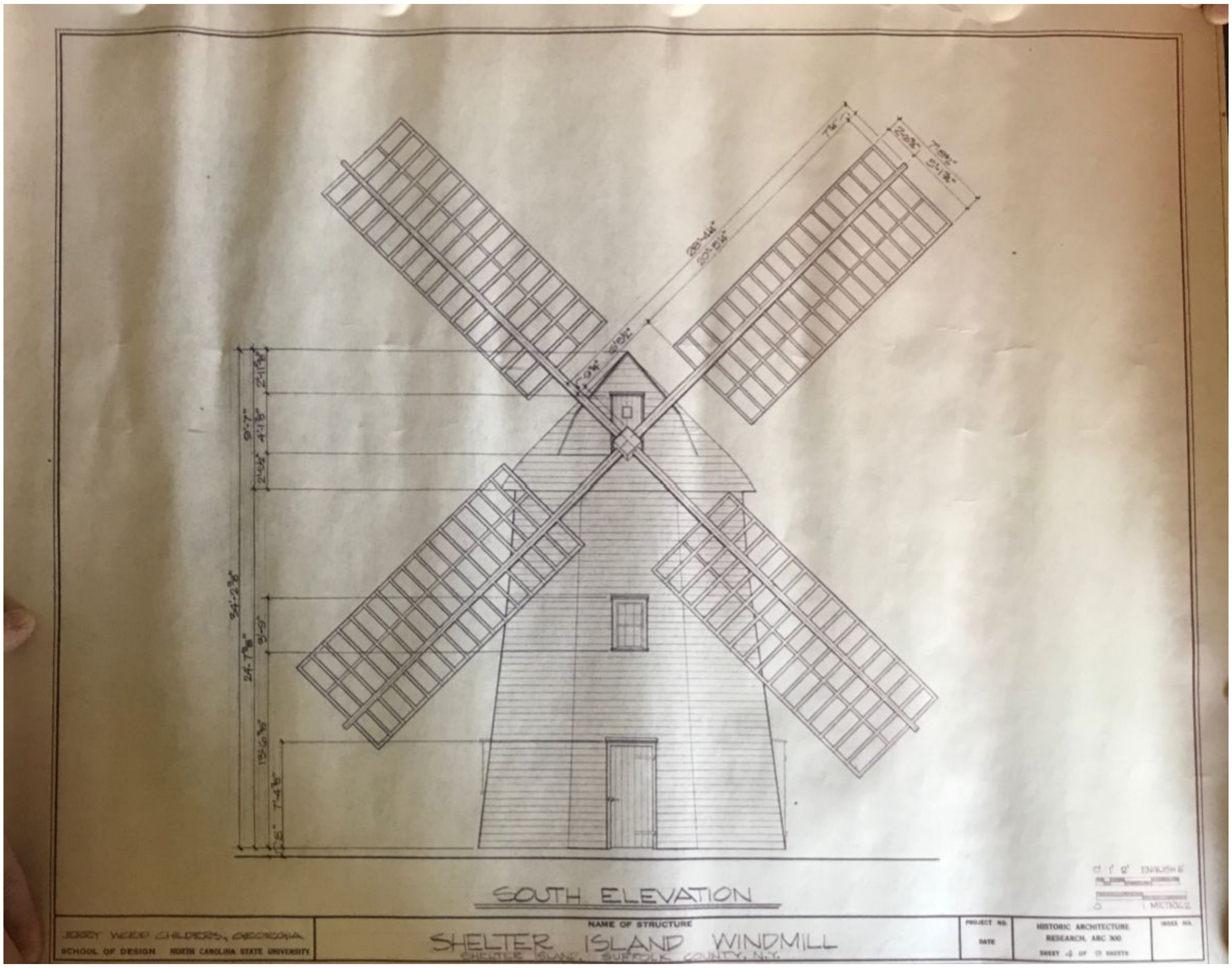

B
A
C
E
D
8'-0"
8'-0"
16'-0" WALL TO WALL @ FLOOR LEVEL 4
PLAN SECTION 4
0 1 2 4 8 ENGLISH 16
0 1 2 3 METRIC 5
Z
NAME OF STRUCTURE
ISLAND WINDMILL
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET 3 OF 9 SHEETS
INDEX NO.


SOUTH ELEVATION
JERRY WEBB CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
INDEX NO.
ENGLISH
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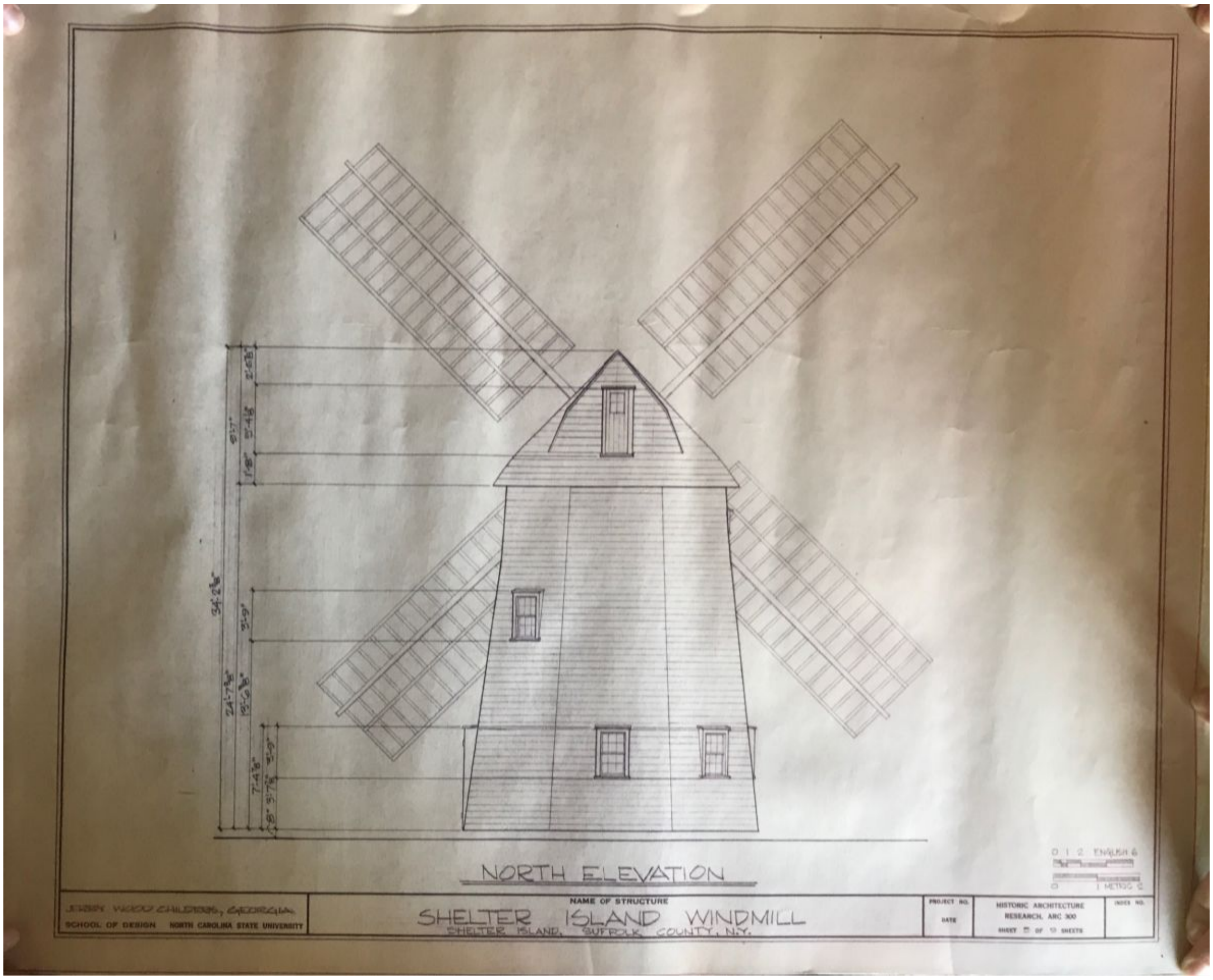
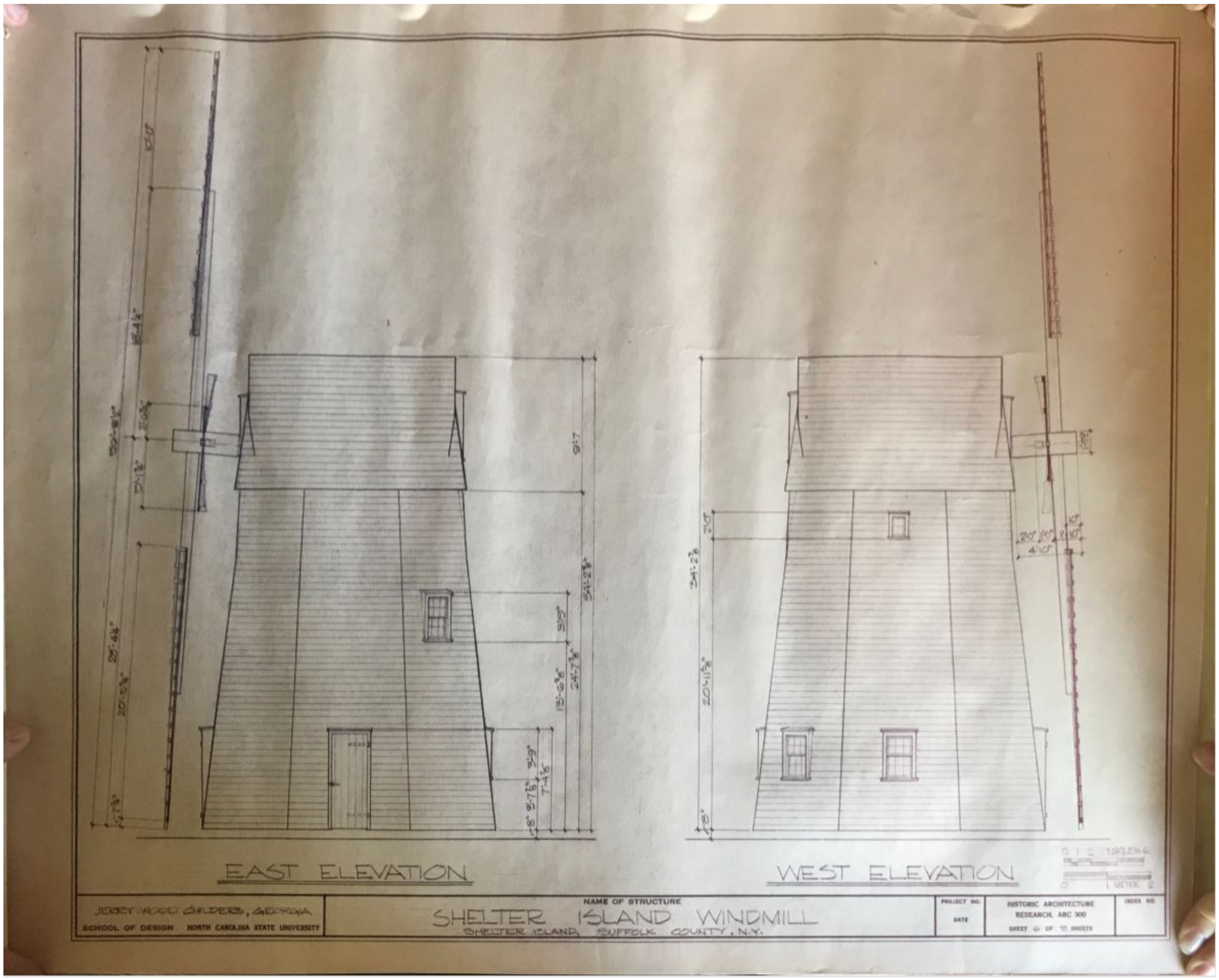
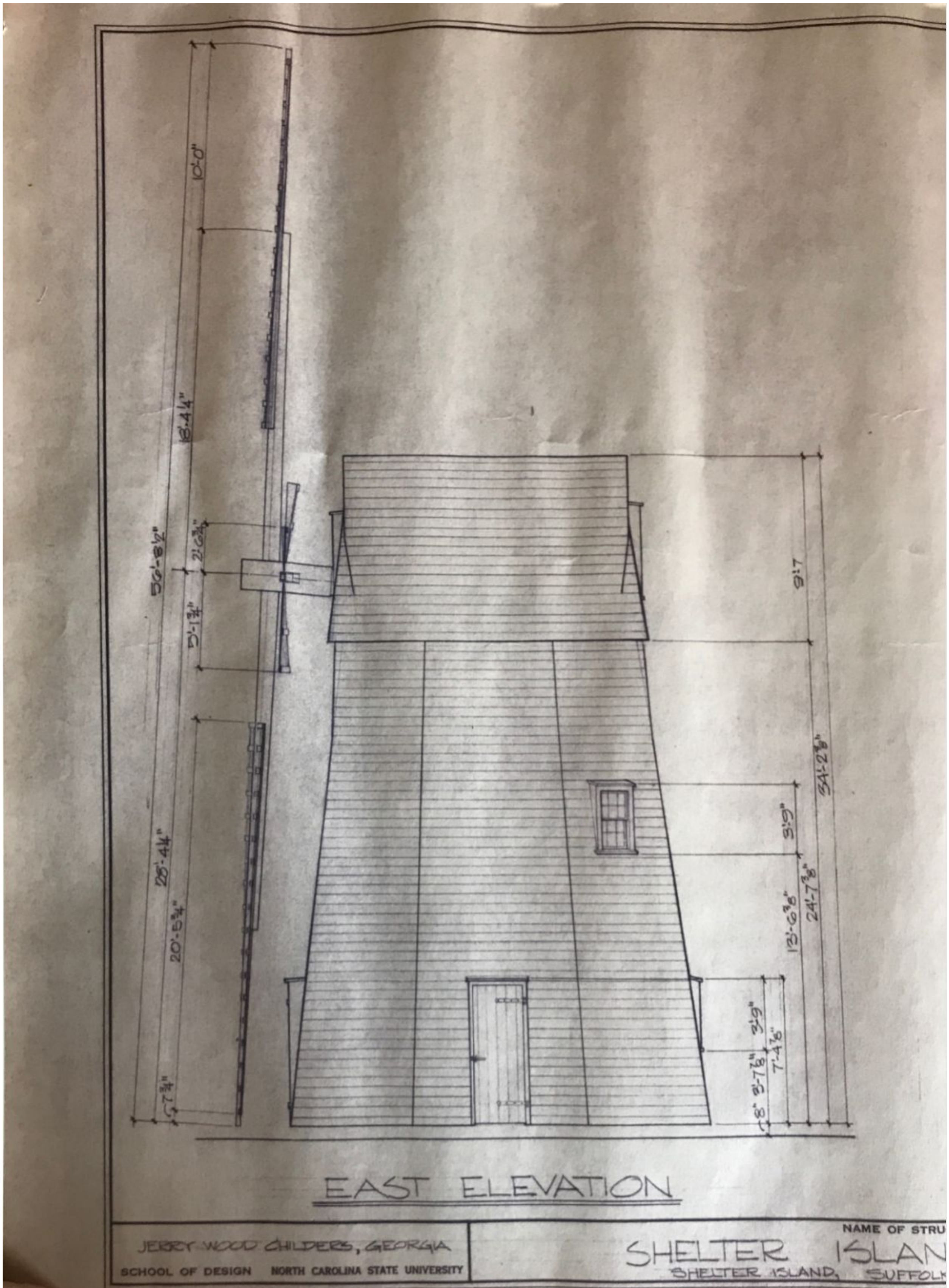
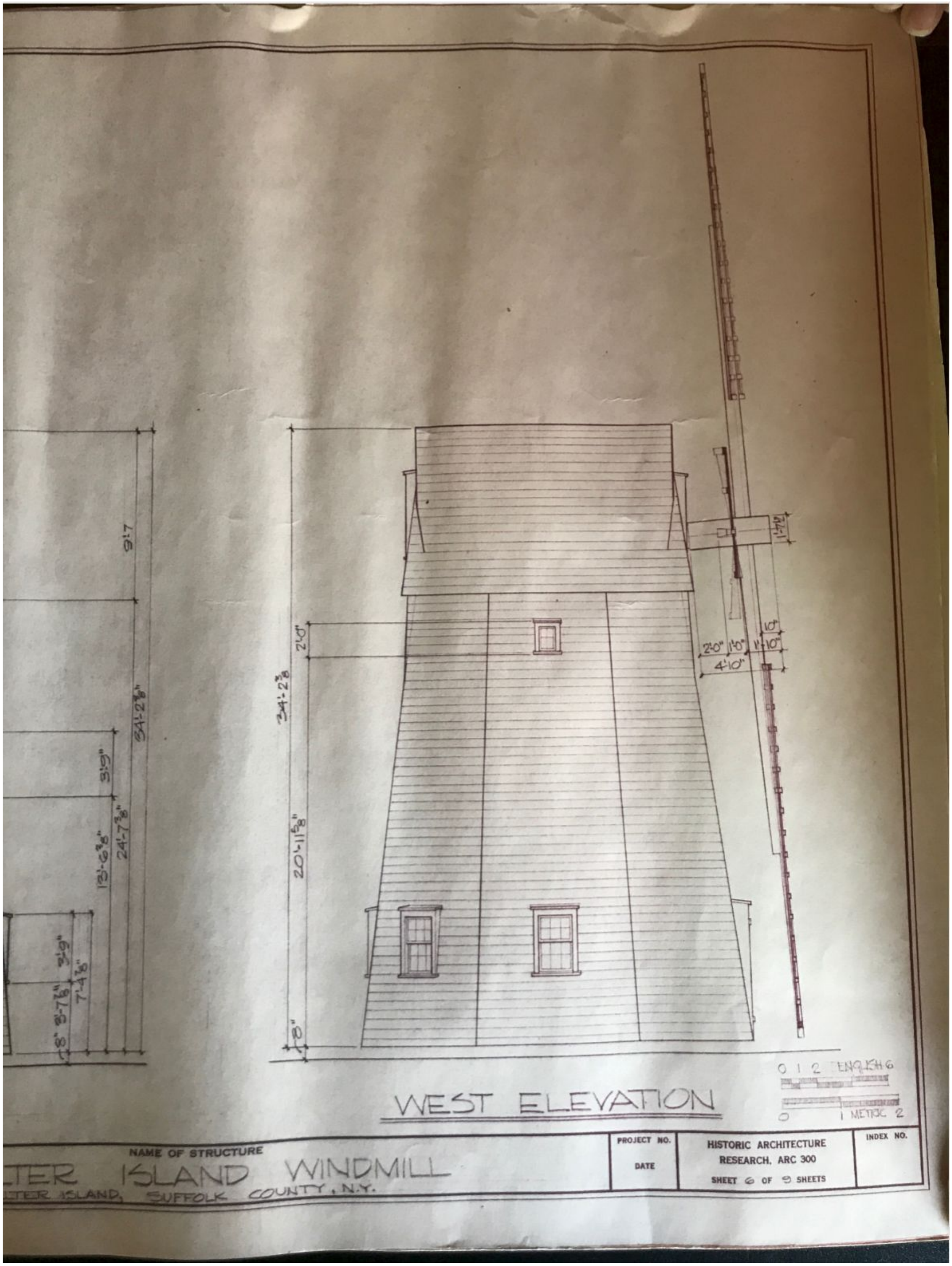
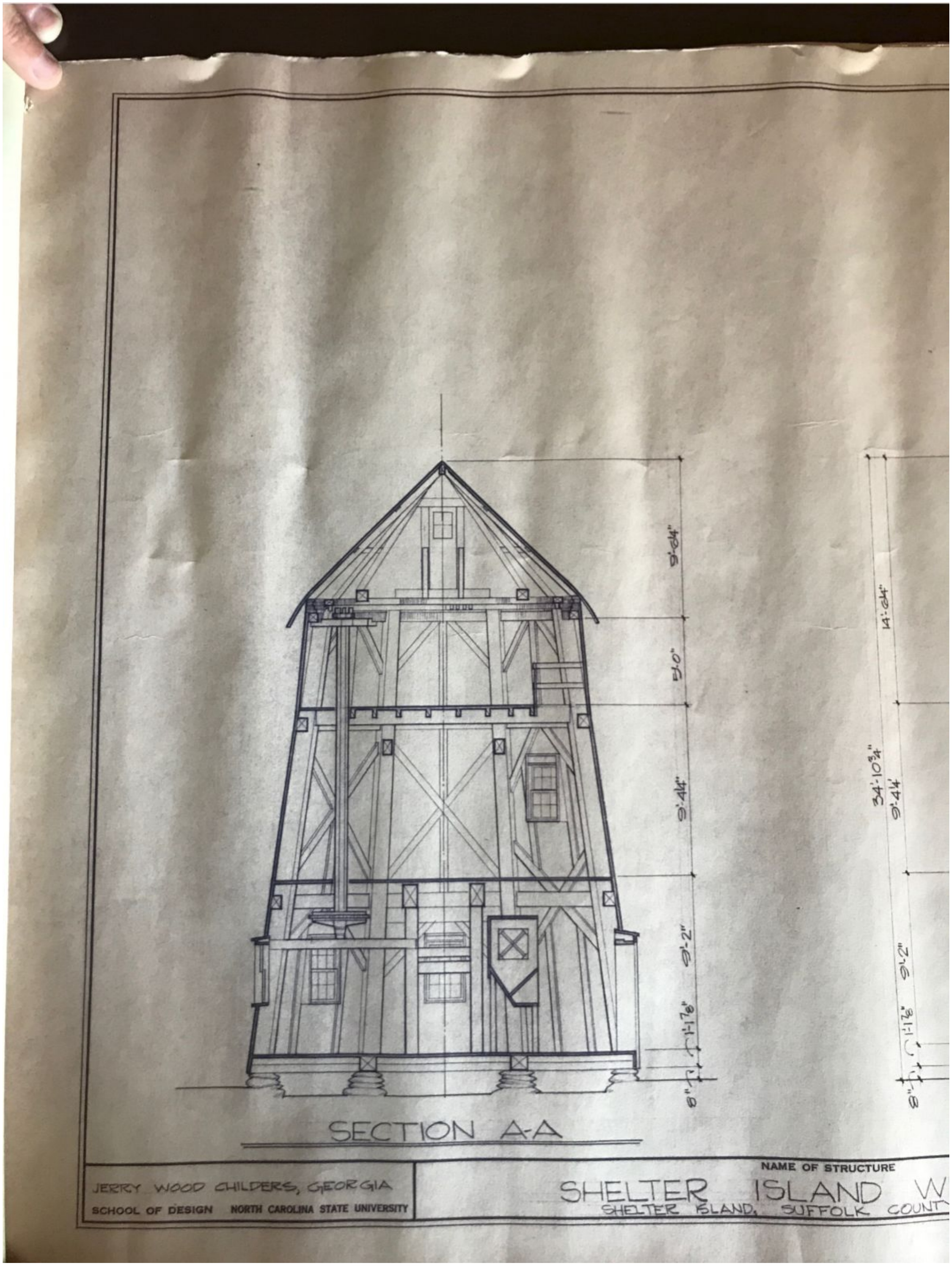

9'-7"
1'-8"
3'-9"
NORTH ELEVATION
0 1 2 ENGLISH 6
0 1 METRIC 2
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET OF SHEETS
INDEX NO.

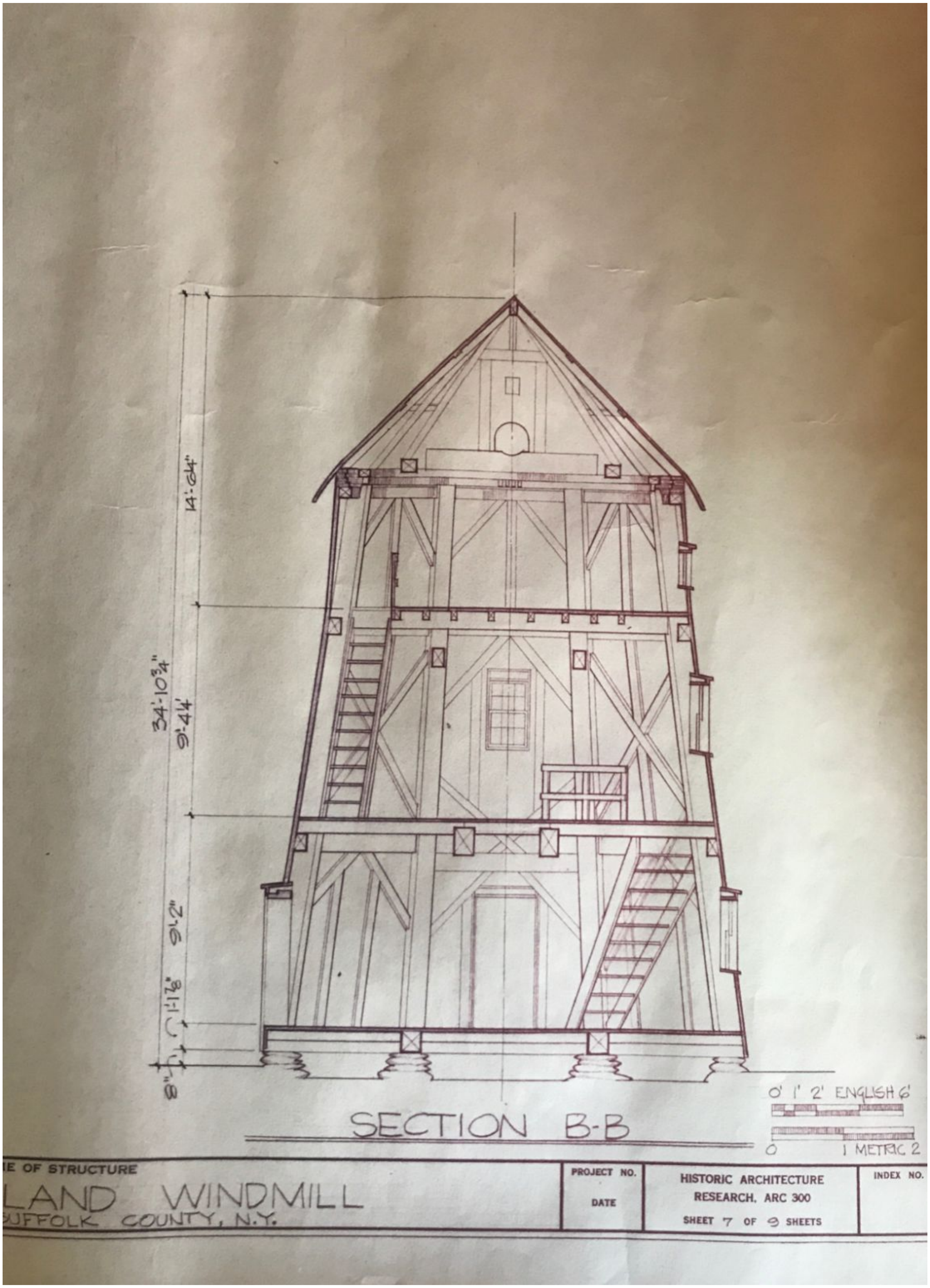

EAST ELEVATION
WEST ELEVATION
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE
RESEARCH, ARC 300
SHEET OF SHEETS
INDEX NO.

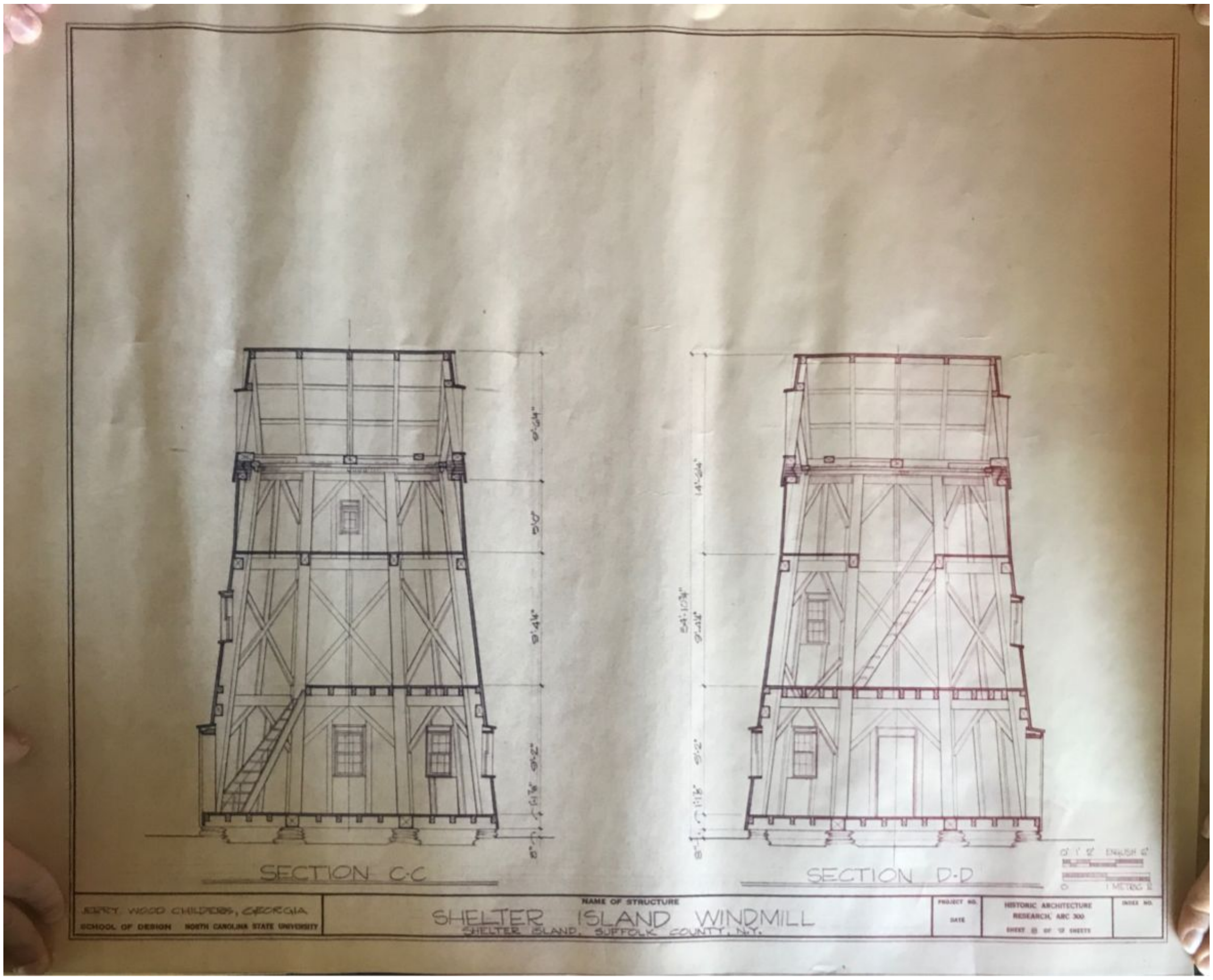

10'-0"
18'-4¼"
56'-8½"
2'-6¾"
5'-1¾"
28'-4¼"
20'-5¾"
7¾"
9'-7
34'-2⅜"
3'-9"
13'-6⅜"
24'-7⅜"
3'-9"
8" 3'-7⅞"
7'-4⅜"
EAST ELEVATION
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRU
SHELTER ISLAN
SHELTER ISLAND, SUFFOLK

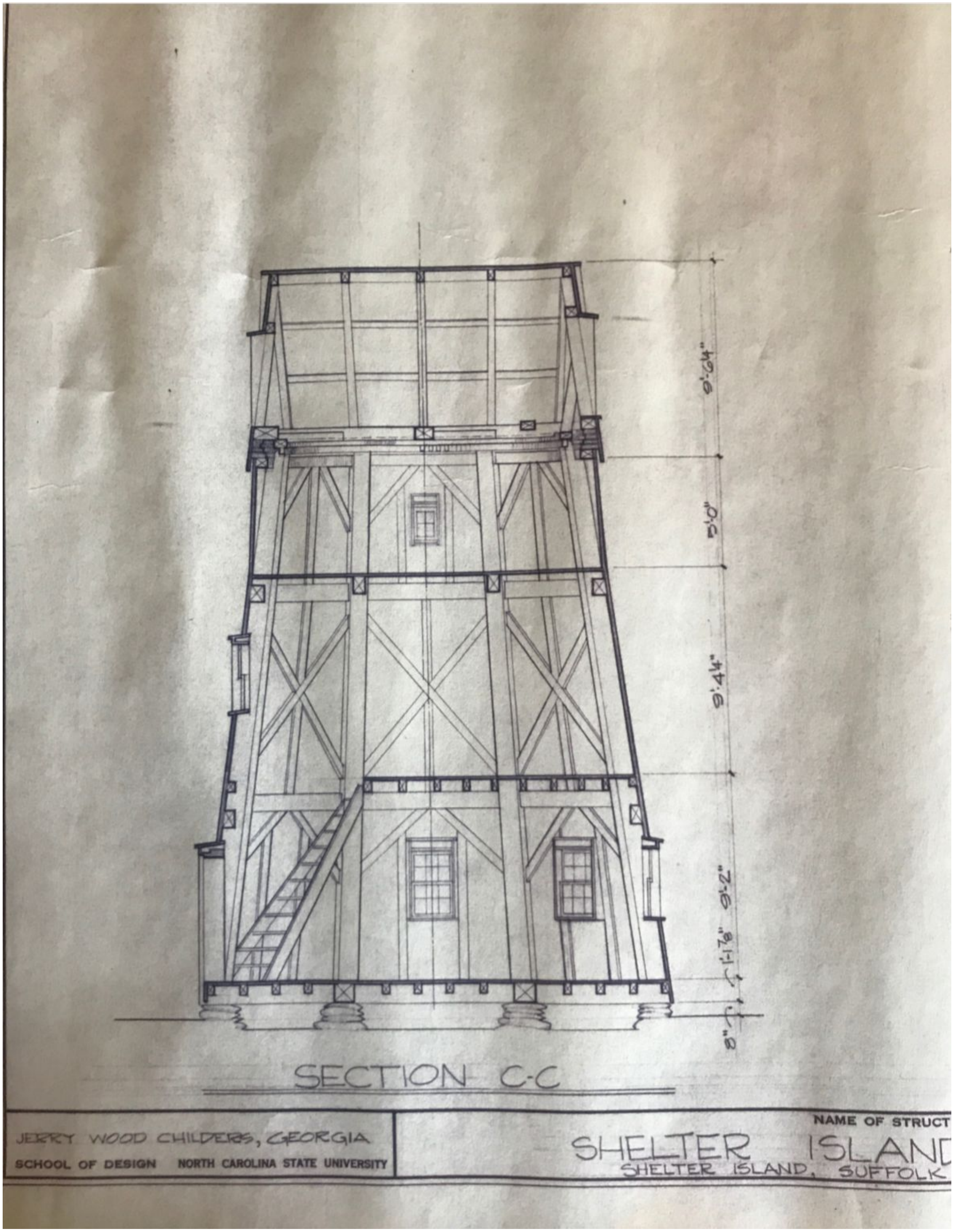

9'7
34'-2⅜"
3'9"
13'-6⅜"
24'-7⅜"
3'9"
7'-4⅜"
8'-7⅜"
7⅜"
24'-2⅜"
2'-0"
20'-11⅝"
1'-7½"
10"
2'-0"
1'-0"
1'-10"
4'-10"
0 1 2 ENGLISH 6
0 1 METRIC 2
WEST ELEVATION
NAME OF STRUCTURE
LTER ISLAND WINDMILL
LTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET 6 OF 9 SHEETS
INDEX NO.

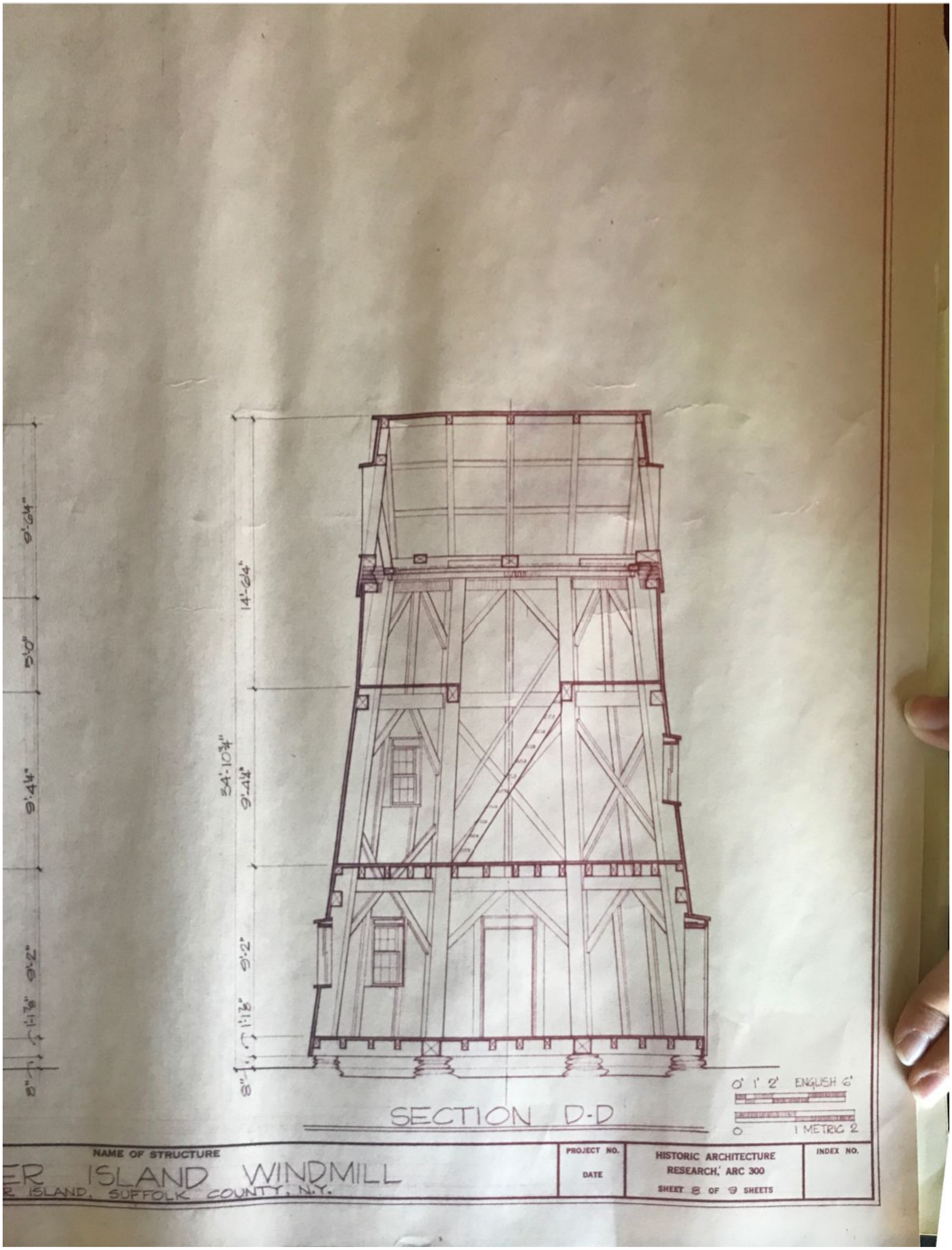

SECTION A-A
SECTION B-B
0 1' 2' ENGLISH 6'
0 1 METRIC 2
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
SHEET 7 OF 13 SHEETS
INDEX NO.

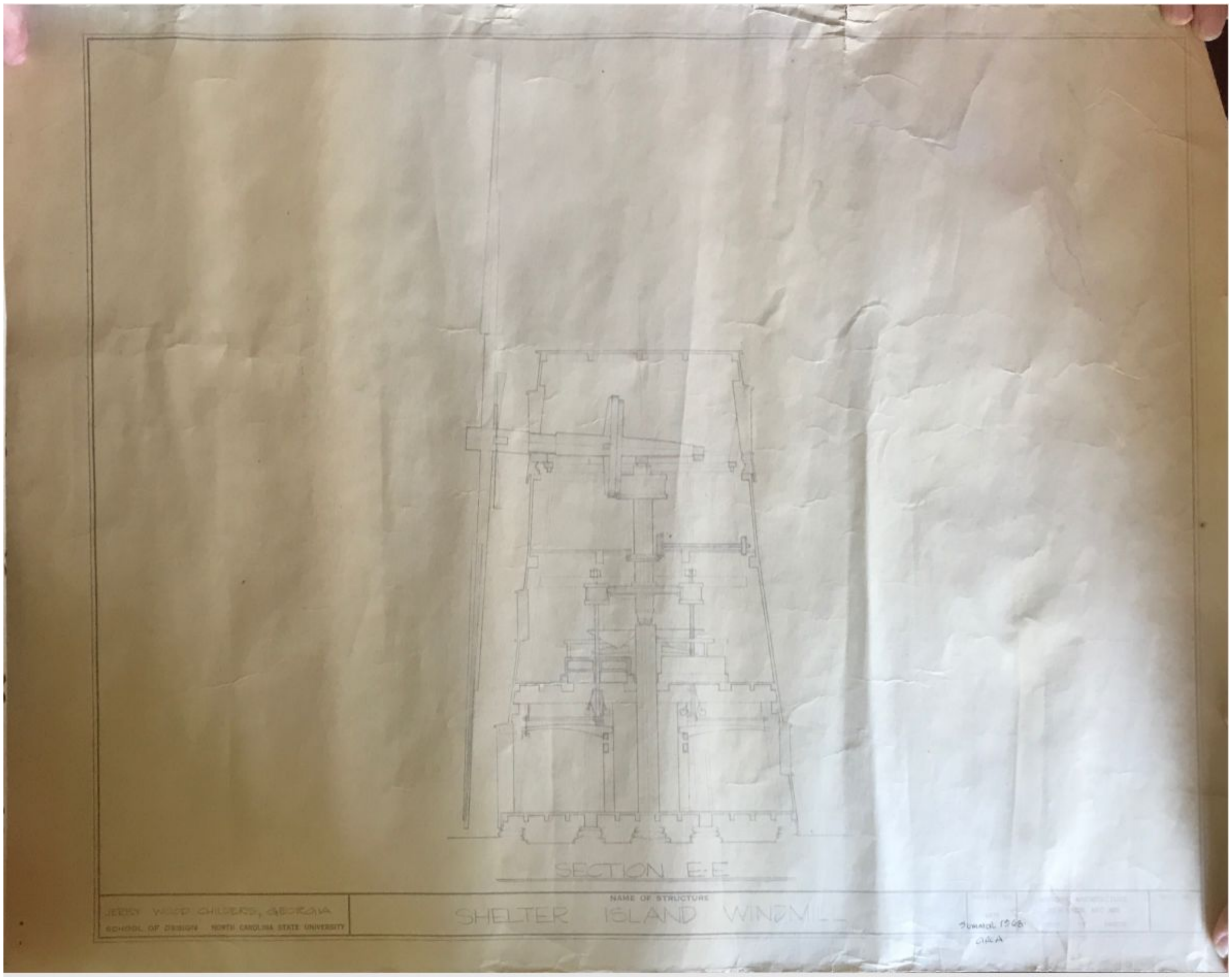

9'-6¼"
5'-0"
9'-4¼"
9'-2"
1'-1⅞"
8"
14'-6¼"
34'-10¾"
9'-4¼"
9'-2"
1'-1⅞"
8"
SECTION A-A
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND W
SHELTER ISLAND, SUFFOLK COUNT

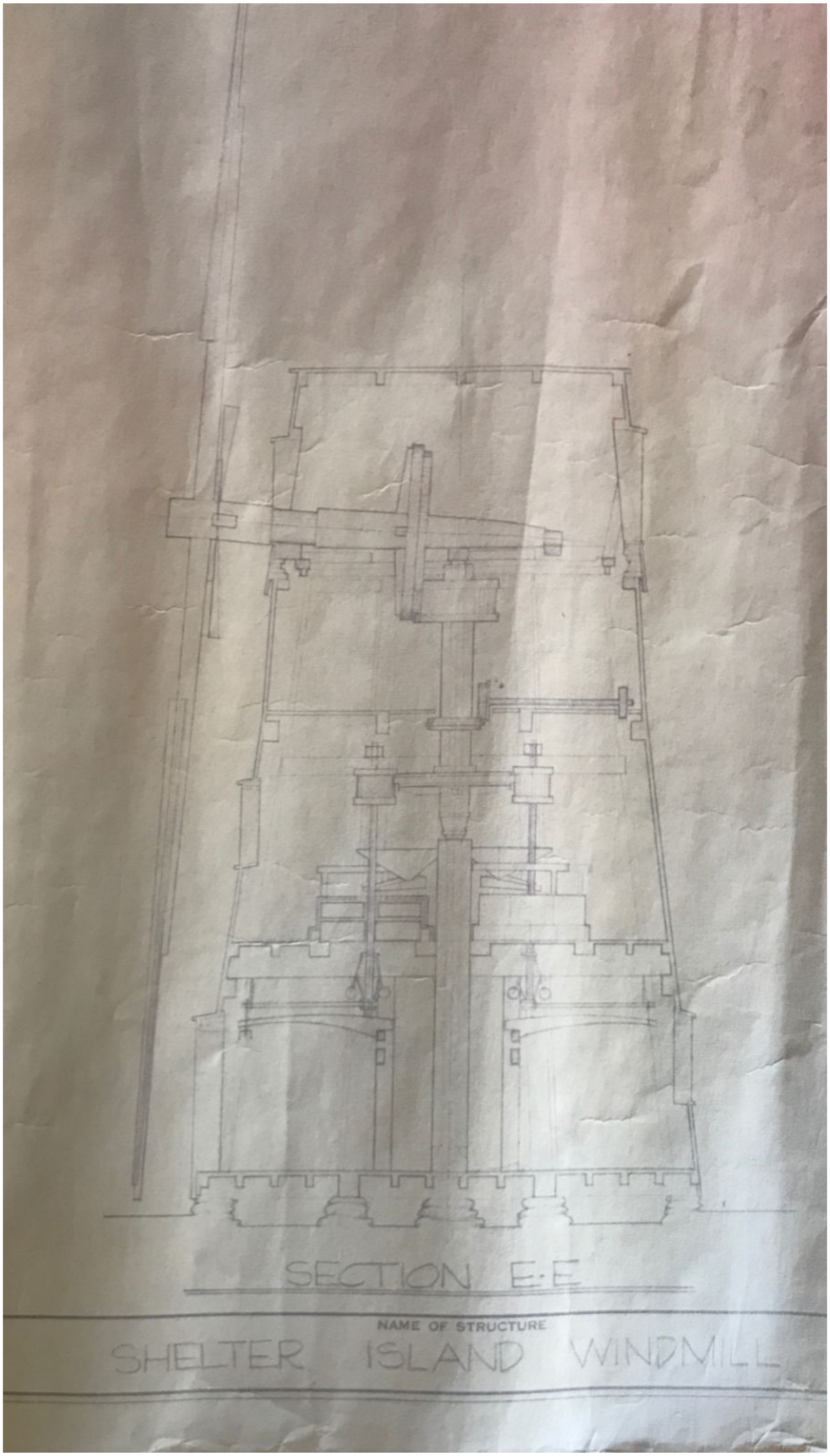

14'-6¼"
34'-10¾"
9'-4¼"
9'-2"
1'-1⅞"
8"
SECTION B-B
0' 1' 2' ENGLISH 6'
0 1 METRIC 2
E OF STRUCTURE
LAND WINDMILL
UFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE
RESEARCH, ARC 300
SHEET 7 OF 9 SHEETS
INDEX NO.


SECTION C-C
SECTION D-D
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
SHELTER ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE RESEARCH, ARC 300
INDEX NO.
ENGLISH
1 METRE


9'-6¼"
5'-0"
9'-4¼"
9'-2"
1'-1⅞"
8"
SECTION C-C
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCT
SHELTER ISLAND
SHELTER ISLAND, SUFFOLK

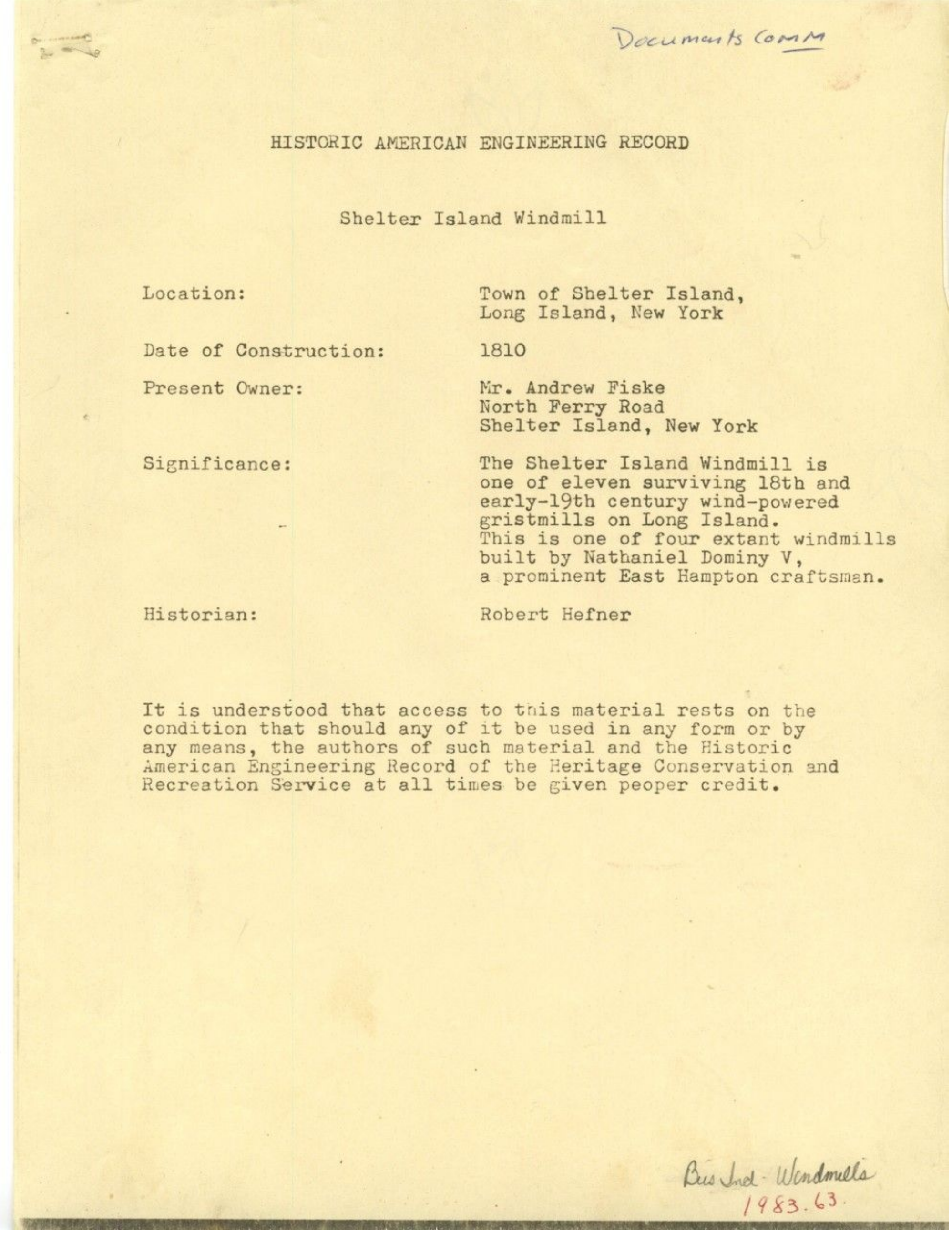

9'-6¼"
5'-0"
9'-4¼"
1'-1⅞"
9'-2"
8"
14'-6¼"
34'-10¾"
9'-4¼"
9'-2"
1'-1⅞"
8"
SECTION D-D
0' 1' 2' ENGLISH 6'
0 1 METRIC 2
NAME OF STRUCTURE
ER ISLAND WINDMILL
R ISLAND, SUFFOLK COUNTY, N.Y.
PROJECT NO.
DATE
HISTORIC ARCHITECTURE
RESEARCH,' ARC 300
SHEET 8 OF 9 SHEETS
INDEX NO.


SECTION E-E
JERRY WOOD CHILDERS, GEORGIA
SCHOOL OF DESIGN NORTH CAROLINA STATE UNIVERSITY
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL
Summer 1968
ORA


SECTION E-E
NAME OF STRUCTURE
SHELTER ISLAND WINDMILL

Appendix B: Historical American Engineering Record

This appendix features the Historical American Engineering Record of the Shelter Island Windmill, which was provided to us by the Shelter Island Historical Society.



Documents Comm

HISTORIC AMERICAN ENGINEERING RECORD

Shelter Island Windmill

Location:	Town of Shelter Island, Long Island, New York
Date of Construction:	1810
Present Owner:	Mr. Andrew Fiske North Ferry Road Shelter Island, New York
Significance:	The Shelter Island Windmill is one of eleven surviving 18th and early-19th century wind-powered gristmills on Long Island. This is one of four extant windmills built by Nathaniel Dominy V, a prominent East Hampton craftsman.
Historian:	Robert Hefner

It is understood that access to this material rests on the condition that should any of it be used in any form or by any means, the authors of such material and the Historic American Engineering Record of the Heritage Conservation and Recreation Service at all times be given peoper credit.

Bus Ind - Windmills
1983.63

CONTENTS

PART I

History of the Windmill

This windmill was built in Southold in 1810 and moved to Shelter Island in 1840. It is the only windmill built on Long Island's north fork to survive, but little is known of its history there.

The mill was built in 1810 for a company whose partners were Nathaniel Overton, Benjamin Horton, Moses Cleveland, Joseph Halliock and Barnabas Case.[1] Nathaniel Dominy was the millwright. Dominy's activity on the north fork shows the extent to which his millwrighting skills were recognized. Dominy also built a sawmill in Southold in 1811[2] and possibly built the Orient Windmill.

It is certain that Dominy had the assistance of local carpenters in building the mill. Dominy's bill to the owners of the mill charges them for 66 days of his own time and 120 days for the time of his apprentices: Asa Miller, Merry Parsons and Lewis Parsons.[3] This makes a total of 186 days labor; when Dominy built the Hook Mill in 1806, he and his crew worked a total of 557 man-days. It is logical that in Southold, where Dominy and his apprentices would have to board, local craftsmen would do as much of the work as possible.

In April 1810 Nathaniel Dominy wrote to Moses Cleveland, the partner in charge of building the new mill, answering some questions about the planned construction of the mill.[4] (See Appendix I) The specifications which Dominy provided for some of the machinery and structural components of the mill, suggest that Cleveland may have had some of the work carried out.

Moses Cleveland himself was a carpenter; the accounts of the mill company for 1821-1823 indicate that Cleveland performed routine maintenance and repairs on the mill. 5

The only knowledge of the windmill's operation in Southold comes from an account book for the mill company entitled "New Mill Book for 1812". 6 This book is primarily the accounts of the mill's five owners, but also records charges to individual customers. Most charges are for from ½ to 3 bushels of wheat, buckwheat, corn, rye, meslin or provender. The accounts indicate that the mill operated throughout the year.

The windmill was purchased in 1840 by Joseph Congdon and moved to Shelter Island where it stood at the center of the village, near the library and high school. 7 One account of the history of the mill states that the mill was moved to Shelter Island to replace another which had burned down. 8 This would be a likely case, as in 1840 there would have been no need for a new mill on Shelter Island.

Congdon, who was a miller, 9 operated the windmill until about 1855 when it was sold to Smith Baldwin. 10 The mill ceased to operate sometime before 1879 when Lillian Horsford purchased it to preserve it as an antique. 11 It is not surprising that the mill ceased operation at this time. The 1860 Census of Industry shows that the mill did little business, at least compared to the windmills of East Hampton. In 1860 the Shelter Island windmill ground 900 bushels of grain, while the Hook Windmill and the Gardiner Windmill in East Hampton ground 5000 bushels each. 12

The mill was put back in operation during 1917-1918 to provide meal and flour for the inhabitants of the Island during the food conservation period of the First World War. 13 In 1926 Miss Cornelia Horsford moved the mill to the grounds of Sylvester Manor, on Shelter Island, where it remains today. 14

PART II

Structure and Machinery

Two documents which pertain to the construction of the Shelter Island Windmill indicate the amount of planning which preceeded the building of the mill and the exact specifications which the millwright worked with. One document is the letter Nathaniel Dominy V wrote to Moses Cleveland in April 1810 (See Appendix I) and the other is a list of mill components entitled "Mill Papers" (See Appendix II).

The purpose of Dominy's letter to Cleveland is not clear. If we did not know that Dominy was the millwright, we would assume that Cleveland was building the mill and had asked Dominy to provide the specifications for certain components. We know that Dominy worked on the mill for only 66 days and could not have been present throughout the project. It is likely that Cleveland did have some of this work done, to Dominy's specifications, before Dominy arrived in Southold to oversee the work himself.

The first item of the letter is Dominy's affirmative response to Cleveland's inquiry whether his "timber" would be sufficient to have two run of stones in the mill. Presumably Cleveland had originally planned a mill with only one run of stones. Dominy then notes that " the top had better be enlarged as much as the bottom or the arms will come too near." This may be a change required in altering plans for a mill with one run of stones to a mill with two run of stones. But further specifications given in the letter do not refer to changes that would be necessary to change a mill from one to two run of stones.

In antoher item Dominy presents Cleveland with the choice to "frame girders across for your bridge beams to lie upon" or to "have the bridge beams lie on those girths which support the upper floor." Cleveland chose the former method. The Shelter Island Mill and the Hook Mill, Dominy's latest mills, are the only Long Island windmills which have separate girders to support the quant sprattle beams. This method allowed greater head room at the second level and allowed a crown wheel and layshaft to be positioned under the ceiling of the second floor. In the Hook Mill this also allowed room for a screener to be installed under the second floor ceiling.

Most of the specifications given in this letter were followed, probably by Nathaniel Dominy himself. The specifications given in the letter for the stone beams, center post, brake wheel, spur wheel and wallower are identical to or close to the dimensions of those components in the Shelter Island Windmill.

The papers concerning the Shelter Island Windmill (the letter from Dominy to Cleveland, the "New Mill Book for 1812", the bill and receipt for Dominy's work and Moses Cleveland's mill account) are found in two packets in the East Hampton Free Library labeled L 628 and L 629. Also found in one of these packets is a sheet which lists dimensions for mill components on one side and on the reverse side is labeled "Mill Papers". (See Appendix II) There is no other identification. It is presumed that this document was part of the planning process for the Shelter Island Windmill and would have been written by Nathaniel Dominy or Moses Cleveland. By comparing the handwriting of these men with that of the document, it cannot be positively attributed to either.

What is provided on this sheet is a fairly complete list of the structural components and machinery of a windmill and their specifications. All the structural members of the tower of the mill are listed except the braces, studs, floor joists and the center post. All structural members of the cap are listed except the rafters. The specifications for the windshaft, stocks, brake wheel and internal capstan winder are given, but none for the spur wheel, wallower or stone nuts.

The specifications given in the list for the height of the first and third stories and the dimensions of the first and second story "interties" are exactly those of the Shelter Island Windmill. The list calls for 96 coggs for the cap rack, which is the number found in the Shelter Island Mill. Other dimensions given in the list are reasonably close to those for the same components found in this windmill. The greatest difference is in the brake wheel. The Shelter Island brake wheel is 7'8" in diameter and has 60 coggs. The brake wheel described in the list is 9' in diameter and has 80 coggs. Only the much larger Beebe Windmill has a brake wheel 9' in diameter.

It is possible that this list does not pertain to the Shelter Island Windmill. But it does demonstrate the planning which must have gone into building each mill.

STONE CRANE

The stone crane in the Shelter Island Windmill is undoubtedly the oldest still in place in a Long Island windmill. The components of this crane are the same as those of the other surviving cranes, but in the Shelter Island Mill the yoke and screw are of wood, not metal. The wooden screw, no longer in the mill, is seen in a photograph published in 1918.[15] Parts of an even older type of stone crane are found in the Hook Mill (see HAER Hook Mill Report). This crane used two wooden screws to raise a block of wood parallel to the spar from which hung two long iron dogs. The Shelter Island Windmill stone crane with its wooden yoke and wooden screw is a transitional step from the stone crane in the Hook Mill to the commonly-found crane with iron yoke and metal screw.

ROLLER BEARING

The roller bearing on which the cap of the Shelter Island windmill turns is made of wood, with iron trolley wheels set in. Wooden segments are spliced together to form the large circular bearing. All the roller bearings found in other mills are formed by two iron bands with wooden spacers in between.

GRAIN SYSTEM

The Shelter Island Windmill is one of three Long Island mills with no grain elevator or sack hoist to assist in moving the grain to the second or third floors. The other two mills are the Gardiner's Island Mill and the Windmill at Watermill. These mills are also the only ones with no screener to clean the grain before grinding.

The Shelter Island Mill does have a large bolter for flour, the reel is 15 feet long with a diameter of 2½ feet. A reel for a corn bolter is in the mill but there is no case for it. The jog scry in this mill is more intact than those found in the other mills. The jog scry has a vibrating screen which sifts out the corn meal and leaves the partly ground corn for a second grinding.

NOTES

(1) Account book "New Mill Book for 1812", manuscript, East Hampton Free Library. The date 1810 is inscribed in a beam at the second floor of the mill.

(2) Nathaniel Dominy V Account Book, 1798-1847, manuscript, Henry Francis du Pont Winterthur Museum.

(3) Bill and receipt, Nathaniel Dominy and Moses Cleveland, 15 December 1810, manuscript, East Hampton Free Library.

(4) Letter, Nathaniel Dominy to Moses Cleveland, 13 April 1810, manuscript, East Hampton Free Library.

(5) Account, Mill company to Moses Cleveland, 1821-1823, manuscript, East Hampton Free Library.

(6) Account Book, "New Mill Book for 1812", manuscript, East Hampton Free Library.

(7) Dr. Clarence Ashton Wood, "The Shelter Island Windmill," Long Island Forum, February 1955, p. 27.

(8) "Shelter Island Windmill," Long Island Forum, December, 1957, p. 236.

(9) Land indenture, Frederick Clarke to Joseph Congdon, 1845, D ed Liber 49, p. 323, Suffolk County Clerk's Office.

(10) Dr. Clarence Ashton Wood, "The Shelter Island Windmill," Long Island Forum, February 1955, p. 27.

(11) "Shelter Island Windmill," Long Island Forum, December 1957, p. 236.

(12) United States Census Office, 8th Census, Census of Industry, Suffolk County, 1860.

(13) Rex Wailes, "Windmills of Eastern Long Island," <u>Newcomen Society Transactions</u>, 1934-1935.

(14) Dr. Clarence Ashton Wood, "The Shelter Island Windmill," <u>Long Island Forum</u>, February 1955, p. 27.

(15) Edward P. Buffet, "Some Long Island Windmills," <u>American Machinist</u>, 17 October 1918.

APPENDIX I

Letter from Nathaniel Dominy V to Moses Cleveland,
13 April 1810.

East Hampton April 13th 1810

Sir, I recieved yours of the 9th Inst. which informs me that if your timber will answer you have concluded to put two run of Stones in your Mill - I believe it will do well. 2nd If you frame girders across for your bridge beams to lie upon 8 feet and 4 Inches from top of stone beams to top of said girders, the lower storey will answer as agreed upon, but if you conclude to have the bridge beams lie on those girths which support the upper floor perhaps the lower storey had better be as much as 10 feet high - 3rd The top had better be enlarged as much as the bottom or the arms will come too near - 4th The stone beams may be 2 Feet & 10 Inches apart & the posts under them stand flush with the inside of the beams & 5 Feet between them the other way - 5th The post in center of Mill may be from 18 to 24 Inches and long enough to rise 4 Feet 8 Inches above the stone beams - 6th The plank rim to be in 6 pieces - 7 Cogg Wheel to be 8 feet diameter - & Spur Wheel 5 Feet 3 I. with 52 Coggs each 3½ by 1¼ and 12 Inches long - Cants of spur wheel 17 Inches wide & 4 thick - Faceing of D^{o} 7 Inches wide and 3 thick - the width of arms 9 In. & 4½ thick - The Wallower 3 feet 10 Inches diameter of plank 2 Inches thick, each head to be double thickness and the plank to cross - 25 Rounds 14 Inches between shoulders and 3 Inches diameter - The rim that holds the coggs for turnin the top of Mill may be 5 Inches thick and 9 or 10 wide - Stocks 34 or 35 Feet long, 8 Inches thick and 10 deep at center and the ends proportioned so as to suit the points when hewed 8 Inches one end & 4½ the other and the thickness of the stock about 3½ or 4 Inches at end - Size of Burr Stones 4 Feet 4 Inches diameter - and the rock Stones 4 Feet 8 or 9 Inches diameter and the runner 17 or 18 Inches through the eye - NB. the Post in center may be crotched on one of the sleepers and a large stone placed under the end - yours &c

Mr. Moses Cleveland - Nathl Dominy jun^{r}

APPENDIX II

Single sheet of paper, on back is written "Mill Papers"

Sills "	4	sticks	20 Feet long	12 by 12 In
Short D°	8	D°	8 F. 3 In.	12 by 6
Posts	8	D°	24 D°	12 - 12
lower Interties	8	D°	7 F. 4 In.	9½ - 5½
2 Storey D°	8	D°	6 F. 5 In.	9 - 5½
Crooked D°	8	D°	5 F. 9 In.	8 - 7

Lower story from foot of Posts to uper side of Interties 9 Feet 2 In.

Second story from uper side of lower to top of uper D° 8 Feet

Third D° from uper side of second to top of crookd D° 6 Feet

Head of Posts to be left 7 Inches above the top of the Interties

2 Beams for top of Mill	12 feet long	9 Inches	by	9
1 D° for D°	15	D°	9	by	10
1 for tail Beam	11	D°	9	-	10
1 of white oak for head	10	D°	12	-	14

Trundlehead spindle 12 Feet long 7 by 7 Inch

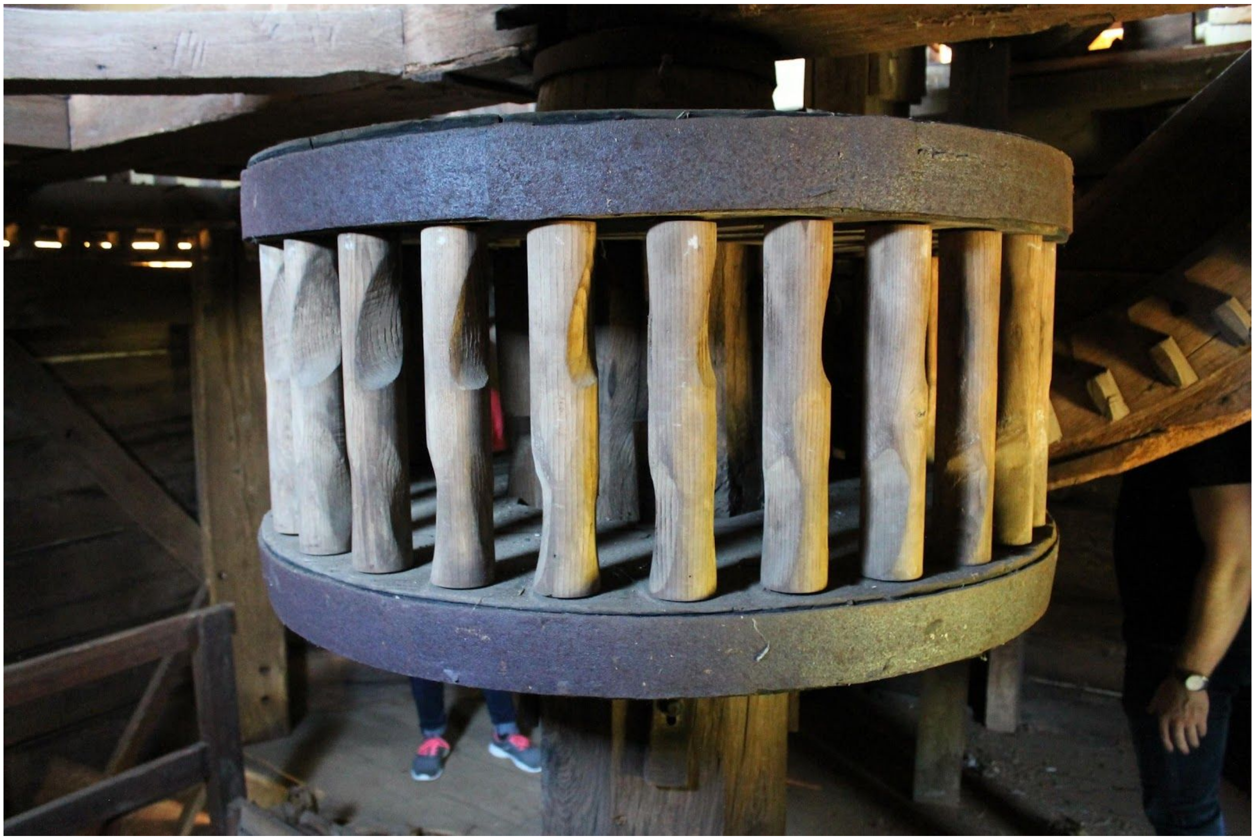
44 Coggs 5 I. long for (bolt?)
2 String peaces for uper flore to lay on
8 Croked
Say 8 for Scantling

APPENDIX II continued

	feet	In.	long	by	Square
2 Stone beams	9	6		12	15
4 Posts under Stone beams	9	6		5	10
Uper rim 7 I. across 6 up and down				6	7
Shaft	15	6		20	20
Cogg Wheel armes	9			4	9
Cogg wheel Cants				4	18
Ditto facing				5	9
2 String beams				10	9
80 Coggs	1	1	4 of them 18 long	1¼	3¼
96 Ditto		10		2½	3¼
12 rounds for trundlehead	1	7	Diameter		2¼
head of trundlehead	12			4	6
Stocks	32				

Appendix C: Photographs of the Windmill

This appendix contains the photos we took on our visit to the Shelter Island Windmill on September 28, 2019.



Appendix D: System Design Budget

This appendix contains the expected budget for implementing the system design we have recommended for the Shelter Island Windmill.

Generator system

- AC Generator squirrel-cage induction, doubly fed induction; $200
- DC permanent magnet: $200-400
- AC to DC rectifier (to take in AC signal and input it into batteries)
- This seems to be done with the charge controller; charge controller $200.00
- Batteries for one day of continuous running; $4,390.00
- DC to AC inverter; $450.00: output is 110V or 220V,
  AC to AC with DC Link; $550

Total for Generator System: Around 6,000 dollars

Metering

- Single phase meter: $138.24 (inclusive of GST)
- Three phase meter: $235.04 (inclusive of GST)
- Reprogram fee compatible meter: $74.00
- Interval meter (commercial solar): $809.60 (inclusive of GST)
- Synergy REBS Application Fee: $26.10

Total Metering: Around 1,282.98 dollars

Controls

- Estimated to be around 4-10% of the cost of wind turbine, cost less of a determining factor when deciding controls compared to what will work with the system design

Safety and Lightning Protection

- Lightning protection systems cost less than 1% of the total capital expenses

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Appendix E: Energy Potential Calculations

This appendix features the calculations necessary to determine the approximate energy potential of the Shelter Island Windmill located at Sylvester Manor Educational Farm.

$$P_m = 0.5\rho\pi R^2 V_w^3 C_p \eta_{total}$$

$$\rho = 1.225\frac{kg}{m^3},\ \mathit{This\ is\ the\ density\ of\ the\ air\ at\ Sea\ level}$$

$$R\ = 8.5m,\ \mathit{Rotor\ radius}$$

$$V_w = 3.43\frac{m}{s},\ \mathit{This\ is\ calculated\ below,\ see\ below}$$

$$C_p = 0.2,\ \mathit{On\ the\ high\ end\ for\ dutch\ windmills\ could\ use\ further\ investigation}$$

$$P_m = 0.5\ (1.225) * \pi * 8.5^2 * 3.43^3 * 0.2\eta_{total}$$

$$P_m = 1122\eta_{total}\ \ Watts$$

$$P_m = 1122(0.98 * \eta_{gears})\ \ Watts$$

<u>Calculating the wind velocity</u>

$$V_2 = V_1\left(\frac{Z_2}{Z_1}\right)^{\alpha}$$

$$V_1 = 3.71\frac{m}{s},\ \mathit{found\ from\ nearby\ weather\ station}$$

$$Z_1\ =\ 10\ m,\ \mathit{Airport\ standard\ for\ measuring\ wind}$$

$$\alpha =\ 0.2,\ \mathit{found\ on\ engineering\ toolbox\ for\ nearby\ bushes\ with\ some\ trees}$$

*Using the equation above to calculate the average wind velocity over the 17 m profile that the sails create.

$$V_2 = \frac{1}{17}\int_0^{17} 3.71 * \left(\frac{Z_2}{10}\right)^{0.2} dz$$

$$V_2 = 3.43\ \frac{m}{s}$$

<u>References</u>

Shelter Island Wind Forecast, NY 11964 - WillyWeather. (n.d.). Retrieved from https://wind.willyweather.com/ny/suffolk-county/shelter-island.html.

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Sarkar, A., & Behera, D. K. (2012). Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy. International Journal of Scientific and Research Publications, 2(2). Retrieved from http://www.ijsrp.org/research_paper_feb2012/ijsrp-feb-2012-06.pdf.

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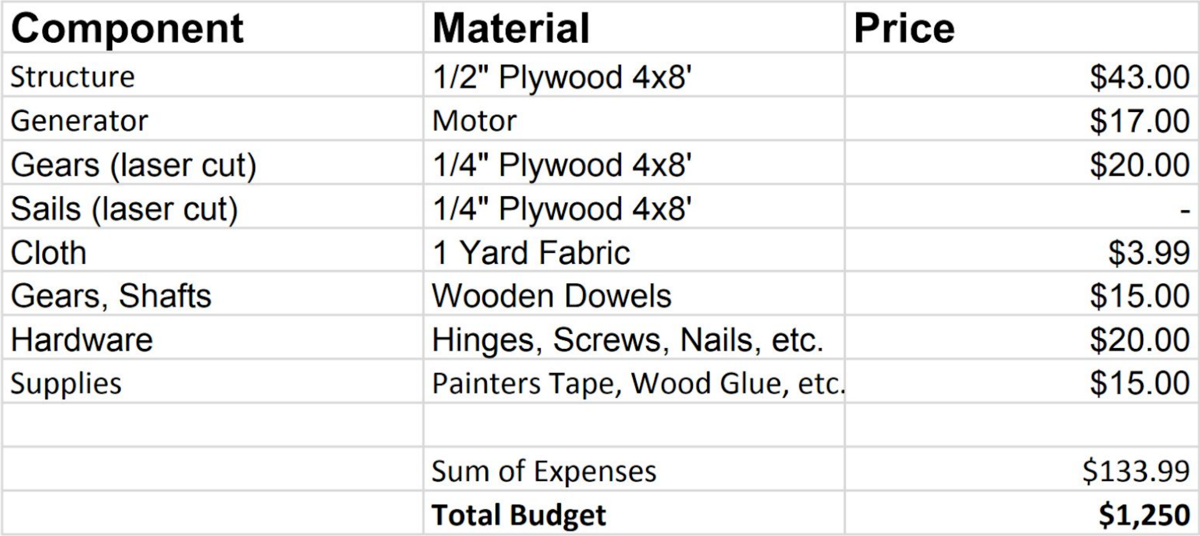
Appendix F: Scale Model Budget

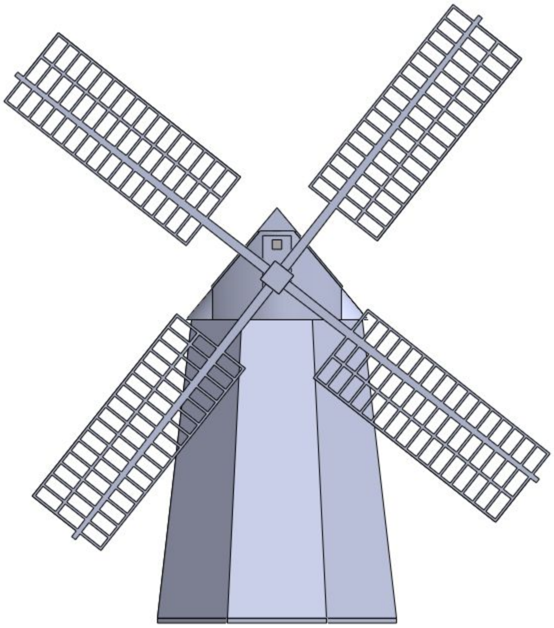
This appendix will contain the budget for the scale model that we have constructed for the purposes of this project.



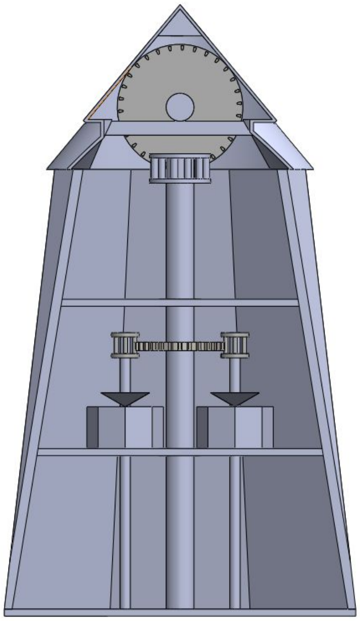
Component	Material	Price
Structure	1/2" Plywood 4x8'	$43.00
Generator	Motor	$17.00
Gears (laser cut)	1/4" Plywood 4x8'	$20.00
Sails (laser cut)	1/4" Plywood 4x8'	-
Cloth	1 Yard Fabric	$3.99
Gears, Shafts	Wooden Dowels	$15.00
Hardware	Hinges, Screws, Nails, etc.	$20.00
Supplies	Painters Tape, Wood Glue, etc.	$15.00
	Sum of Expenses	$133.99
	Total Budget	**$1,250**

Appendix G: Solidworks Assembly and Components

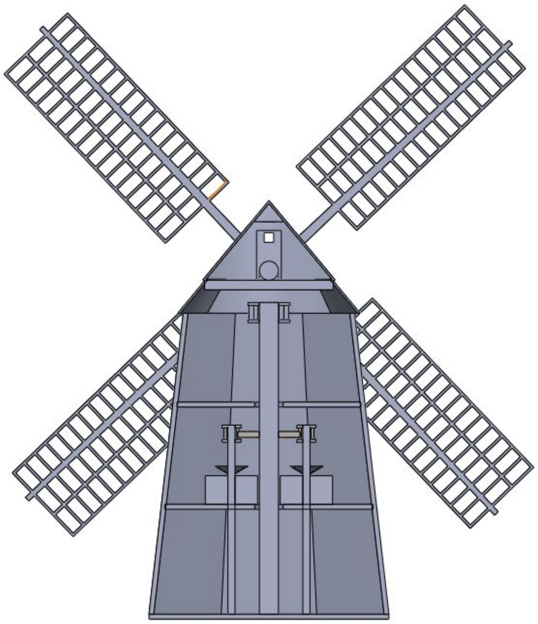
This appendix contains the Solidworks assembly of the scale model as well as a detailed view of each component.



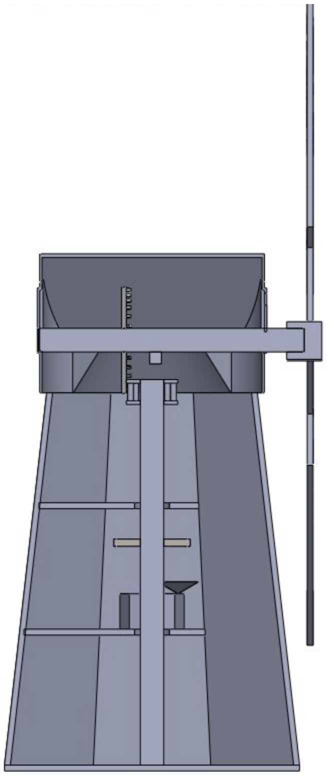
Front View Including Sails



Front Section View Including Gears



Back Section View Including Gears and Blades



Side Section View Including Sails and Gearing

Appendix H: Mechanical Calculations for a Dutch Windmill

This appendix contains the mechanical calculations for the Shelter Island Windmill based on the efficiency of a dutch windmill. The findings are the RMP, the omega, and the torque at the maximum and relative minimums for the windmill to operate at a wind speed of 3.43 m/s which is an average value from local wind data.

The RPM was calculated by the equation;

$$RPM = \omega * \frac{2\pi}{60}$$

The equation used for the omega which has the units rad/s was;

$$\omega = \frac{V}{r}$$

The equation used to calculate torque was;

$$\tau = \frac{P}{\omega}$$

To calculate the values for the system we followed the steps below starting with the calculations for the sails and continuing down through the system. We assumed a radius of 8.5 m for the sails. The values were then found for the sail and carried down to the wind shaft which requires the same torque and power as the sails. The wind shaft is then connected to the brake wheel which also requires the same torque and power. The gear ratios are then used to find the RPM, the omega, and the torque for the rest of the system. The gearing ratios are located below.

Gear Ratios for the Mechanical System in the Shelter Island Windmill	
Brake wheel : Wallower	(60:28) = (15:7)
Wallower : Bolter Gear 2	(28:19)
Bolter Gear 2: Bolter Gear 1	(19:28)
Great Spur Wheel : Lantern Pinion 1	(52:14) = (26:7)
Great Spur Wheel: Lantern Pinion 2	(52:13)

Table 1: Gear Ratios for the Mechanical System in the Shelter Island Windmill

<table>
<tr><th colspan="8">Calculations for the Relative Max for a Dutch Windmill</th></tr>
<tr><th colspan="8">The assumptions: tip speed ratio = 2.5, # of blades = 4, Blade efficiency = 0.2, air density =1.25 kg/m^3, wind speed = 3.43 m/s</th></tr>
<tr><td>Components</td><td>Tip Speeds (m/s)</td><td>Power (Watts)</td><td>Radius (m)</td><td>Gear Ratio</td><td>RMP</td><td>Omega (rad/s)</td><td>Torque (N · m</td></tr>
<tr><td>Sails</td><td>9</td><td>1000</td><td>9</td><td></td><td>10</td><td>1</td><td>1000</td></tr>
<tr><td>Wind Shaft</td><td>4</td><td>1000</td><td>0.3</td><td></td><td>10</td><td>1</td><td>1000</td></tr>
<tr><td>Brake Wheel</td><td>0.9</td><td>1000</td><td>1</td><td>2</td><td>10</td><td>1</td><td>1000</td></tr>
<tr><td>Wallower</td><td>4</td><td>1000</td><td>0.6</td><td>2</td><td>20</td><td>2</td><td>500</td></tr>
<tr><td>Bolter Gear 1</td><td>6</td><td>1000</td><td>0.4</td><td>1</td><td>20</td><td>2</td><td>500</td></tr>
<tr><td>Bolter Gear 2</td><td>10</td><td>1000</td><td>0.3</td><td>1</td><td>30</td><td>3</td><td>400</td></tr>
<tr><td>Great Spur Wheel</td><td>1</td><td>1000</td><td></td><td>0.4</td><td>20</td><td>2</td><td>500</td></tr>
<tr><td>Lantern Pinion 1</td><td>5</td><td>1000</td><td>0.3</td><td>4</td><td>80</td><td>8</td><td>100</td></tr>
<tr><td>Lantern Pinion 2</td><td>2</td><td>1000</td><td>0.3</td><td>1</td><td>80</td><td>9</td><td>100</td></tr>
</table>

Table 2: Calculations for the Relative Max for a Dutch Windmill

<table>
<tr><th colspan="8">Calculations for the Minimum Tip Speed</th></tr>
<tr><th colspan="8">The assumptions: tip speed ratio = 2, # of Blades = 4, Blade efficiency = 0.12, air density =1.25 kg/m^3, wind speed = 3.43 m/s</th></tr>
<tr><td>Components</td><td>tip speeds (m/s)</td><td>Power (Watts)</td><td>radius (m)</td><td>Gear Ratio</td><td>RMP</td><td>Omega (rad/s)</td><td>Torque (N · m)</td></tr>
<tr><td>Sails</td><td>7</td><td>700</td><td>9</td><td></td><td>8</td><td>0.8</td><td>800</td></tr>
<tr><td>Wind Shaft</td><td>3</td><td>700</td><td>0.3</td><td></td><td>8</td><td>0.8</td><td>800</td></tr>
<tr><td>Brake Wheel</td><td>0.7</td><td>700</td><td>1</td><td>2.1</td><td>8</td><td>0.8</td><td>800</td></tr>
<tr><td>Wallower</td><td>3</td><td>700</td><td>0.6</td><td>2.1</td><td>20</td><td>2</td><td>400</td></tr>
<tr><td>Bolter Gear 1</td><td>5</td><td>700</td><td>0.4</td><td>1</td><td>20</td><td>2</td><td>400</td></tr>
<tr><td>Bolter Gear 2</td><td>9</td><td>700</td><td>0.3</td><td>1.5</td><td>20</td><td>3</td><td>300</td></tr>
</table>

Great Spur Wheel	1	700		0.37	20	2	400
Lantern Pinion 1	4	700	0.3	3.7	60	6	100
Lantern Pinion 2	1	700	0.3	1.1	70	7	100

Table 3: Calculations for the Minimum Tip Speed

Calculations for the Minimum Blade Efficiency							
The assumptions: tip speed ratio = 4.1, # of Blades = 4, Blade Efficiency = 0.01, air density =1.25 kg/m^3, wind speed = 3.43 m/s							
Components	tip speeds (m/s)	Power (Watts)	radius (m)	Gear Ratio	RMP	Omega (rad/s)	Torque (N·m)
Sails	10	60	9		20	2	30
Wind Shaft	7	60	0.3		20	2	30
Brake Wheel	1	60	1	2.1	20	2	30
Wallower	6	60	0.6	2.1	30	4	20
Bolter Gear 1	9	60	0.4	1	30	4	20
Bolter Gear 2	20	60	0.3	1.5	50	5	10
Great Spur Wheel	2	60		0.37	30	4	20
Lantern Pinion 1	9	60	0.3	3.7	100	10	4
Lantern Pinion 2	3	60	0.3	1.1	100	10	4

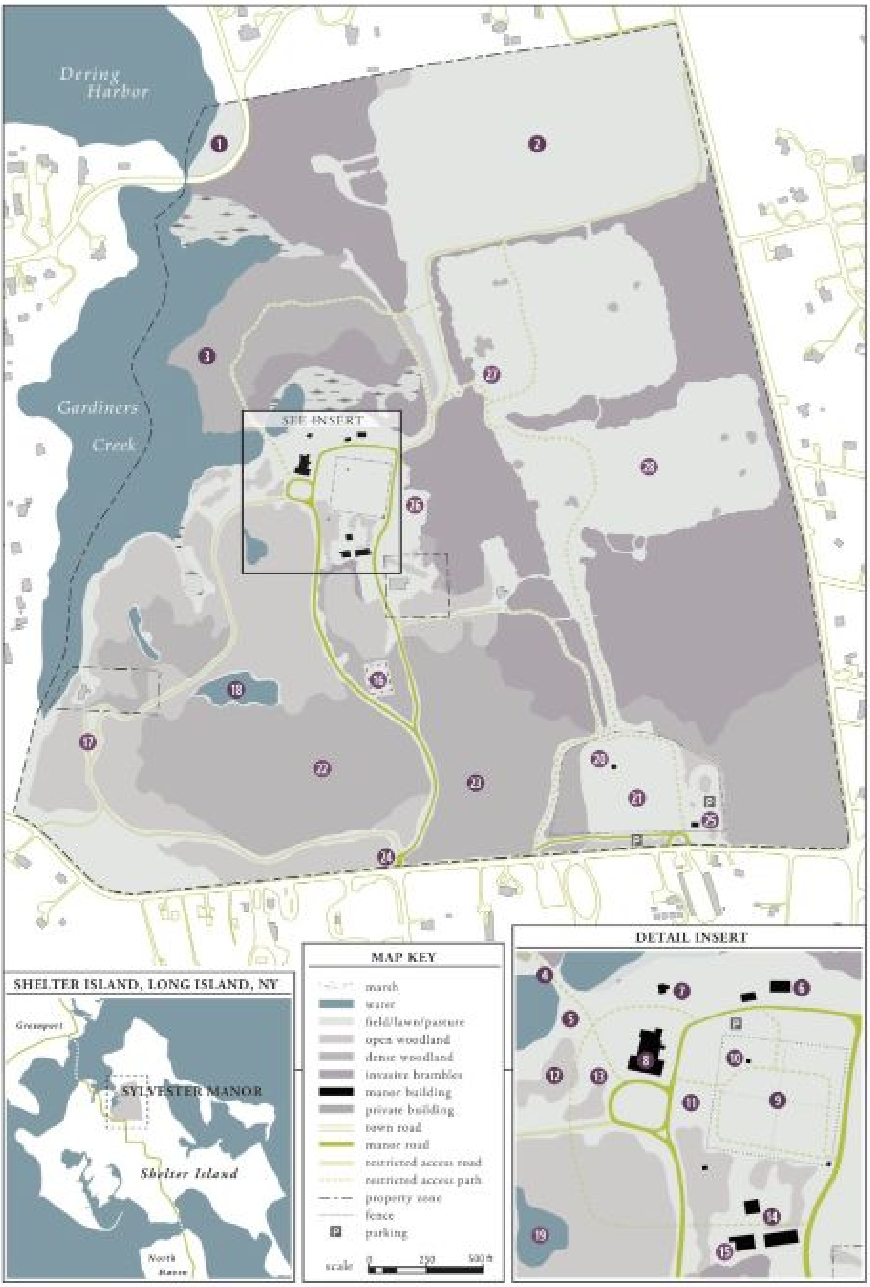
Table 4: Calculations for the Minimum Blade Efficiency

Power Efficiency 39%		
Component	Power (Watts)	Torque (N · m)
Wind Shaft	1000	1000
Lantern Pinion	390	39

Table 5: *Calculations for the Relative Max for a Dutch Windmill at 39% Efficient*

Appendix I: Map of Sylvester Manor Educational Farm Grounds

This appendix contains a map of the Sylvester Manor Educational Farm grounds and a detailed list of each numbered location. The Shelter Island Windmill can be found at location 20 (Art & Architecture Quarterly, 2015).



“1 — Dering Harbor Beach is named for Thomas Dering, Manor Proprietor from 1752 to 1785 who figured in the Revolutionary War. In the 1600s, European ships anchored off the beach, and row boats ferried supplies to and from the Manor’s core.

2 — At 26-acres, the Big Field has offered an agricultural vista for centuries and is a remnant of a much larger farm. It was preserved through the sale of development rights in 2012, protecting over 83 acres of productive farmland including this field and the Old Fields to the south, see 14 below.

3 — Native Manhansett tribespeople maintained a small village on Manhansett Neck after Nathaniel Sylvester arrived in 1652 on lands inhabited for millennia. In 2009, Sylvester Manor owner Eben Ostby donated a permanent conservation easement on 22 creekfront acres to Peconic Land Trust.

4 — The Land Bridge was reconstructed around 1909 on the site of a former 17th-century tide-powered sawmill spanning a neck of Gardiners Creek.

5 — Goods brought over in ships from the Netherlands, England and Barbados were transferred ashore by rowboat at the Historic Water Landing. Grain, barrel staves, salt, meat, and livestock were shipped out around the Atlantic, to local ports, the Caribbean, and Europe.

6 — The Engine Barn is home to tractors, chainsaws, mowers, leaf-blowers and the like.

7 — The Furnace House, believed to be an 18th century building, was once home to Eben Norton Horsford’s summer chemistry studio.

8 — The 1737 Manor House was built by Brinley Sylvester (1694-1752) to serve as his home and the symbolic center of Shelter Island. Designed in the new Early Georgian style of Newport, Rhode Island, the house replaced the original 1652 Manor House, a First Period building with a red tile roof. A Historic Structure Report completed in 2013 confirms that beams from the original Manor House were repurposed in the 1737 attic.

9 — The Historic Garden, linked to Brinley Sylvester’s time, features a long axial path off the SE corner of the house. The garden was divided into sections for fruit trees, vegetables, flowers and shrubs. The original beds were redeveloped as tastes and needs changed, most notably by Cornelia Horsford and Alice Fiske. Volunteer efforts to revive the garden are underway.

10 — The 18th Century Privy in the garden is a four-seater outhouse with one tot-sized training seat. Gardeners may have used “humanure” from the privy for compost.
11 — Tradition has it that Nathaniel and Grizzell Sylvester brought the first boxwoods to America. The Boxwoods on the lawn may be scions of the original specimens, and can be traced back at least to the late 18th century.

12 — The enormous Copper Beech on the back lawn was a gift to the Manor from Asa Gray in the mid-1800s. Gray, called “the father of American botany,” wrote the first standard textbook on the subject and introduced Darwin’s theory of evolution to this nation. Please do not climb on this very old and fragile tree.

13 — The 17th-century English maritime Cannon was unearthed by landscapers in the 1950s. It was buried, according to legend, to hide the manor’s British ties from Dutch soldiers who circled the house in 1674 during the 3rd Anglo-Dutch War.

14 — The Long Barn and Small Barn contain the Manor’s woodshop, field office, tool storage supply depot and storage space. This area has been the center of our working farm for over 100 years.

15 — Originally used as a milking parlor for heritage cattle, the Benjamin Glover Barn shelters our collection of old farm tools, vehicles, and furniture.

16 — The “Burying Ground of the Colored People of Sylvester Manor since 1651”, so commemorated in 1884 by the Horsford family, reportedly contains the remains of as many as 200 Native Americans and enslaved Africans and their descendents. Sacred ground, the plot is fenced but no gravestones exist, and the identities of those buried here are not known. In 2013, archaeologists conducting ground penetrating radar surveys confirmed multiple burials at the site.

17 — The Quaker Cemetery Monument commemorates the role Nathaniel Sylvester, one of the earliest Quaker converts, played in sheltering early Friends from the Puritan persecutions in the 1650s. Present-day Friends now hold Meetings here weekly in spring, summer and fall. The adjacent Creek Cottage is a private residence, built in the 1740s to house the Island’s first minister.

18 — Pepperidge Pond is named for the tall Nyssa Sylvatica trees growing on its south bank.

19 — Daffodil Pond is spring-fed and was probably used to water Nathaniel Sylvester’s livestock. Each spring, the south-facing bank sprouts in thousands of daffodils.

20 — The 1810 Dominy Windmill was used to grind wheat into flour for over 100 years. Built on the North Fork of Long Island, it was brought by barge and ox-team to the center of Shelter Island in the mid 1800's. It was last used to grind flour during food shortages in World Wars I and II.

21 — The Windmill Field is home to our market garden. Over 80 vegetable varieties are grown here, and are sold at our farmstand, to restaurants, and to our Community Supported Agriculture subscribers, who help fund the farm early in the season and share the bounty that unfolds.

22 — The Pine Forest was planted around 1900, at a time when it was believed that pines scrubbed the air and were therefore a remedy for tuberculosis.

23 — The Oak Forest, a mixed hardwood forest of mostly second-growth trees, is the largest woodland at the Manor and runs from the Quaker Cemetery all the way to the Windmill Field. Stands of white and red oaks attracted Nathaniel Sylvester to Shelter Island for their utility in crafting the barrels so indispensable to his partners in the West Indies, used to ship sugar, rum, and molasses.

24 — The 1915 Manor Gates greet visitors from the center of town. Designed in Colonial Revival style by landscape engineer James Greenleaf, they provide a grand approach to the winding drive that ends at the front door of the Manor House.

25 — The Farmstand was built in 2011 using lightning-struck pines milled on the property. Its mortise and tenon timber frame echoes technologies employed in the Windmill and Manor House. In 2013, the Farmstand was enclosed and expanded in response to growing needs, using trees felled by Superstorm Sandy.

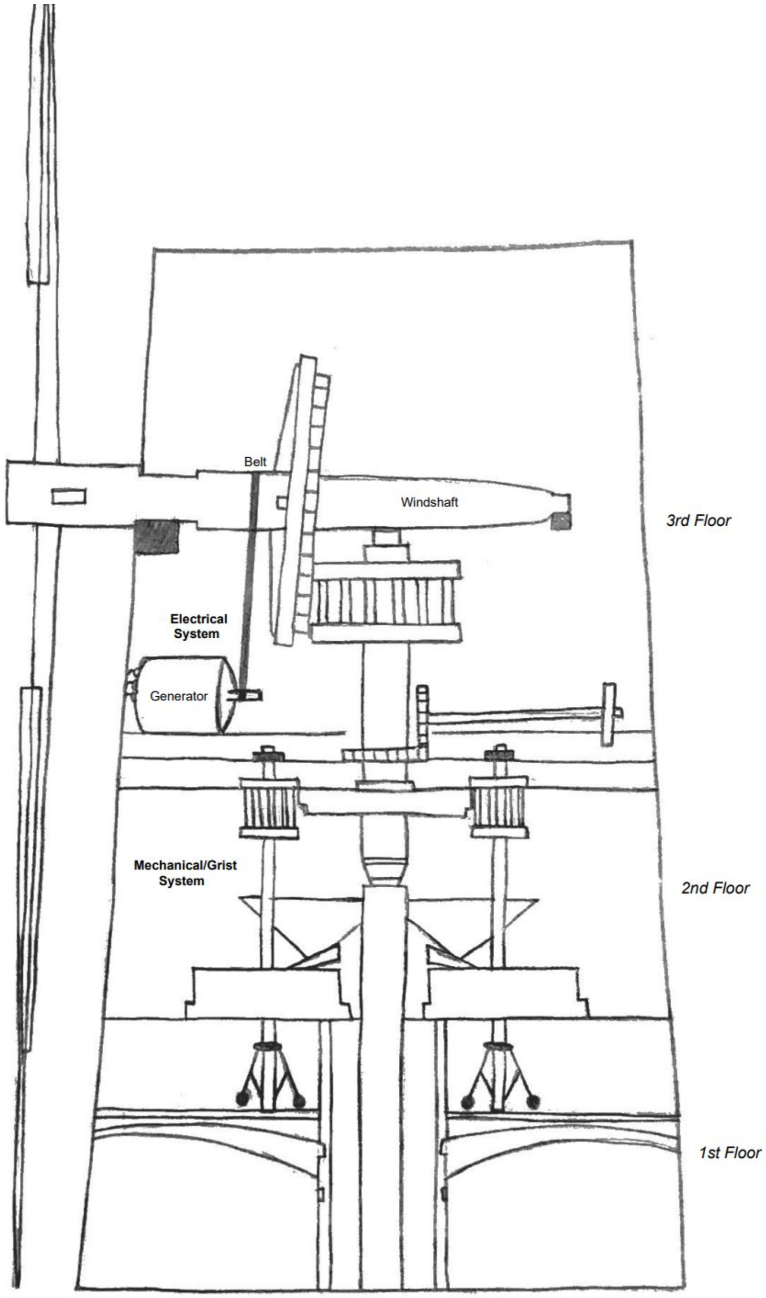
26 — Our Greenhouse is a simple way to mitigate our climate in winter and spring. We start our seedlings here — over 100,000 per year.

27 — The Watermelon Patch is, we believe, one of the oldest continuously cultivated fields at the Manor.

28 — Work continues in our Oldfields area in an effort to revive historic farmland, saving it from the choke of invasive vines. In early 2013, 44 acres of historic farmland were cleared and are being returned to active agriculture, offering exciting new possibilities for pasture restoration, cultivation and archaeological study."

Appendix J: Electro-Mechanical System Design Diagram

This appendix contains a diagram of the proposed electro-mechanical system design for the Shelter Island Windmill.



Appendix K: Educational Poster

This appendix contains the educational poster to accompany the scale model in Sylvester Manor Educational Farm's educational efforts.

SPIN THE SHELTER ISLAND WINDMILL

BUILT

in 1810 by Nathaniel Dominy and his team of carpenters in 186 days

WIND POWER

has produced over 300 *billion kWh* of energy in 1 year in the U.S

SCALE MODEL

includes gearing and electrical system, spin and watch it light up!

BACK ON THE FARM

the energy produced can power lights for the windmill, greenhouse, or farmstand!

MECHANICAL ENGINEERING STUDENTS AT WORCESTER POLYTECHNIC INSTITUTE

"This project has empowered us to use our skills to make an impact. We are grateful for the opportunity to work with such a dynamic, community-driven organization"

Carly Campbell **Anna Carriero** **Alaa Hassan** **Brandon Weyant** **Georgie Wood**