

Gateway Wind Turbine Design
Major Qualifying Project Report:
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By

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Abstract

This project developed a framework to determine the feasibility of retrofitting a wind turbine onto a pre-existing structure. After an initial screening based on a set of criteria, the framework then analyzed candidate's life cycle costs and structural effects on the building in order to determine a feasible turbine. The framework was then applied to the Gateway Park Phase II building to investigate the possibility of retrofitting a wind turbine.

Capstone Design

The Accreditation Board for Engineering and Technology (ABET) has set standards to assure quality and stimulate innovation in applied science, computing, engineering, and engineering technology education. The ABET believes that, “Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political.”¹ This project fulfilled this requirement in that it addressed a number of these listed considerations.

Economic

As with many civil engineering projects, this project was constrained by economic feasibility. The design of the project accounted for cost of materials, as well as for the cost of installations and reinforcements as needed to complete the design. The maintenance costs and the economic benefit of the power produced were also calculated based on the expected lifetime of the turbine. The economic benefits were closely examined, and a final cost analysis showed the advantages of one retrofit design over another. The financial information gathered allowed for a final recommendation of the most suitable design.

Sustainability

The aspect of sustainability was a major driving force behind the inception of this report. With the available technology, it is rare to find a large modern building that is fully sustainable. Therefore, buildings are heavily reliant on non-renewable energy methods for powering their structure. This project aimed to decrease reliance on non-renewable energy by providing a source of clean power to supplement the building’s energy consumption. A completed design provided an option for a more sustainable building that can partially rely on sustainable energy.

Constructability

The turbine is expected to create a new source of point load, vibration, and torsion once it is retrofitted to the existing building. This could have resulted in the need for further reinforcement, depending on the design alternative at hand. Therefore, the constructability

¹ "ABET Vision and Mission." *ABET* - N.p., n.d. Web. 16 Oct. 2012. <<http://www.abet.org/vision-mission/>>.

constraint was a major point of consideration during the execution of the project. The group examined different methods for reinforcement that might be of greater ease than others are, as well as utilized standard turbine models to allow for construction that is more manageable.

Ethical

The American Society of Civil Engineers (ASCE) outlines a list of principles in their code of ethics by which every engineer should abide. The list of principles states that each engineer should “uphold and advance the integrity, honor and dignity of the engineering profession by:

1. Using their knowledge and skill for the enhancement of human welfare and the environment;
2. Being honest and impartial and serving with fidelity the public, their employers, and clients;
3. Striving to increase the competence and prestige of the engineering profession; and
4. Supporting the profession and technical societies of their disciplines.²”

This project upheld the same principles stated above throughout the scope of work, from initial conception through the final design completion.

Health and Safety

The structural analysis of the alternatives ensured that the existing structure remains safe and habitable. The group ensured that the structural integrity of the building could be upheld following turbine installation. Calculations were also performed to verify that column sizes were adequate to resist combined axial and flexural loads that are commonly experienced by a building structure. This required analysis of the loading caused by the turbine and ensuring factors of safety are satisfied. Through these steps, the health and safety of the public was made secure.

² ASCE. "Code of Ethics." *American Society of Civil Engineers*. N.p., n.d. Web. 16 Oct. 2012. <<http://www.asce.org/Leadership-and-Management/Ethics/Code-of-Ethics/>>.

Authorship

All members of the project group, Tyler Chambers, Ryan Garcia and Ryan McNamara, made an equal contribution to the major qualifying project. The following sections were contributed to by the specified person:

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Methodology	Ryan Garcia, Ryan McNamara
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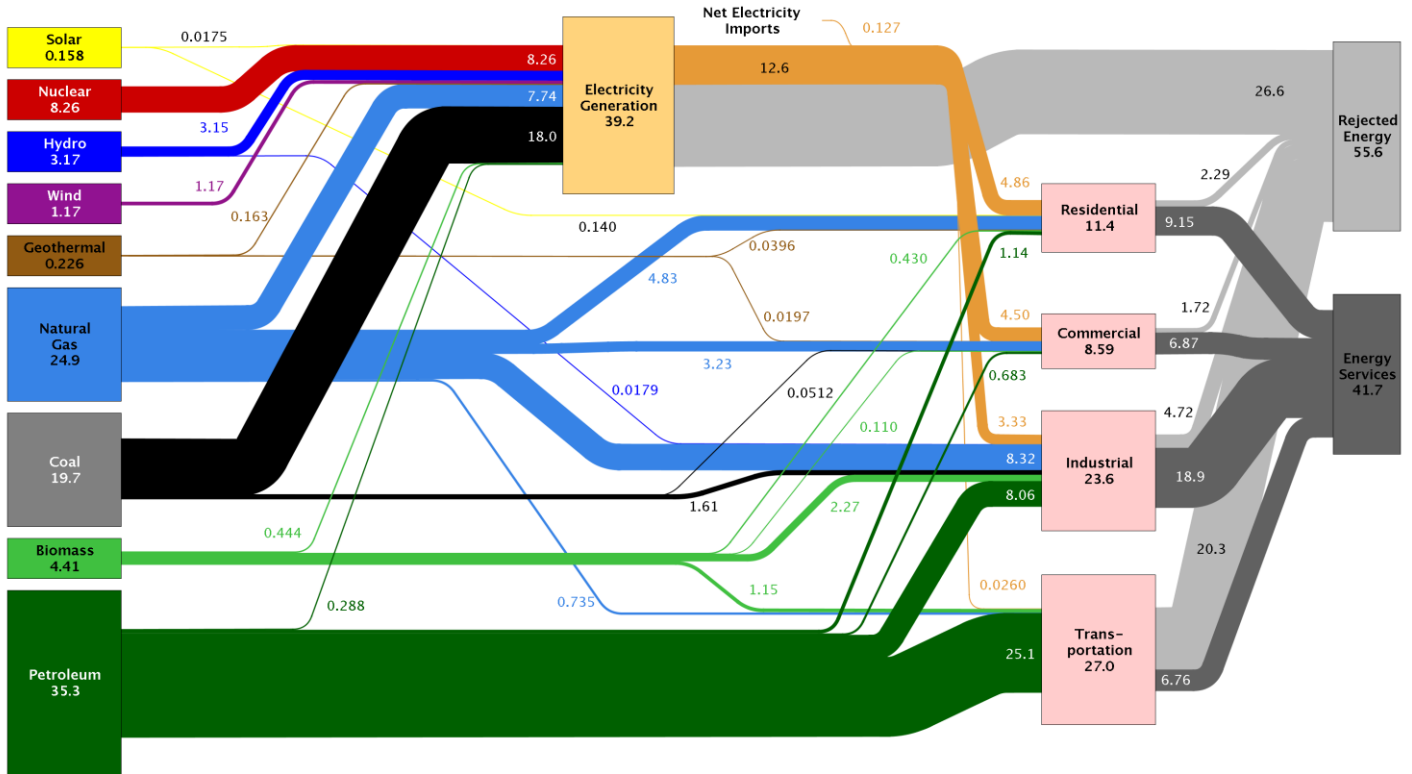
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Introduction

Rising oil costs, depleting coal and natural gas reserves, and increased carbon dioxide emissions destroying the ozone layer have led to an increased demand in renewable energy. Governments and corporations are trying to do their part to rely on “green” energy and decrease greenhouse emissions. Everyone wants to decrease their carbon footprint by polluting less, but how is this accomplished? One alternative energy source is wind energy. Typically, this is done by converting wind to electricity using wind turbines. Over the past thirty years, this technology has developed into one of the cleanest and least expensive energy alternatives. Wind energy currently provides only 1.17% of the nation’s total energy and is the second leading renewable energy source, after water energy, despite its negligible impact on the environment and long life of energy production, as seen in Figure 1. Petroleum and Coal, two of the worst polluting energy sources account for 55% of the total energy consumed in the U.S.³ As a technical institution of higher learning, it is WPI’s responsibility to be a leader in renewable energy, which the college has done well. Missing from WPI’s green energy plan, however, is a significant portion of wind energy. Wind energy has been previously used in Worcester, such as the Holy Name Catholic High School’s 242ft tall, 600kw, horizontal axis wind turbine that produces enough energy for 135 homes, or Wal-Mart’s 12 ultra-quiet micro-turbines. The addition of a clean energy generating wind turbine would be beneficial for the environment and reinforce WPI’s efforts to be a leader in sustainability.

³ "Estimated U.S. Energy Use in 2011." *Lawrence Livermore National Laboratory*. N.p., Oct. 2012. Web.

Estimated U.S. Energy Use in 2011: ~97.3 Quads



Source: LLNL 2012. Data is based on DOE/EIA-0384(2011), October, 2012. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Figure 1: U.S. Energy Use⁴

A new building in Gateway Park, simply called Phase II in this report, provides an outstanding opportunity for the application of a wind turbine. The building stands taller than most others around it and is in Worcester where wind speeds reach as high as 55 miles per hour. The O’Connell Development Group, the company constructing this 92,000 square foot building, located at 50 Prescott Street, intends to achieve a LEED (Leadership in Energy and Environmental Design) certification, much like most of WPI’s other buildings. State of the art technology in the sustainability field makes this site ideal for the investigation of a wind turbine retrofit. In this Major Qualifying Project, a framework was created for evaluating wind turbines on a building and the structural impact of a retrofit.

⁴ Lawrence Livermore National Laboratory. "Energy Flow." *Environment, Science, Technology & Health*. USEmbassy.org.uk, n.d. Web.

Background

It is important for a strong understanding of energy, structural, and financial components of a retrofit project to be developed prior to the execution of the steps in this project. An understanding of the core concepts involved in such a project allows for the methodology to be carried out fluidly.

Buildings and Power Consumption

Power consumed by buildings varies greatly depending on the use, location, and size. To encourage responsible energy consumption, a system was devised to give certification to buildings that successfully limited their power consumption known as LEED certification. The evaluation for LEED certification is essentially a point system where buildings gain points based on environmental impact, energy efficiency, waste minimization, and many more categories. One important category that buildings are evaluated on is how much renewable energy the building uses. The minimum renewable energy a building can utilize is five percent and a perfect score is at least twenty percent. The electricity consumption of the building being proposed for a wind turbine retrofit project is an important factor in determining just how much of an impact a retrofitted turbine may have in terms of cost and energy savings.

The building for which the group has chosen to investigate is located at 50 Prescott Street, as seen in Figure 2 below. The O'Connell Development Group (ODG) broke ground on 21 April 2011 for this building, which is 92,000 square feet and cost \$32 million. This building is four stories tall and will house several companies as well as "three [WPI] university programs: the new Bio-Manufacturing Education and Training Center (BETC); an expanded Fire Protection Engineering Department and research laboratory; and the graduate division of WPI's School of Business."⁵ While WPI owns the land upon which the building is built, ODG owns the building and will rent out space to its tenants, including WPI. This practice, while somewhat convoluted and complicated, protects WPI from the liability of finding tenants for the building and maintaining it. This building, much like nearly all of WPI's new buildings, is being built with the intent to achieve LEED (Leadership in Energy and Environmental Design) certification.

⁵ <<http://wp.wpi.edu/connection/2011/04/21/groundbreaking-ceremony-held-for-next-building-at-gateway-park/>>



Figure 2: The site of construction for the Gateway Part II building to be used for retrofit.

Wind Analysis

Wind turbines can be a great source of renewable energy. In order for these turbines to be effective, they must be located in an area with a sufficient amount of wind. According to the National Renewable Energy Laboratory wind power is considered in seven different classes according to wind speed, listed in Table 1. In order for a wind turbine to be effective, it must be in an area with a class 3 wind power at minimum⁶. This translates to approximately 11.5 mph at 10 meters above the ground, and 14.3 mph at 50 meters. Table 1 shows the seven different wind power classes with the wind power densities and wind speeds that are associated with the classes at both 10 meters and 50 meters above ground level, specific to Massachusetts.

⁶ Center, U. S. D. O. E. R. R. D. "Wind Energy Resource Atlas of the United States."
<<http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html>>

Table 1: Wind power classification system.

(b) Denotes speed is based on the average speed distribution of equivalent wind power density.

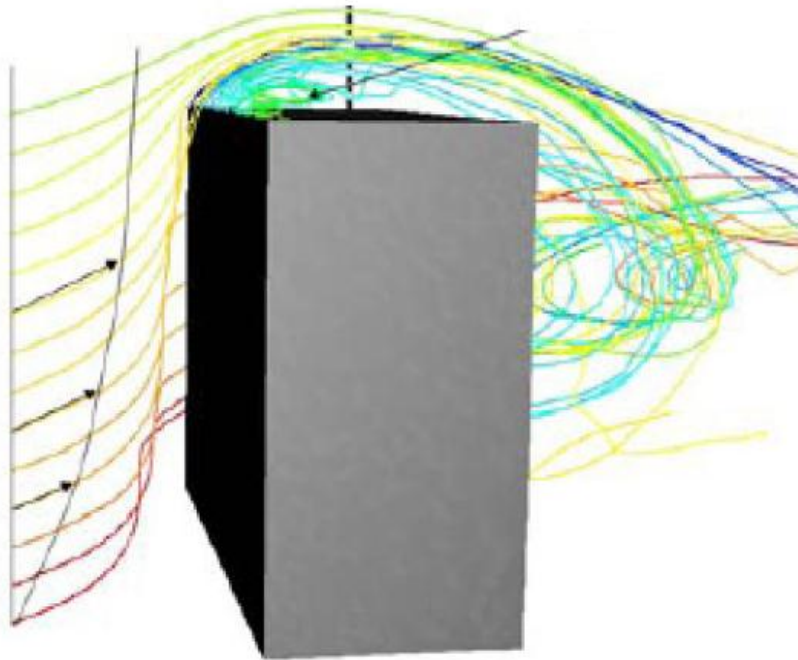
Wind Power Class [*]	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m ²)	Speed ^(b) m/s (mph)	Wind Power Density (W/m ²)	Speed ^(b) m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

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Wind, like most other things in nature, always looks for an outlet where there is the least resistance. This is often between hills, mountains, peaks, and in the case of Worcester, buildings. In a study of roof surface wind speed distribution on low-rise buildings, it was concluded that wind speeds could increase up to 60% along edges of buildings, corners, and protruding elements.⁸ High local wind speeds are caused by the contours that exist in these elements. Figure 3, below, represents the effects that a building has on a wind flow that is generally horizontal. There is a clear indication that increased wind speeds do exist over generally flat roofs. These high local wind speeds could produce energy if they are efficiently harnessed. Research into what altitudes above the building produce the most efficiency and into the exact locations for the placement of turbines could make wind energy a very viable option in the Gateway Park area.

⁷ Center, U. S. D. O. E. R. R. D. "Wind Energy Resource Atlas of the United States." <<http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html>>

⁸ Cochran, Leighton, Jon Peterka, and Russ Derickson. "Roof Surface Wind Speed Distributions on Low-Rise Buildings." *Architectural Science Review* 42.3 (1999): 151-60. Web.



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Figure 3: A diagram of wind speed above structures using Betz's Law.

Types of Wind Turbines

The two most common categories are HAWTs and Vertical Axis Wind Turbines (VAWTs). The advantages and disadvantages of each vary depending on a number of factors including wind patterns, site location, and power output requirements.

As it stands, the level of research in HAWTs is much greater than VAWTs, and as a result, horizontal turbines of comparable size generally generate a greater level of energy than vertical turbines. Table 2: Comparison of Vertical Axis Wind Turbines & Horizontal Axis Wind Turbines provides detailed information regarding important differences between large and small VAWTs and HAWTs.

⁹ Ragheb, M. "Wind Turbines in the Urban Environment." 10 March 2012. <https://netfiles.uiuc.edu/mragheb>. PDF. 23 Sept 2012.

Table 2: Comparison of Vertical Axis Wind Turbines & Horizontal Axis Wind Turbines

Turbine	Description	Rated Output	Design Life	Cut in Speed	Noise	Weight	Advantages	Disadvantages	Source
FLOWIND 19-m	Large VAWT	300 kW	15 Years	14.5 mph	60 db - Silent	33888 lb	-Effective in skewed wind flow -Not affected by crosswinds -Silent	-Experience high vibrations -Less research than HAWTs -Not self starting	Floating Wind Farms Corp
Quiet Revolution QR5	Small VAWT	6 kW	25 Years	8.9 mph	Silent	600 lb	-Generator near ground level for easy maintenance	-Lower operating range -Usually requires higher Cut-in speed	Vertical Axis Wind Turbines by M. Ragheb
V112-3.0 MW	Large HAWT	3000 kW	20 Years	6.7 mph	100 db (Hand Drill)	70,000 lb	-Self starting -Wider operating range -Stability from blades location	-Large, stiff blades result in noise -Heavy support design -Must be positioned upwind	Vestas Wind Turbines
Skystream 3.7	Small HAWT	2.1 kW	20 Years	6.7 mph	40 db (Normal Conversation)	170 lb	-Lower cost (high production volume)	-Difficulty operating at close to ground level	Southwest Windpower

Turbine Life Expectancy and Maintenance Costs

The life expectancy of a turbine is the first essential factor in analyzing the lifetime cost of a turbine. The expected lifetime is also used in determining energy production. A company in Denmark, called Wind Measurement International (WMI), conducted a study where they analyzed 5,000 wind turbines of different technological generations and determined the average lifespan. All turbines analyzed by WMI, despite when the design and technology for each turbine was developed, were all manufactured and installed in the same general timeframe, eliminating the discrepancy caused by advances in maintaining the structural and mechanical components and age of parts. This study found that modern turbines typically have 120,000 hours of power generation. This assumes approximately 66% operation time over their 20-year life spans, which accounts for periods of insufficient wind and inoperability due to maintenance.¹⁰ Lifetime energy production, the second essential factor, is the amount of money that will be saved by the electricity generated by the wind turbine throughout its lifetime. To determine this amount, simply multiply hours of operation estimated by Wind Measurement International by the hourly power generation specified by the turbine manufacturers. This determines the lifetime energy production of a turbine, which is then multiplied by the cost of power. The result is the total amount of money saved on electricity costs, due to energy production of the turbine. The third factor in the cost of the turbine is maintenance cost. In the same study, describe above, Wind Measurement International determined that the average maintenance costs for modern turbines ranged from 1.5% to 2.0% of the base cost each year over the 20 year lifespan. The total lifetime money generated by a turbine can be determined by subtracting the lifetime maintenance and base cost of each turbine from the total money earned throughout the lifetime of each turbine from its energy production, which produces a net value. At a certain point in a turbine's lifetime, major overhaul maintenance will be necessary. This may involve replacing major components in the gear box or power converter. WMI estimated the cost of this for most turbines to be 20% of its original cost. This extends the life of the turbine by approximately five to ten years. Depending on the energy production and original cost of the turbine, all of these factors can be used to determine whether the turbine is feasible and whether overhaul maintenance is profitable by using a life cycle analysis model. This model accounts for inflation and the year in which revenue or cost is incurred. The result is a current value of the investment.

¹⁰ "Wind Turbines." *Wind Measurement International*. N.p., n.d. Web. 18 Feb. 2013.

Structural Assessment

Before investigating the possibility of a turbine retrofit project, it is important to analyze the structure of the building to which it will be attached. Gateway Park II has a braced steel frame structure composed of W-shape beams, girders and columns. The bay sizes are 22' by 36'9" and 22' by 30'6" typically. In order to decrease eccentricity and high forces on small beams and girders, the ideal location on the roof for this turbine, due to its weight and size, would be on top of a column. There are, however, several factors that must be accounted for in the loading of columns.

The loads which typically affect a column are dead load, live load, wind load, and snow load. The dead load that the column must be able to support is the weight of the building located within the tributary area of the column. The weights of the building that are included are the weights of the floors which consist of all of the structural members that are on that floor (beams, girders, MEP, etc.). The dead load is a constant value that remains constant throughout the lifetime unless changes are made to the structural members. The dead load affects the structure by compressing the columns vertically.

For most buildings, the live load is determined by using building codes which assign live loads in the format of force per square foot. The live load can often be uneven and can have many effects on the structure. The live load, similarly to the dead load, acts vertically on the columns and compresses them.

The wind load is the force caused by environmental wind on the face of the structure. The wind load can be determined by multiplying the design wind pressure by the surface of the area exposed to the wind. The wind load that is applied to the face of the structure is then distributed laterally to each of the columns that are present at that face. The wind force can contribute to buckling of columns and could possibly cause flexural failure of columns in extreme cases.

The final load which most commonly affects columns is the snow load. The snow load is the weight of accumulated snow over an area. The snow load occurs at the top of the column which is most often the roof level. The snow load has to be taken into account especially in areas prone to a substantial amount of snow because the snow can cause a vertical compressive force on the column which in severe cases could greatly stress the column.

Design for Combined Axial and Flexural Loading

In construction, it is common for columns to be subjected to a combination of bending and axial forces, such as those mentioned above. These combinations can be examined under a

first-order analysis. Under a first-order analysis, loads acting as applied bending forces such as wind are taken into account. In practice however, it is favorable to extend one's analysis to a second-order analysis. This analysis encompasses the magnification effects that take place when a column deflects, causing a larger moment, which in turn causes larger lateral deflection. In addition, some additional bending force may be introduced by slight eccentricity of loading at the top of the column, since it is near impossible to center a load exactly on a column.¹¹ Lateral loads on a column become increased by eccentric compressive forces. The required total flexural strength of a member must at least equal the sum of the first-order and second-order moments. Chapter H of the *AISC Steel Manual, "Design of Members for Combined Forces and Torsion,"* provides a means to address members subject to axial force and flexure about one or both axes.

Design Load Combinations

It is important as a civil engineer to account for the different loads mentioned previously that a column may be exposed to, as they all impact the structure differently. When determining if a given column, beam, or girder can support the load it is exposed to, load combinations are used to ensure each type of load is properly accounted for. The American Society of Civil Engineers provides guidance for this method in the *ASCE 7-10 Manual, Chapter 2*. Common load combinations can be found in Figure 4. The coefficients for each equation shown in the figure are probability-based to provide for potential overload. In each equation, one load is considered to be at its maximum lifetime value, while the other loads present assume an "arbitrary point-in-time" value.

1. $1.4(D + F)$
2. $1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.8W)$
4. $1.2D + 1.6W + L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $1.2D + 1.0E + L + 0.2S$
6. $0.9D + 1.6W + 1.6H$
7. $0.9D + 1.0E + 1.6H$

Figure 4: ASCE Load Combinations¹²

¹¹ McCormac, Jack C., and Stephen F. Csernak. *Structural Steel Design*. Boston: Prentice Hall, 2012.

¹² McCormac, Jack C., and Stephen F. Csernak. *Structural Steel Design*. Boston: Prentice Hall, 2012

Some columns in buildings supporting a large tributary area may be permitted to have their live load magnitude decreased through the use of the live load reduction factor, KLL. This allows the civil engineer to decrease the live load in design calculations, permitting the use of smaller, lighter, and less expensive members. The reasoning behind live load reduction is that when a column supports a large tributary area, it is unlikely that the entire area will be subjected to the full designed live load at a single point in time. In addition to some special cases, the criteria for being able to use this method is that the live load element factor, found in Table 3, multiplied by the tributary area of the member must be greater than 400 square feet. Elements with less wind load, such as interior gravity columns, are at less of a risk of buckling, and therefore have higher values. The structural drawings created by Perkins + Will for the Gateway Park Phase II incorporated live load reduction.

Table 3: Live Load Element Factor, KLL obtained from Perkins + Will Structural Drawings

Element	$K_L L^2$
Interior columns	4
Exterior columns without cantilever slabs	4
Edge columns with cantilever slabs	3
Corner columns with cantilever slabs	2
Edge beams without cantilever slabs	2
Interior beams	2
All other members not identified including: Edge beams with cantilever slabs Cantilever beams One-way slabs Two-way slabs Members without provisions for continuous shear transfer normal to their span	1

Finite Element Analysis

When conducting a structural analysis it is often beneficial to use software that is capable of conducting a finite element analysis. Finite element method takes a complicated domain and sub divides it into a series of smaller regions in which differential equations are approximately solved. By solving for each of these individual regions, the overall behavior of the domain in its entirety can be determined.¹³ Finite element analysis can be utilized in situations where it would otherwise be challenging or impossible to calculate by hand. Modes of failure that were investigated through the use of ANSYS are shown in Table 4. Models created in ANSYS can be run through simulations that solve for a number of structural properties such as stress, strain, and deformation.

¹³ "Finite Element Method 1. Basic Definition." *Scribd*. N.p., n.d. Web. 10 Oct. 2012.
<<http://www.scribd.com/doc/25520844/Finite-Element-Method-1-Basic-Definition>>.

Table 4: Table of possible failure mechanisms to be investigated.

<u>Member</u>	<u>Loads to Consider</u>	<u>Possible Failure Mechanisms</u>
Columns	<ul style="list-style-type: none"> • Dead load- weight of turbine(turbine directly on top of column), self-weight, load from girders • Wind Load- moment caused by wind • Ice Load- weight of ice on turbine and snow on roof • Live load- load from girders 	<ul style="list-style-type: none"> • Lateral bracing failure • Buckling • Shear failure • Flexural failure • Compressive yielding

Methodology

When determining a suitable wind turbine to retrofit onto a building, several possible candidates based on power consumption of the building and wind in the region may be in question. Wind speed must satisfy the minimum wind speed of the turbine and the turbine should produce an adequate amount of energy, based on its cost. These candidates can then be ranked and stratified based on important initial factors in order to narrow the selection. For this project, the most important factors were wind requirements, power consumption, cost and community considerations. Candidates can be ranked in each category and then the best possible candidates can be selected to move on to final selection.

In final selection, it is important to analyze the turbines' structural impact on the building and to perform an in-depth cost analysis for the life cycle of the turbine. The structural impact should be estimated using local building codes and national building codes based on the material of the structure, such as ASCE. These estimates should then be backed-up by modeling the structure on a computer software and adding the loads caused by the column to analyze complete impact on the structure. Important aspects of structural impact to analyze are combined axial and lateral loading, P-Delta analysis, and structural reinforcement. An in-depth cost analysis should include turbine base cost, installation cost, maintenance cost, and revenue from power production throughout the life cycle of the turbine. These values should be determined using the present worth method, so as to determine the value of the overall investment.

Once the structural analysis and in-depth cost analysis have been performed for each turbine, it is time to select the best candidate. Generally, the turbine with the highest present worth investment value will be selected, but this must be weighed against the structural impact. If significant structural reinforcement is needed to hold the turbine or if P-Delta analysis

proves to be detrimental to the structure, then it may not be worth the added cost and danger associated with the additional stress on the building.

Initial Selection

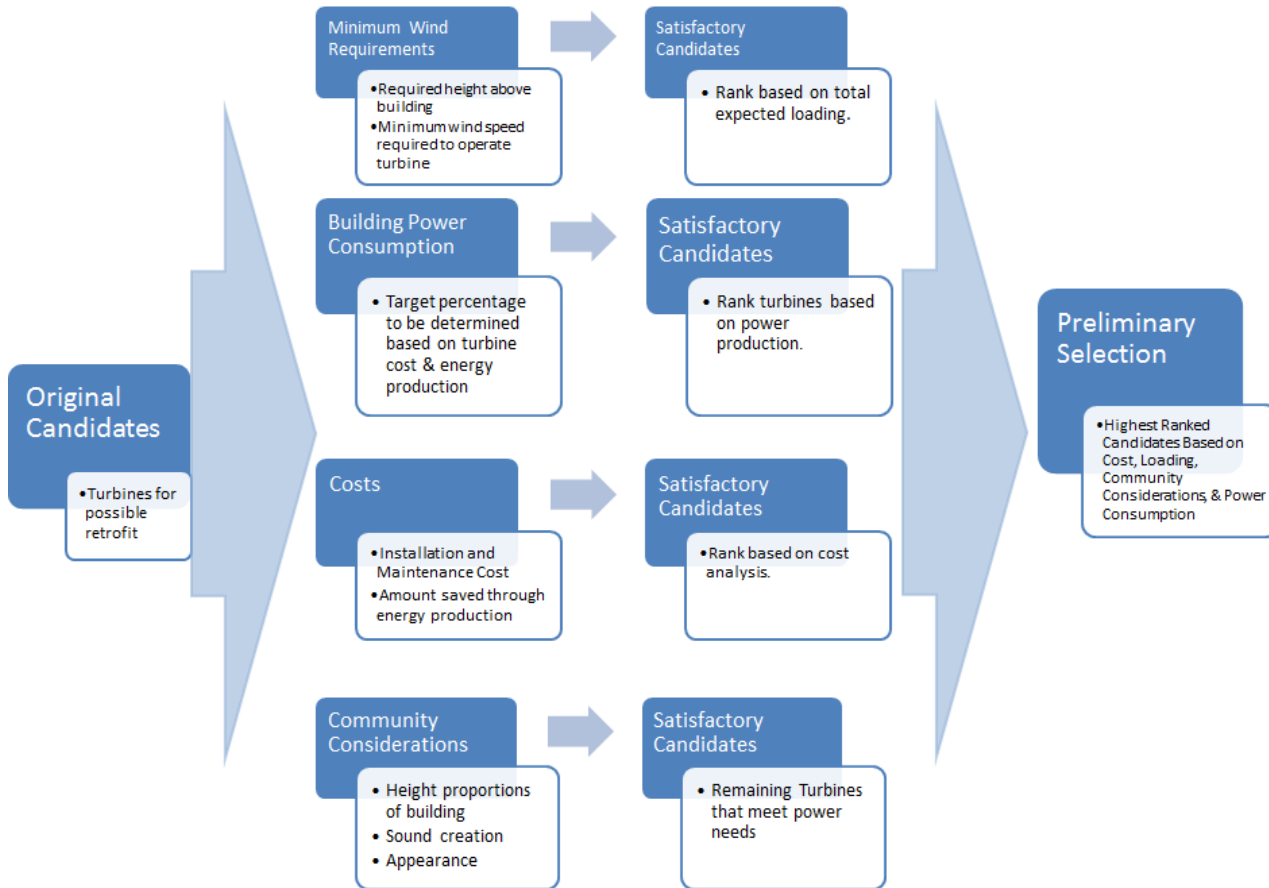


Figure 5: Flowchart illustrating initial turbine selection process.

Possible turbine candidates to be analyzed should initially be chosen based on size and energy production. The candidates for this project were a small, medium and large vertical axis wind turbine and a small, medium and large horizontal axis wind turbine. It is important to find turbines that have varying sizes and functions. In Figure 5, the initial selection process is shown. Each candidate was rated on four categories: minimum wind requirements, energy production in relation to the total energy needs of the structure to be used for retrofitting, base costs, and community considerations, as discussed later in “Ranking System.”

Minimum Wind Requirements

Each and every wind turbine has a minimum wind speed required before the turbine can begin operating, which can differ by model. This speed is commonly referred to as the “cut in speed.” Factors that can affect wind speed and potentially create problems depending on the cut in speed of a turbine include geographic location and height above the ground. Of particular use for determining wind using these factors was the Wind Energy Resource Atlas of the United States. This atlas provides wind speeds in geographic areas of the United States based on both location and height. In Worcester, MA the average wind speed year round is 11.5 mph¹⁴. At the edge of a roof, the air is extremely turbulent which could positively affect these wind speeds. Turbulent air is caused when the wind flows over the edge of the roof and separates into streams which cause the turbulent air. Vertical axis wind turbines are not affected by turbulent air, so their height above the building does not affect their efficiency. Horizontal axis wind turbines, however, are ineffective in turbulent air.¹⁵

As a result, calculations were performed to find a suitable height above the building for installation, in which the turbulent layer could be avoided. Wind streams generally pass at an upward angle of about 30° from the rooftops horizontal. Turbulent air is found below this stream, making it is possible to determine an appropriate height the structure for a horizontal axis wind turbine¹⁶. A model should be constructed from the knowledge that the airflow over a building creates a bubble of turbulent air twice the height of the building and extending horizontally 20 times the height of the building beyond it.¹⁷ A design program such as AutoCAD is able to scale these dimensions according to the structure proposed for retrofit. With the exact dimensions of this building an equation can be formulated through Microsoft Excel to calculate the height of the dome at any position of the building.

Determining Building Power Consumption

In 2006, the Energy Information Administration (EIA) began performing a survey of thousands of buildings throughout the United States in order to achieve an understanding of the country’s power consumption. The information they gathered was compiled into a series of

¹⁴ Center, U. S. D. O. E. R. R. D. "Wind Energy Resource Atlas of the United States."

<<http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html>>

¹⁵ "Vertical Axis Turbines vs. Horizontal Axis Turbines." *Crosswind Power*. N.p., n.d. Web. 5 Oct. 2012.

<http://www.crosswindpower.com/index.php?option=com_content&view=article&id=19&Itemid

¹⁶ Ragheb, M. "Wind Turbines in the Urban Environment." *uiuc*. N.p., 10 Mar. 2012. Web. 11 Dec. 2012.

<<https://netfiles.uiuc.edu/mragheb/www/NPRE%20475%20Wind%20Power%20Systems/Wind%20Turbines%20in%20the%20Urban%20Environment.pdf>>.

¹⁷ "Turbine Site Selection." *Solacity Inc.*. N.p., n.d. Web. 12 Oct. 2012.

<<http://www.solacity.com/SiteSelection.htm>>.

tables that organized energy consumption of buildings by location, building activity, building size and date of construction.¹⁸ According to the tables presented in the EIA energy survey, one can get an estimated number of the amount of electricity consumed on a yearly basis per square foot by the building in question. The resulting average kWh/ft² can then be multiplied by the building's square footage to obtain an estimate of total electricity consumed per year.

Ranking System

In order to objectively select the best candidates to proceed to a final selection, a rating system was developed. The group had to establish a scoring scheme for evaluating each turbine with respect to the four categories. Also, a weighting strategy was devised to combine the individual scores into a total score for each turbine. The scoring system that was devised was specific for each one of the four categories.

Each turbine was ranked in order of minimum wind speed, with the lowest minimum wind speed scoring the best. If there were a tie any category, the higher number was repeated and the corresponding subsequent ranks were skipped. For example, if the two best turbines had the same value, they were each awarded a six and the next best turbine was given a four.

Next, they were ranked on power production versus cost. Yearly power production was calculated and compared to the total yearly power consumption of the building. The yearly power consumption was then compared to the base cost of each turbine to determine energy production per dollar. Each turbine was then ranked in order of highest energy production per dollar. The last level of criteria for screening the four alternatives concerns potential noise pollution created as a result of turbine operation as well as aesthetic appeal in the urban environment.

Each turbine was ranked in three categories of community considerations: height, appearance, and noise. Noise and height were determined by contacting the manufacturers and each turbine was rated with lower heights and lower noise production rated highest. Appearance was rather subjective, but accounted for modern designs, small profiles, etc. The three categories were then assigned values of importance, referred to as 'weight.' The ranking in each category was multiplied by the category's weight and then the sum for each turbine was determined. The highest values were then assigned the highest rank for the overall community considerations category. Similar to community considerations, each category of analysis was assigned a weight. The ranking of each turbine was multiplied by the category's respective

¹⁸ EIA.gov. "Electricity Consumption and Expenditure Intensities for Non-Mall Buildings" Web. 20 Nov. 2012. <www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/2003set10/2003pdf/c14.pdf>.

weight and the sum was determined. The two turbines with the highest rankings were selected to be further analyzed.

Final Turbine Selection

Final turbine selection consisted of a structural analysis and cost analysis of the turbine candidates found most feasible after the completion of an initial selection. An outline of the final turbine evaluation framework is presented in Figure 6. Structural analysis consisted of determining loads already present on the proposed column for turbine placement, the turbine itself, and modeling these loads through use of structural software. A computer program known as ANSYS was chosen to analyze the loading. Use of this program involved the construction of the building geometry, application of the determined loads, and interpretation of the results produced through a solved finite element analysis. Cost analysis was comprised of several factors, including installation costs, turbine unit costs, and the cost of structural reinforcement if deemed necessary by a structural analysis.

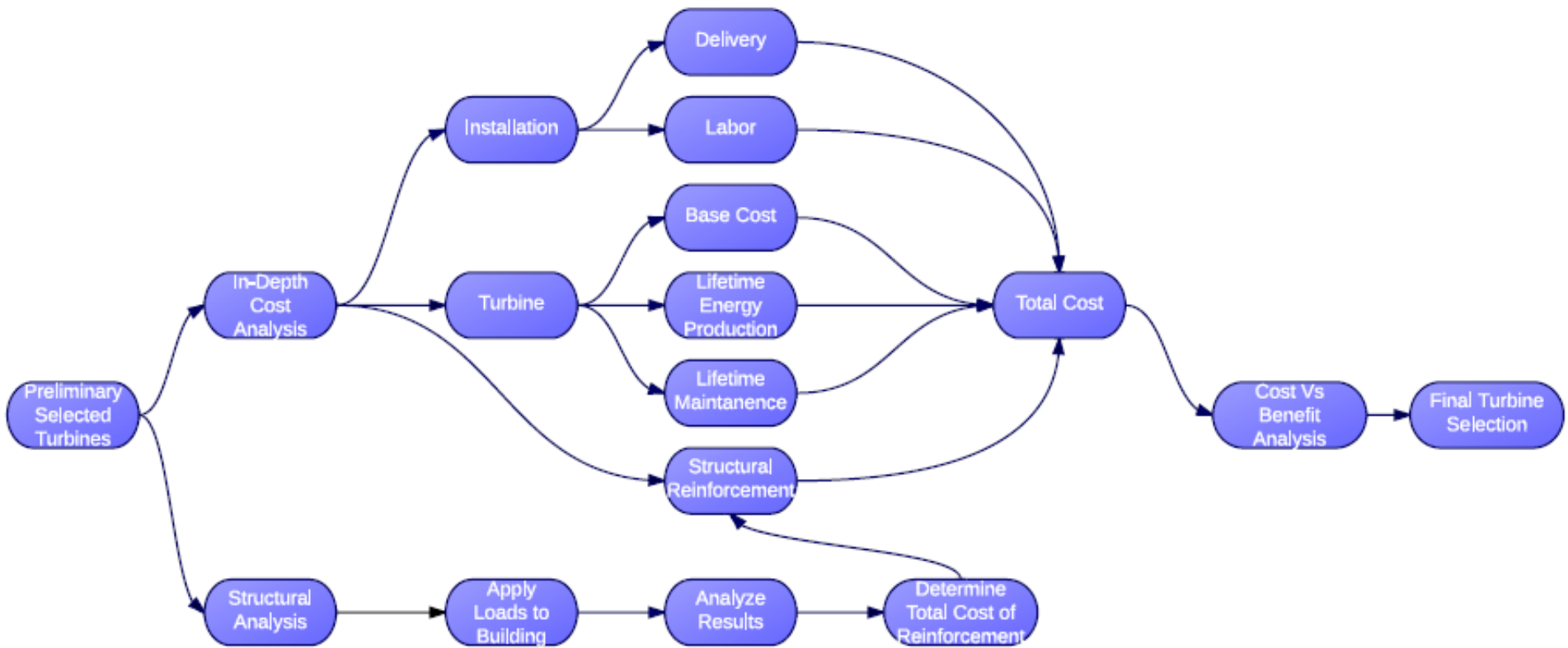


Figure 6: Final Turbine Selection

Structural Analysis

In order to assess the structural feasibility of a retrofitted turbine, the initial loading conditions on the column of the building to be retrofitted must be determined. There are axial and lateral loads that the columns in the building have been previously designed to withstand. From here on, this initial loading condition will be known as Scenario 1. Scenarios 2 and 3 consist of the initial loading conditions, in addition to the loading due to the first and second turbine candidates to graduate from the initial selection process.

Structural Loads

When applying a wind turbine to a column the main loads that had to be taken into account were dead load, live load, wind load, ice load, and snow load. The dead loads acting on the column were calculated by using the structural drawings by Perkins + Will. The weights of all of the structural members affecting each floor were added up and using the tributary area of the column the dead loads were calculated. Figure 7 at the end of this section shows the tributary area of the W12x53 column under investigation. The weights of the turbines used were found online through various brochures and specifications in catalogues made by the manufacturer of the turbines. The live loads acting on the column were also calculated by using the structural drawings by Perkins + Will. Standard values for live load based on floor and room use are listed in the structural drawings so using those values and the tributary area the live loads were calculated for each floor.

The wind loads acting on the column were calculated using *ASCE 7*. The calculation for the wind load was based on the 3 second wind gust, and the category II risk building. Since there are no codes specific to wind turbines the wind load acting on the turbine was calculated using *TIA/EIA-222* the structural standards for steel antenna towers and antenna supporting structures. The calculation for the wind load was based on the velocity pressure of the wind, the effective projected area of the structural components of the tower, and the gross area of one tower face.

Similar to the wind load on the turbine, the ice load acting on the turbine was calculated using *TIA/EIA-222*. The ice load was calculated using the nominal thickness of ice for the region, the mid height of the tower section, and the cross sectional area of the ice.

The snow load for the roof was calculated using *ASCE 7*. The snow load was calculated using the exposure factor, the thermal factor, importance factor, and the ground snow load. The projected horizontal area of the turbine is how the snow load was applied to the turbine.

The dynamic effects on the wind turbine also had to be taken into account. The dynamic effect which has the most effect when a turbine is retrofitted to a building is the frequency at which the turbine operates. If the frequency the turbine operates coincides with the natural frequency of the column then that could cause the column to fail. The frequency at which the turbine operates was determined through various brochures for the turbines found online. The natural frequency had to be calculated using computer software to ensure that those two frequencies do not coincide, which would have a destructive effect on the building's structure.

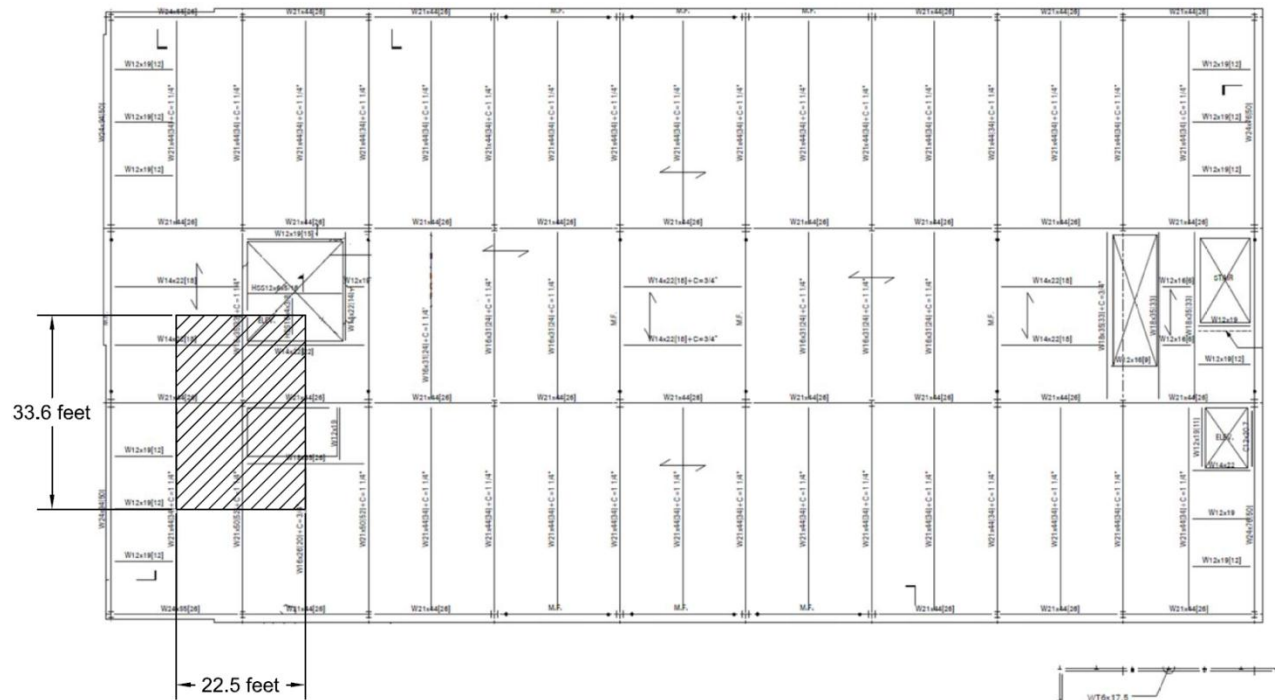


Figure 7: Size of the tributary area for the W12x53 column shown on a structural plan drawing by Perkins+Will.

ANSYS

A model of the column, in which the proposed turbine candidates were applied, was constructed using the computer software ANSYS. The exact dimensions, cross sectional area, and mechanical properties were inserted into ANSYS in order to conduct the structural analysis. The wind turbine was modeled as a hollow steel tower which is used to support the turbine. The tower is 3 feet in diameter with a thickness of 1 inch which are the actual dimensions of the tower used to support the wind turbine. The units within the model were all in inches and pounds to ensure accurate results. Interpretation of these units was necessary for presenting

the structural findings in the results. Using the model of the column and applying the calculated loads, the group was able to accurately analyze the impact that a wind turbine has on the column. Essential components of ANSYS models, such as the one created for this retrofit, are presented in Table 5.

Table 5: Components of ANSYS used in a column's structural analysis.

Essential Components of ANSYS Analysis	
Endpoints	Create nodes for the start and end of the column at each floor
Column	Connect the endpoints with a column
Properties	Input the mechanical properties of the column i.e. modulus of elasticity, Poisson's ratio etc.
Cross Section	Input correct dimensions of cross section
Meshing	Mesh the column depending on the number of floors in order to analyze the forces on each floor
Boundary Conditions	Apply the necessary boundary conditions specific to the building
Loading	Based on previous calculations apply the loads to the column where they are acting
Analysis	Solves for axial stress, flexural stress, axial strain, flexural strain, deflection

Cost Benefit Analysis

Many factors determine the cost of a retrofitted wind turbine. Installation costs of the turbine must be determined, such as delivery and labor. The operational cost of the turbine must also be determined, which include base cost and predicted maintenance. Also important in the operational costs is the revenue through energy production. In some cases, structural reinforcement of the building in order to support the turbine is necessary. All of these factors combine to determine the total cost.

Installation Costs

Installation costs of a turbine are a significant portion of the total initial cost. This includes several aspects, such as grid connection, transportation, consultancy services, and erection. The group analyzed a report titled *Estimation of Cost of Energy From Wind Energy Conversion Systems*, by John Olav Tande in order to determine installation costs. This report analyzed all of the above stated aspects of cost, as well as many others. The article also described in great detail the total cost analysis of installing and operating a turbine, including maintenance costs and energy production. Using the values in this article, based on cost per kilowatt of energy produced, it is determined that installation of a turbine costs approximately \$1200 per kilowatt it produces. The group determined the installation cost of each turbine by multiplying this rate by the energy it produces, as shown in its sales manual. These numbers were then added to a present worth spreadsheet to determine its total impact on the lifetime cost of the turbine.

Turbine Costs

Turbine cost is based on three aspects, base cost, lifetime energy production, and lifetime maintenance costs. The base cost of a turbine is the amount a company charges for all necessary parts, including the rotor, rotor blades, and tower but not including installation. This was determined by contacting the turbine manufacturing companies and researching their websites for each particular model considered by the group. Energy production was determined using the study by WMI, described in the background of this report, to determine total lifetime operating hours and multiplying it by the turbine energy production rate. This number was then multiplied by the total cost. This number was then input into a spreadsheet to determine the present worth of the energy produced.

The third factor in the cost of the turbine is maintenance cost. In the same study, describe above, Wind Measurement International determined that the average maintenance costs for modern turbines ranged from 1.5% to 2.0% of the base cost each year over the 20 year lifespan. The group assumed a 2.0% annual maintenance cost and multiplied this by the

base cost of each turbine. This number was then input yearly into the same present worth spreadsheet described above. Major overhaul maintenance was determined to be at the 20 year point and extend the life of the turbine by 5 years, based on the WMI study. Major overhaul maintenance is determined to cost about 20% of the base cost of a turbine, as determined by WMI. The cost of overhaul maintenance was determined and entered into the present worth spreadsheet. The total lifetime money generated by each turbine was determined by subtracting the lifetime maintenance and base cost of each turbine from the total money throughout the lifetime of each turbine from its energy production. The turbine with the highest present worth has the highest financial benefit and is the most valuable investment for WPI.

Gateway Park Phase II Retrofit Results

Initial Selection

Initial selection consisted of determining initial candidates and narrowing them down to two turbines to be analyzed in depth. These initial candidates were determined based on the minimum wind requirement, wind analysis of Worcester, and power consumption of the building. Candidates were then evaluated in wind requirements, cost, energy production and community considerations in order to find the best two candidates.

Minimum Wind Requirement

It is evident from Figure 8, constructed in accordance with data from the *Methodology – Minimum Wind Requirements* section, on the following page that HAWT's closer to the center of the building would have to be raised much higher to avoid the turbulent air than if they were placed closer to the edge. The equation provided in Figure 8 calculates this height based on the turbine's position.

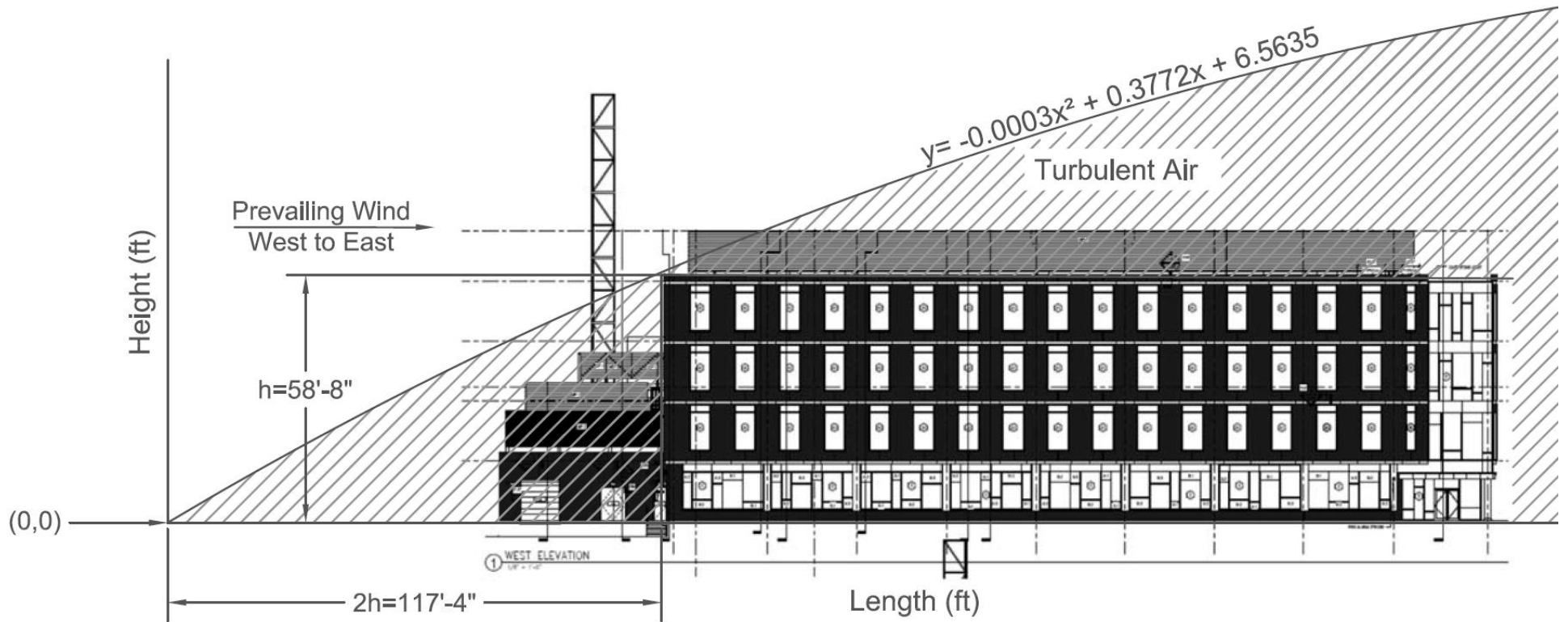


Figure 8: Diagram indicating the turbulent wind zone across the Gateway Park Phase II Building.

Gateway Building Power Consumption

The values obtained from the US Energy Survey table and used in the calculation of the Gateway Phase II energy consumption estimation are summarized in Table 6. The average kWh/ft² value was multiplied by the square footage of the Gateway Phase II building to obtain an estimate of 1173 MWh of electricity consumed per year.

In the initial screening, cost each year was compared to the estimated savings in energy per year due to the turbine. The calculations were performed using the current energy rate for Worcester, MA of \$0.17 kWh.¹⁹ With a building size of approximately 92,000 square feet, the group has estimated the Gateway Park Phase II building to cost \$199,410 per year in electricity.

Table 6: Building electricity consumption data taken from the Energy Information Administration survey.

Classification	Electricity Consumption (kWh/ft ²)
Building Activity - Educational	11.0
Floorspace - 50,001 to 100,000	13.0
Census Region - New England	10.8
Construction Date - After 2003	16.2
Average = 12.75 kWh/ ft ²	

Ranking Results

Each turbine was ranked and stratified based on minimum wind requirements, power production, cost and community considerations. Minimum wind requirement is the slowest wind speed that the turbine can function on. Each company provided the value for minimum wind requirement. As shown in Table 7: Initial Selection Factors, four turbines only needed 6.7mph winds, while the other two turbines needed 8.9mph and 14.5mph. These turbines were assigned a ranking, with 6 being the best (lowest minimum) and 1 being the worst. All turbines were then ranked on power production per base cost. The two large turbines were found to have the highest energy production per dollar, followed by the two medium turbines. Each turbine was then ranked based on community considerations, which consisted of height, appearance, and noise production. Method for determining ranking from community considerations can be found in the Ranking System section of the Methodology in this report.

¹⁹ Johanson, Caylee. "Wind Turbine for Residential Use" *Wentworth Institute of Technology*. 7 Feb. 2011. Web. <<http://myweb.wit.edu/hallowellz/Design1.html>>.

Each category was then assigned a weight, based on importance to the project. Each turbine was given a rank in each respective category, as shown in Table 8, which was then multiplied by the weight and summed. The highest combined value determined the two best candidates. The V112-3.0MW large horizontal axis turbine received a high rating but it was deemed not feasible because of its immense size in relation to the building. Its height was over three times that of the building, and it would not be feasible to install it on top of the Gateway Park Phase II. The Yenny and Aeolos medium turbines received the highest scores and were both deemed feasible. These turbines moved on to final selection.

Table 7: Initial Selection Factors

Turbine	Type	Min Wind Requirements		Power Production		Costs			Community Considerations	
		Satisfy Minimum Wind Requirement	Min Wind Speed (mph)	Power Production (MWh/year)	% of Building Usage	Base cost	Amount saved per year on energy production	kWh/\$	Sound	Aesthetics
Flowind	Large VAWT	N/A	14.5	2,629.74	224.19%	\$4M	\$447,056	0.657	See "Community Considerations" Table	
Quiet Revolution QR5	Small VAWT	N/A	8.9	52.59	4.48%	\$26k	\$8,941	2.023		
V112-3.0 MW	Large HAWT	yes	6.7	26,297.40	2241.89%	\$3M	\$4,470,558	0.002		
Skystream 3.7	Small HAWT	yes	6.7	18.41	1.57%	\$20k	\$3,129	0.920		
Aeolos 20 kW	Medium HAWT	yes	6.7	175.32	14.95%	\$26.2k	\$29,804.40	6.692		
Yenny YEVH 10 kW	Medium VAWT	N/A	6.7	87.66	7.47%	\$30k	\$14,902.20	2.922		

Table 8: Community Considerations

Community Considerations		Height	Appearance	Noise	Total	Rank
Turbine	Type	Weight: 4	Weight: 4	Weight: 2		
		Ranking (6 is best)	Ranking (6 is best)	Ranking (6 is best)		
Flowind	Large VAWT	2	2	3	22	2
Quiet Revolution	Small VAWT	5	4	6	48	5
V112-3.0 MW	Large HAWT	1	1	1	10	1
Skystream 3.7	Small HAWT	4	6	2	44	4
Aeolos 20 kW	Medium HAWT	3	3	6	36	3
Yenny YEVH 10	Medium VAWT	6	5	6	56	6

Table 9: Initial Turbine Selection

Turbine	Type	Min Wind Requirements		Power Production Vs Cost		Community Considerations		Total Score	
		Weight	4	Weight	4	Weight	2		
		Ranking (4 is best)		Ranking (4 is best)		Ranking (4 is best)			
Flowind	Large VAWT	1		1		2		12	
Quiet Revolution QR5	Small VAWT	2		3		5		30	
V112-3.0 MW	Large HAWT	6		6		1		50	Not Feasible
Skystream 3.7	Small HAWT	6		2		4		40	
Aeolos 20 kW	Medium HAWT	6		5		3		50	Winner
Yenny YEVH 10 kW	Medium VAWT	6		4		6		52	Winner

Final Selection

The two candidates to receive the highest scores in the initial selection framework detailed in the Methodology were the Aeolos 20 kW and the Yenny YEVH 10 kW. Following the steps laid out for a final selection, these candidates proceeded to a structural analysis.

Structural Analysis

Safety is of the utmost importance in this project. Therefore, it is essential that the structural integrity of the building be upheld in the throughout installation of the turbine and during the lifetime of the building, afterwards. To ensure this, the group analyzed the structural effects of the turbine using LRFD provisions for required strength and design strength.

Loading Conditions

Loading conditions on the column were taken from structural drawings provided by Perkins+Will, in conjunction with standards obtained from the *Massachusetts State Building Code*. Loads applied to the turbine itself were calculated per *780 CMR 3108.0 for Radio and Television Towers* based on similar geometry and industry standard. The proposed location for turbine placement, and used in structural analyses can be seen in Figure 7. Therefore, the proposed turbine will be located atop a W12x53 steel column with yield strength of 50 ksi. Throughout this report, the column from the footing to the second floor will be described as “Column 1,” from the second floor to the third floor as “Column 2,” third floor to the fourth floor as “Column 3,” and from the fourth floor to the roof level as “Column 4.”



Figure 9: Column Labeling of Gateway Park Phase II Building

Axial Loads

Axial loads are those that act vertically downwards on the W12x53 column.

Dead Load Components

Column 1 must be able to support the dead weight of the three floors above, in addition to the weight of the roof. The dead weight of each floor and the roof is dependent on the components that comprise it including but not limited to beams, girders, and slabs on the roof. Refer to Appendix B for the specific components of these dead weights.

Live Load Components

Column live loads, if not specified by the structural drawings, were obtained by the *Massachusetts Building Code* standards. The live loads, or loads that the column is expected to be subjected to during service, are classified by building use. The structural drawings by Perkins+Will indicated that columns 2 through 4 were designed under the Offices & Lab live load classification at 100 psf, and the roof at 20 psf. For design live loads of 100 psf or less and a tributary area greater than 400 square feet, as in this case, the live load could be reduced according to equation 1 below from the Gateway Park Phase II structural drawings by Perkins+Will:

Equation 1: Live Load Reduction, from Perkins+Will

$$L = L_o \left(0.25 + \frac{15}{\sqrt{K_{LL} A_T}} \right)$$

Where:

- L_o = Basic design live load (kips)
- A_T = Loaded area tributary to the member (ft^2)
- K_{LL} = Live load element factor (see Table 3)

Snow Load Components

With the proposed site for the turbine being located in New England, snow loads on the roof of the structure are of concern. The equation for snow loads, taken from *ASCE 7* Equation 7.3-1 is as follows:

$$p_f = 0.7 C_e C_{t/s} p_g$$

Where:

- P_f = Flat roof snow load
- C_e = Exposure factor, 1.0 for exposed roof
- C_t = Thermal Factor, 1.0 for heated structures
- I_s = Importance Factor, 1.0 for educational / office structures
- p_g = Ground Snow Load, 55 psf for Worcester, MA

Turbine Dead Weight

As previously stated, the two turbines that advanced from the preliminary selection phase are the Yenny YEVH 10 kW and Aeolos 20 kW. From the turbine's specification sheets, the turbines weigh 485 pounds and 2112 pounds, respectively. Following installation, these turbines will remain in their location for the duration of their life. For this reason, their weights are treated as dead loads in axial loading calculations.

Turbine Ice Load

In accordance with *Section 780 CMR 3108.0 for Radio and Television Towers*, the potential for ice to form on the surface of towers must be calculated. The ice thickness is calculated as:

$$t_d = 2.0t * I_i f_z K_{zt}^{0.35}$$

Where:

- I_i = Importance Factor
- $f_z = (z/33)^{0.1}$ (z = Height of Midpoint)
- K_{zt} = Topographic Factor

Then, following the calculation of ice thickness, the cross sectional area is computed as:

$$A_i = t_d (D_c + t_d)$$

Where:

- A_i = Cross Sectional Area of Ice
- D_c = Diameter of Tower

Table 10 provides a summary of the axial loads that have been used in a detailed structural analysis. The loads per square foot have been multiplied by the column's tributary area to produce the equivalent point load acting vertically and downward at the top of each column.

Table 10: Axial loading summary

Column Axial Loading			
	Category	Source	Load On Column
Roof	Dead Load	Structural Drawing (42.25 psf)	31.96 k
	Live Load	ASCE 7-10 (20 psf)	15.12 k
	Snow load	ASCE 7 Eq. (7.3-1)	29.11 k
Floors	Dead Load	Structural Drawings (42.24 psf)	1st: 0 k 2nd: 31.96 k 3rd: 35.96 k 4th: 35.96 k
	Live Load	Structural Drawings 1st Floor = 150 psf, Offices/Lab = 100 psf, 25 psf	1st: 0 k 2nd: 75.6 k 3rd: 75.6 k 4th: 75.6 k
Turbine	Turbine Dead Load	Yenny YEVH 10 kW	.49 k
		Aeolos 20 kW	2.11 k
	Ice Load	780 CMR 3108.0	.01 k

Lateral Loads

Loads that are applied perpendicular to the axis of the column fall under the category of lateral loading. This consists primarily of wind loads distributed along the length of each column and distributed along the height of the turbine's tower. Distributed wind loads along the length of each column were calculated per ASCE 7. Distributed wind along the height of the tower, however, was calculated per TIA / EIA – 222 as follows:

$$F = q_z G_H [C_F A_E + \sum (C_A A_A)] \leq 2q_z G_H A_G$$

Where:

- Wind Force, F in pounds on the structure

- Velocity pressure, $q_z = 0.00256K_zV^2$ for wind speed V in mi/h and K_z , velocity pressure exposure coefficient evaluated at height, z
- Gust response factor, $G_H = 1.69$ for tubular towers
- Force coefficient, $C_F = 0.59$ for tall cantilevered tubular pole structures,
- Effective projected area of structural components is one face A_E is equal to the tower's height multiplied by its diameter,
- $\sum(C_A A_A)$ applies to linear appurtenances (does not apply to wind turbine tower)
- A_G is the gross area of one tower face in ft^2 (for tubular tower, $A_G = \text{diameter} \times \text{height}$)

A summary of the lateral loads is provided in Table 11.

Table 11: Summary of lateral loads.

Column Lateral Loads			
	Category	Source	Load
Columns	Wind load	ASCE 7	1st: 605 lbs/ft 2nd: 1210.5 lbs/ft 3rd: 1210.5 lbs/ft 4th: 1210.5 lbs/ft
Turbine	Wind Load	TIA / EIA - 222	217 lbs/ft

Verify Modes of Failure

In order to ensure the structural integrity of the building following turbine installation, each of the modes of failure previously presented in Table 4 were verified. In order to perform these verifications, available strengths were calculated for Axial Strength, Flexural Strength, and Combined Axial and Flexural Strength. Then, ANSYS was used to calculate each of the required strengths for the listed components for comparison to the maximum available capacity of the column. This was performed for each of the three scenarios.

Axial Strength

The available design axial capacity of a W12x53 column was calculated by the equation:

$$P_u \leq \phi F_{cr} A_g$$

Where:

- P_u = Available Compressive Strength

- F_{cr} = Critical Stress
- A_g = Gross Area
- $\phi = 0.9$

The total load required according to the calculations in Table 12 cannot exceed the available design axial capacity. This table shows the calculated available strength, as well as the axial loads applied at each column. A check mark symbol (✓) indicates that the column has passed the axial strength check.

Table 12: Required Axial Strength vs. Available Axial Strength

Axial Strength				
	Available Strength (kips)	Scenario 1 (kips)	Scenario 2 (kips)	Scenario 3 (kips)
Column 1	478	295 ✓	298 ✓	300 ✓
Column 2	478	216 ✓	219 ✓	217 ✓
Column 3	478	138 ✓	141 ✓	139 ✓
Column 4	478	60.8 ✓	63.3 ✓	61.4 ✓

Flexural Strength

Design flexural strength of a steel member is governed by the equation:

$$M_u \leq \phi F_y Z$$

Where:

- M_u = Ultimate Flexure

- F_y = Steel Strength, 50 ksi
- Z = Section Modulus of member 425 in³
- ϕ = 0.9

The ultimate flexure of the beam cannot be exceeded by the flexure created as a result of a wind load being distributed along the length of each column. Table 13 provides the calculated available flexure, and the flexure associated with each scenario on the columns. A check mark symbol (✓) indicates that the column has passed the flexural strength check.

Table 13: Available flexural strength vs. Required flexural strength.

Flexural Strength				
	Available Flexural Strength (k*ft)	Scenario 1 (k*ft)	Scenario 2 (k*ft)	Scenario 3 (k*ft)
Column 1	292	.605 ✓	.605 ✓	.605 ✓
Column 2	292	1.21 ✓	1.21 ✓	1.21 ✓
Column 3	292	1.21 ✓	1.21 ✓	1.21 ✓
Column 4	292	1.21 ✓	1.21 ✓	1.21 ✓

Combined Axial and Flexural Strength

In construction, it is common for columns to be subjected to a combination of bending and axial forces. In this project, wind loads act as a bending force. In addition, some additional bending force may be introduced by slight eccentricity of loading at the top of the column,

since it is near impossible to center a load exactly on a column. Lateral loads on a column become increased by eccentric compressive forces. A steel column must be able to resist this combination of forces. Therefore, equation (H1-1a) & (H1-1b) of the *AISC Steel Manual* is used to verify the appropriate strength as follows:

$$(H1-1a) \quad \frac{Pr}{P_c} + \frac{8}{9} \left[\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right] \leq 1.0$$

$$(H1-1b) \quad \frac{Pr}{2P_c} + \left[\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right] \leq 1.0$$

Where:

- P_r = Required Axial Strength
- P_c = Available Axial Strength
- M_r = Required Flexural Strength
- M_c = Available Flexural Strength

For each column in the three scenarios, the combined ratios of flexure and axial loads according to equation (H1-1a) if $\frac{Pr}{P_c} > 0.2$ or (H1-1b) if $\frac{Pr}{P_c} < 0.2$, must not exceed 1.0. As mentioned previously, however, magnification of loads is introduced when a column bends due to lateral loads. Therefore, the required flexural strength factor, M_r , is magnified using the factors B_1 and B_2 to produce:

$$M_r = B_1 M_{nt} + B_2 M_{1t}$$

Where:

- B_1 = Moment amplifier
- M_{nt} = Factored moment, no-sway analysis
- B_2 = 1.0 due to braced frame
- M_{1t} = Factored moment, sway analysis

Using the updated M_r factor, equation (H1-1a) is modified to account for magnification in the form of AISC Equation (A-8-3) as follows:

$$pP_r + b_x M_{rx} + b_y M_{ry} \leq 1.0$$

The detailed calculations for equation (A-8-3), including the definitions of individual variables are located in Appendix C, while a summary of the results is located below in Table 14. A check mark symbol (✓) indicates that the column has passed the combined axial and flexural strength check.

Table 14: Summary of combined axial and flexural ratios.

Combined Axial & Flexural Loading			
$pP_r + b_x M_{rx} + b_y M_{ry} \leq 1.0$			
	Scenario 1	Scenario 2	Scenario 3
Column 1	0.90 ✓	0.92 ✓	0.90 ✓
Column 2	0.73 ✓	0.74 ✓	0.71 ✓
Column 3	0.55 ✓	0.57 ✓	0.54 ✓
Column 4	0.33 ✓	0.35 ✓	0.29 ✓

Normal Stress and Strain

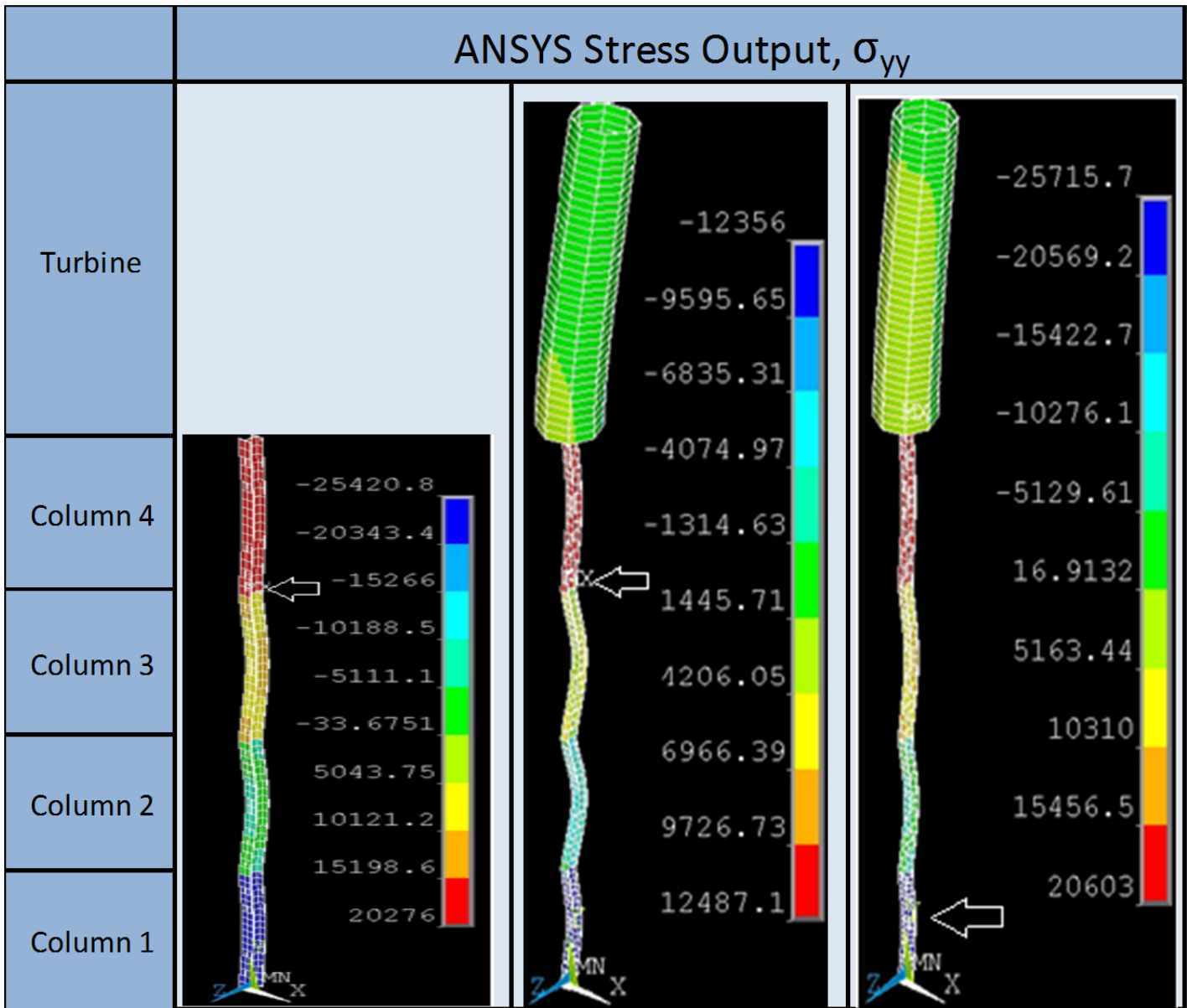
The use of finite element analysis through ANSYS provided the opportunity to obtain column's response in terms of stress-strain that would normally be too complex by hand. Therefore, the maximum normal stress and strain values were obtained from ANSYS for the columns of each scenario and compared to the maximum allowable values. The findings are presented on the following two pages in Table 15 and Table 16. For Table 16, ANSYS provides combined axial and flexural stresses in the column in terms of pounds per square inch. The maximum stress located in each scenario of the column is indicated by an arrow along the length of the member. For Table 16, the strain values are given by ANSYS as a percentage. Once again, the arrows indicate where along the length of the column the highest stress was experienced for each scenario. The annotated calculations for maximum allowable capacities are located in Appendix C. A check mark symbol (✓) indicates that the column has passed the respective check for the maximum allowable stress and strain.

The use of finite element analysis through ANSYS provided the opportunity to obtain column's response in terms of stress and strain that would normally be too complex to solve by hand. Therefore, the maximum normal stress and strain values were obtained from ANSYS for the columns of each scenario and compared to the maximum allowable values. The findings are presented on the following two pages in Table 16 and Table 18.

Table 15: Table of Stress due to combined axial and lateral loading effects, supplemented by corresponding ANSYS models.

	Combined Normal Stress Checks, σ_{yy}		
	Maximum Allowable Stress = 56.83 ksi		
	Scenario 1 (ksi)	Scenario 2 (ksi)	Scenario 3 (ksi)
Column 1	25.42 ✓	24.68 ✓	25.72 ✓
Column 2	10.18 ✓	9.26 ✓	10.28 ✓
Column 3	10.12 ✓	9.28 ✓	10.31 ✓
Column 4	20.28 ✓	19.57 ✓	20.60 ✓

Table 16: ANSYS stress in y,y direction



To create Table 16, each of the three scenarios was solved for normal stress in the y,y direction. As seen in each of the ANSYS images, the y-axis vertically, where (0,0,0) represents the base. The images provided under the scenarios show the solved analyses, which indicate the different magnitudes of normal stress experienced by the column. The color coded legend to the right of each scenario indicates the stress values in terms of psi. Compression governs for each scenario in the lower column, and tension governs for column 4. Of particular interest, are the maximum values for each column, shown under the heading "ANSYS Stress Output." It is important for the structural integrity of the column that the maximum stress values be less than 56.83 ksi. An arrow indicates where the greatest stress is experienced in each of the three

scenarios. The annotated calculations for maximum allowable capacities are located in Appendix C. A check mark symbol a check mark indicates that the column has passed the respective check for the maximum allowable stress.

Table 17: Table of Strain due to combined axial and lateral loading, supplemented by corresponding ANSYS models.

	Combined Loading Strain Checks, ϵ_{yy}		
	Maximum Allowable Strain = 0.196%		
	Scenario 1 (in/in)	Scenario 2 (in/in)	Scenario 3 (in/in)
Column 1	0.088% ✓	0.089% ✓	0.089% ✓
Column 2	0.035% ✓	0.034% ✓	0.035% ✓
Column 3	0.035% ✓	0.035% ✓	0.036% ✓
Column 4	0.070% ✓	0.070% ✓	0.071% ✓

Table 18: ANSYS strain in y,y direction

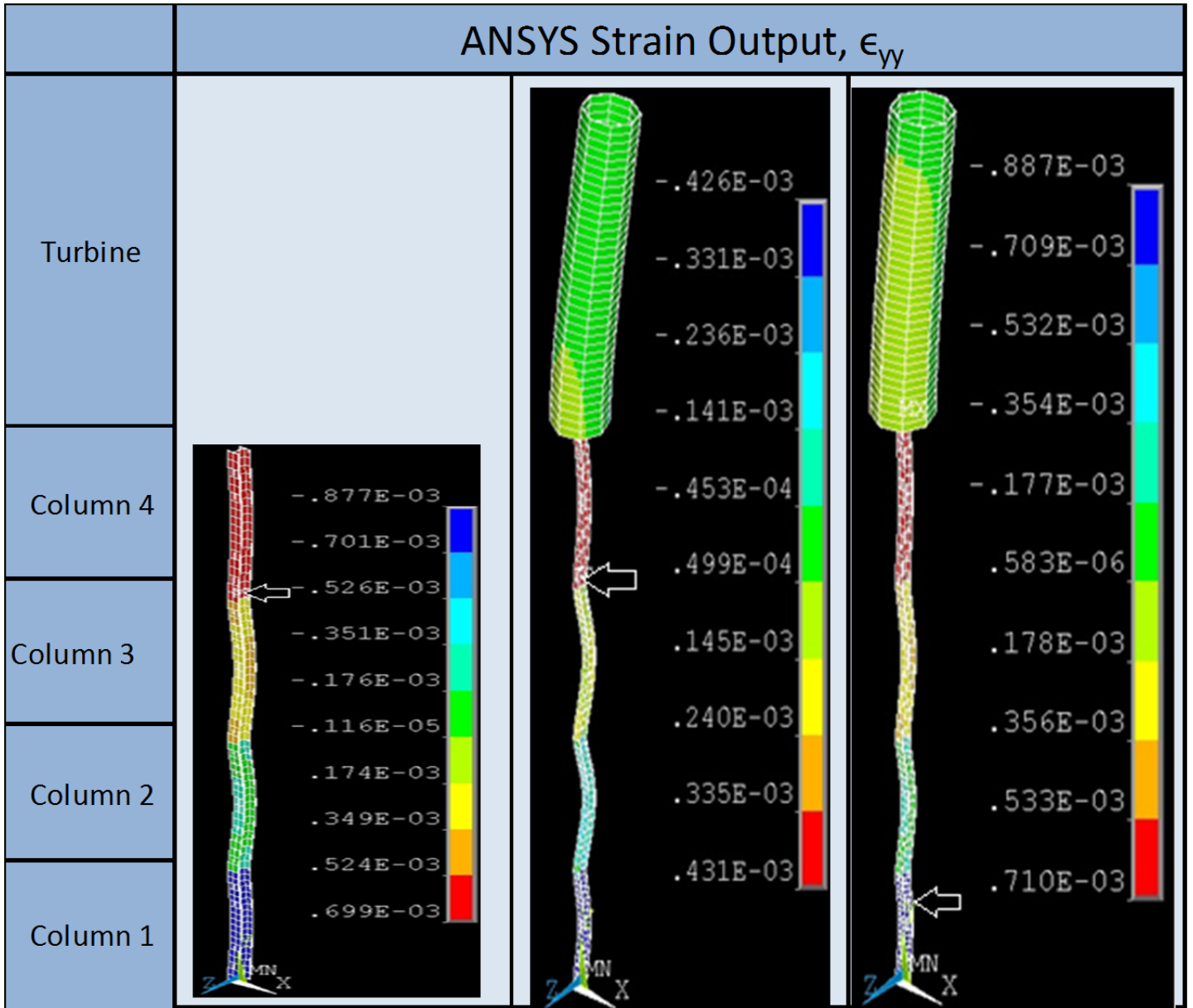


Table 18 was created in a similar manner to table 16, however the model was solved for strain in the y,y direction. The y-axis runs vertically, and a legend to the right of each scenario indicates the values of strain due to applied axial and flexural loads. The maximum values for strain of each column in the solved scenarios passed the check against a maximum allowable strain of 0.196%, indicated by a check mark. An arrow indicates where the maximum strain in the y, y direction occurs for each scenario. The annotated calculation for maximum allowable strain is located in Appendix C.

Cost Benefit Analysis

Table 19: Life Cycle Cost, Present Worth Method shows a breakdown of several aspects of cost and revenue. The project life cycle is the predicted amount of years that the turbine is expected to be operational. This was determined to be 25 years, based on a study by Wind Measurement International, as described in the background of this report. The discount rate is the estimated inflation each year, which is generally 3% in the United States. There are three columns in the spreadsheet. The first column lists the type of costs, broken into the following categories: construction costs, replacement costs, operation and maintenance costs, and total present worth life cycle costs and the remaining columns are for each turbine analyzed where values are shown for each cost aspect. Construction costs include turbine base cost and installation cost. The group determined values for these costs using methods described in the Cost Analysis section of this report in the Methodology. Replacement costs consisted of overhaul maintenance. Overhaul maintenance is when a turbine requires major parts replacement or in-depth repairs. This typically happens after twenty years and extends the life of a turbine by about five years.

Operation and maintenance costs consisted of maintenance and energy production. Maintenance is estimated at three percent of the turbine base cost. Energy production was determined using methods described in the Turbine Life Expectancy and Maintenance Costs section of the Background in this report. The values for energy production account for periods of low wind and inoperability due to maintenance. Total present worth life cycle costs shows the total investment value of purchasing each turbine. In order to determine this value, the spreadsheet adjusts each cost based on inflation and the year the cost or revenue is incurred to determine its present value. These numbers are then combined to subtract the costs from the total revenue. As seen in the spreadsheet, the Aeolos turbine has the highest present worth, due to its lower construction costs and higher revenue through energy production. The Aeolos is valued at \$293,246 and the Yenny is valued at \$121,966. This means that if the investment is made to purchase these turbines, the expected profit on the investment for the Aeolos is \$293,246, based on the current value of US Dollars.

Table 19: Life Cycle Cost, Present Worth Method

Project Gateway Wind Turbine Design					
Location Worcester, MA					
PROJECT LIFE CYCLE (YEARS)		25			
DISCOUNT RATE (% in decimals)		3%			
		Aeolos		Yenny	
		-		-	
		-		-	
		-		-	
Construction Costs		Est.	PW	Est.	PW
A)	Turbine Cost	26,200	26,200	30,000	30,000
B)	Installation Cost	24,000	24,000	12,000	12,000
C)	_____	_____	_____	_____	_____
Total Initial Cost Impact (IC)			50,200		42,000
Initial Cost PW Savings					8,200
Replacement/Salvage Costs		Year	Factor		
A)	Overhaul Maintenance	20	0.5537	5,240	2,901
B)	_____	_____	_____	_____	_____
Total Replacement/Salvage PW Costs				2,901	3,322
Operation/Maintenance Cost		Escl..00	PWA		
A)	Maintenance		17.413	524	9,124
B)	Energy Production		17.413	(20,414)	(355,471)
C)	_____		_____	_____	_____
Total Operation/Maintenance (PW) Costs				(346,347)	(167,288)
Total Present Worth Life Cycle Costs				(293,246)	(121,966)
Life Cycle (PW) Savings					(171,280)

PW - Present Worth PWA - Present Worth of Annuity

Structural Results Interpretation

An investigation into the structural integrity of the columns following turbine installation proved that the W12x53 columns were sufficient.

Combined Axial & Lateral Loading

In all models, tension governs near the top of the column and compression governs near the bottom, so the group can analyze each section of the column using the same method. Table 10 and Table 11, representing axial load and lateral loading, show that the columns are more than sufficient to support the indicated loading. As discussed earlier, however, it is essential that magnification effects from a second-order analysis are taken into consideration when examining the columns. For this reason, one of the most important pieces of data that came from the structural analyses is the information presented in Table 12, Combined Axial & Flexural Loading. The magnified ratios of axial loads to flexural loads cannot exceed a value of 1.0. As seen in this table, a value of 0.92 represents the combined axial and lateral loading case that came the closest to a maximum of 1.0. In order to ensure structural stability, it was decided that it would be beneficial to perform a supplementary P-delta analysis. In this way, the previously calculated required moment, M_r , used in the AISC Equation (H1-1a) would be verified.

P Delta Analysis

When a column is subjected to a moment along its unbraced length the column will displace laterally in the bending plane. Due to this it will result in an increased moment that is equal to the axial compression force times the induced displacement. It is important to complete this analysis on a column in order to determine if the column will fail due to the deflection in the lateral direction.²⁰ In lieu of ANSYS, the P Delta analysis was performed using a software known as Risa 2D. The column modeled was Column 1 from Scenario 3, which is the worst case scenario. Using the same loading conditions as was used in ANSYS, RISA solved for the maximum moment as 17 k*ft and a lateral deflection of 0.075. The RISA output can be seen below in Figure 10. Three nodes were used within the center of the column in order to ensure that the column deflection outputs were accurate. An axial compressive force of 300 k resulted in a modified moment of 39.5 k*ft through a P Delta analysis which can be seen in Appendix F under the heading P Delta Analysis of Column 1 Scenario 3. This value was compared to the modified moment of 36.77 k*ft from the second-order analysis calculated previously in

²⁰ McCormac, Jack C., and Stephen F. Csernak. "Bending and Axial Force." *Structural steel design*. 5th ed. Boston: Prentice Hall, 2012. 350. Print.

Appendix C under the heading Magnification Factors. The values obtained by approximate analyses and software are reasonably close. Additionally, both are well below the failure by yielding which governs with a value of 120 k*ft (Calculated in Appendix C under the heading F2 - Doubly Symmetric Compact I-Shaped Members & Channels Bent about their Minor Axis).

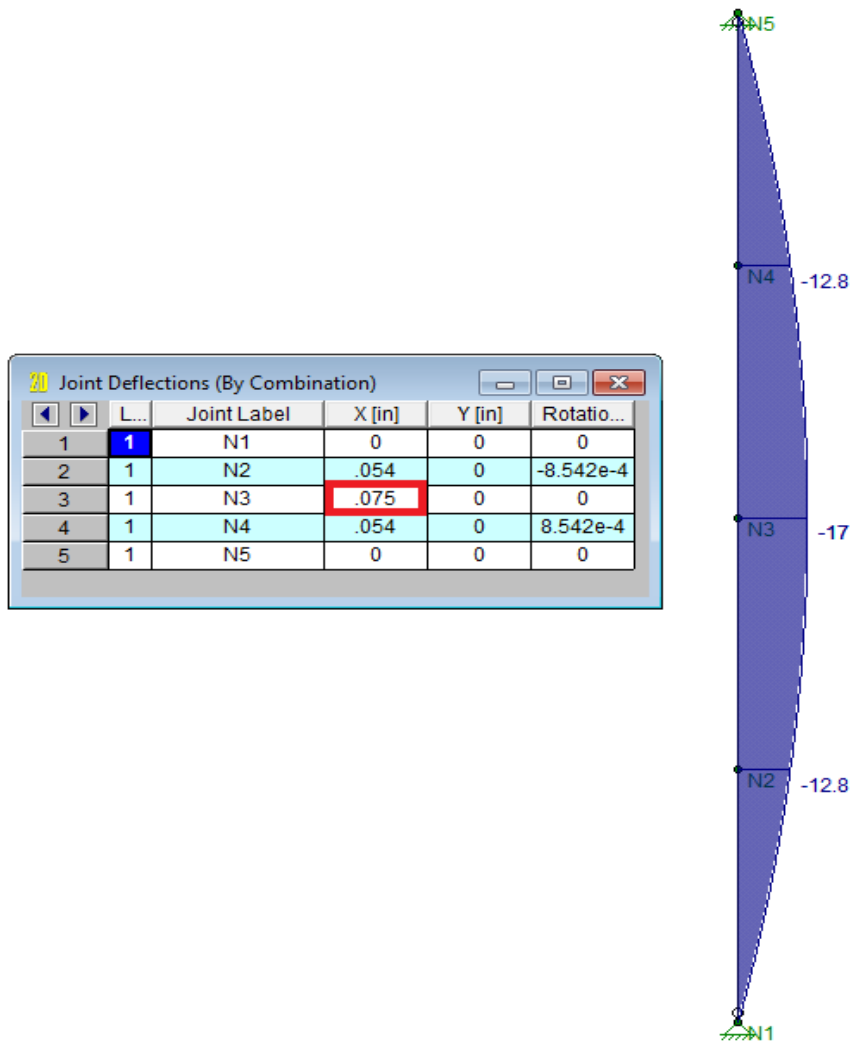


Figure 10: Moment and deflection used for P Delta analysis

Structural Reinforcement

Although the W12x53 column did not fail under the turbine's load, there may be instances where a member does fail under increased loading. If this occurs, there are multiple

options for reinforcement. One of the most common types of reinforcement for steel members is to weld or bolt steel plates to the cross section. The main purposes of this type of reinforcement is to increase the cross sectional area or to add to its moment of inertia so that it has increased axial and flexural capabilities. Various methods of welding or bolting steel plates to the columns section are shown below in Figure 11.



Figure 11: Increasing the Inertia of Columns through Welding or Bolting Steel Plates²¹

Another option for reinforcing is through the application of heat either by welding or by flame-cutting. Both of these options have a “concentrated source of heat input which produces a highly non uniform temperature distribution and thus produce residual stresses with a relatively high magnitude.”²² These residual stresses will be at the yield point in tension at the weld or at the flame-cut edge. Due to this fact, the residual stress distribution may be considered favorable because the tensile residual stresses are positioned so that the critical portions of the cross section remain elastic under a compressive load. The favorable residual stress distribution that results from laying the weld bead at the tips of the columns flange results in an improved column strength. The effect of increasing the columns strength through reinforcing by welding is shown below in Figure 12.

²¹ "Column reinforcement techniques - Constructalia." *The Steel Construction Website*. N.p., n.d. Web. 5 Feb. 2013. <<http://www.constructalia.com/english/renovation>

²² Tall, Lambert. "The Reinforcement of Steel Columns." *The Reinforcement of Steel Columns*. N.p., n.d. Web. 3 Feb. 2013. <ctgttpp.edu.free.fr/Update/p-delta%20effect.pdf>.

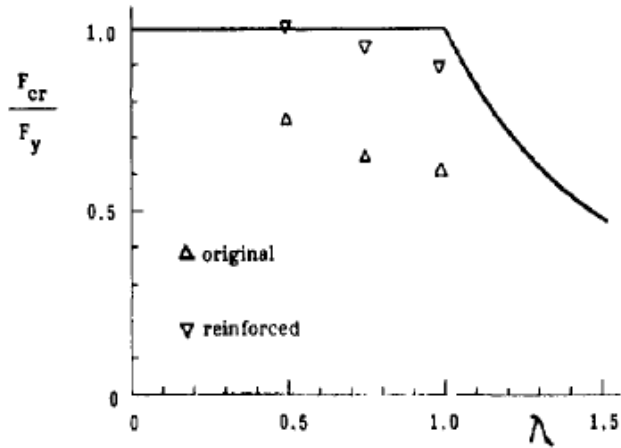


Figure 12: Strength of Columns Reinforced by Welding²³

Discussion of Cost Analysis

Costs were broken down into three categories: Installation costs, and turbine cost and revenue. Turbine cost and revenue includes maintenance and revenue generated through energy production. All costs and revenue were then entered into a spreadsheet to determine their present investment value, taking into account estimated lifetime costs.

Installation Costs

Installation costs were determined by analyzing a study on estimating total cost of wind energy systems. This study found that for most turbines, the overall installation cost tends to be approximately \$1,200 per kilowatt the turbine produces.²⁴ Using this rate, the group multiplied the cost by the power production in the sales manual of each turbine. Results can be found in the Table 19. These values were added to the present worth calculations, as described below.

Turbine Costs

Turbine costs were then determined, including base cost, energy production, and maintenance. Base cost was determined by contacting the turbine manufacturing companies and researching their websites for each particular model researched by the group. Base costs for each turbine can be found in Table 7 of the Methodology Section. In order to determine

²³ Tall, Lambert. "The Reinforcement of Steel Columns." *The Reinforcement of Steel Columns*. N.p., n.d. Web. 3 Feb. 2013. <ctgttp.edu.free.fr/Update/p-delta%20effect.pdf>.

²⁴ "Estimation of Cost of Energy From Wind Energy Conversion Systems." *IEA Wind*. Ed. David O. Tande. N.p., 1994. Web.

maintenance costs and lifetime energy production, the group determined the estimated lifetime of each turbine by analyzing a study done by Wind Measurement International, as described in the background section of this report. Modern turbines, such as the Aeolos and Yenny analyzed in this study, typically have 120,000 hours of power generation. This assumes approximately 66% operation time over their 20-year life spans. The group multiplied the hours of power generation by each turbine's power generation per hour and then the cost of energy to determine the money saved through energy production. In the same study described above, Wind Measurement International determined that the average maintenance costs for modern turbines ranged from 1.5% to 2.0% of the base cost each year over the 20 year lifespan. The group assumed a 2.0% annual maintenance. Major overhaul maintenance was also determined by this study to be approximately 20% of the original base cost of a turbine. The group determined this would be performed at the 20 year mark, since that is the expected lifetime of the turbine and that the life would be extended five years, based on the WMI study.²⁵

Structural Reinforcement Cost

Although the turbine applications studied herein did not produce an overload within the column, there may be situations in which a turbine exerts a load unsafe for an existing column. In that case, structural reinforcement would be necessary. It can be expected that this would introduce new costs in order to ensure the structural integrity. The most common costs that are associated with structural reinforcement are the cost of materials and labor. There are different costs that are associated with each type of reinforcement some costs are higher than others. Reinforcing using steel plates can be slightly more costly than other reinforcing options depending on how many plates need to be applied to the cross section. This is because not only does the steel have to be paid for but also whatever material is being used to attach it whether it is bolts or welds. Ideally, it would be most cost effective to use the welding or flame-cutting technique mentioned earlier because steel plates would not have to be purchased. Despite the benefits of this method, added stresses require an additional steel plate. In general, the residual stresses caused by reinforcement would require significant quality control and would incur added costs.

²⁵ "Wind Turbines." *Wind Measurement International*. N.p., n.d. Web. 18 Feb. 2013.

Conclusion

The purpose of this project was to investigate the feasibility of retrofitting a wind turbine onto the roof of an existing building. Wind energy, the effect buildings have on wind streams, and structural impacts of loads on a building's roof structure were thoroughly researched in order to establish a means by which a turbine could be selected from a pool of possible candidates for a building retrofit. Studying these areas provided essential information necessary for determining what factors associated with a turbine retrofit made a candidate feasible. Upon investigation of these factors, a detailed process for initial selection and final selection was created.

Initial candidates were selected based on factors such as possible energy savings and sizing restrictions of the location being proposed for a retrofit. An initial screening process ranked each of the candidates according to expected power production versus building power consumption, height of the turbine tower, and community considerations. Specification sheets obtained from turbine manufacturers were the primary sources of data entering the initial selection stage. The highest ranking turbines then proceeded to a final selection process.

At this final selection stage, each turbine underwent a detailed structural analysis in order to check their suitability for a retrofit. *ASCE 7-10 Minimum Design Loads of Buildings and Other Structures* in conjunction with the *AISC Steel Construction Manual* were primary sources for obtaining design equations necessary to verify the structural integrity of the building's column. Forces applied from the base of the roof to the top of the turbine's tower were governed by equations from the *Massachusetts State Building Code (780 CMR)*. Finite element analyses were conducted on the supporting column using ANSYS to determine stresses and strains developed within the column due to the placement of a turbine.

With the structural effects of each turbine candidate in hand, a final cost analysis was performed that took into consideration unit costs of each turbine, expected maintenance costs, savings incurred through turbine energy generation, initial installation of the turbine, and structural reinforcement to columns that may be required due to overloading. Examining profit and loss over the life of the turbine showed which turbine candidate was the most feasible option for a retrofit.

The execution of this project ultimately allowed for an evaluation framework to be developed for the retrofitting of a wind turbine onto a building. The methodology presented within the report can be modified to suit the needs and specific conditions of individual retrofit projects. Prospective projects may utilize information presented in the background and methodology to expedite the process of steps such as locating wind patterns, calculating

turbulent air flow, acquiring cost benefit spreadsheets and narrowing down turbine candidates. Given that data on the performance of retrofitted turbines is extremely limited, performance factors of turbines are only estimates. As more data is made available in coming years, the performance factors of turbines can be altered in order to provide more realistic estimations for energy output and, in turn, cost benefit analyses.

With respect to the site investigated in this report, it was deemed extremely feasible to retrofit the Gateway Park Phase II building with an Aeolos 20 kW wind turbine. Through lifetime cost analysis of the installation costs, turbine costs, and energy production, the Aeolos turbine was found to have a present worth of nearly \$300k, while the Yenny's present worth was only about \$120k. The Aeolos had a lower cost in all aspects and produced more energy, making it the clear choice, financially. The Aeolos turbine was estimated to be capable of producing 14.95% of the needed power for the Gateway Phase II building, while the Yenny turbine only produced 7.47% of the buildings consumed energy. In the structural analysis of the column that would support the turbine, it was found that both turbines had almost negligible effect on the column in axial stress, flexural stress, combined axial and flexural stress, and P-delta analysis. Despite the Aeolos turbine weighing more than 4 times as much as the Yenny turbine, it only caused an axial stress increase of less than 2% and was well below the capacity of the column. This was also true for all other structural aspects of the column. Due to the negligible structural impact of the Aeolos 20kW turbine and its superior energy production, it is the clear choice to be retrofitted onto the Gateway Park Phase II building.

Appendix A: Proposal

Gateway Wind Turbine Design

A Proposal for a Major Qualifying Project Report:

Submitted to Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

By

Tyler Chambers

Ryan Garcia

Ryan McNamara

Date: October 17, 2012

Approved:

Professor Mingjiang Tao

Professor Leonard D. Albano

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Problem Statement

Modern buildings need heat and electricity to perform their design functions and uphold the quality of life that has come to be standard today. These buildings, despite the rising concerns over global climate change and use of fossil fuels, continue to be powered off of national energy grids.²⁶ Wind turbines are a viable option for helping to supplement the energy needs of today's structures. By harnessing urban wind flow through a retrofitted wind turbine, energy supply costs and fossil fuel usage can be reduced. Modern buildings must be structurally reinforced to ensure that it can withstand the loads, forces, and vibrations associated with a retrofit design.

Objective

The purpose of this project is to retrofit an existing building with one or multiple wind turbines in order to provide sustainable energy that will reduce the building's dependency on the non-renewable energy grid. The site chosen for retrofit is the Gateway Park Phase II building at Worcester Polytechnic Institute (WPI). After suitable wind turbine options are identified through an initial screening, their implementation will be further analyzed and evaluated in terms of structural and financial considerations. This project will propose recommendations based on the findings for structural reinforcement as well as for suitable wind turbine designs.

Scope of Work

This project shall be divided into two main components. The first will consist of selecting a turbine or turbines that, based on factors such as cost, size and energy production, would be suitable for further investigation. Then, the feasibility of these options will be thoroughly examined from both a structural and cost perspectives. The structural analysis will be performed with the aid of ANSYS finite element package to ensure the design is structurally sufficient. The cost analysis will provide information concerning the costs of each alternative, including any costs for additional structural reinforcement, and the eventual savings in electricity costs. The workload will be shared equally among all three members of the group, as fulfillment of the capstone design requirement for each member.

²⁶ Parker, Dave. *Microgeneration: Low Energy Strategies for Larger Buildings*. Elsevier/ Architectural Press, 2009.

Background

This section will provide a brief background on wind turbines as well as lay the framework for a structural analysis of retrofitting a turbine to a building. Figure 1, shown below, provides an overview of the topics to be covered in this section and how they are related to the overall picture of the project.

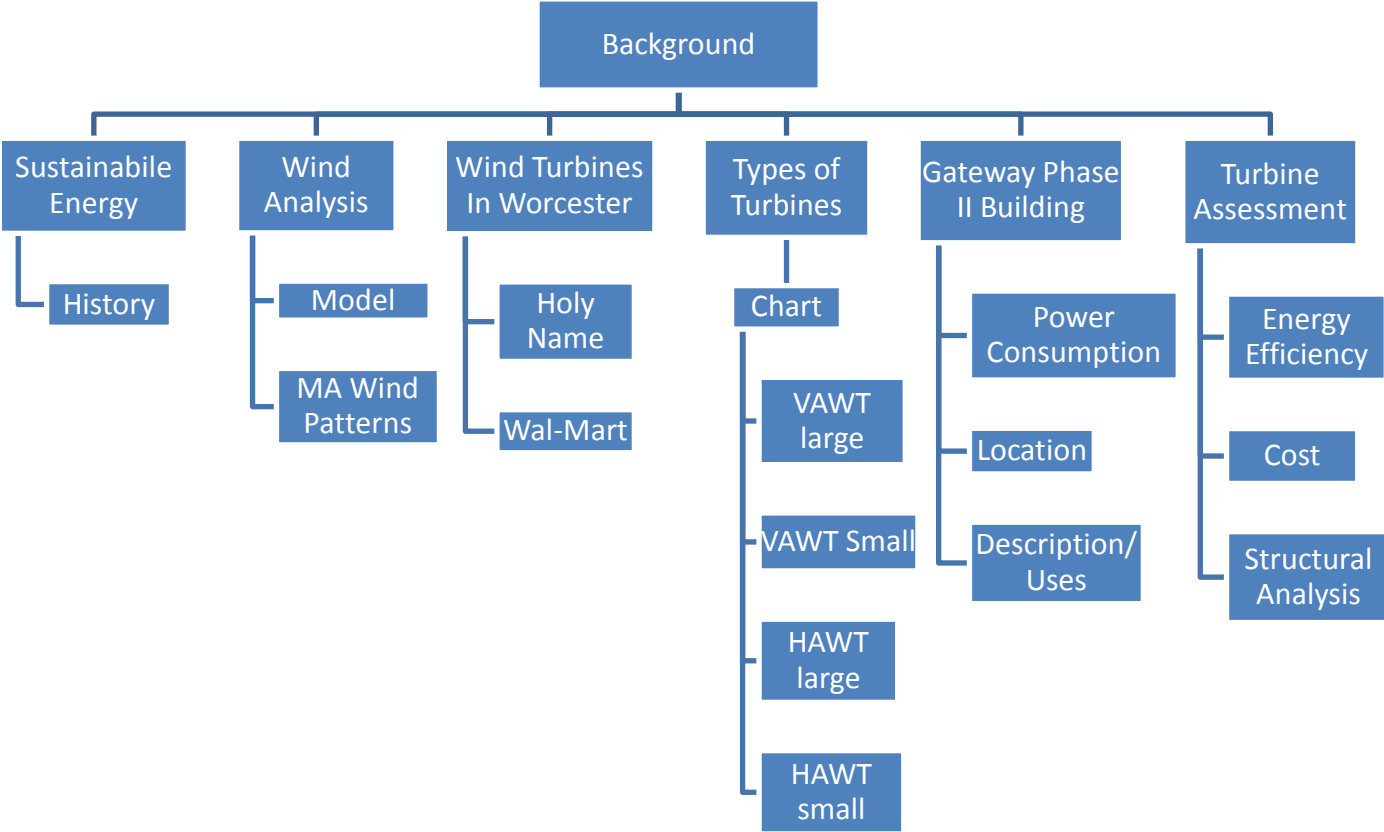


Figure 13: A summary of the background section.

Sustainable Energy

The United States Environmental Protection Agency defines sustainability as “creating and maintaining the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and

future generations.”²⁷ At the world’s current rate of power consumption and fossil fuel use, it is jeopardizing the energy sources for future generations, unless investments are made in alternative technologies. An integral part to accomplishing this task is the creation and implementation of new sustainable methods for supplementing power consumption needs.

Wind power is a form of energy conversion in which turbines convert the kinetic energy of wind into mechanical or electrical energy that can be used for power.²⁸ By incorporating a wind turbine or turbines onto a building’s structure, part of the buildings energy consumption can be offset by the electrical power that is provided by the turbines. Wind energy is even more efficient for small homes in rural areas where a turbine can potentially provide more than what is consumed; so much so that it can be sold back to the electricity provider. Aside from the financial savings, wind energy also cuts back on CO2 emissions since it is a form of “clean” energy.

Between 2010 and 2011, wind energy in the United States accounted for 32% of all new electric capacity additions as well as for \$14 billion in new investments.²⁹ Of all wind turbine components installed in the US, 70% were manufactured domestically.³⁰ Technical innovations are also paving the way for lighter, more efficient turbines. Multiple types of turbine designs have arisen from these innovations.

Wind Analysis

Wind turbines can be a great source of renewable energy. In order for these turbines to be effective, they have to be in an area with a sufficient amount of wind. According to the National Renewable Energy Laboratory wind power is considered in seven different classes according to wind speed, which can be seen in Table 1. In order for a wind turbine to be effective, it must be in an area with class 3 wind power at minimum³¹. This translates to approximately 11.5 mph at 10 meters above the ground, and 14.3 mph at 50 meters. Table 1

²⁷ Congress, U. S. "National Environmental Policy Act of 1969." *Public Law* 91-190 (1969): 1075.

²⁸ Encyclopedia Britannica, Inc. "Wind Power." 2012. *Encyclopedia Britannica Online Academic Edition*. 15 October 2012. <<http://www.britannica.com/EBchecked/topic/645063/wind-power>>.

²⁹ <<http://energy.gov/articles/energy-report-us-wind-energy-production-and-manufacturing-surges-supporting-jobs>>

³⁰ Transmission & Distribution World. "U.S. Wind Energy Production and Manufacturing Surge." 15 Aug 2012. *General OneFile*. 2012.

<http://go.galegroup.com/ps/i.do?id=GALE%7CA299811201&v=2.1&u=mlln_c_worpoly&it=r&p=ITOF&sw=w>.

³¹ Center, U. S. D. O. E. R. R. D. "Wind Energy Resource Atlas of the United States." <<http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html>>

shows the seven different wind power classes with the wind power densities and wind speeds that are associated with the classes at both 10 meters and 50 meters above ground level.

Table 20: Wind power classification system.³²

(b) Denotes speed is based on the average speed distribution of equivalent wind power density.

Wind Power Class *	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m ²)	Speed ^(b) m/s (mph)	Wind Power Density (W/m ²)	Speed ^(b) m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

Wind, like most other things in nature, always looks for an outlet where there is the least resistance. This is often between hills, mountains, peaks, and in the case of Worcester, buildings. In a study of roof surface wind speed distribution on low-rise buildings, it was concluded that wind speeds could increase up to 60% along edges of buildings, corners, and protruding elements.³³ High local wind speeds are caused by the contours that exist in these elements. Figure 2, below, represents the effects that a building has on a wind flow that is generally horizontal. There is a clear indication that increased wind speeds do exist over generally flat roofs. These high local wind speeds could produce energy if they are efficiently harnessed. Research into what altitudes above the building produce the most efficiency and into the exact locations for the placement of turbines could make wind energy a very viable option in the Gateway Park area.

³² Center, U. S. D. O. E. R. R. D. "Wind Energy Resource Atlas of the United States." <<http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html>>

³³ Cochran, Leighton, Jon Peterka, and Russ Derickson. "Roof Surface Wind Speed Distributions on Low-Rise Buildings." *Architectural Science Review* 42.3 (1999): 151-60. Web.

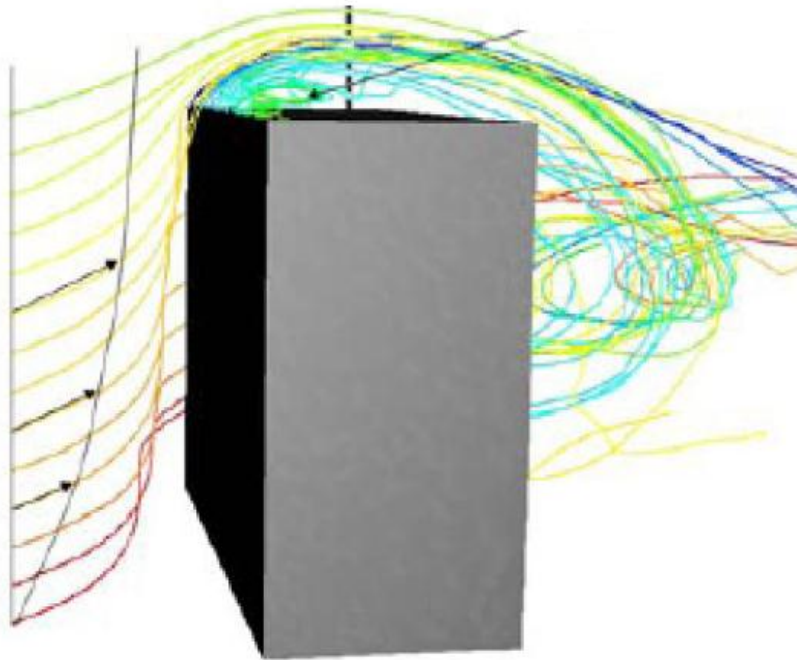


Figure 14: A diagram of wind speed above structures using Betz's Law.³⁴

Wind Turbines in Worcester

In the group's research, one of the most useful sources of information was case studies of other wind turbines that were built. Case studies gave proof that wind turbines were an effective method for sustainable energy production and provided insight as to what factors are important for consideration. Case studies also gave the ability to learn from mistakes made in similar, previous studies and take those errors into account during the course of this project. There are very few regulations and building codes that govern wind turbines, especially those on a horizontal axis, because of how new the technology is. This is another reason that case studies are a very important research topic for the group when it comes to understanding the structural dimensions and limitations of a wind turbine. Due to the nature of wind energy, it is also very important to understand the environment in which one intends to build. In order to gain an understanding of the specific constraints and considerations of building a wind turbine in Worcester, Massachusetts, the group studied several turbines currently in the city. The two

³⁴ Ragheb, M. "Wind Turbines in the Urban Environment." 10 March 2012. <https://netfiles.uiuc.edu/mragheb>. PDF. 23 Sept 2012.

main case studies were the small turbines at the new Wal-Mart on Route 146 and the large wind turbine at Holy Name Catholic High School.

Wal-Mart is making a very strong effort to be an industry leader in alternative energy. The company's goal is to eventually power all of their stores and distribution facilities with 100% renewable energy³⁵. One initiative that they have started is installing micro turbines on top of light posts in the parking lots of their stores. When a new Wal-Mart store was constructed in Worcester, they utilized this energy source, using 12 micro horizontal axis wind turbines. These turbines supplement 5% of the power used by the store, which is rather effective considering their minimal impact to the environment and community, as well as low cost. Local neighbors were concerned about the noise and appearance of these turbines, but both concerns have been found to be needless.⁹ The turbines are engineered to be nearly silent; so much so that the noise created by the wind hitting the light post is actually louder than that of the turbine. The size of the turbines is also rather insignificant to the size of the light posts, ensuring that they do not clutter the skyline in any way. This case study was effective in showing the group alternatives to the very large, expensive wind power producers, such as the Holy Name turbine. Although the large turbines are very effective, it is important to consider other low-cost alternatives that cause a smaller impact, but still supplement energy production.

Holy Name Catholic High School first considered building a wind turbine in 2005 when they realized that rising energy costs would very soon exhaust all their funds and force the school to significantly change how it is run or go bankrupt. In 2006, a WPI Interactive Qualifying Project was conducted to analyze the feasibility of constructing a wind turbine on the school's campus. The project was performed by Hans Erik Jensen, Brian Foley, Tyler Forbes, and Adam Young and was advised by Professor Alexander Emmanuel. The project analyzed cost, construction considerations, building codes, environmental impact, energy consumption, meteorological data, neighborhood considerations and much more. Considering all the aforementioned factors, they determined it would be feasible for Holy Name to construct a wind turbine.

According to the IQP, the location of Holy Name is ideal for wind power³⁶. It is on top of a hill with few buildings around it and winds that regularly reach speeds of up to 55 mph. The campus is 45 acres and is located on Granite Street in Worcester, MA. Later in 2006, Holy Name authorized Sustainable Energy Developments from Ontario, NY to begin construction of the

³⁵ "Walmart Tests the Wind." - *Worcester Telegram & Gazette*. N.p., n.d. Web. 30 Oct. 2012.
<<http://www.telegram.com/article/20100502/NEWS/5020330/0>>.

³⁶ Young, Adam S. Student author -- ME, et al. *Wind Power Feasibility Study for Holy Name High School.*, 2006. Web.

freestanding, 600kW horizontal axis turbine, capable of powering 135 homes. Using sensors and computers, the 242ft tall turbine automatically rotates to face perpendicular to the wind so its 75ft long blades can generate the most electricity possible. It weighs 200,000 lbs and required 500,000 lbs of concrete for its foundation. The total cost of the project was \$1.6M, which was supplemented by a \$575k grant from the MA Technology Collaborative and \$900k in grants and donations. Yearly energy costs for Holy Name were around \$100-125k, which allowed the school to build this turbine for about the same cost it would have paid for electricity and heat in one year.

The project has been an incredible success, surpassing all initial estimates of effectiveness. The school only uses about 54% of the power and sells the rest back to the power company, generating revenue for the school.³⁷ It not only transformed energy from a great expense to profit for Holy Name, but it also gained recognition for the school. It was easy for Holy Name to find donations and grants for this project, because of the support of "Going Green." In relevance to the group's project, the Holy Name turbine is probably far bigger than something that the group would be able to retrofit onto a building in Gateway because of its size and weight. Holy Name is also a far more desirable location for a wind turbine, because of its elevation above the surrounding areas and high wind speeds, but this project is a good reference for social, economic, and permitting concerns involved with the local area.

Types of Wind Turbines

Holy Name Catholic High School determined that a Horizontal Axis Wind Turbine (HAWT) would be the most feasible design for their school. The two most common categories are HAWTs and Vertical Axis Wind Turbines (VAWTs). The advantages and disadvantages of each vary depending on a number of factors including wind patterns, site location, and power output requirements.

As it stands, the level of research in HAWTs is much greater than VAWTs, and as a result, horizontal turbines of comparable size generally generate a greater level of energy than vertical turbines. Table 2 provides detailed information regarding important differences between large and small VAWTs and HAWTs.

³⁷ "Wind Power ; Holy Name Pioneering Green Energy: ALL Edition." *Telegram & Gazette*: A.14. 2006. Web.

Table 21: Comparison of Vertical Axis Wind Turbines & Horizontal Axis Wind Turbines

Turbine	Description	Rated Output	Design Life	Cut in Speed	Noise	Weight	Advantages	Disadvantages	Source
FLOWIND 19-m	Large VAWT	300 kW	15 Years	14.5 mph	60 db - Silent	33888 lb	-Effective in skewed wind flow -Not affected by crosswinds -Silent	-Experience high vibrations -Less research than HAWTs -Not self starting	Floating Wind Farms Corp
Quiet Revolution QR5	Small VAWT	6 kW	25 Years	8.9 mph	Silent	600 lb	-Generator near ground level for easy maintenance	-Lower operating range -Usually requires higher Cut-in speed	Vertical Axis Wind Turbines by M. Ragheb
V112-3.0 MW	Large HAWT	3000 kW	20 Years	6.7 mph	100 db (Hand Drill)	70,000 lb	-Self starting -Wider operating range -Stability from blades location	-Large, stiff blades result in noise -Heavy support design -Must be positioned upwind	Vestas Wind Turbines
Skystream 3.7	Small HAWT	2.1 kW	20 Years	6.7 mph	40 db (Normal Conversation)	170 lb	-Lower cost (high production volume)	-Difficulty operating at close to ground level	Southwest Windpower

Table 2 is effective in showing that there is no turbine alternative that is far superior to the others for all applications. In a wide-open and rural location, a large HAWT has a clear advantage over its counterparts. There are few obstacles to interfere with the wind's flow, and the noise created by the turbines operation will not be a factor. The towers can also be tall in order to reach high speed winds located at greater elevations. At these elevations, ice build-up can become a potential hazard. When moisture accumulates on the blades of an HAWT and freezes, "ice-slinging" can occur. The turbine would have to be shut down under these circumstances. In an urban setting, however, wind flow can become skewed from buildings and highway interference. It is in these situations that a VAWT is the most efficient design. With a vertical axis, a turbine can operate in highly variable wind directions, allowing it to generate energy at even low elevations. The variable winds at low elevations, however, produce unwanted vibrations that must be accounted for in the turbine's design. VAWTs produce virtually no sound during operation, which is of high importance if they are to be near homes or retrofitted onto structures.

The table also further divides HAWTs and VAWTs into large and small. The power generation of the small turbines is not comparable to that of its larger counterparts; however, they do possess their own advantages. The cut-in speeds of these micro-turbines are about 50% of larger turbines. The cut-in value is the speed of wind that must be present in order for the turbine to function. Micro-turbines are easily mounted onto buildings and homes, and produce little to no vibration or noise once installed. It is important that all factors are carefully weighed when planning to implement a wind turbine.

Gateway Park Phase II Building

The building for which the group has chosen to investigate the installation of a wind turbine is referred to as Gateway Park Phase II and is located at 50 Prescott Street, as seen in Figure 3 below. The O'Connell Development Group (ODG) broke ground on 21 April 2011 for this building, which will be 92,000 square feet and cost \$32 million. This building is four stories tall and will house several companies as well as "three [WPI] university programs: the new Bio-Manufacturing Education and Training Center (BETC); an expanded Fire Protection Engineering Department and research laboratory; and the graduate division of WPI's School of Business."³⁸

³⁸ <<http://wp.wpi.edu/connection/2011/04/21/groundbreaking-ceremony-held-for-next-building-at-gateway-park/>>

While WPI owns the land upon which the building is built, ODG will own the building and will rent out space to its tenants, including WPI. This practice, while somewhat convoluted and complicated, protects WPI from the liability of finding tenants for the building and maintaining it. This building, much like nearly all of WPI's new buildings, is being built with the intent to achieve LEED (Leadership in Energy and Environmental Design) certification.

The evaluation for LEED certification is essentially a point system where buildings gain points based on environmental impact, energy efficiency, waste minimization, and many more categories. One important category that the building is evaluated on is how much renewable energy the building uses. The minimum renewable energy the building uses is five percent and a perfect score is at least twenty percent. The electricity consumption of the Gateway Park Phase II building is an important factor in determining just how much of an impact a retrofitted turbine may have.



Figure 15: The site of construction for the Gateway Part II building to be used for retrofit.

Turbine Analysis

The analysis of the turbines will take place in two steps. The initial and final screening are discussed in detail in the Methodology section, however a brief understanding of the work to be carried out is useful for the description of a turbine analysis. The first screening will consist of an assessment of all alternatives in respect to minimum wind requirements, power production, costs, and community considerations. Each turbine has what is known as a "cut-in speed," as is shown in Table 2. This is the minimum wind speed that the turbine

requires in order to operate. Power production varies greatly for each turbine depending on the wind conditions, the type of turbine, and its location.

Energy efficiency is very important for a wind turbine and is covered in the initial screening. Wind energy is not always consistent or strong, so a wind turbine must be able to convert wind energy to electricity very efficiently. Factors that influence this are the size of the fan blades, design of the airfoil, resistance of electronics, heat production, and several other factors. An efficient wind turbine has large, lightweight fan blades with adjustable pitch and a flawless airfoil design. The ratio of how much electricity a turbine produces on average as a pose to how much electricity would be produced at peak operation is known as the turbine's capacity factor. Proper analysis of these categories will ensure the selection of the most efficient and effective models to proceed to the second step which is an in-depth analysis.

A useful tool in determining efficiency and overall feasibility of sustainable projects is the program RETScreen Version 4. RETScreen is an excel based program that allows the user to input information about their project in order to determine the feasibility of the proposed project over its lifespan. After entering details about the specific project, a cash flow diagram is automatically created to show the potential costs and benefits. Table 4 in the Methodology chapter shows the parameters that are specific to this project, along with a brief explanation of each.

The final screening of the turbines will be performed only on the highest ranking turbines according to the preliminary screening. For this in-depth analysis, multiple aspects of a turbine will be studied. They are as follows:

A structural analysis is one of the in-depth pieces of work to be performed on those turbines initially selected. It is obvious that if the largest possible wind turbine were to be placed on top of Gateway Park Phase II, it would produce the most energy. However, the group must consider the stresses and strains caused by a wind turbine on a building and select a turbine that the group's building can support feasibly. The most simple of these loads is the dead weight of the turbine. Most commercial buildings are not built to withstand large point-loads on their roofs, so the group will need to ensure the roofing structure can support the group's turbine(s). Vertical axis wind turbines produce a significant amount of vibration, caused by the orientation of rotation of the fan blades that can affect the structural stability of the group's building. Lastly, the group must determine the effects of the horizontal force applied to the turbine by the wind and its effects on the structure of the building. Vibration and wind force are the live loads the group will have to account for in the structural analysis. The computer program ANSYS will be utilized in this structural analysis. ANSYS is a computer program that

effectively and accurately measures the loading, stresses, strains, deformations, etc. of the structural elements in a building. As stated by the program's brochure:

"ANSYS is a finite element analysis software package that is used to break down structural and thermodynamics problems that are too difficult to solve by hand or with an ordinary calculator into a number of "finite elements." A solution is generated for each element, and they are combined to create an overall solution to the problem. In addition to solution generation tools, comprehensive analysis and graphics tools are also included, which allow the user to effectively visually model various types of systems."³⁹

This program is a very effective tool used by professional engineers in many different career fields and will be an important tool in this design.

In the design of the tower, the load that is applied to the tower due to the wind has to be taken into account. The tower itself shall be designed to resist wind loads in accordance with *TIA/EIA-222*, the structural standards for steel antenna towers and antenna supporting structures. The equation that will be used to calculate the force in pounds on this structure is:

$$F = q_z G_H [C_F A_E + \sum(C_A A_A)] \leq 2q_z G_H A_G \quad (1)$$

The terms from equation one are listed below and taken from *TIA/EIA-222*:

- Wind Force, F in pounds on the structure
- Velocity pressure, $q_z = 0.00256K_z V^2$ for wind speed V in mi/h and K_z , velocity pressure exposure coefficient evaluated at height, z
- Gust response factor, $G_H = 1.69$ for tubular towers
- Force coefficient, $C_F = 0.59$ for tall cantilevered tubular pole structures,
- Effective projected area of structural components is one face A_E is equal to the tower's height multiplied by its diameter,
- $\sum(C_A A_A)$ applies to linear appurtenances (does not apply to wind turbine tower)

³⁹ <<http://css.engineering.uiowa.edu/sware/ANSYS.php>>

- A_G is the gross area of one tower face in ft^2 (for tubular tower, $A_G = \text{diameter} \times \text{height}$)

Using average wind speeds and the values listed, it is possible to calculate the total force acting on the wind turbine.

Cost is a driving force that all engineers must be conscious of in construction projects. Therefore, cost is both a part of the initial screening and the more detailed feasibility analysis. It is easy for an engineer to become focused on effectiveness and reliability, but to disregard cost. Some major components of the cost to be included in the initial screening include the base price of the turbine models, and the kWh of energy produced per dollar. In the final selection, costs will be scrutinized even further. The costs in these calculations will encompass the entire project, from base price of the turbine, to installation, reinforcement, and benefit over the life of the turbine. This project will require a strong balance of cost and efficiency in all aspects of design.

Capstone Design

The Accreditation Board for Engineering and Technology (ABET) has set standards to assure quality and stimulating innovation in applied science, computing, engineering, and engineering technology education. The ABET believes that, "Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political."⁴⁰ This project fulfills this requirement in that it is closely related to a number of these listed considerations.

Economic

As with many civil engineering projects, this project will be constrained by economic feasibility. The design of the project will account for cost of materials, as well as for the cost of installations and reinforcements as needed to complete the design. The maintenance costs and the economic benefit of the power produced will also be calculated based on the expected lifetime of the turbine. The economic benefits will also closely be examined, and a final cost analysis will show the advantages of one retrofit design over another. The financial information gathered will allow for a final recommendation of the most suitable design.

Sustainability

The aspect of sustainability is a major driving force behind the inception of this project proposal. With the available technology, it is rare to find a large modern building that is fully sustainable. Therefore, buildings are heavily reliant on non-renewable energy methods for powering their structure. This project will aim to decrease that reliance on non-renewable energy by providing a source of clean power to help to supplement the building's energy consumption. A completed design will provide an option for a more sustainable building that can partially rely on sustainable energy.

⁴⁰ "ABET Vision and Mission." *ABET* -. N.p., n.d. Web. 16 Oct. 2012. <<http://www.abet.org/vision-mission/>>.

Constructability

The turbine is expected to create a new source of point load, vibration, and torsion once it is retrofitted to the existing building. This will result in the need for further reinforcement, depending on the design alternative at hand. Therefore, the constructability constraint will be a major point of consideration during the execution of the project. The group will examine different methods for reinforcement that might be of greater ease than others, as well as utilize standard turbine models to allow for construction that is more manageable.

Ethical

The American Society of Civil Engineers (ASCE) outlines a list of principles in their code of Ethics by which every engineer should abide. The list of principles states that each engineer should “uphold and advance the integrity, honor and dignity of the engineering profession by:

1. Using their knowledge and skill for the enhancement of human welfare and the environment;
2. Being honest and impartial and serving with fidelity the public, their employers, and clients;
3. Striving to increase the competence and prestige of the engineering profession; and
4. Supporting the profession and technical societies of their disciplines.⁴¹

This project will uphold the same principles stated above throughout the scope of work, from initial conception through the final design completion.

Health and Safety

The structural analysis of the alternatives decided upon in the project will ensure that the existing structure remains safe and habitable. The group will ensure that the structure of the building complies with all local building codes. This will require analysis of the loading caused by the turbine and ensuring factors of safety are satisfied. Through these steps, the health and safety of the public will be made secure.

⁴¹ ASCE. "Code of Ethics." *American Society of Civil Engineers*. N.p., n.d. Web. 16 Oct. 2012. <<http://www.asce.org/Leadership-and-Management/Ethics/Code-of-Ethics/>>.

Methodology

This Major Qualifying Project will consist primarily of the selection and analysis of a wind turbine retrofitted onto an existing structure in Gateway Part II, as well as recommendations for making the design structurally sound. Figure 4, shown below, provides the most general breakdown of this section which is the Preliminary Selection, and Final Selection. What each of these sections encompasses has been described in this chapter.

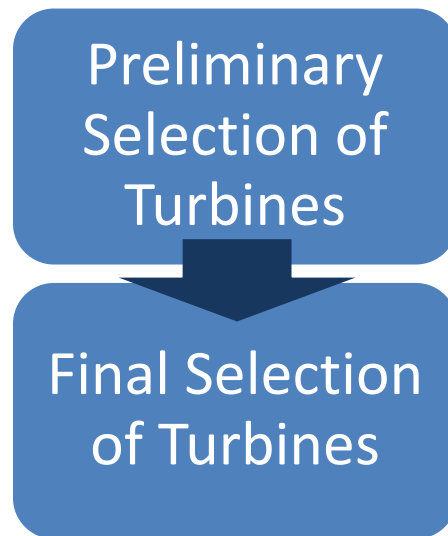


Figure 16: Overview of Methodology

Preliminary Selection of Turbines for Analysis

The process involved in the preliminary selection of turbines can be seen in the Initial Feasible Turbine Selection Flow Chart below. It requires placing each of four possible alternatives in Table 2 through a screening process to determine which turbines qualify for an even greater in-depth structural and cost analysis, which constitutes the Final Selection of Turbines portion of the methodology hierarchy above.

Placing four turbine candidates through a screening process to determine feasible options for further analysis is the first step in the methodology. This screening process, shown below, is explained in the sections following the flow chart and will help narrow down potential candidates. By adhering to the process laid out in Figure 5, the number of turbines that will advance to an in-depth analysis will be narrowed down to only the most feasible candidates.

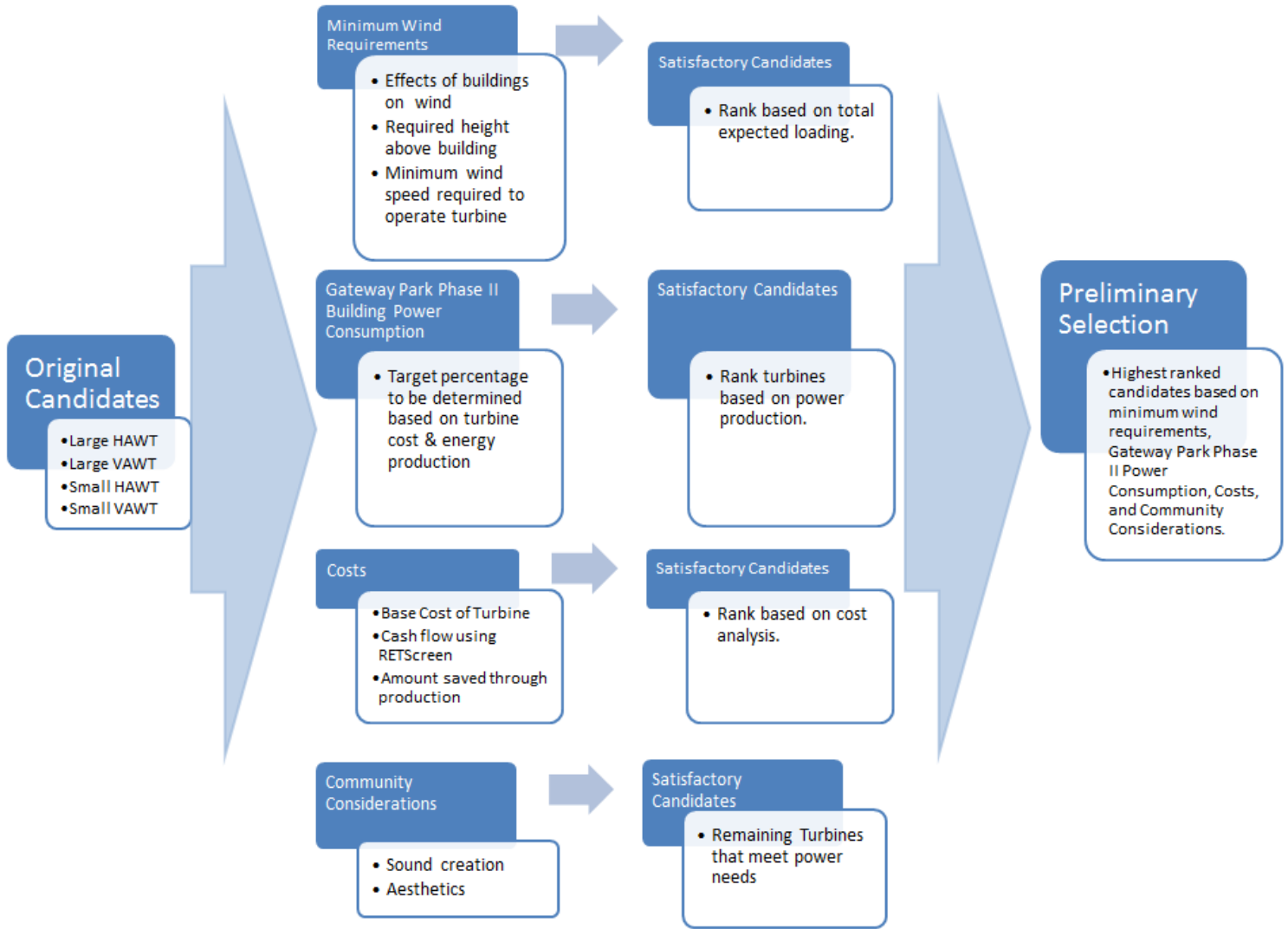


Figure 17: Process for preliminary selection of wind turbines

Minimum Wind Requirements

There are four wind turbines that will be investigated. They consist of the large vertical axis wind turbine, small vertical axis wind turbine, large horizontal axis wind turbine, and small horizontal axis wind turbine. These turbines have a minimum wind speed required to operate of 14.5 mph, 8.9 mph, 6.7 mph, and 6.7 mph respectively. In Worcester, MA the average wind speed year round is 11.5 mph⁴². At the edge of a roof, the air is extremely turbulent which could positively affect these wind speeds. Turbulent air is caused when the wind flows over the edge of the roof and separates into streams which cause the turbulence. Vertical axis wind turbines are not affected by turbulent air, so their height above the building does not affect their efficiency. Horizontal axis wind turbines, however, are ineffective in turbulent air. Therefore, calculations have to be performed in order to find a suitable height above the building for installation in which the turbulent layer can be avoided. Knowing that the wind stream passes in an upward angle of about 30° from the rooftops horizontal and that all the air below that is turbulent, it is possible to determine a height above that turbulent air for the horizontal axis wind turbine⁴³. It is evident from Figure 6 that HAWT's closer to the center of the building will have to be raised much higher to avoid the turbulent air than if they were placed closer to the edge. The equation provided in Figure 6 calculates this height based on the turbines position.

⁴² Center, U. S. D. O. E. R. R. D. "Wind Energy Resource Atlas of the United States."
<<http://rredc.nrel.gov/wind/pubs/atlas/titlepg.html>>

⁴³ Ragheb, M. "Wind Turbines in the Urban Environment." *uiuc*. N.p., 10 Mar. 2012. Web. 11 Dec. 2012.
<<https://netfiles.uiuc.edu/mragheb/www/NPRE%20475%20Wind%20Power%20Systems/Wind%20Turbines%20in%20the%20Urban%20Environment.pdf>>.

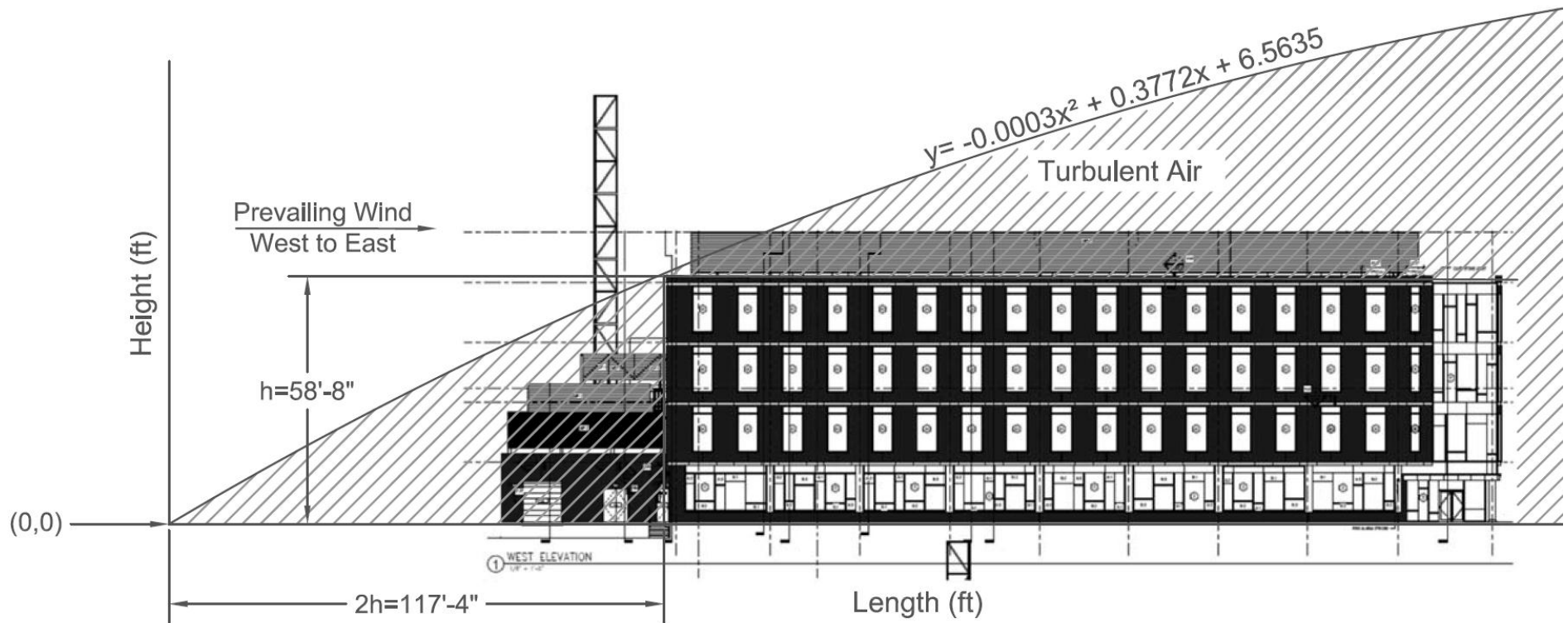


Figure 18: Diagram indicating the turbulent wind zone across the Gateway Park Phase II Building.

Gateway Phase II Building Power Consumption

In 2006, the Energy Information Administration (EIA) began performing a survey of thousands of buildings throughout the United States in order to achieve an understanding of the country's power consumption. The information they gathered was compiled into a series of tables that organized energy consumption of buildings by location, building activity, building size and date of construction.⁴⁴ The values obtained from this table are summarized in Table 3. The average kWh/ft² value was multiplied by the square footage of the Gateway Phase II building to obtain an estimate of 1173 MWh of electricity consumed per year.

Table 22: Building electricity consumption data taken from the Energy Information Administration survey.

Classification	Electricity Consumption (kWh/ft ²)
Building Activity - Educational	11.0
Floorspace - 50,001 to 100,000	13.0
Census Region - New England	10.8
Construction Date - After 2003	16.2
Average = 12.75 kWh/ ft ²	

Preliminary Costs

In the initial screening, the sum of the costs listed in the cost section of Figure 5 for each year will be compared to the estimated savings in energy per year due to the turbine. The estimated time that it will take for each turbine alternative to cover these costs will also be determined. These calculations will be performed using the current kWh rate for Worcester, MA of \$0.17 kWh.⁴⁵ With a building size of approximately 92,000 square feet, the group has estimated the Gateway Park Phase II building to cost \$199,410 per year in electricity. The program RETScreen 4 will be utilized as a tool in viewing costs and savings due to the turbines' power production. Entering values characteristic to each turbine into RETScreen allows the program to produce an estimate of how much money will be produced over the life of the turbine. The program also takes into consideration the location of the project, wind patterns of

⁴⁴ EIA.gov. "Electricity Consumption and Expenditure Intensities for Non-Mall Buildings" Web. 20 Nov. 2012. <www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/2003set10/2003pdf/c14.pdf>.

⁴⁵ Johanson, Caylee. "Wind Turbine for Residential Use" *Wentworth Institute of Technology*. 7 Feb. 2011. Web. <<http://myweb.wit.edu/hallowellz/Design1.html>>.

the area, inflation, cost of electricity, and initial costs from turbine costs and installation prices. A summary of important values needed for RETScreen 4 are listed in Table 4.

Table 23: Summary of important RETScreen 4 parameters.

RETScreen 4 Parameters		
Parameter	Importance	
Power System	Turbine Power Capacity	The measured maximum, or rated, capacity of a manufacturer's wind turbine to produce electric power.
	Turbine Capacity Factor	A ratio of the actual output of a turbine over time to the theoretical output of a turbine operating at maximum efficiency. Most often between 30% and 35%.
	Electricity Exported to Grid	This value is calculated as a result of the the power capacity of a particular turbine and its associated capacity factor.
Financial Analysis	Project Life	The estimated life of a turbine provided in the turbine specifications. Necessary for estimating feasibility and representing cash flow over the life of the project.
	Debt Ratio	A ratio of the funds able to be provided up front to the total cost of the project.
	Annual Operation & Maintenance	An estimation of the yearly cost of operation and maintenance that is accounted for in computing a cash flow diagram.

Community Considerations

The last level of criteria for screening the four alternatives concerns potential noise pollution created as a result of turbine operation as well as aesthetic appeal in the urban environment. Typically, noise regulations are designed for noises resulting from sources such as traffic or industry. Field studies suggest, however, that turbine noise causes higher levels of annoyance and stress than other noises at the same sound level. In Massachusetts, the noise limit has been set to 50 dBA.⁴⁶ Exact noise levels can be taken directly from the specification sheets for each alternative to see how they compare to the limits set by Massachusetts.

⁴⁶ Wind-Watch.org. "First International Symposium on Adverse Health Effects from Wind Turbines." *wind-watch.org*. 29 Oct. 2010. Web. 20 Nov. 2012. <docs.wind-watch.org/01-sww_symposium_presentation_no_global_standards.pdf>.

Final Turbine Selection

The preliminary turbine selection will narrow the turbine alternatives down to the two most feasible which will then be analyzed more in depth. Figure 7 gives insight as to the steps to be taken in order to perform this final turbine selection.

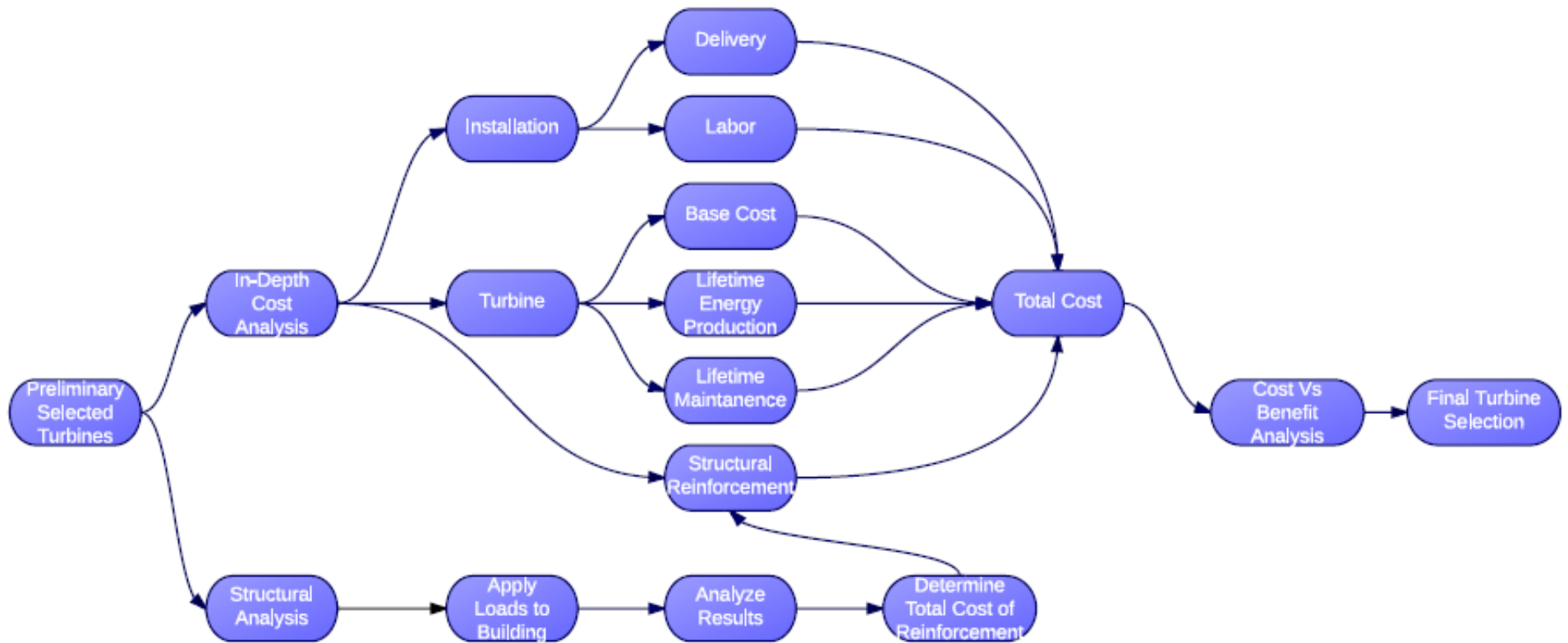


Figure 19: Flow chart for the Final Turbine selection process

Structural Analysis

Structural analysis will consist of several steps. These steps are determining the loading, applying the loads to the building, analyzing the results, and determining the total cost of reinforcement. This will help the group to determine the possible effects the wind turbine could have on the structural members of the building.

Determine Loading

The main loads to be analyzed are dead load, wind load, ice load, and live load. Additionally, consideration will be given to vibration induced by the wind turbine. The first load to be determined is the dead load. Dead load on a building typically consists of just the weight of the structure. For this project, the dead load will consist of the turbine's weight, taken from the manufacturing company's specifications. This dead load will be added to the dead loads of the building which consist of the tributary area supported by a structural member, or floor weight. This can be found in the structural drawings by Perkins + Will, the design company. Dead load is in a constant location and has a constant magnitude throughout the entire lifetime of the structure. Because of this, it typically only needs a small safety factor. Dead load affects the structure by compressing the structural columns vertically. When applied to a beam, it causes moment and shear force. This may cause lateral torsional buckling, shear failure, or flexural failure.

Wind load is the force caused by environmental wind on the face of a structure. This is found by multiplying the force per square foot due to a 50-year wind by the surface area of the side most often exposed to wind. A fifty-year wind is the highest expected wind speed in a 50-year period and can be found in the Massachusetts Building Code (*TIA-EIA-222*). As stated previously, there are no specific regulations on wind turbines because of how new the technology is, so the regulations for a radio tower will be used. Wind forces can contribute to buckling of columns and may cause flexural failure of columns in extreme cases. Wind load may also contribute to local flange buckling because of the stress it can add at a connection from the tower to a beam.

Ice load, as its name implies, is a load caused by the weight of frozen water on a structure. This is a very prominent problem in New England because of the harsh winters and, as a result, is largely focused on in the Massachusetts radio tower building codes. This load is determined by determining volume of ice on exposed structural elements, assuming a constant radial thickness of ice. The total load is then determined using an ice density of 56 pounds per cubic feet. Ice load acts similar to dead load, but changes throughout the life of a building and can be unevenly distributed.

The final type of load the group will analyze is live load. For most buildings, live load is determined using building codes that assign live loads in the format of force per square foot. For this project, the group will use the building codes for an office building, because it provides the description of designed use most similar to the Gateway Park Phase II building. Live load can often be uneven and have many effects on the structure. It can cause beams to buckle or undergo compressive yielding. On beams and girders, live load can cause shear failure, flexural failure, lateral-torsional buckling and fatigue failure. There will be nearly no live loads on the turbine, since all other factors are already taken into account, but the live load values from the structural drawings will still be incorporated into calculations of loads placed on the structural members.

An operating turbine possesses a natural frequency due to its rotation, which can produce large amounts of vibration if it coincides with the natural frequency of the buildings structure. Ideally, the mass of the roof will prevent any vibration from occurring. For accuracy, however, the turbines natural frequency will be compared to that of the building.

All of the above forces will be analyzed to determine if the current structural elements can support the loads or if they will require structural reinforcement for each possible turbine. Following the calculation of individual loads, they will be inserted into the ANSYS model to analyze its effect on the structure of the building. This analysis will help the group to determine which turbine candidate will have the least impact on the current structure and require the least reinforcement. Table 4 provides a summary of the loadings described in this section, while Table 5 gives insight as to what considerations must be taken when analyzing different types of structural members.

Table 24: Summary of loading references.

<u>Load</u>	<u>Design Reference</u>	<u>Description</u>
Dead Load	<p style="text-align: center;"><i>ASCE 7-10 Chapter 3 and 5</i></p>	<p>Dead loads are those that are constant in magnitude and fixed in location throughout the lifetime of the structure. Includes weight of the structure. Determined by multiplying volume of each construction member and multiplying by its density.</p>
Wind Load	<p style="text-align: center;"><i>TIA-EIA-222 Section 2.3.1</i></p> <p style="text-align: center;"><i>ASCE 7-10</i></p>	<p>Horizontal forces caused by wind pushing on the side of the structure. This is calculated as a uniform surface load applied to the surface area of one face of the structure. The force of wind is found using the expected highest wind load in a fifty year period 10 meters above the ground.</p>
Ice Load	<p style="text-align: center;"><i>TIA-EIA-222 Section 2.3.1</i></p>	<p>The radial thickness of ice applied uniformly around the exposed surfaces of the structure. Density of ice for calculations is 56 pounds per cubic feet.</p>
Live Load	<p style="text-align: center;"><i>ASCE 7-10 Chapter 4</i></p>	<p>Consists of occupancy loads in the building. Building codes provide standard weights per surface area of floors and roofs of a building, depending on its intended function. This load is multiplied by the surface area of each floor and the roof. This also includes snow load as a special live load since roof snow load and turbine load may be of concern.</p>

Table 25: Effects of on Members from Table 4

<u>Member</u>	<u>Loads to Consider</u>	<u>Possible Failure Mechanisms</u>
Beams	<ul style="list-style-type: none"> • Dead load- weight of turbine, self-weight, service load • Live Load- service load • Ice Load- weight of ice on turbine and snow on roof 	<ul style="list-style-type: none"> • Flexural failure • Shear failure • Lateral-torsional buckling • Fatigue failure • Local flange buckling
Girders	<ul style="list-style-type: none"> • Dead load- load from beams, self-weight • Live Load- load from beams 	<ul style="list-style-type: none"> • Flexural failure • Shear failure • Lateral-torsional buckling • Fatigue failure • Local flange buckling
Columns	<ul style="list-style-type: none"> • Dead load- weight of turbine(turbine directly on top of column), self-weight, load from girders • Wind Load- moment caused by wind • Ice Load- weight of ice on turbine and snow on roof • Live load- load from girders 	<ul style="list-style-type: none"> • Lateral bracing failure • Buckling • Shear failure • Flexural failure • Compressive yielding

ANSYS Model

A structural analysis must be performed on the Gateway Park Phase II building to determine the effects of the turbine on the building’s structure. To do this, ANSYS and finite element analysis will be used to model the building and analyze the stresses and deformations caused by the wind turbine candidates that passed the preliminary screening. Modeling options in ANSYS include modeling the entire building or just specific structural members of the building where the loads from the turbine will be placed. Table 6 outlines the process of modeling a turbine candidate using ANSYS to determine the structural effects.

The decision whether to model a single column, or more will be based on a number of factors including time constraints, the turbines location on the building, and the simplicity of the design. A full model of the structural components of the Gateway building may be very time consuming. The available time in the project will be a major factor in making this decision. The turbines location on the building, or point of loading, also influences which structural members

are affected. This could be a determining factor in choosing to model a single column, or perhaps adjacent supports as well. Lastly, the simplicity of the design is important. A very detailed and complex model may detract from showing what components of the building are affected most.

Table 26: Procedure to be used for ANSYS structural analysis

Ansys Analysis	
Procedure	Definition
Endpoints	Create endpoints for the start and end of the column
Beam	Connect the endpoints with a beam
Properties	Input the properties of the beam i.e. modulus of elasticity, poisson's ratio etc.
Meshing	Mesh the column depending on the number of floors in order to analyze the forces on each floor
Loading	Based on previous calculations apply the loads to the column where they are acting
Analysis	Perform the necessary analyses to determine necessary reinforcement

Construct Building Geometry

In order to create this ANSYS model the group has to model the structural elements of building exactly as they are in the building. It must first be decided if it would be more efficient to model the entire building or just the specific structural members where the turbine(s) are going to be added to the building. Modeling will be performed using the structural blue prints of the building, which were designed by Perkins & Will. By using the structural building plans, the group will be able to use exact dimensions of the structural members and spacing. Necessary properties of the structural components such as moment of inertia and modulus of elasticity can also be obtained from these documents which will make the analysis as accurate as possible. Upon completion of the building's model, the loads acting on the wind turbine can be applied to the building.

Apply Loads

With the expected loads calculated and an ANSYS model completed, the application of the loads to the building can commence. The turbine will be modeled in ANSYS as a structure on top of the building for which loads can be applied. After that is accomplished, the group will then be able to input the correct magnitudes of the loads and the directions, which they are applied. After the loads are applied to the model, the results of the structural analysis can be interpreted.

Interpret Results

With a completed ANSYS model, the effects of the turbine candidates on the building can be analyzed. This will include looking at the deformations of the structural members caused by the loads and also the stresses on the members. The results from these analyses are displayed through ANSYS both graphically and with actual values in tabular form. With the structural information provided by ANSYS, the group can proceed to determine what reinforcements will be necessary to maintain the structural soundness of the building.

Determine Needed Reinforcement

It is probable that reinforcements will be needed to ensure that the building is safe. ANSYS will show which structural components of the building are affected most by the turbine, which will allow the group to suggest solutions to reinforce the building. Studying the stresses and deformations can show exactly how much reinforcement is needed in those problem areas. Then, using *AISC Steel Construction Manual*, the group can find appropriate members needed to support these loads. Following the determination of required structural reinforcement, the analysis will proceed down the building to the foundation level.

Analyze Foundation Impact

At this point in the structural analysis, the loads will be known along the load path from the roof to the foundation of the building. The forces acting at the foundation and their magnitudes will allow for the use of basic geotechnical equations paired with boring logs obtained from Gateway Park Phase II preliminary studies performed by New Hampshire Boring, Inc. to determine if the foundation is adequate.⁴⁷ If the foundation isn't structurally sound then the group will provide a design for a foundation that can adequately support the loads above. With the last of the structural reinforcement determined, it is possible to proceed to the cost aspect of the project.

⁴⁷ New Hampshire Boring, Inc. "Boring and Test Pit Logs." 21 July 2005.

In-Depth Cost Analysis

Following the structural analysis and final screening, the various costs incurred throughout the project will be available. This will allow for an in-depth cost analysis to determine the cost benefits of each of the possible turbines. The costs that will be taken into consideration are described below.

Turbine

The cost of the turbine is a rather straightforward cost that requires little calculation. Most often it can be taken directly from the manufacturer's catalogue, which is the price that will be used in the analysis.

Installation Cost

Installation is a highly variable cost. The cost of installation depends on where the turbine will be placed, who will be completing the installation, and how long the installation may take. A 10% contingency will be added to this portion of the cost as is common in construction projects. This contingency is to account for unforeseen circumstances such as material availability problems, strikes, extra work items, and price escalation.

Structural Reinforcement Cost

The cost of the reinforcement required for the building due to the turbine's loads is one of the many costs that will be incurred by the project. The cost of this reinforcement will be determined using the weight and the length of the new reinforcement members paired with their associated costs and installation prices.

Total Cost

In all aspects of the group's analysis, one of the group's biggest focuses will be on cost. Everything the group will do will have a cost associated with it and it is the group's responsibility to ensure this cost is reasonable and justified. The group will analyze initial costs and long-term costs. The main factors of the group's initial cost will be installation, reinforcement, and the turbine. Long-term costs will consist of maintenance and money saved through power production based on its life expectancy.

Initial costs will likely be high compared to long-term costs, but are only a one-time expense. The turbine cost will be very simple to determine and is usually provided by the supplying company. This will depend on which model the group select and the size of it. Installation is typically performed by the supplying company or another contractor. The group will determine this cost by analyzing other similar projects and through information from the

manufacturer of the turbine. The cost that will require the most analysis on the group's part is the reinforcement. The group will need to determine, based on the group's structural analysis of the loading, how much reinforcement the turbine will require.

Long-term costs are difficult to predict, but can be forecasted based on the producing company's analysis and case studies of similar turbines. There will be necessary maintenance costs of the turbine in order to keep it running in optimal shape. There will also be maintenance costs associated with the structural reinforcement of the turbine. Cracks and other signs of strain may show up on the structure supporting the turbine and the costs of repairing these are directly attributable to the turbine. Offsetting the other costs is the amount of money saved by the turbine's energy production. Based on the expected energy output, the money saved each year by the turbine will be calculated using projected electricity costs. Both of these factors will be determined for the entire expected life of the turbine.

Cost vs. Benefit Analysis

The cost of the project will consist partly of the onetime turbine and installation price. The remainder of the cost will consist of yearly estimated operation and maintenance over the life of the project, and the yearly estimated cost of energy consumption. This number was calculated in the Gateway Phase II Power Consumption section to be approximately \$199,410 per year. Since the electricity generated is not expected to exceed the building's consumption, the benefit of the project will be the money saved on the annual electricity cost. Upon entering the values indicated in Table 4 into RETScreen 4, the program will output a cash flow diagram over the course of the project life. The project will be modeled as connected to the central grid. This means that the inflow of cash in the program is merely the amount of money earned from selling electricity back to the grid. This would only occur if the turbines provided more power than what the building consumed, which is not expected to be the case. The cash flow diagram created by RETScreen does not take into account the annual cost of electricity. Therefore, the dollar amount shown each year on the cash flow diagram should be subtracted from \$199,410 in order to arrive at the new cost of electricity for that year.

Final Turbine Selection

After compiling all of the analyses and research, the group must select which turbine will be the best choice. As seen in the final selection flow chart of Figure 7, there will be many factors that contribute to this decision. The key factors the group will use in the final selection will be the total cost, which includes the base turbine cost, installation, needed structural reinforcement as well as several long term factors including energy production and maintenance. These factors will be compared to several other factors, such as appearance,

noise, time of installation and expected lifetime. Major factors, such as cost, time of construction, time to recuperate costs, and expected lifetime will be given a number value and ranked in order of importance. Each turbine will be evaluated on a scale of one to ten, with ten being the best, for each of these factors and then multiplied by the ranking system. The turbine with the highest score will be the first choice. However, the group reserves the right to change its decision based on unpredictable or unquantifiable factors. The final turbine selected will be the most suitable and feasible turbine to be retrofitted to Gateway Park Phase II.

Schedule

The following schedule shows the timeline that the group will complete each section of the project in. It is in the form of a Gantt chart. The colors denote which section of work they are from. Following the proposal, writing of the final paper will be done concurrently with all other portions of work. Preliminary selection will be completed by the end of B term, allowing the group all of Winter Break and C Term to perform the final turbine selection and analysis. Analysis and final selection will be completed by the fifth week of C Term, providing the group with adequate time to finalize their final report. This two week time period can also act as flux time in case any unforeseen complications arise. Figure 8 provides a detailed timeline.

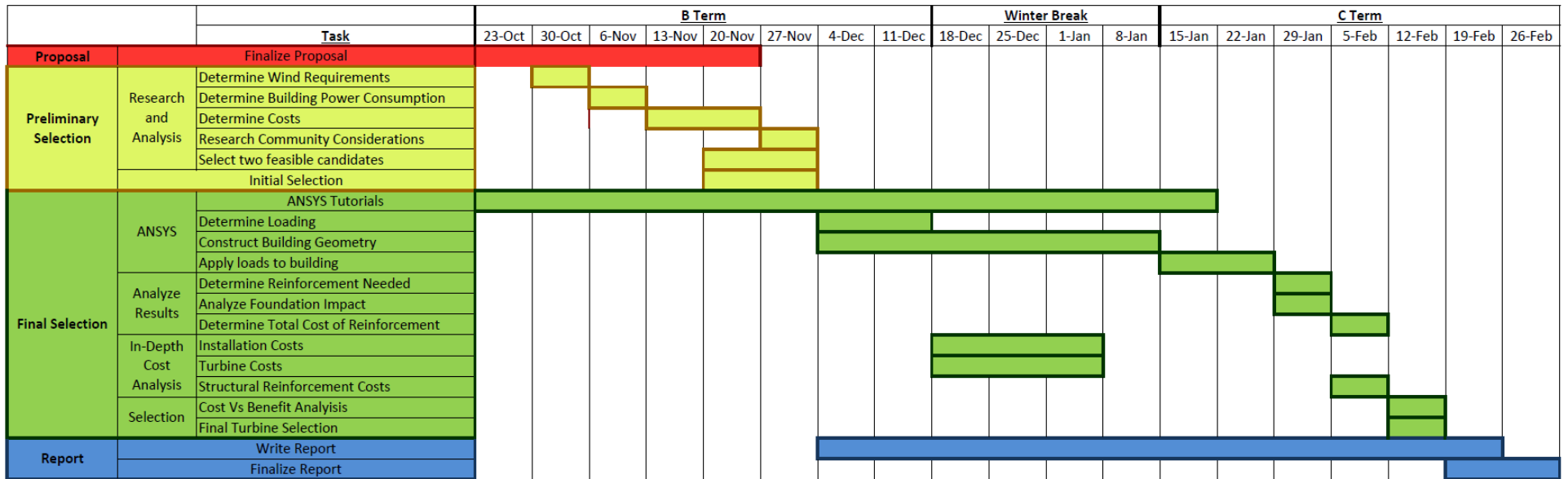


Figure 20: Tentative B and C Term Schedule

Appendix B: Components of Roof and Floor Dead Loads

Roof Dead Load					
#	Beam	lb/ft	Length (ft)	Beam/Girder Wt	Total wt of member type
5	W12X	19	11	209	1045
3	W10X	12	5.5	66	198
9	W12X	19	10	190	1710
1	W8X	28	20	560	560
1	W16X	26	23	598	598
1	C8X	11.5	18	207	207
36	W21X	44	36.75	1617	58212
8	W16X	26	30.5	793	6344
10	W18X	35	30.5	1067.5	10675
4	W10X	15	48	720	2880
3	W21X	44	200	8800	26400
4	W30X	99	30	2970	11880
6	W12X	19	11	209	1254
2	W10X	15	110	1650	3300
3	W10X	19	11	209	627
1	W12X	44	11	484	484
4	W12X	40	11	440	1760
2	C8X	11.5	10	115	230
3	W10X	12	10	120	360
2	W12X	16	10	160	320
1	W18X	50	30	1500	1500
1	W12X	40	30	1200	1200
2	W10X	19	30	570	1140
3	W12X	19	12	228	684
		Total Weight of Members (lbs)		133,568.00	
		Roof Area (ft ²)		20,800.00	
		Roof Dead Load (lb/ft ²)		6.42	
		Concrete Dead Load (lb/ft ²)		33.23	
		Metal Decking Dead Load (lb/ft ²)		2.60	
		Total Dead Load		42.25	

Floor Dead Load						
#	Beam	lb/ft	Length (ft)	Beam/Girder Wt	Total wt of member type	
2	W24X	55	23	1265	2530	
32	W21X	44	22	968	30976	
6	W21X	44	23	1012	6072	
6	W12X	19	12	228	1368	
3	W14X	22	23	506	1518	
6	C14X	22	22	484	2904	
2	W12X	19	15	285	570	
11	W12X	19	13	247	2717	
1	W18X	35	22	770	770	
4	W14X	22	12	264	1056	
33	W21X	44	36.75	1617	53361	
2	W24X	94	36.75	3454.5	6909	
1	W16X	26	26	676	676	
2	W24X	76	36.75	2793	5586	
10	W18X	35	30.5	1067.5	10675	
6	W16X	31	30.5	945.5	5673	
		Total Weight of members (lbs)			133,361.00	
		Floor Area (ft ²)			20,800.00	
		Beam Dead Load (lb/sqft)			6.41	
		Concrete Dead Load (lb/sqft)			33.23	
		Metal Decking Dead Load (lb/sqft)			2.60	
		Total Dead Load			42.24	

Appendix C: Doubly & Singly Symmetric members Subject to Flexure and Axial Force

Chapter H1 Doubly & Singly Symmetric members Subject to Flexure and Axial Force					
	$\frac{P_r}{P_c} > 0.2$		Where:		
				P _r	Required Axial Strength 295 k
				P _c	Available Axial Strength 478 k
		So Use Equation (H1-1a)			
	$\frac{Pr}{Pc} + \frac{8}{9} \left[\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right] < 1.0$		Where:		
				M _r	Required Flexural Strength
				M _c	Available Flexural Strength
F2 - Doubly Symmetric Compact I-Shaped Members & Channels Bent about their Major Axis					
	Check Compactness:		Where:	b _f	Flange Width 10 in
	$\frac{b_f}{2t_f} < 0.38 \sqrt{\frac{E}{F_y}}$			t _f	Flange Thickness 0.575 in
	$\frac{h}{t_w} < 3.76 \sqrt{\frac{E}{F_y}}$	*Both Sections are Compact		E	Steel Modulus of Elasticity 29000 Ksi
				F _y	Steel Yield Strength 50 Ksi
				h	Web Height 12.1 in
				t _w	Web Thickness .345 in
	1) <u>Failure by Yielding</u>				
	$M_n = M_p = F_y * Z_x$		Where:	Z _x	Plastic Section Modulus 77.9 in ³
	<i>Mn = 325 K*ft</i>				
	2) <u>Lateral Torsional Buckling</u>		Where:	Cb	LTB Mod Factor 1.0
	$M_n = Cb \left[M_p - (M_p - 0.7F_y S_x) \frac{L_b - L_p}{L_r - L_p} \right]$			S _x	Section Modulus 70.6 in ³
				L _b	Dist of Bracing 14.67 ft
				L _p	Plastic Limit Dist 8.76 ft
				L _r	Elastic Limit 28.2 ft
	<i>Mn = 289 K*ft GOVERNS</i>				

F2 - Doubly Symmetric Compact I-Shaped Members & Channels Bent about their Minor Axis						
1)	<u>Failure by Yielding</u>		Where:	Z _y	Plastic Section Modulus	29.1 in ³
	$M_n = M_p = F_y * Z_y$	Mn = 121.25 K*ft GOVERNS				
2)	<u>Flange Local Buckling</u>					
	* Limit State of Flange Local Buckling Does Not Apply					
Back to Chapter H1						
Chapter H1 Doubly & Singly Symmetric members Subject to Flexure and Axial Force						
	Equation (H1-1a):		Where:	M _{rx}	Required Flexural Strength (x)	0
	$\frac{Pr}{P_c} + \frac{8}{9} \left[\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right] < 1.0$			M _{ry}	Required Flexural Strength (y)	32.25 K*ft
				M _{cx}	Available Flexural Strength (x)	289 K*ft
	0.85 < 1.0 OK			M _{cy}	Available Flexural Strength (y)	121 K*ft
				P _r	Required Axial Strength	295 k
				P _c	Available Axial Strength	478 k

Magnification Factors							
Equation (A-8-3)					Where:	P_r	Required Axial Strength 295 k
						B_1	M_{nt} Modification Factor 1.14
						B_2	M_{lt} Modification Factor 1 (Braced Frame)
						Modified M_r	Required Flexural Strength 36.77 k*ft
						C_m	Moment Modification factor 1
						α	LRFD Factor 1
						P_{e1}	Euler's Buckling Strength 2409.88 k
						p	Table 6-1 Magnification Factors 2.09x10 ⁻³
						b_x	3.45x10 ⁻³
						b_y	8.15x10 ⁻³

0.92 < 1.0 OK

Appendix D: Bending Stress

Bending Stress Sample Calculations						
					Where:	
	$\sigma = \frac{Mc}{I}$				M	Bending Moment
					c	Distance to Neutral Axis 6.05 in
	$M = \frac{wL^2}{8}$				I	Moment of Inertia 425 in. ⁴
					L	Length of Column 14.6 ft
					w	Distributed Load 1210 lb/ft

Maximum Allowable Bending

$$M_u \leq \Phi F_y * Z$$

Appendix E: Combined Bending and Axial

Combined Bending & Axial Sample Calculations								
	$P_{ueq} = P_u + M_{ux}m + M_{uy}mu$				Where:	P_{ueq}	Equivalent Axial Load	388.5 k
						m	1st Approx Magnification Factor	1.7
						u	Subsequent Approximation Factor	1.5

Appendix F: P Delta Analysis

P Delta Analysis of Column 1 Scenario 3							
$M_r = M_{lt} + P_{nt}\Delta$							
				Where:	M_r	Increased Moment due to P Δ Effect	39.5 k*ft
$M_r = 17 + (300)(0.75)$							
$M_r = 39.5 > 36.77$					M_{lt}	Moment due to Lateral Loads	17 k*ft
* M_r Compared to Modified M_r from Magnification Factors Table					P_{nt}	Axial Compression Force	300 k
					Δ	Deflection Caused by Compression Force	0.75 in