FEASIBILITY STUDY

OF THE INCORPORATION OF

WIND TURBINES AT JET BLAST DEFLECTORS

By

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A Thesis Submitted in Partial Fulfillment
of the Requirements of the Degree of
Master of Science in
Aviation Administration

Middle Tennessee State University
December 2018

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Dedicated to my Guru, family and friends.

Thank you all for your love and support

Acknowledgements

I would like to take this opportunity to express my deepest thanks to people who have helped in completing a research of this magnitude. First, I would like to offer my sincere thanks to my Guru, Phani Kumar, for his continued support over the years. I feel blessed to be under the guidance of him. He was the one who guided and motivated me to pursue my master's degree in Aviation Administration majoring Aviation Management. Next, I would like to thank my parents and my brother for their unwavering support and continuous encouragement throughout my years of study. My parents have raised me, taught me, loved me, supported me, encouraged me, and helped me get through this struggling period in the most positive way. This accomplishment would not have been possible without these people.

I would like to convey my sincere gratitude and respect for my thesis advisor, Dr. Mark N. Callender, for his continuous guidance, patience, motivation and immense knowledge. The door of Dr. Callender's office was always open whenever I had a question about my research and was very generous in giving his time to offer me valuable feedback that helped me improve my work. I've also had a fantastic experience of working under him as a graduate teaching assistant while completing my graduate coursework. I would also like to extend my sincere thanks to Dr. Paul Craig for providing me his guidance, insights and efforts throughout the course of this research. I'm very grateful to all the faculty members of the Aerospace Department for providing me the opportunities and tools to accomplish my goals. Special thanks to John Black for his support.

Finally, I would like to honor my friends who stood by me whenever I needed them with a thank you. A special mention to: Sriman, Vinay, Siddarth, Sanith, Pooja, Akhila, and Naina. Cheers to you all!

Abstract

Airports require vast amounts of energy to power their operations. They operate around the clock: 24 hours a day, 365 days per year. Given this, they have a huge ability to save energy. Airport operators have a global goal of reducing their CO2 emissions by 50% by 2050. To minimize the electrical energy usage at airports, the airports could take some initiatives such as the installation of wind turbines. Installation of wind turbines at airports would be beneficial as there is a lot of wind blowing in and around airports because of the landings and take offs of aircraft. During engine run-ups, aircraft exhaust huge amount of high velocity wind. Erecting small wind turbines at key locations could yield great results as there are many aircraft which fly from all the airports every day.

Unlike many other thesis methodologies, this research does not involve any participants, surveys, interviews or tests for the data collection process. All the data required for the analysis will be composed by performing extensive desk research. The main procedure of this research is taking the jet blast velocity profiles of different aircraft and the numbers of landings will be used to know how much wind is generated by the aircraft. The jet blast from the aircraft is used to rotate the turbines that in turn generate power that can be used for other airport electricity purposes. The power generated by the turbines will be calculated by computing average wind flow rate at the blast fence.

Findings from this research will be beneficial for airport operators as well as to governmental organizations associated with aviation in finding a way to minimize the cost cuttings by saving electrical energy given out from the wind turbines and working collectively for the betterment of the environment.

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CHAPTER I - INTRODUCTION

Airports require vast amounts of energy to power their operations. They operate around the clock: 24 hours a day, 365 days per year. Given this, they present many opportunities to save energy. Airport operators have a global goal of reducing their CO_2 emissions by 50% by 2050 (“Optimize electricity usage”, n.d.). To minimize electricity usage at airports, airport operators need to implement the best possible energy management strategy. Energy usage at airports is divided into two parts, 70% for electricity and 30% for heat (“Optimize electricity usage”, n.d.). This research will focus primarily on electricity usage and its management. The units of energy are kilowatt-hours. The kilowatt-hour is a unit of energy equivalent to one kilowatt of power expended for one hour of time. The kilowatt-hour is not a standard unit in any formal system, but it is commonly used to measure energy (Rouse, 2006). According to the same study (“Optimize electricity usage”, n.d.), airports consume up to 180 Million kWh per year in electricity. Sixty percent of this energy is consumed by the terminals and the other 40% is consumed by lighting, hangars, parking, maintenance, workshops, and other buildings. To minimize the electrical energy usage at airports, the airports could implement initiatives such as the installation of wind turbines. Installation of wind turbines at airports would be beneficial as there are substantial amounts of wind blowing in and around airports both naturally and due to the landings and take offs of aircraft. Natural wind is wind caused due to the natural movement of air in the atmosphere. Separate from this, aircraft engines and propellers produce vast amounts of high velocity wind. Erecting small wind turbines at key locations could yield energy savings as there are many aircraft that fly from airports every day. Because of this research, the entire world can come to know this potential method of saving electricity, which could save money for airport operators.

Airports have a moral responsibility to protect the planet and a fiduciary responsibility to the economy. Both could be achieved by implementing this strategy. This strategy could reduce greenhouse gases as well as provide additional efficiencies that translate into cost savings. Conclusions drawn from this research will give an outlook to the airport operators of how much electricity is being saved if wind turbines are installed near the airport's jet blast deflectors (JBD).

Review of Literature

Wind Turbines

A wind turbine is a system that transforms the kinetic energy available in wind into mechanical or electrical energy that can be utilized for any required application. Wind turbines generate electricity that can be utilized locally or transported to a desired location through a grid. Wind turbines work on a basic principle. The energy in the wind turns a propeller-like device known as a turbine. The turbine is attached to a main shaft, which turns a generator to make power. Simply put, a wind turbine is the inverse of an electric fan. Rather than utilizing electricity to make wind, wind turbines use wind to make electricity. A clear depiction of a wind turbine and its mechanism is shown in Figure 1 ("How do wind Turbines work?", 2014).

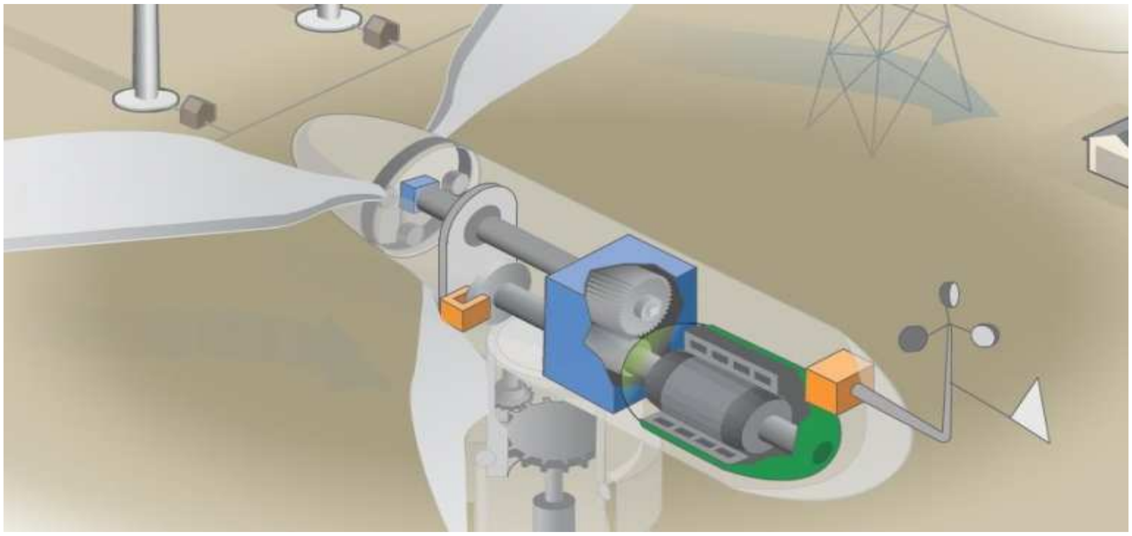

Figure 1. Wind Turbine Mechanism.

Wind turbines are of two basic types: the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT). HAWTs usually have two to five blades depending on their power generating capacity. In a HAWT, the rotational axis of the blades is parallel to the wind stream whereas, in a VAWT the rotational axis of the blades is perpendicular to the wind stream (Tong, 2010, p.16). Examples of both a HAWT and a VAWT are shown in Figures 2 and 3 respectively.

Figure 2. Horizontal Axis Wind Turbine.

Figure 3. Vertical-Axis Wind Turbine.

The amount of electric power generated by a turbine is measured in Watts. A Watt is the basic unit of power. Kilowatts (kW) and Megawatts (MW) are the most commonly used units to describe the power generating capability of wind turbines. The power output of a wind turbine depends on several factors: blade length, shape, and weight. Longer wind turbine blades will generate higher power as the swept area of the wind turbines with longer blades is higher (“How much Power Can a Wind”, 2015). Usually commercial wind turbines vary from 1 kW to 2.5 MW (“Utility-Scale”, n.d.). According to a study by the U.S Department of Energy (“Small Wind Electric Systems”, 2006), the formula for power (kW) generated by wind turbines is described in Equation 1.

$$Power = \frac{1}{2}\, C_p \rho A V^3 \qquad (1)$$

In Equation 1, The power output will be in Kilowatts (kW). C_p is the capacity factor of the wind turbine. According to Andrew (2014), “a capacity factor of a wind turbine is the average power generated, divided by the rated peak output”. C_p usually varies from 0.25 to 0.45. ρ is the density of the air. According to the International Standard Atmosphere (ISA), the density of air at sea level and at 15□ is 0.0023769 slug/ft^3 (Helmenstine, 2017). V is the wind speed in feet per second (fps). A is the swept area of the blade in square feet. The swept area of a wind turbine is described in Equation 2.

$$A = \pi r^2 \qquad (2)$$

Although the power output of the wind turbine demonstrates the power generating capacity of the wind turbine, the best measure of a wind turbine’s performance is its energy output (“Small Wind Electric Systems”, 2006). The energy production of a wind turbine is determined by multiplying the power output by the number of hours the wind turbine generates power in one month. The energy output of a wind turbine is calculated in Equation 3.

$$Energy = PNt \tag{3}$$

In Equation 3, the energy output will be in Kilowatt-hours (kWh). P is the power output of the wind turbine as described in Equation 1. N represents the number of months the wind turbines produced the power and t represents the amount of time in hours that a wind turbine produced power in a month.

Use of Wind Turbines at Airports

In 2009, Minneapolis-St. Paul International Airport set up ten wind turbines ("Minneapolis International", n.d.). Wind turbine locations were selected based on several factors (i.e. wind patterns) that provided the most suitable environment for aircraft takeoffs and landings. The airport operators installed ten 1 kW wind turbines on the roof top of the airport fire station to make use of the wind. The turbines were expected to produce a maximum of 10 kW of electricity per hour. The power generated by the wind turbines was used to power the airport's fully electric Cushman Motors e-ride utility vehicle. The Metropolitan Airport Commission (MAC) expected that the installation of the wind turbines would minimize the expenditures on fuel by powering the airports electric utility vehicles with the electricity produced by the wind turbines. The total cost for installing the turbines was $94,000, and they are expected to last for more than 20 years ("Minneapolis International", n.d.).

In 2008, a fleet of miniature wind turbines was installed at Boston Logan International Airport. According to the Massachusetts Port Authority ("Twenty Wind Turbines", 2008), twenty wind turbines, each six feet (ft) in diameter and weighing 90 pounds (41 kg), were attached to the roof parapet walls of the Logan Office Centre. The Boston airport authority was expecting the wind turbines to produce a total of approximately 100,000 kWh electricity annually. The expected electricity of 100,000 kWh is equal to 3% of the building's energy requirements. The turbines were a part of a demonstration project and were designed to operate in turbulent wind conditions at both low and high wind speeds ("Twenty Wind Turbines", 2008). The installation of the wind turbines at the airport was intended to cut energy costs by $13,000 per year. The turbines were strategically placed to capture the turbulent flow of air blowing from the harbor towards the building, and the turbines were specifically placed to suit the urban environment ("Twenty Wind Turbines", 2008).

Eastern Wind Power (EWP), is a Cambridge-based green energy design and development company that came up with a new idea for creating a VAWT. Their VAWT was developed in partnership with Siemens Industry. The main purpose of this newly developed wind turbine was to produce 50 kW of power by withstanding accelerated winds passing between tall buildings. EWP erected its full scale 50 kW wind turbine at Martha's Vineyard Airport in 2010. This turbine passed all safety tests and withstood winds between 65 to 70 mph. The safety tests included exposing the wind turbines to Martha's Vineyard mixture of salt air, rain and snow, which resulted in some changes in connections and incorporating fittings of stainless steel. In addition, the turbine was subjected to winds up to 110 mph in a controlled test environment that used a twin-engine Saab turboprop powered airplane at full throttle (Hefler, 2013).

East Midlands Airport, the second largest cargo airport in the United Kingdom, worked with wind turbine manufacturers and the Civil Aviation Authority (CAA) for nearly three years and completed a project of installing four 250 kW wind turbines. The blade diameter of the wind turbines was 30 meters and the height of the turbines was 45 meters including the blade radius of 15 meters ("East Midlands", 2011). The turbines were able to generate 5% of the airport's total electricity usage. That is equivalent to the electricity usage of 150 houses ("East Midlands", 2011). The installation of the wind turbines was expected to save 300 tons of carbon emissions each year. This airport was awarded a Green Apple Environment Award in 2011 for the fifth consecutive year ("East Midlands", 2011).

The National Aerospace Laboratory of the Netherlands has a research organization known as NLR Air Transport Safety Institute (NLR-ATSI). According to NLR-ATSI, erection of wind turbines may interrupt the airspace and indirectly affect aircraft operations. In the Netherlands, research suggests that an increase in the number of wind turbines around smaller airports may become hazardous to general aviation ("Wind Turbines near Airport", n.d.). For instance, two wind turbines were installed in the year 2014 near an airport in Spondon, Derby. The total expenditure for installing two 130m tall turbines was 7 million euros. The pair of wind turbines was expected to generate 10,000 MWh of electricity annually, which is equivalent to the electricity needed for 3,000 houses. However, the turbines were not allowed to operate as they appeared on the radar screens of ATC and were causing problems for the air traffic controllers (Collins, 2014).

According to Jones (2012), there were 19 Giga Watts (GW) of wind projects that were blocked due to radar difficulties in the UK, Finland, Sweden, Germany, Czech Republic, France, Spain, Greece and Ireland. The difficulties confronted by installing wind turbines close to airports have been raised because wind turbines cause interference that can affect the air traffic controllers' displays. Wind turbines can show up as aircraft to ATC radar systems, creating difficulty in detecting aircraft flying over wind turbines (Airports Vs Wind Farms, 2011). To overcome the issues related with wind turbines at airports and to make wind turbines compatible with airports, a new holographic radar system was being developed by UK tech firm Avelliant (Grozdanic, 2012). This radar can distinguish between the spinning blades of aircraft and the blades of wind turbines. This new radar pinpoints the blades of any turbine within a radius of twenty nautical miles of the airport, which will help open more locations for placement of wind turbines in and around airports. This innovation could be added to airports' current radar framework and, by identifying the rotating movements of the turbines from the radar screen in the ATC system, it makes it possible to utilize land around airports for harnessing wind energy (Grozdanic, 2012). Technological developments aside, it is important for the world to realize that both wind turbines and radars can exist together. However, small wind turbines do not pose any problem to the ATC system because the radars in use can only detect the movement of tall wind turbines.

Jet Blast Deflector

A JBD is a safety instrument that diverts the high-speed exhaust from an aircraft engine and/or propeller in order to prevent harm and/or damage. JBDs can be utilized as protection from helicopter and fixed-wing aircraft prop/rotor/jet wash. JBDs were first used at airports in the late 1950's after the inception of large piston powered and jet aircraft. High speed winds produced from prop wash and jet exhaust were causing damage to equipment, other aircraft, and the work force. JBD design was intended to prevent such damage by diverting the dangerous winds upward. JBDs were designed to withstand heat and high velocity winds. JBDs can be stationary, metal or fiberglass walls or movable boards that are raised and lowered by hydraulic or pneumatic pistons (Anderson et al, 2010).

A JBD research project was completed by the aviation students of San Jose State University. The students came up with a design of a JBD in such a way that a wind turbine is incorporated in the jet blast deflector itself. The design was named the Airfield

Wind Air Turbine Technology (AfWATT). The major highlight of this design was that it did not alter the structural integrity of the existing JBD (Anderson, Borman, Hevia, Lewis, Miller, Williams, 2010).

Research Questions

The main purpose of the research is to answer to the following questions:

1. What are the potential issues with installing wind turbines at the ends of the runways near JBDs at the Nashville International Airport (KBNA)?
2. What would be the appropriate size of the wind turbines if they could be installed near the JBDs at the Nashville International Airport?
3. What would be the optimal arrangement of the wind turbines near JBDs at the Nashville International Airport?
4. How much electricity could be saved in one year after installing wind turbines near JBDs at the Nashville International Airport?
5. What would be the break-even point, given the cost of the wind turbine system if installed near JBDs at the Nashville International Airport?

CHAPTER II - METHODOLOGY

The potential issues of installing wind turbines at the ends of the runways near JBDs were addressed by consulting the design standards for runways and runway associated elements such as runway safety areas (RSA), obstacle free zones (OFZ), object free areas (OFA), blast pads, clearways, and stop ways in the FAA Advisory Circular (AC) 150/5300-13A about airport design. The other regulatory issues such as wind turbine height limitations were addressed based upon the rules and regulations document, 14 CFR Part 77. 14 CFR Part 77 emphasizes the rules and regulations of objects that may affect the navigable airspace.

The appropriate size of the wind turbines was selected by taking the height of JBDs at KBNA into consideration, as the height of the wind turbines should not exceed the height of JBD in order to meet the design standards and rules mentioned in the AC 150/1500-13A and 14 CFR Part 77 respectively. The height of jet blast deflectors was also considered in determining the height of the wind turbines. The wind turbine selected also met the requirement of having a fin on the back of its blades so that it can turn according to the direction of wind to capture natural wind when there is no jet blast velocity from an aircraft. An optimal arrangement of wind turbines near the JBDs was determined based on the jet blast velocity profiles of the aircraft, given the length of the JBDs and the diameter of the wind turbine blades.

Nashville International Airport was considered for this research and the flight data consisting of number of takeoffs and landings from KBNA, and the types of aircraft that arrive and depart from KBNA in one month required for the analysis was received from an employee at KBNA (Gelband.B, Personal Communication, October 9, 2017). The flight data consisted of total aircraft operations from KBNA for the month of September 2017. The number of takeoffs from runway 13/31 at KBNA was determined by using the filter functionality in Microsoft Excel software. Only the takeoffs were considered for the research as the purpose of the research was to make the wind turbines rotate using the jet blast velocities from the aircraft during takeoffs.

The flight data was used to calculate the amount of electricity that could be produced in one year using wind turbines near the JBDs. Then the number of takeoffs per month was determined by totaling the number of aircraft whose jet blast velocity contours could reach the JBDs. The aircraft were then grouped based on their size and engine arrangement. The wind speeds and durations were calculated for the different groups of aircraft. The amount of power generated by the wind turbines was calculated by substituting all the appropriate values into Equation 1. The energy produced was determined from the derived power output and the number of takeoffs from runway 13/31 at KBNA for the month of September 2017. The energy produced by the wind turbines was determined by assuming that the number of takeoffs were consistent every month throughout the year because the monthly air traffic report of KBNA from January to September indicated that the number of aircraft operations were consistent and the difference in the number of aircraft operations per month was negligible. In addition to the energy produced by the wind turbines due to aircraft, the research also includes the energy output of the wind turbines due to natural wind by determining the average wind speed at BNA through websites related to weather.

The amount of money saved by KBNA was calculated by multiplying the energy savings by the cost of electricity per kWh at KBNA. The number of months it takes for KBNA to recover the cost of installing the wind turbine system was then determined by dividing the total cost of the wind turbine system with the amount saved by KBNA through energy savings in one month.

The data for this research was drawn from previous studies and official websites. This research did not involve any statistical data analysis methods to derive a conclusion. Various figures and tables were used to show the outcome of the power generated by the wind turbines.

CHAPTER III - DATA ANALYSIS

Regulatory Issues

It is important to maintain the safety of flight while attempting innovative ideas of developing the sources of renewable energy such as installing wind turbines at airports. The FAA has enhanced the existing regulations on dynamic vertical structures that might cause obstruction to aviation (Fohr, n.d.). The primary idea of the research is to install wind turbines near the JBDs at the end of the runway 13/31 at KBNA to generate power. To install the wind turbines near the JBDs, the FAA AC 150/1500-13A about airport design must be reviewed as it provides approved methods for meeting the regulations in 14 CFR part 77. The 14 CFR part 77 establishes the standards and requirements for construction of objects that affect the navigable airspace. These documents provide sufficient information on the potential issues that might arise during the system design. Other supporting documents such as FAR part 139, FAA Order 5200.8, Order 6030.20F on electrical power policy, AC 150/5220-23 frangible connections, and FAA Order 5190.6B on FAA airport compliance manual were reviewed.

Firstly, the airport design standards of the runways and the runway safety areas were addressed according to the CFR part 139, FAA Order 5200.8 (1999) and AC 150/1500-13A by FAA (2014). The CFR part 139 (Electronic Code of Regulations, 2014) states that the RSA's should be authorized by the administrator during any construction, expansion or reconstruction in the RSA. The RSA must be free of potential hazard ruts, humps, or other surface variations. The draining of the RSA must be done to prevent water accumulation. The RSA must be suitable to dry conditions by supporting snow removal, aircraft rescue and must support the passing of aircraft without causing any damage to the aircraft. No objects other than the objects that are used for the functioning of aircraft operations must be located in the RSA (Electronic Code of Regulations, 2014).

According to FAA Order 5200.8, the RSA should follow the standards written in AC 150/1500-13A airport design at airports that are certified under 14 CFR Part 139. In case of any construction in the RSA, the airport must ensure that the proposed construction program is approved by the regional airports' division manager according to the determinations mentioned in Order 5200.8. The data of regarding the RSA at an airport shall be collected and maintained by the regional airport's division regarding the objects that are in the RSA. The data will include the dimensions of the RSA beyond each runway and the standards that apply to each RSA at that airport. Any new construction in the RSA should follow the determinations made in the Order 5200.8. The RSA determinations are made based on the documentation carried out by the regional airport division on whether the RSA meets the standards contained in AC 150/5300-13A. This document states that whenever a new construction is involved on the runway, the project shall also provide the purpose of the improvement of the RSA in accordance with the standards contained in the AC 150/5300-13A. The RSA improvement documentation should also project the effects of the new construction on an airport's capability, load bearing strength of the pavement and the changes made to the original pavement (Federal Aviation Administration, 1999). Appendix 3 in the AC 150/5300-13A also states that the jet blast gusts average more than 20 mph and cover over 2000 feet, which may cause injury to the personnel, damage to the structures and equipment installed behind the aircraft in the RSA (Federal Aviation Administration, 2014).

According to the AC 150/1500-13A, the Runway Safety Area (RSA) is the area after the end of the runway prepared for mitigating the risk of damaging aircraft in case of runway excursion from the runway. The dimensions of the RSA in airports that serve scheduled air carriers extend 250 feet on either side from the runway centerline and 1000 feet long from each end of the runway. It is important to note that no construction is allowed within the RSA while the runway is open for operations. The RSA dimensions may be altered if the runway is limited to aircraft operations that requires smaller RSA. In addition to this, no temporary objects such as people and vehicles are permitted in the RSA (Federal Aviation Administration, 2014). It is essential to be proactive regarding the design standards surrounding the runway safety area as per FAA as it might affect the safety of aircraft. The AC also states that while citing the location for radar antenna systems, the presence of wind turbines should be taken into consideration as they may cause reflectivity issues for the radar. The radar antenna systems are used to scan through 360 degrees to give the ATC a display of range and elevation of all aircraft within 60 nautical miles of the airport.

The primary regulatory issue for the system design was that the RSA should not have any objects located in that area unless and until it is required for the functioning of the aircraft operations. Even the objects that are constructed in the RSA should be mounted on frangible structures of the lowest height of not higher than 3 inches. The AC 150/5220-23 defines the types of frangible mountings that can be used in the airfield safety areas. According to AC 150/5220-23, an object in the airfield safety area should have minimal mass and be able to absorb minimum amount of energy during an impact. It also states that if an aircraft impacts an object on the airfield, it should not lose its momentum, should not change its direction and should suffer minimum structural damage. The equipment mounted on the frangible connection should break in case of any accidental impact of an aircraft and must preclude any chance of electrical wires wrapping around the aircraft after the collision with the object. The frangible connections in the RSA must withstand the jet blasts and should not impose any additional force on the aircraft in case of collision. Any frangible connection that is not listed in the AC should undergo testing and obtain certification and approval from the Federal Highway Administration (FHWA) (Federal Aviation Administration, 2009).

The main idea of the research deals with generating power from the wind turbines, it is important to consider the FAA standards on electrical power policy defined in FAA Order 6030.20F. This Order establishes and defines the policies and provides the guidelines for implementation of power systems supporting the National Airspace System (NAS). All the Continuous Power Airports (CPA) are equipped with NAS power systems. The Order 6030.20F states that any new electrical equipment installed in the airport should be compatible with the NAS equipment and power systems and should not negatively affect the existing system. The new equipment should not be connected to the existing equipment until it is proven that the new equipment will not cause any problem to the existing one. The new power systems must obey the environmental and energy efficiency requirements as stated in Order 6030.20F. The new equipment should be tested prior to the installation to ensure the compatibility. The proposed system should be cost effective and reliable by avoiding any unnecessary expenditures (Federal Aviation Administration, 2004).

The length of the precision instrument runway 13/31 at BNA is 11,029 feet and the total takeoff runway available is 10288 feet (“Nashville International Airport”, (n.d.). There are two JBDs installed at BNA, one on each end of runway 13/31. A JBD is installed at 598 MSL, 1100 feet southeast of runway 31’s threshold and the other JBD is installed at 568 MSL, 1167 feet northwest of runway 13’s threshold as shown in Figures 4 and 5. On the end of runway 13, the JBD is 280 feet wide and 14 feet high. The JBD on the end of runway 31 is 14 feet high and approximately 212 feet wide. Both of the JBDs are designed and constructed in accordance with FAA AC 150/5300-13A airport design standards (“Nashville International

Airport", (n.d.)). A clear depiction of the locations, lengths and heights of both JBDs are shown in Figures 6, 7 and 8.

Figure 4. Distance from threshold of runway 31 to JBD.

Figure 5. Distance from threshold of runway 13 to JBD.

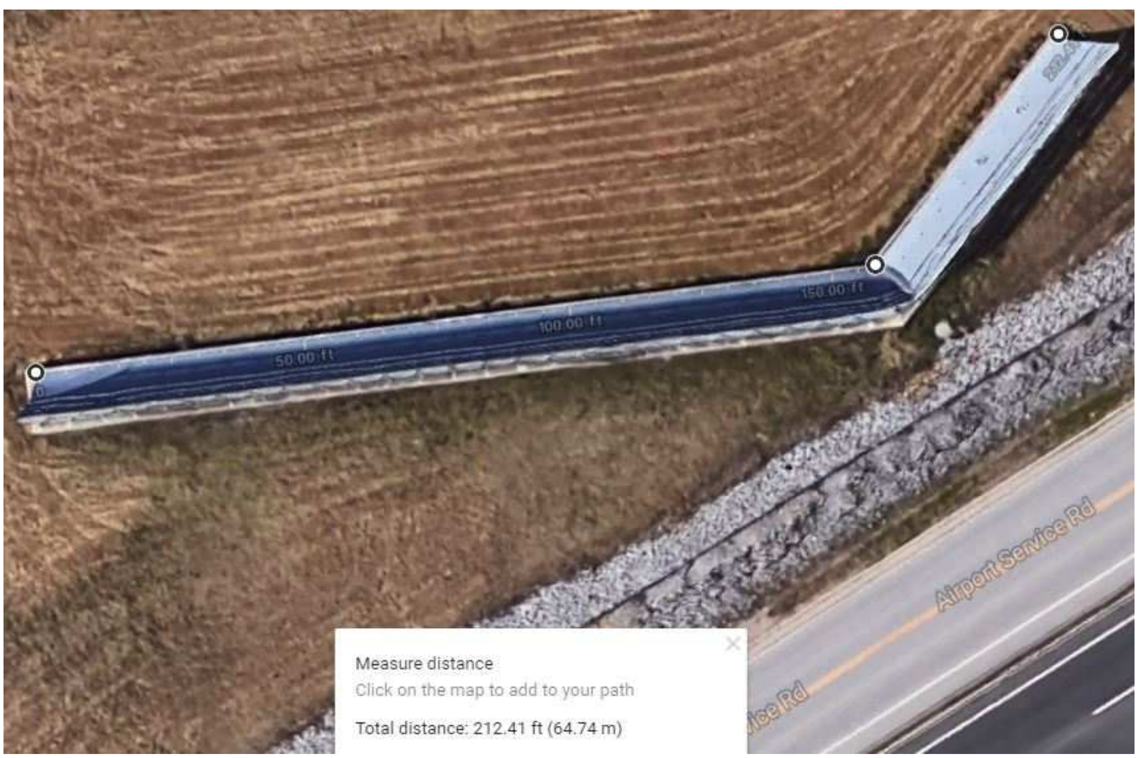

Figure 6. Length of the JBD at the end of runway 31.

Figure 7. Length of the JBD at the end of runway 13.

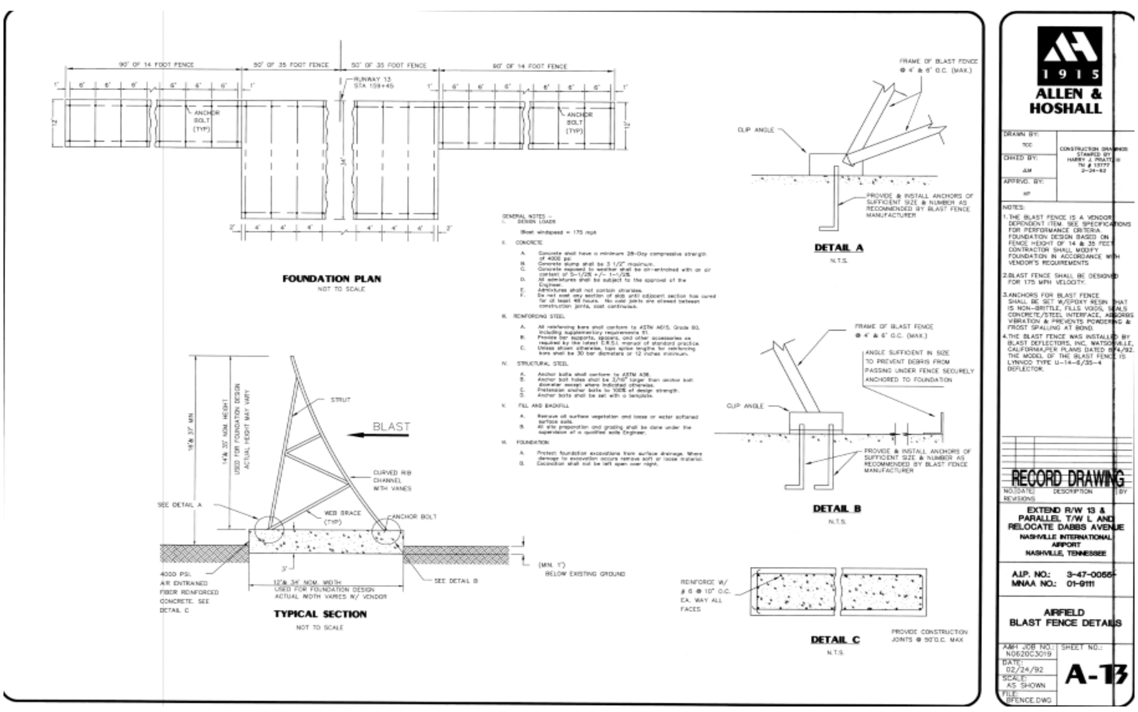

Figure 8. Height and Length of the JBD at the end of runway 13.

The FAA controls the US airspace above the minimum altitude of flight and should be informed before any construction more than 200 feet tall, so an evaluation study can be performed. Usually the wind turbines do not create any harm if they are installed within a few miles of an airport. But this research focuses on installing the wind turbines in the airfield at the ends of the runway 13/31 in BNA airport. The 14 CFR Part 77 states that any construction in the approach surface on a 10,000 feet runway should follow the slope of 50 feet (Horizontal) to 1 feet (Vertical) ratio (Electronic Code of Federal Regulations, 2018). Hence, the permissible height of the installed wind turbine at the ends of the runway 13/31 is 22 feet and 23.34 feet on the end of runway 31 and runway 13 respectively, given the permissible height on the approach surface.

In summary, the primary issue in installing the wind turbines near the JBDs would be the prohibition of any construction of objects in the RSA except the objects that are used for functioning. If the airport demands an installation of objects according to the design standards suggested by the AC, the object should be mounted on a frangible structure not higher than 3 inches that does not cause any harm to the aircraft in case of runway excursions. Secondly, the proposed height of the wind turbine and the system should abide by the rules and regulations defined by the 14 CFR Part 77 i.e. proposed construction in the approach surface should follow the 50:1 ratio from the threshold on runway 13/31 at BNA, given the length and type of the runway 13/31.

System Design

Nashville International Airport recorded a total of 17,204 operations in September 2017 including both takeoffs and landings. According to the monthly traffic report of BNA in 2017 (“Airport Data”, (n.d.)), the average of total operations of all the 12 months in the year

2017 is 17,191, which is approximately equal to the number of operations recorded in September 2017. Among the total 17,204 operations in September 2017, 8999 departures and 8205 arrivals were recorded. It is essential to only consider the departures from runway 13/31 because only runway 13/31 has the JBDs installed on both ends at BNA.

The flight data was received in a Microsoft Excel sheet from an employee at BNA and consisted of all of the operations at BNA in September 2017. The filter functionality in Microsoft Excel was used to filter the takeoffs to identify only those from runway 13/31. The data also displayed all of the aircraft types that departed from runway 13/31. All of the various types of aircraft were noted, and their respective aircraft manuals were referred to check whether the jet blast velocity of that aircraft during takeoff would reach the JBDs. According to AC 150-5300/13A (2012), a jet blast is defined as the wind forces produced by a jet engine with very high wind velocities and temperatures. A jet blast during takeoff can cause severe injuries to personnel, damage to the airport facilities and equipment. A large jet engine aircraft can produce a jet blast velocity of 120 mph behind the tail of the aircraft during takeoff. These jet blasts can extend up to maximum of 1600 feet depending on the size of the aircraft as shown in Figures 9-19(Morrison, 1993).

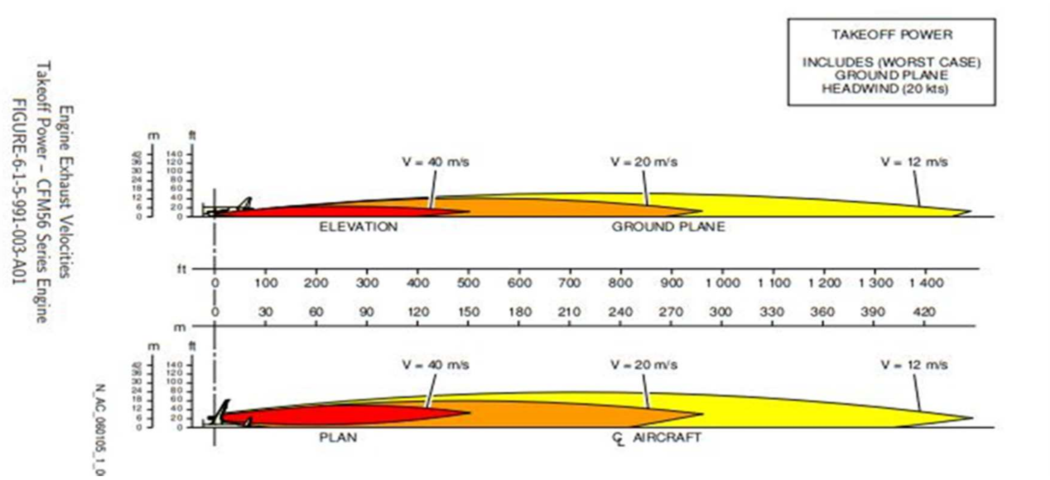

Figure 9. Takeoff Exhaust Velocity Contour of A319 aircraft. Adapted from Aircraft Characteristics Airport and Maintenance Planning by Airbus, 1995, Engine Exhaust Velocity Contours, 6-1-5, p.2.

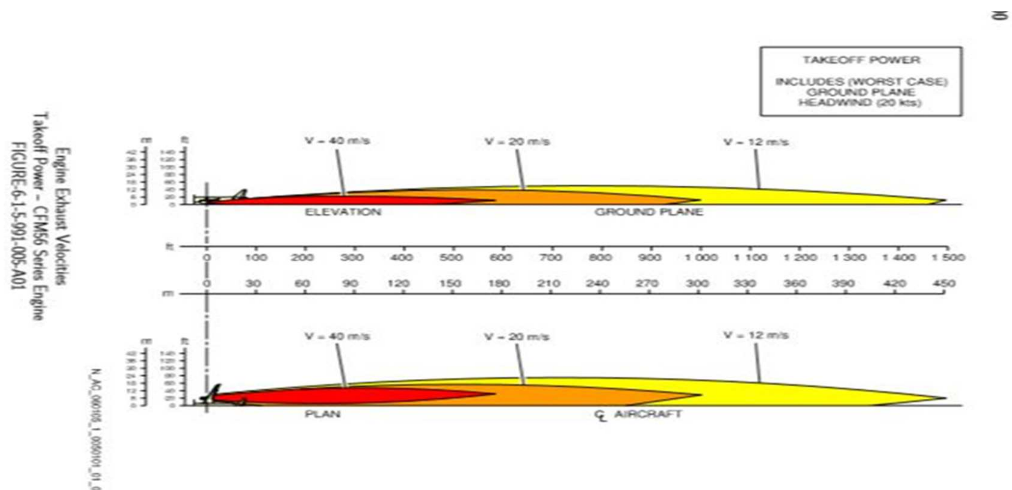

Figure 10. Takeoff Exhaust Velocity Thrust Contour of A320 aircraft. Adapted from Aircraft Characteristics Airport and Maintenance Planning by Airbus, 1985, Engine Exhaust Velocity Contours, 6-1-5, p.2.

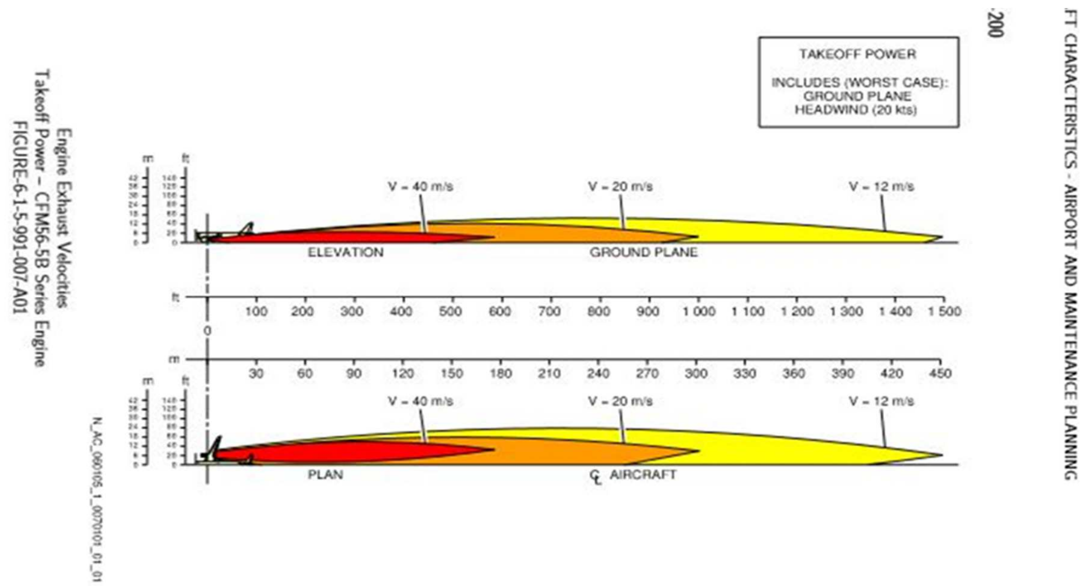

Figure 11. Takeoff Exhaust Velocity Contour of A321 aircraft. Adapted from Aircraft Characteristics Airport and Maintenance Planning by Airbus, 1992, Engine Exhaust Velocity Contours, 6-1-5, p.2.

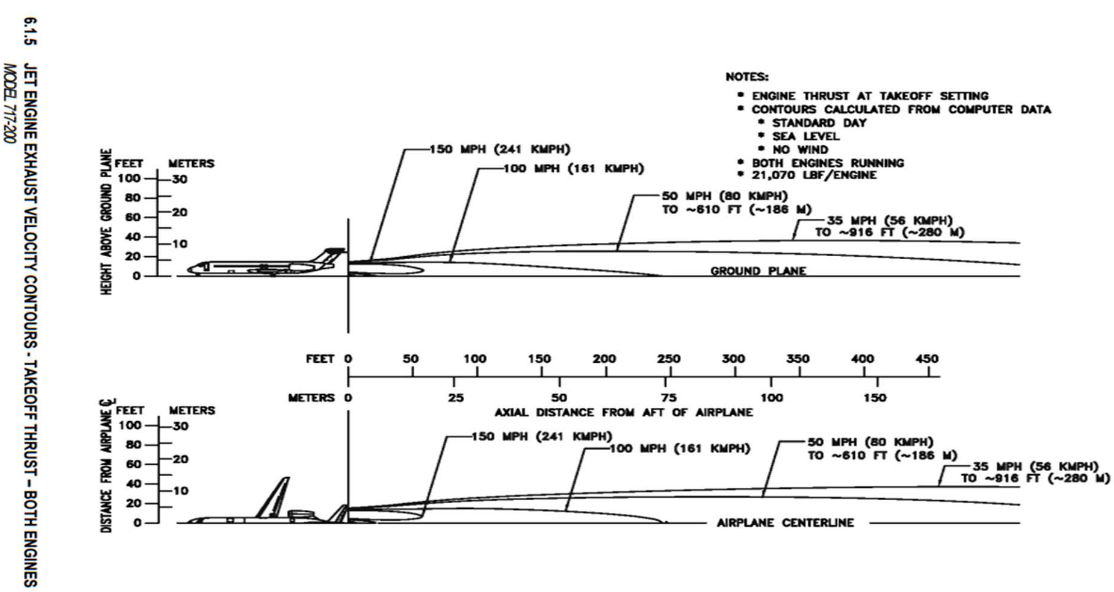

Figure 12. Takeoff Exhaust Velocity Contour of B712 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 2014, Jet Engine Exhaust Velocity Contours, 6.1.5, p.60.

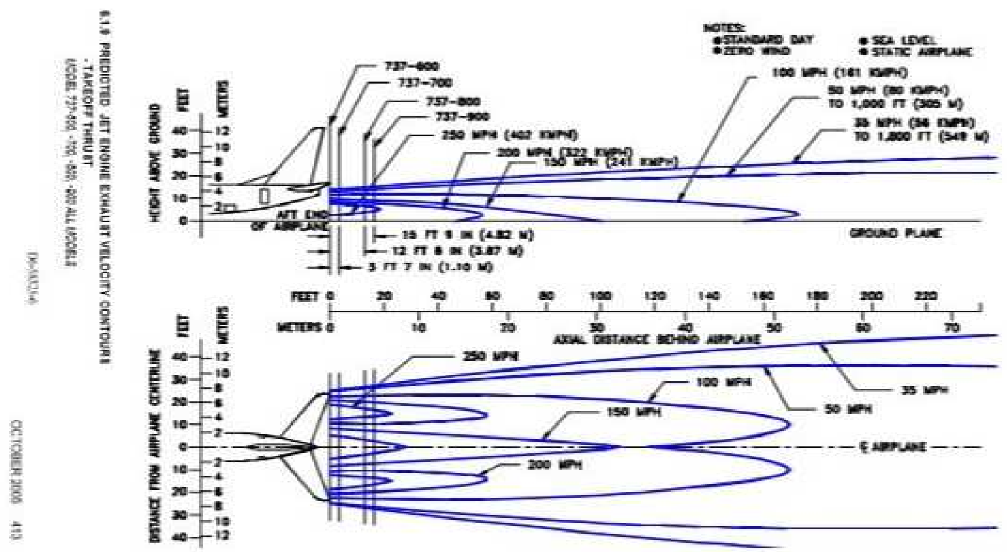

Figure 13. Takeoff Exhaust Velocity Contour of B737, B738, B739 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 2005, Jet Engine Exhaust Velocity Contours, 6.1.9, p.413.

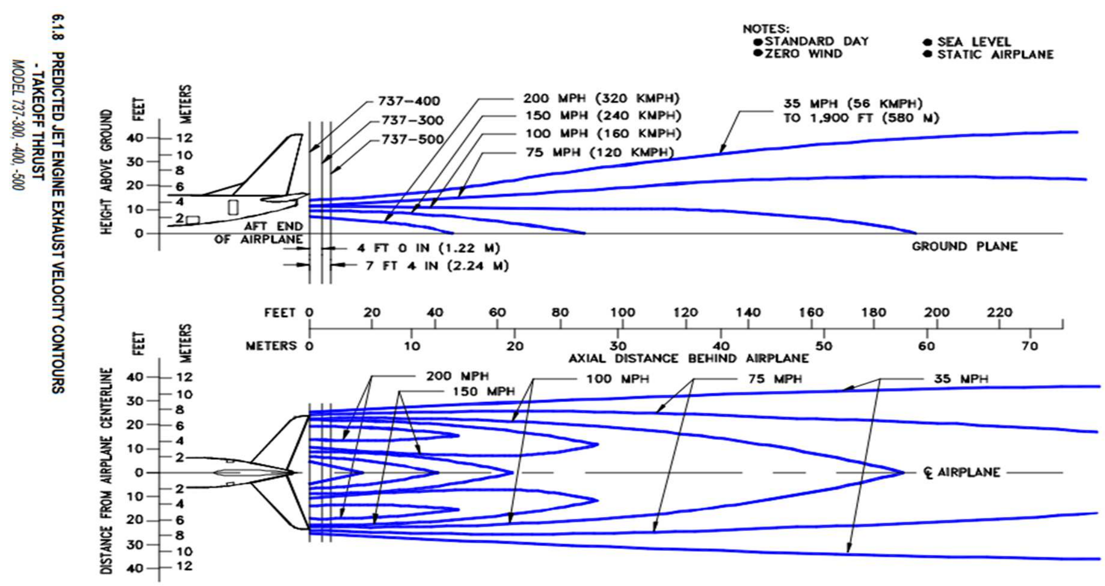

Figure 14. Takeoff Exhaust Velocity Contour of B733 and B734 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 2005, Jet Engine Exhaust Velocity Contours, 6.1.8, p.412.

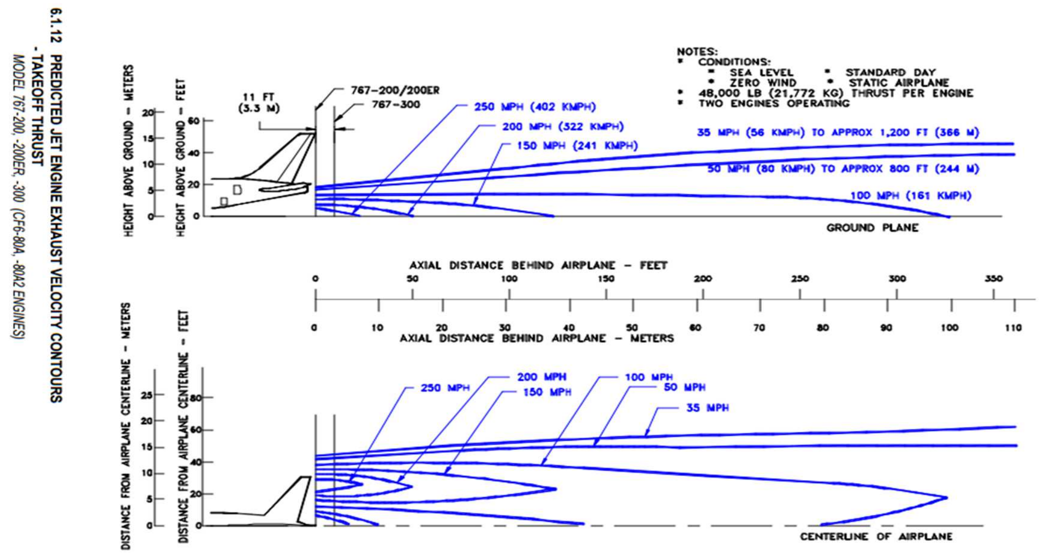

Figure 15. Takeoff Exhaust Velocity Contour of B762 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 2005, Jet Engine Exhaust Velocity Contours, 6.1.12, p.166.

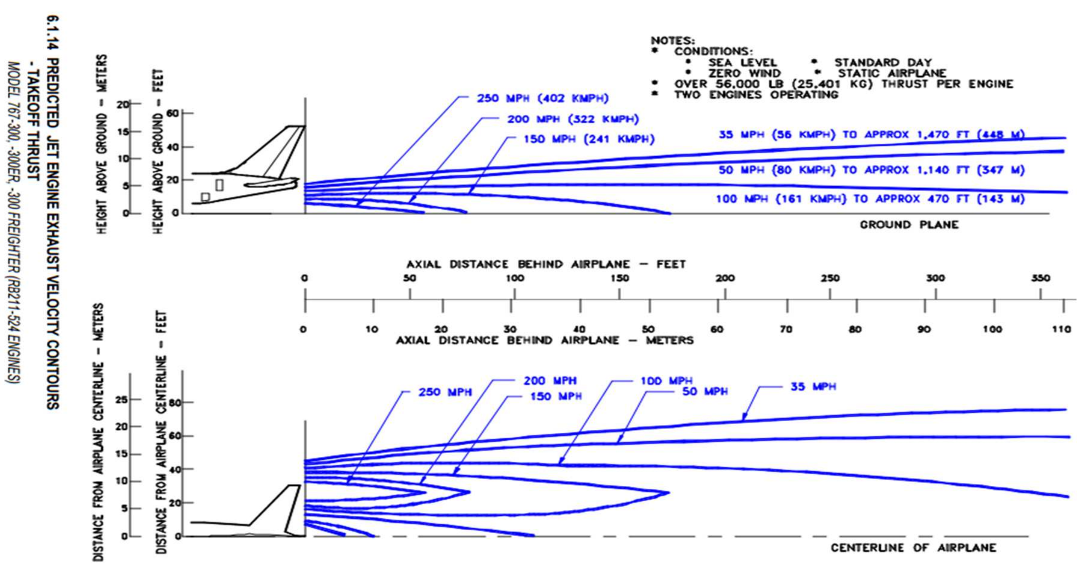

Figure 16. Takeoff Exhaust Velocity Contour of B763 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 2005, Jet Engine Exhaust Velocity Contours, 6.1.14, p.168.

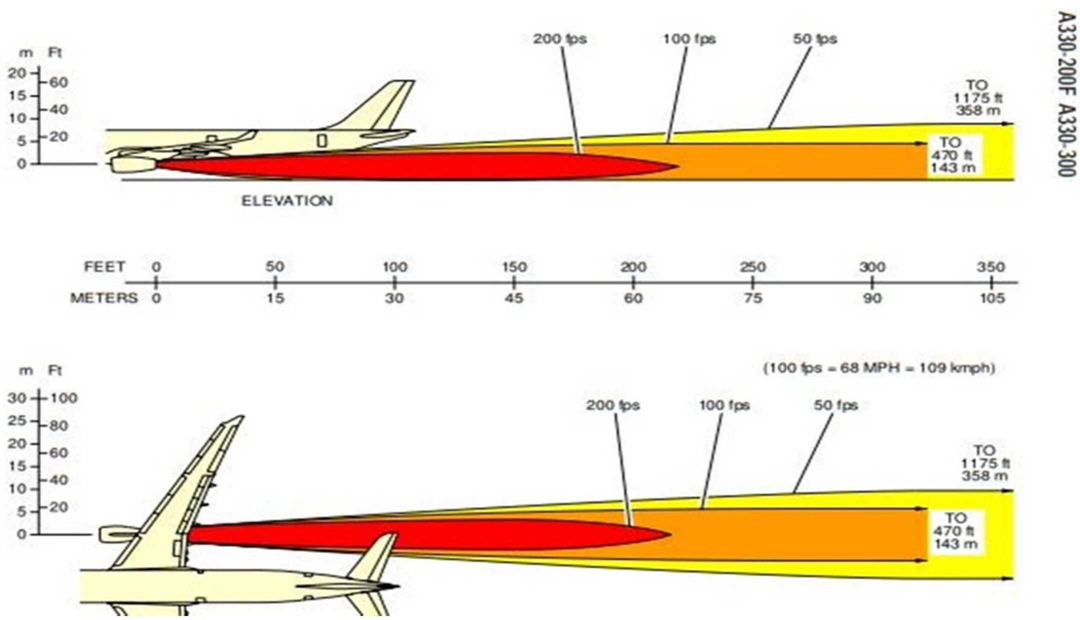

Figure 17. Takeoff Exhaust Velocity Contour of A332 aircraft. Adapted from Aircraft Characteristics Airport and Maintenance Planning by Airbus, 1992, Engine Exhaust Velocity Contours, 6-1-5, p.3.

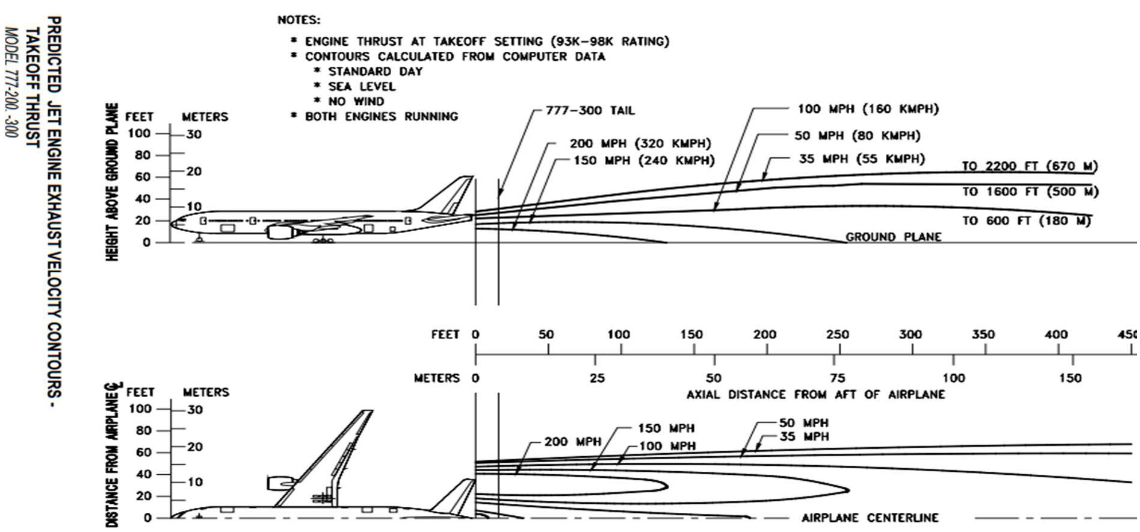

Figure 18. Takeoff Exhaust Velocity Contour of B772 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 1999, Jet Engine Exhaust Velocity Contours, 6.1.3, p.97.

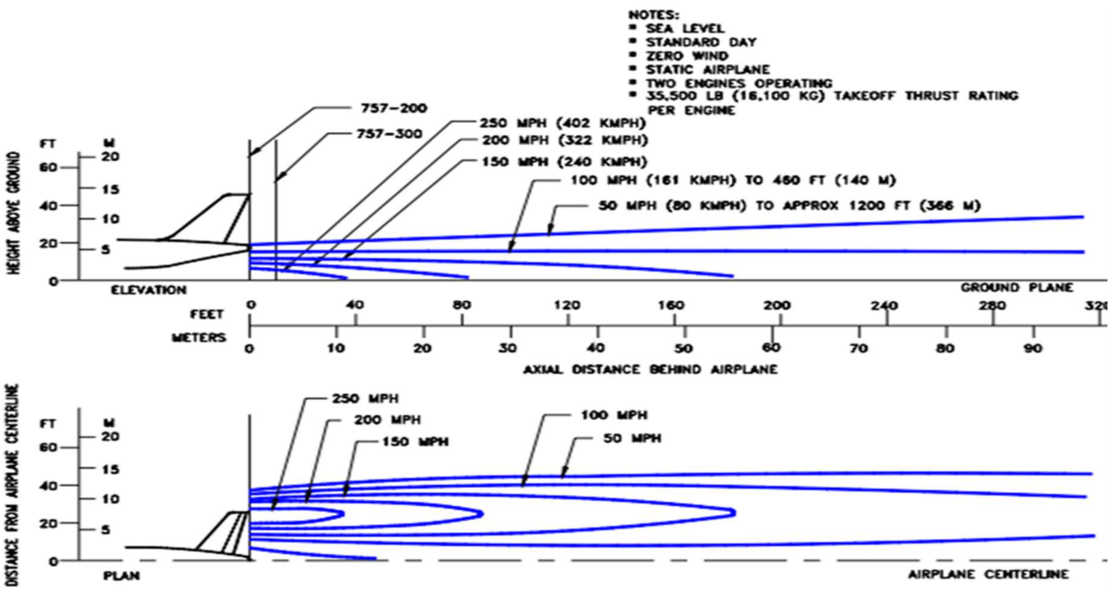

Figure 19. Takeoff Exhaust Velocity Contour of B752 and B753 aircraft. Adapted from Airplane Characteristics for Airport Planning by Boeing, 1999, Jet Engine Exhaust Velocity Contours, 6.1.3, p.107.

The jet blast velocity contours provide a clear depiction of the distribution of jet blast of an aircraft. The distribution of jet blast includes the length and width, to which the wind velocities can extend behind the tail of the aircraft during takeoff as shown in Figures 9-19. The aircraft that have a jet blast velocity capable of reaching the JBDs of runway 13/31 during takeoff were noted, and the number of takeoffs of those aircraft was calculated.

According to the aircraft manuals of different aircraft (Boeing 717-200, 2014; Boeing 737, 2013; Boeing 757, 2002; Boeing 767, 2005; Boeing 772, 1998; Airbus 319, 2018; Airbus 320, 2018; Airbus 321, 2018; Airbus 332, 2018), only the A319 and larger aircraft produce jet blast velocities that can reach up to 1,200 feet. Furthermore, the number of takeoffs from runway 13/31 was 2,065 (Gelband, Personal Communication, October 9, 2017). Among the aircraft performing these 2,065 takeoffs, A319s, A320s, A321s, and B712s have the least jet blast velocity. Their jet blast velocity profiles indicate that a velocity of 26.8

mph will reach the JBDs on both ends of the runway 13/31 as shown in Figures 9-12. The percentage of the aircraft that have a jet blast velocity of 26.8 mph at the JBDs is 17%. All of the other aircraft that departed from runway 13/31 have jet blast velocities of more than 26.8 mph capable of reaching the JBDs. Other aircraft to include the B737, B738, B733, B739, B762, B763, B734 and A332 have a jet blast velocity of 35 mph that can reach the JBDs as shown in Figures 13-17. The total percentage of the aircraft with a jet blast velocity of 35 mph and less than 50 mph is 80%. This translates to 1655 aircraft of the 2,065 aircraft that departed from runway 13/31 in September. The jet blast velocity of the B752, B772 and B753 is 50 mph at the JBDs on runway 13/31 as shown in Figures 18 and 19. The percentage of aircraft that departed from BNA in September of 2017 that have at least 50 mph jet blast velocity that reached the JBD was 3%. A total of 352 aircraft have jet blast velocities of 26.8 mph among the 2,065 takeoffs per month on runway 13/31 as mentioned in Table 1.

Table 1

Percentages based on the aircraft type and number of takeoffs (B. Gelband, Personal Communication, October 9, 2017).

Type	Number of takeoffs	Percentages	Thrust Velocity at the JBD in mph
B737	1067	51.1%	35
B738	439	21.2%	35
A319	200	9.7%	26.8
A320	120	5.8%	26.8
B733	106	5.2%	35
B752	53	2.5%	50
B739	27	1.3%	35
B712	31	1.5%	26.8
B762	7	0.5%	35
B763	4	0.3%	35
B734	4	0.3%	35
B753	3	0.25%	50
A321	1	0.1%	26.8
A332	1	0.1%	34
B772	2	0.15%	50

Therefore, considering that the jet blast velocities reaching the JBDs on runway 13/31 to be either 26.8 mph, 35 mph or 50 mph, power calculations were performed using these values in order to estimate the potential energy production by a wind turbine system.

The following part of the research was to determine the appropriate size of the wind turbine, given the standard airport design methods and rules to follow so that the wind turbines do not obstruct the navigable airspace. According to the AC 150/5220-23, any object that is installed in the RSA should have minimal mass and should be able to collapse easily in case of an event. Determining the size of the wind turbine primarily depends on the power producing capacity and the cost of the wind turbine, given the height and width of the jet blast velocities during takeoff. The size and cost of the wind turbines serve as essential parameters of the optimal arrangement of the wind turbine system. The system was designed to accommodate the width of the jet blast velocity contour of the aircraft departing from runway 13/31. The jet blast velocity contours extend up to 80 feet in width as shown in Figures 9-19. The system was also designed to accommodate the height of the jet blast velocity contours of the aircraft departing from runway 13/31. The jet blast velocities of the aircraft at 1200 feet can reach up to 20 feet high based on the jet blast velocity contours shown in Figures 9-19. The idea of installing the wind turbines appears sensible if the height of the wind turbines does not exceed the JBDs as the JBDs are not causing any obstruction to the navigable airspace. Given that the jet blast velocity contours vary for different aircraft, it is essential to consider these differences during the selection of wind turbines as the selected wind turbine should be capable of capturing the maximum amount of the jet blasts in order to produce as much energy as possible.

Another consideration in selecting a wind turbine is that the wind turbine should have a fin on the back of its rotor so that it turns according to the direction of the wind, as the research also focuses on using the natural wind at the BNA airport to rotate the wind turbine. The wind turbine's cut in speed, rated speed and cut off speed are important technical characteristics of wind turbines that were considered during the selection process. The speed at which a wind turbine starts rotating and begins to produce energy is called cut in speed, and the speed at which the wind turbine can generate the most electricity is called the rated wind speed of the wind turbine (Technology, (n.d.)). The cut off speed of the wind turbine is defined as the wind speed at which the wind turbine is brought to rest to avoid damage. The amount of power generated remains constant until the wind velocity reaches the cut off speed of the wind turbine ("How do Wind Turbines Serve", (n.d.)). A wind turbine's cut in wind speed should be less than 8 mph as the average wind speed at the Nashville International Airport is 8 mph throughout the year ("Wind & Weather Statistics", n.d.). The wind turbine with a cut in speed less than 8 mph would make the wind turbine rotate and generate power even when there are no departures on runway 13/31 in BNA. The wind turbine's rated speed should be closer to 35 mph as 80% of aircraft have jet blast velocities of 35 mph that can reach till the JBDs. However, if the wind turbine has a rated wind speed of 26 mph and majority of aircraft have a jet blast velocity of 35 mph, the power output remains constant till the wind speed reaches the cut off speed of the wind turbine.

Wind turbine selection was performed based on the requirements that were discussed. The wind turbines that were examined include: Bergey 1kW Excel Wind turbine, Primus Windpower Air 30, Nature Power Wind Turbine, SkyMax Wind turbine, and Silentwind 24V Wind Turbine. The reason for considering these wind turbines is that they were commercially available with accessible information about their specifications and prices. All of them have a cut off speed of more than 110 mph except the Bergey 1kW Excel Wind turbine. The cut in speed, cut off speed, rated wind speed, rotor diameter, maximum power output and cost of these wind turbines are included in Table 2.

Table 2

Types of Wind Turbines and their Specifications

Wind Turbine Type	Cut in Wind speed (mph)	Cut off Wind Speed (mph)	Rated wind speed (mph)	Rotor Diameter (ft)	Maximum Power output (Watts)	Cost of wind turbine ($)
Silentwind	4.9	110	32.9	3.77	420W	$1649
Primus Air	3.3	110	28	3.83	400W	$849
SkyMax	5.6	110	26.8	5.08	500W	$549
NaturePower	7	110	42	5.82	2000W	$2499
Bergey	8	N/A	24.6	8.2	2000W	$4995

All of these wind turbines have a cut in speed of less than 8 mph and a rated wind speed of at least 24.6 mph. The Bergey wind turbine has a rotor diameter of 8.2 feet and a peak output of 2,000 watts. The cost of single Bergey wind turbine is $4995 ("The Excel 1kw Wind Turbine, (n.d)). The Primus Air 30 wind turbine is primarily designed for charging small batteries, RVs, cabins etc. The Primus Air 30 with a rotor diameter of 3.83 feet needs 8 mph to start rotating. The cut off speed of a Primus Air 30 is 110 mph. The cost of a Primus Air 30 is $849, and its rated wind speed is 28 mph ("Primus Owner's Manual, 2013). Subsequently, the cost of a Nature Power wind turbine is $2499. The key specifications of Nature Power wind turbine are, it has a blade diameter of 5.82 feet with a startup speed of 7 mph and maximum rated output of 2000 watts ("Nature Power Wind Turbine", (n.d)). The SkyMax wind turbine is a 500-watt wind turbine with a startup speed of 5.6 mph and a rated wind speed of 26.8 mph. The blade diameter of the SkyMax wind turbine is 5.08 feet and cost of a single SkyMax wind turbine is $549 ("SkyMax Wind 500 Watt", (n.d.)). Lastly, the Silentwind 24v wind turbine being ultralight and durable with rated power output of 420 watts costs $1649 per wind turbine. The blade diameter of Silentwind wind turbine is 3.77 feet and starts rotating at a wind speed of 4.9 mph. The rated wind speed of Silentwind is 32.8 mph ("Silentwind 24v Turbine", (n.d.)).

According to Andrew (2014), the capacity factor of a wind turbine usually ranges between 0.25-0.45. The capacity factors of all the wind turbines selected were not mentioned in their respective specifications manual and as this research intends to provide a conservative estimate of energy output, the capacity factor will be taken as 0.25 to be on the lower end of the output. Larger wind turbines were not considered for the research as any installations on the RSA shouldn't cause any damage to the aircraft in case of any accidental runway excursion of an aircraft as stated in AC 150-5300/13A (Federal Aviation Administration, 2014).

The duration of the power output of the wind turbine should be estimated in order to determine the energy output of the wind turbine at a specific wind speed. One aircraft from each group of aircraft that give out three different jet blast velocities was considered for further calculations. Among all the aircraft that produce 26.8 mph of jet blast velocity, the A319 was considered. Similarly, B763s and B752s were considered among different aircraft that produce a jet blast velocity of 35 mph and 50 mph respectively. All five wind turbines that were considered for the research have a rated wind speed below 50 mph. The power output of the wind turbines was calculated with respect to three wind speeds: 1) power output at the rated wind speed of the wind turbine or the jet blast velocity of the aircraft, whichever is lower (P_1), 2) power output at average wind speed (P_2), and 3) power output at 8 mph (P_3), the average natural wind speed at BNA.

The rated wind speeds of different turbines are mentioned in Table 2. The power output at the rated wind speed will be calculated by taking the velocity to be the rated wind speed of the turbine if it is lower than the jet blast velocity of the aircraft. As the aircraft starts its takeoff run, the jet blast of the aircraft reaching the JBDs also decreases. The power output of the average wind speed is calculated by taking the mean of the rated wind speed or the wind speed of the jet blast velocity whichever is lower and the velocity of the average natural wind at BNA (8 mph). The reason for taking the average wind speed is because as the aircraft moves to takeoff, the jet blast velocity reaching the JBDs also gradually decreases. The maximum length that the jet blast can reach was read from the jet blast velocity contours of the aircraft as shown in Figures 9-19.

First, the power outputs of the Silentwind wind turbine were calculated at the three different wind speeds with respect to the jet blast velocities of the A319, B763 and B752. The power output of the wind turbine at a wind speed of 26.8 mph was calculated by taking the capacity factor to be 0.25. The velocity of 26.8 mph if converted to feet per second is 39.3 fps. The obtained power output is then multiplied by 0.001355 to convert the power output into kW ("Power Conversion", (n.d.)). The rated power output (P_1) of the Silentwind wind turbine with respect to A319's jet blast velocity was determined by using Equation 1 and presented in Equation 4.

$$P_1 = \frac{1}{2}(0.25)(0.0023769)(11.16)(39.3^3)(0.001355)$$

$$P_1 = 0.272 \text{ kW} \quad (4)$$

The jet blast velocity of B763 is 35 mph. Therefore, it is essential to calculate the power output of the wind turbine by taking the wind speed as 32.9 mph as the rated wind speed of the Silentwind wind turbine is 32.9mph and the Silentwind wind turbine does not generate any additional power if the wind speed is higher than its rated wind speed. The power output of Silentwind wind turbine if the wind speed is 32.9 mph is shown in Equation 5.

$$P_1 = \frac{1}{2}(0.25)(0.0023769)(11.16)(48.25^3)(0.001355)$$

$$P_1 = 0.503 \text{ kW} \quad (5)$$

The power outputs of the Silentwind wind turbine during takeoffs of A319 and B763 is 0.272 kW and 0.503 kW respectively. Similarly, the rated power output of the Silentwind Wind turbine during B752 takeoffs was calculated with respect to the rated wind speed of the wind turbine since the jet blast velocity of the B752 aircraft (50 mph) is greater than the rated wind speed of the wind turbine (32.9 mph). The rated power output (P_1) of the wind turbine during B752 takeoff will be same as the rated power output during B763 aircraft as mentioned in Equation 5 because the jet blast velocity of the aircraft is higher than the rated wind speed of the wind turbine.

Secondly, the average power outputs of the Silentwind wind turbine was calculated with respect to A319, B763, and B752 aircraft. The mean wind speed was determined by taking the mean of the of the rated wind speed or the wind speed of the jet blast velocity, whichever is lesser, and the velocity of the average natural wind at BNA (8 mph). The mean wind speed during A319's takeoff is 17.4 mph. The average power output of Silentwind wind turbine during A319's takeoff was calculated by taking the wind speed as 17.4 mph as mentioned in Equation 6.

$$P_2 = \frac{1}{2}(0.25)(0.0023769)(11.16)(25.52^3)(0.001355)$$

$$P_2 = 0.074 \text{ kW} \quad (6)$$

The average power output of the Silentwind wind turbine is the same for the B763 and the B752 aircraft. The mean of the rated wind speed of the wind turbine (32.9 mph) and the average natural wind speed at BNA (8 mph) is 20.45 mph. The average power output of Silentwind wind turbine for B763 and B752 aircraft is shown in Equation 7.

$$P_2 = \frac{1}{2}(0.25)(0.0023769)(11.16)(29.99^3)(0.001355)$$

$$P_2 = 0.120 \text{ kW} \quad (7)$$

The power output of the Silentwind wind turbine at the average natural wind speed was determined by inserting 8 mph as the wind speed into Equation 1 as shown in Equation 8.

$$P_3 = \frac{1}{2}(0.25)(0.0023769)(11.16)(11.7^3)(0.001355)$$

$$P_3 = 0.0071 \text{ kW} \tag{8}$$

Three different power outputs were calculated for Bergey wind turbine as well. The rated wind speed of the Bergey wind turbine is 24.6 mph. The jet blast velocity of a A319 aircraft is 26.8 mph at the JBD and the jet blast velocities of B763 and B752 aircraft are 35 mph and 50 mph respectively. The jet blast velocities of A319, B763 and B752 are greater than the rated wind speed of the Bergey wind turbine. Hence, the rated power output (P_1) of Bergey wind turbine was calculated by considering the wind speed as 24.6 mph as mentioned in Equation 9.

$$P_1 = \frac{1}{2}(0.25)(0.0023769)(52.81)(36.08^3)(0.001355)$$

$$P_1 = 0.991 \text{ kW} \tag{9}$$

The average power output of the Bergey wind turbine was determined by considering the wind speed to be the mean of the rated wind speed of the Bergey wind turbine (24.6) and the natural wind speed at BNA (8 mph). The average wind speed obtained was 16.3 mph during all takeoffs. The average power output of Bergey wind turbine is determined by taking 16.3 mph as the wind speed as mentioned in Equation 10.

$$P_2 = \frac{1}{2}(0.25)(0.0023769)(52.81)(23.90^3)(0.001355)$$

$$P_2 = 0.288 \text{ kW} \tag{10}$$

The power output of the Bergey wind turbine at the average natural wind speed was determined by inserting 8-mph as the wind speed into Equation 1 as shown in Equation 11.

$$P_3 = \frac{1}{2}(0.25)(0.0023769)(52.81)(11.7^3)(0.001355)$$

$$P_3 = 0.0338 \text{ kW} \tag{11}$$

The power outputs for all of the wind turbines were calculated as well and are presented in Table 3.

Table 3

Wind Turbines, power outputs of each wind turbine at rated wind speed (P_1), average wind speed (P_2), and natural wind speed (P_3).

		P_1 (kW)	P_2 (kW)	P_3 (kW)
Silentwind				0.0071
	A319	0.272	0.074	
	B763	0.503	0.120	
	B752	0.503	0.120	
Primus				0.0073
	A319	0.280	0.076	
	B763	0.319	0.085	
	B752	0.319	0.085	
SkyMax				0.0129
	A319	0.492	0.134	
	B763	0.492	0.134	
	B752	0.492	0.134	
Nature Power				0.0171
	A319	0.645	0.176	
	B763	1.436	0.332	
	B752	2.487	0.521	
Bergey				0.0338
	A319	0.991	0.288	
	B763	0.991	0.288	
	B752	0.991	0.288	

The energy production of the Silentwind wind turbine is determined by multiplying the power output by the time that the wind turbine generated power in one month. The three power outputs of the Silentwind wind turbine at the rated wind speed of the wind turbine, at the average wind speed, and at 8 mph were each multiplied by the time that the wind turbine generated power at these wind speeds in one month ("National Wind Watch", (n.d.)). To calculate the energy created by the wind turbines, the duration of time that the jet blast velocities of the aircraft reached the JBDs was determined. Firstly, the acceleration of the aircraft is determined by using Newton's 2nd Law of Motion as shown in Equation 12.

$$F = ma \tag{12}$$

From Equation 12, Acceleration (a) is determined.

$$a = F/m \tag{13}$$

As an aircraft begins the takeoff roll, a frictional force acts opposite to the aircraft's direction on the runway where the thrust of the aircraft acts in the direction of the aircraft's motion. A simplified equation to determine the Force (F) acting on an aircraft is presented as Equation 14.

$$F = T - F_{rr} \tag{14}$$

In Equation 14, F_{rr} represents frictional force and T represents thrust of an aircraft. The frictional force of an aircraft is determined by multiplying the coefficient of rolling resistance (μ) of an aircraft by the total weight (W) of the aircraft as shown in Equation 15.

$$F_{rr} = \mu W \tag{15}$$

The mass of the aircraft is determined by dividing the weight of the aircraft by the acceleration due to gravity (g) as described in Equation 16.

$$m = W/g \tag{16}$$

The equation to determine the acceleration of the aircraft during takeoff was determined by substituting Equations 14 to 16 in Equation 13. The equation for acceleration is shown in Equation 17.

$$a = (T - \mu W)g/W \tag{17}$$

The thrust and mass of the A319 aircraft were taken from the aircraft manual; the thrust equaling 54,000 lbs and the mass equaling 166,000 lbs ("Airbus 319", 1995). The value of the coefficient of rolling resistance is 0.04 for a rubber tire moving on a concrete surface (Anderson, 1999). Calculating the acceleration by substituting the thrust, mass and rolling resistance values of the A319 in the Equation 17 is shown in Equation 18.

$$a = \frac{((54000) - (0.04)(166000))(32.2)}{166000}$$

$$a = 9.18 \text{ ft/sec}^2 \tag{18}$$

Similarly, the acceleration for the B763 and the B752 were calculated as 8.60 ft/sec^2 and 8.86 ft/sec^2. From Figure 9, it can be observed that the jet blast of the A319 reaches up to 1500 feet with a jet blast velocity of 26.8 mph. The JBDs on the runway 13/31 are 1100 feet and 1167 ft, respectively, away from the displaced threshold point where aircraft start takeoff runs. Therefore, the time that jet blast deflectors and hence wind turbines were exposed to jet blasts of aircraft during a takeoff was calculated using basic kinematic equation presented in Equation 19.

$$X_f = X_i + V_i t_1 + \frac{1}{2} a {t_1}^2 \tag{19}$$

X_f is the final position that the aircraft will have when the jet blast velocity of a specified magnitude reaches the JBDs (and the wind turbines) installed on runway 13/31 as the aircraft undergoes its takeoff roll. X_i is the initial point, at which the aircraft starts a takeoff. V_i is the initial velocity of the aircraft when it is at X_i., a is the acceleration of the aircraft presented in Equation 17, and t_1 is the time the aircraft takes to reach X_f. The initial point, at which the aircraft starts is taken to be 0, and the initial velocity of the aircraft before it starts moving is 0. From Equation 19, t_1 was determined and is presented in Equation 20.

$$t_1 = \sqrt{2\left(X_f - X_i\right)/a} \tag{20}$$

The value of X_f is 400 feet for an A319. The time t_1 was calculated by substituting these values into Equation 20 as shown in Equation 21.

$$t_1 = \sqrt{2(400)/9.18}$$

$$t_1 = 9.33 \text{ seconds} \tag{21}$$

The duration of time that the A319's jet blast at 26.8 mph that will reach the JBDs after the aircraft starts moving on the runway is 9.33 seconds. Similarly, the t_1 for the B763 and the B752 is 9.27 and 4.74 seconds respectively.

The next task was to determine the duration of time, during which the jet blast velocity of the A319 decreased from 26.8 mph to 8 mph. For this, the distance covered as the jet blast velocity of the A319 decreased to 8 mph was estimated. This was done by creating a graph in Microsoft Excel of jet blast velocities at several distances behind the aircraft. The data was taken from the jet blast velocity contours of the A319, B763, and B752 as shown in Figure 9, 16, and 19. The graph of the A319's jet blast as a function of distance from the aircraft is shown in Figure 20. Similarly, the graphs for the B763 and the B752 are plotted and shown in Figures 21 and 22.

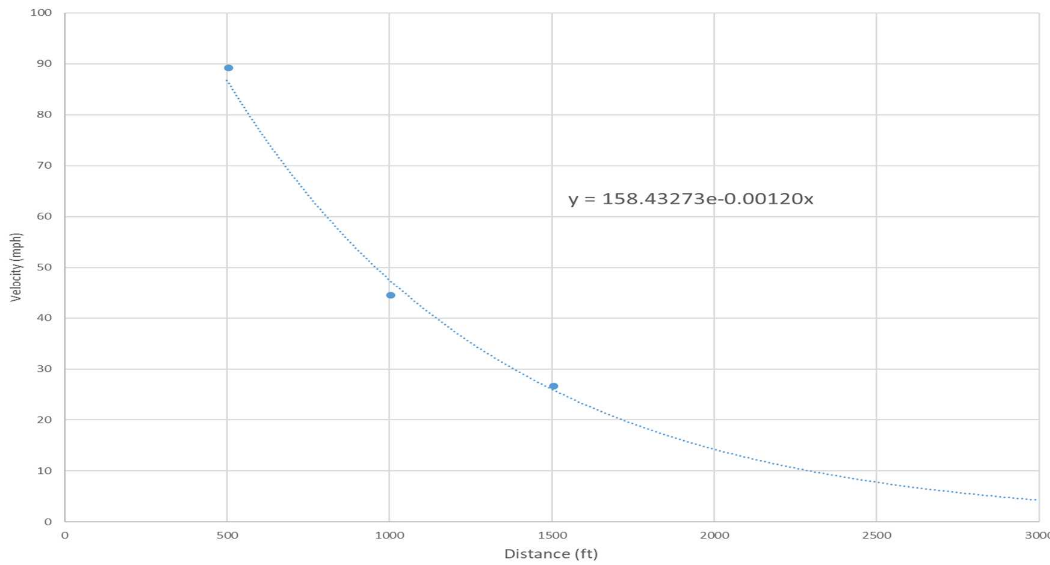

Figure 20. Graph of the A319's jet blast velocity as a function of distance behind the aircraft.

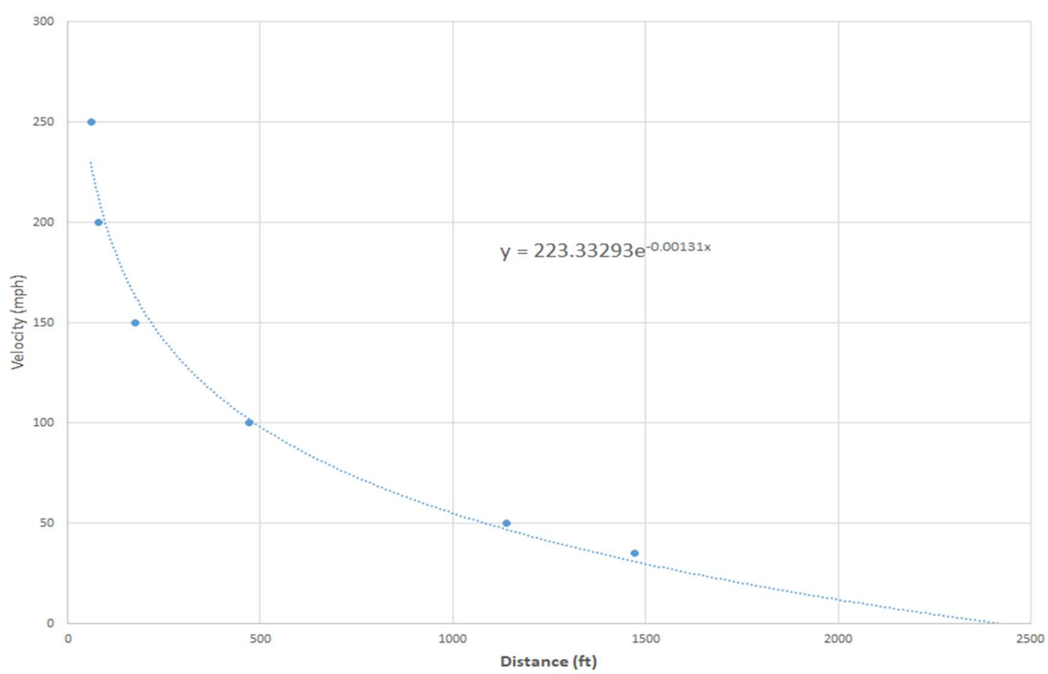

Figure 21. Graph of B763 jet blast velocity as a function of distance behind the aircraft.

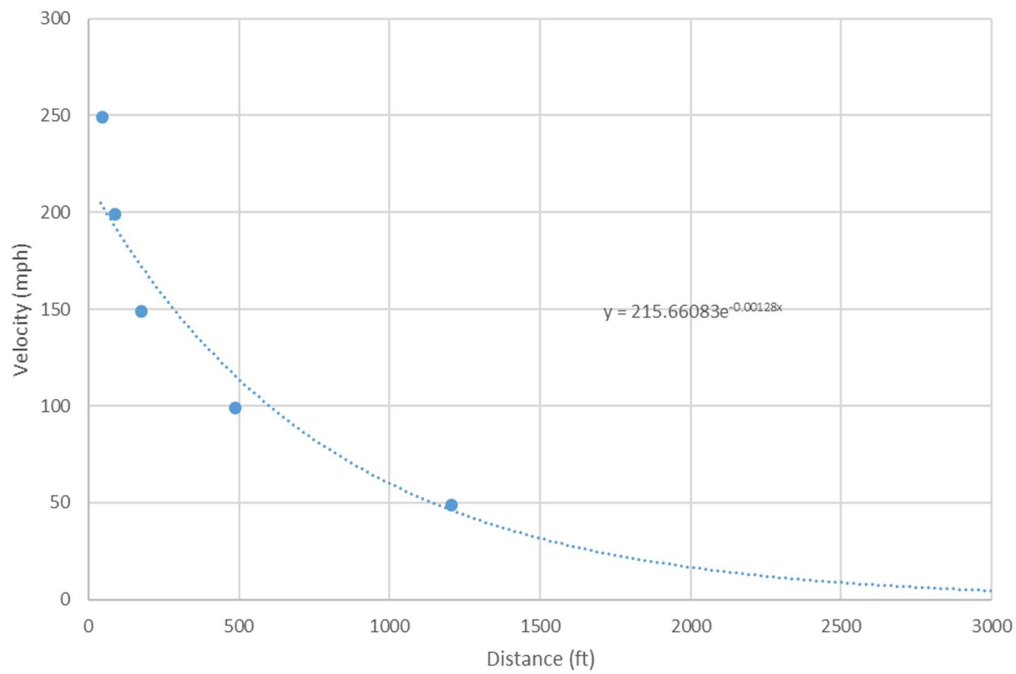

Figure 22. Graph of B752 jet blast velocity as a function of distance behind the aircraft.

The data presented in the Figure 20 was used to determine the distance that the A319's jet blast velocity took to decrease to 8 mph from 26.8 mph. Trendline tool in Microsoft Excel was used to determine this distance. To determine this distance, the function of jet blast velocity with respect to the distance behind the A319 was derived from Figure 20 and is shown in Equation 22.

$$y = 158.43273e^{-0.00120x} \tag{22}$$

The variables, y and x, in Equation 22 represent jet blast velocity of the aircraft and the distance of the jet blast velocity behind the A319 respectively. Solving Equation 22 for the distance with respect to the velocity is shown in Equation 23.

$$x = -\left(\ln \frac{y}{158.43273}\right) / (0.00120) \tag{23}$$

As the average wind speed at the BNA is 8 mph, the distance the aircraft moves while producing jet blast that reaches the JBDs untill it decreases to 8 mph for an A319 is calculated by substituting 8 mph in the place of y in Equation 23 as shown in Equation 24.

$$x = -\left(\ln \frac{8}{158.43273}\right) / (0.00120)$$

$$x = 2488 \text{ ft} \tag{24}$$

As Equation 24 reveals, the A319's jet blast extends 2,488 ft behind the aircraft, at which point it has diminished to the background natural wind speed (8 mph). Figure 9 shows that the A319's jet blast velocity is at least 26.8 mph for a distance of 1,500 ft behind the aircraft. With a takeoff starting point 1,100 ft from the JBD's, and hence the wind turbines, on Runway 13/31, the wind turbines will be exposed to a jet blast velocity of at least 26.8 mph for the first 400 ft of the takeoff roll. This means that the next 988 ft of the takeoff roll will expose the wind turbines on Runway 13/31 to a jet blast velocity diminishing from 26.8 mph to 8 mph according to Equation 22. The next step was to determine the time (t_2) that it took the A319 to travel the remaining distance of 988 ft. To find the t_2 value, the initial velocity, V_i, of the A319 was determined since the aircraft had already started its takeoff roll. The initial velocity of the A319 was determined by multiplying the acceleration of the aircraft (a) and the time (t_1) of the A319 as shown in Equation 25.

$$V_i = at_1 \tag{25}$$

Substituting the acceleration of A319 and time (t_1) in Equation 24 will give the initial velocity (V_i) value for A319 presented in Equation 26.

$$V_i = (9.18)(9.33)$$

$$V_i = 85.64 \text{ fps} \tag{26}$$

The V_i values of the A319, the B763, and the B752 are 85.64 fps, 79.72 fps, and 41.99 fps. The value of t_2 was determined by substituting the desired values for the A319 into Equation 27 which is derived from Equation 19.

$$t_2 = \frac{-V_i \pm \sqrt{(V_i^2) - 2a\,(X_i - X_f)}}{a} \tag{27}$$

The results of t_2 will have both positive and negative values. However, it is essential to consider only the positive value as time cannot be negative as shown in Equation 28.

$$t_2 = \frac{-(85.64)\ \pm \sqrt{(85.64^2) - 2(9.18)\,(0 - 988)}}{9.18}$$

$$t_2 = 6.71 \tag{28}$$

The t_2 values of the A319, the B763 and the B752 are 6.71 sec, 7.44 sec, and 10.28 sec respectively. The data for the previous calculations for the A319, the B763, and the B752 to include t_1 and t_2 are presented in Table 4. As seen in Figure 22, an exponential curve fit was used for the B752's jet blast velocity data. It can be seen that the curve does not exactly match the data; however, this curve fit was used in order to be consistent with the curve fits utilized for the B763's and the A319's jet blast velocity data.

Table 4

Three different types of aircraft and their specifications such as thrust, weight, acceleration, time.

	A319	B763	B752
Thrust (lbs)	54,000	126,600	80,400
Weight (lbs)	166,000	412,000	255,000
a (ft/sec^2)	9.18	8.60	8.86
t_1 (sec)	9.33	9.27	4.74
X_i for t_1 (ft)	0	0	0
X_f for t_1 (ft)	400	370	100
t_2 (sec)	6.71	7.44	10.28
V_i for t_2 (fps)	85.64	79.72	41.99
X_i for t_2 (ft)	0	0	0
X_f for t_2 (ft)	988	1071	1372

Similar to the power outputs, the energy outputs of the Silentwind wind turbine was calculated in three types: the energy output from the rated power output (E_1), the energy output from the power output at the average jet blast velocity (E_2), and the energy output from the power output at the average natural wind speed (E_3). It has been calculated that the duration of impact of jet blast (t_1) of all the aircraft that provide jet blast velocities similar to the A319 aircraft on the wind turbines per take off is 9.33 seconds. The impact of the aircrafts' jet blast on the JBD is constant for that time. As the number of aircraft that provide a jet blast velocity of 26.8 mph were 352 in the month of September 2017, the duration of the wind speed for 352 takeoffs was 0.91 hours for the month of September 2017. The duration of 0.91 hours was calculated by multiplying the number of takeoffs and 9.33 seconds of time taken per one takeoff converted into hours. Calculating the energy output, E_1, for the month of September by substituting the desired values in Equation 3 is shown in Equation 29.

$$E_1 = (0.272)(1)(0.91)$$

$$E_1 = 0.247 \text{ kWh/per month} \tag{29}$$

The duration of the wind speed due to 1655 aircraft that provide 35 mph jet blast velocities for 9.27 seconds per one takeoff will be 4.26 hours for the month of September 2017. The energy output of the wind turbine at the rated speed of the wind turbine due to all the aircraft providing jet blast velocities similar to the B763 aircraft that provide 35 mph jet blast velocities per take off was determined in Equation 30.

$$E_1 = (0.503)(1)(4.26)$$

$$E_1 = 2.144 \text{ kWh/per month} \tag{30}$$

The duration of the wind speed due to 58 aircraft that provide 50 mph jet blast velocities for 4.74 seconds per one takeoff will be 0.076 hours for the month of September 2017. The energy output of the wind turbine at the rated speed of the wind turbine due to all the aircraft providing jet blast velocities similar to the B752 aircraft that provide 50 mph jet blast velocities per take off was determined in Equation 31.

$$E_1 = (0.503)(1)(0.076)$$

$$E_1 = 0.038 \text{ kWh/per month} \quad (31)$$

The energy output of the Silentwind wind turbine at the rated wind speed due to all the aircraft is 2.431 kWh for the month of September 2017. The average energy output of the Silentwind wind turbine was determined by considering t_2 as the duration of the jet blast from the A319, the B763 and the B752. The duration of time t_2 for the A319, the B763 and the B752 is 6.71 sec, 7.44 sec, and 10.28 sec respectively. As the number of aircraft that provide a jet blast velocity of 26.8 mph were 352 in the month of September 2017, the duration of the wind speed for 352 takeoffs was 0.65 hours for the month of September 2017. The duration of 0.65 hours was calculated by multiplying the number of takeoffs and 6.71 seconds of time taken per one takeoff converted into hours. Calculating the energy output, E_2, due to all the aircraft providing jet blast velocities similar to the A319 for the month of September was calculated by substituting the desired values in Equation 3 as shown in Equation 32.

$$E_2 = (0.074)(1)(0.65)$$

$$E_2 = 0.048 \text{ kWh/per month} \quad (32)$$

The duration of the wind speed caused due to 1655 aircraft that give out 35 mph jet blast velocity for 7.44 seconds per one takeoff will be 3.42 hours for the month of September 2017. The average energy output of the wind turbine at the rated speed of the wind turbine due to all the aircraft providing jet blast velocities similar to the B763 aircraft that give out 35 mph jet blast velocities per take off was calculated as shown in Equation 33.

$$E_2 = (0.120)(1)(3.42)$$

$$E_2 = 0.413 \text{ kWh/per month} \tag{33}$$

The duration of the wind speed caused due to 58 aircraft that give out 50 mph jet blast velocities for 10.28 seconds per one takeoff will be 0.16 hours for the month of September 2017. The energy output of the wind turbine at the rated speed of the wind turbine due to all the aircraft providing jet blast velocities similar to the B752 aircraft that provide 50 mph jet blast velocities per take off was calculated as shown in Equation 34.

$$E_2 = (0.120)(1)(0.16)$$

$$E_2 = 0.019 \text{ kWh/per month} \tag{34}$$

The energy output of the Silentwind wind turbine for the average wind speed and time t_2 is 0.481 kWh. The rated energy outputs and average energy outputs of Silentwind, Primus, SkyMax, Nature Power, and Bergey wind turbines with respect to the time t_1 and t_2 are presented in Table 5.

Table 5

Energy outputs of all five wind turbines due to rated wind speed and average wind speed with respect to duration of time t_1 and t_2

		E_1 (kWh)	E_2 (kWh)
Silentwind			
	A319	0.247	0.048
	B763	2.144	0.413
	B752	0.038	0.019
	Total Energy	2.431	0.481
Primus			
	A319	0.255	0.048
	B763	1.363	0.290
	B752	0.024	0.013
	Total Energy	1.643	0.354
SkyMax			
	A319	0.448	0.087
	B763	2.098	0.460
	B752	0.037	0.021
	Total Energy	2.584	0.570
Nature Power			
	A319	0.588	0.114
	B763	6.122	1.137
	B752	0.189	0.083
	Total Energy	6.900	1.335
Bergey			
	A319	0.904	1.187
	B763	4.223	0.986
	B752	0.075	0.046
	Total Energy	5.203	1.219

The cumulative number of hours that the Silentwind wind turbine would generate energy at the rated wind speed and average wind speed is 9.48 hours. Therefore, the number of hours that the Silentwind wind turbine would generate energy at the 8-mph average wind speed through the month of September would be 710.52 as the total number of hours in the month of September is 720. The energy produced in the month of September 2017 due to the natural average wind speed was calculated and shown in Equation 35.

$E_3 = (0.0071)(1)(710.52)$

E_3 = 5.098 kWh (35)

The energy output of a single Silentwind wind turbine, if the wind speed was 8 mph, throughout the month of September 2017 would be 5.098 kWh. With wind turbines placed in front of the JBDs, it is highly unlikely for the wind turbines to get 8 mph natural wind constantly throughout the month. If the wind blows from the direction of the JBD, the JBDs would block the wind flow, and the wind turbines would not get the natural wind to generate power. The idea is to install wind turbines on both ends of the runway, therefore, if one end of the runway gets the natural wind, wind turbines on the other end will not get any wind. As this section does not focus on the number of wind turbines to be installed near the JBDs, it is significant to consider only half of the energy output from a single wind turbine that is generated due to natural wind at BNA. Therefore, the energy output for the month of September 2017 from a single Silentwind wind turbine due to natural wind is 2.549 kWh. The total energy output of a Silentwind wind turbine due to 2,065 takeoffs plus the natural wind is 5.461 for the month of September 2017. Similarly, the total energy output of the Primus, SkyMax, Nature Power and Bergey wind turbines in the month of September 2017 are 4.626 kWh, 7.769 kWh, 14.290 kWh, and 18.440 kWh respectively. These energy values are presented in Table 6.

Table 6

Wind Turbines, energy outputs of each wind turbine at rated wind speed, average wind speed, 8 mph and total energy output per month

Wind Turbine Type	Energy output at rated speed of wind in kWh (E_1)	Energy output at average speed in kWh (E_2)	Energy output at 8 mph in kWh (E_3)	Total energy in kWh (E)
Silentwind	2.431	0.481	2.549	5.461
Primus Air	1.643	0.354	2.628	4.626
SkyMax	2.584	0.570	4.614	7.769
Nature Power	6.900	1.335	6.054	14.290
Bergey	5.203	1.129	12.017	18.440

Cost-Benefit Analysis

The cost of a single Silentwind wind turbine is $1,649 and the amount of electricity generated by a single Silentwind wind turbine was 5.461 kWh in the month of September 2017. The energy produced by a single Silentwind wind turbine in a year would be 65.53 kWh. Similarly, the amount of energy generated by a Primus wind turbine in the month of September 2017 was 4.626 kWh and would produce 55.51 kWh in a year. The cost of a single Primus wind turbine is $849. The cost of a SkyMax wind turbine is $549, and it would have generated 7.769 kWh of energy in the month of September 2017. A single SkyMax wind turbine would have generated 93.22 kwh of energy annually. The cost of a single Nature Power wind turbine is $2,499, and the amount of energy generated by a Nature Power wind turbine in the month of September 2017 would have been 14.290 kWh. The energy produced by a single Nature Power wind turbine in a year would have been 171.48 kwh. The cost of a single Bergey wind turbine is $4,995, and the amount of energy that a Bergey wind turbine would have generated in a month is 18.440 kWh. A single Bergey wind turbine would have produced 221.28 kWh in a year.

In order to find the most efficient wind turbine among all five wind turbines in terms of energy producing capacity with respect to the wind turbine’s cost, the ratio of energy produced by a single wind turbine in a year to the cost of the wind turbine was determined. The ratios for the single Silentwind, Primus, SkyMax, Nature Power, and Bergey wind turbines were found to be 0.019, 0.032, 0.084, 0.034, and 0.022 respectively. Among all five wind turbines, it is clear that the SkyMax wind turbine produces the most energy per dollar invested. The other four wind turbines are less than half as effective. In spite of this, the investigation continued to consider all of the wind turbines for comparison.

According to the monthly traffic report from BNA in 2017 ("Airport Data", (n.d.)), the average monthly operations was 17,191, which is approximately equal to the number of operations recorded in September 2017. It seems reasonable to calculate the energy output from a single wind turbine for a year using the September data, since the difference in the number of operations in September 2017 and the monthly average is very small.

The jet blast velocities of all of the aircraft taking off from BNA (B737, B738, B733, B752, B739, B762, B763, B734, B753, A332, B772, A319, A320, A321, and B712) extend at least 1,200 feet and to a maximum of 40 feet on each side of the centerline of the aircraft as shown in Figures 9-19. The JBD at the end of runway 13 is 280 feet wide and 14 feet high. On runway 31, the JBD is 14 feet high and approximately 212 feet wide. The number of wind turbines to be placed in front of the JBDs was determined based upon the rotor diameter of the wind turbine, the width of the jet blast velocities, and a gap of two feet between each turbine to avoid collision between the blades of adjacent wind turbines. Since the rotor diameter of the Silentwind wind turbine is 3.77 feet, installation of 15 wind turbines on each end of the runway would be possible, given the 80 feet width of the jet blast velocities, and a gap of two feet between each wind turbine. If 15 Silentwind wind turbines were installed on one end of the runway, then a total of 30 Silentwind turbines would be installed on both ends of the runway 13/31. If 15 Silentwind wind turbines were installed on one end of the runway, the total energy generated by these wind turbines in a year would be 982.98 kWh. The energy generated by wind turbines installed on one end of the runway was sufficient, because only wind turbines at one end or the other would get the jet blast velocities from each takeoff. However, the installation cost of the entire system and the payback period calculations included the total number of wind turbines at both ends of the runway 13/31, given that takeoffs are in both directions and that the natural wind would have come from either direction.

Nashville electricity statistics show that the average commercial electricity rate in Nashville is 10.32¢ per kWh ("Nashville Electricity Rates", n.d.). Thus, the total cost saved by 15 Silentwind wind turbines per year by generating electricity would have been $101.44. The US Department of Energy offers a federal tax credit to new wind energy systems of any size in the amount of 30% of the purchase price after one year of the installation of the system ("The Federal Incentives for Wind", 2013). Since the cost of installing the system would be $49,470, 30% of this cost would have been credited back to the BNA airport after one year. Thus, $14,841 would have been credited back. If $101.44 were saved in a year and $14,841 would have been credited back, it would take 341.37 years from the installation date to recuperate the cost of the system. The calculations for the payback period are shown in Equation 36.

$$Payback\ Period = \frac{(49470)-(0.30)(49470)}{101.44}$$

$$Payback\ Period = 341.37\ years \tag{36}$$

The data related to the number of wind turbines that could be installed at the JBDs, the total energy output by a single wind turbine in a year, the amount saved by BNA on one wind turbine in a year, the total cost of the system, and the payback period for systems when considering all five wind turbines are presented in Table 7.

Table 7

Types of Wind Turbines, Total Energy Output by a single wind turbine in a year, Amount Saved by BNA on one wind turbine in a year, Cost of the Wind turbine, Number of Wind Turbines that can be Installed, and Pay Back Period of the Wind Turbines.

Wind Turbine Type	Number of Wind Turbines	Amount Saved by BNA in one year ($0.1032/kWh)	Cost of Wind turbine ($)	Total Energy output in a year (kWh)	Total Cost of Wind turbines ($)	Payback period (years)
Silentwind	30	$101.44	1649	982.98	49,470	341.5
Primus Air	30	$85.93	849	832.68	25,470	207.48
SkyMax	20	$96.21	549	932.28	10,980	79.88
NaturePower	20	$176.96	2499	1714.80	49,980	197.70
Bergey	16	$182.68	4995	1770.24	79,920	306.24

From Table 7, it can be observed that in terms of energy, the Bergey and the Nature Power wind turbines have the highest outputs of 1,770.24 kWh and 1,714.80 kWh in a year respectively, with the number of each type wind turbine that could be installed being 20 and 16. The Silentwind and the SkyMax stand third and fourth in terms of total energy output with 982.98 kWh and 932.28 kWh in a year. The number of these wind turbines that could be installed are 30 and 20 respectively. The Primus wind turbine system would produce the least 832.68 kWh from 30 wind turbines. The SkyMax wind turbine is first in terms of its payback period. It would take 79.88 years to recuperate its costs. The Nature Power and the Primus wind turbine systems would have payback periods of 197.70 and 207.48 years. The Bergey and the Silentwind wind turbine system would take the largest amount of time to recuperate their costs, 306.24 years and 341.37 years respectively.

It can be observed from this comparison that the SkyMax wind turbine system is the most effective of the commercially available wind turbines considered in this investigation. The SkyMax wind turbine met the wind requirements with respect to the jet blast velocities of aircraft and the average natural wind speed at BNA. The height of the SkyMax wind turbine falls within the permissible height that was calculated according to the standards of 14 CFR Part 77. A total of twenty of these wind turbines could be placed in front of the JBDs on both ends of runway 13/31 at BNA. Both the cut in speed and the rated speed of the SkyMax met the requirements for a wind turbine system at BNA. The SkyMax comes with a 3-year warrantee. All of this makes the SkyMax the most effective wind turbine for consideration in this project (“SkyMax Wind 500 Watt”, (n.d.)).

CHAPTER IV – CONCLUSION

This research proposed an innovative way of harnessing the untapped wind energy (either created by aircraft or by nature) at BNA. The goal of the research was to design a wind turbine system in front of the JBDs at BNAs that would generate electricity from departing aircraft jet blasts. This system could reduce energy costs for the airport, in addition to contributing to a cleaner environment.

Referring to Figures 1-4, the appropriate location for the wind turbine systems was determined to be 3 feet in front of the JBDs. Ten SkyMax wind turbines could be installed on each end of the runway 13/31 leaving a gap of two feet between each wind turbine. Calculations performed in the data analysis section indicate that installing twenty SkyMax wind turbines could potentially generate 932.28 kWh of electricity per year based upon data from BNA in 2017. The installation of twenty SkyMax wind turbines was estimated to cost around $10,980, after a federal tac credit, and was estimated to generate approximately 932.28 kWh of electricity in a year. The system was calculated to break even in 79.88 years.

Considering the amount of time this system would take to recuperate its cost implementation, even using the most cost-effective wind turbines, it is not worth pursuing at this time. On the other hand, the installation of this system at BNA, or any other airport would indicate that the airport is environmentally sensitive even if the result of this research shows that it is not financially justifiable. For this system to be feasible at BNA, the efficiency of the wind turbines would need to improve, and the number of takeoffs would need to increase. These conditions may not be realized at BNA, but they might at elsewhere. This system could prove useful at an airport located in a region with higher natural winds and more operations possibly of larger aircraft having higher jet blast velocities. The system being installed at such airport would generate more energy and would have a reduced time to breakeven.

Future research in this area could be performed with efficient and cost-effective wind turbines as they become available. Research could also be conducted at busier airports and at airports with higher average natural wind speeds. As technology improves, wind turbine efficiency will improve, and costs could come down to the point where the systems become more reasonable with respect to the costs that they incur. A future study could be performed on the requirements of a wind turbine system installed at an airport in order to determine the number of takeoffs it would need to make the system feasible at airports, so that the breakeven point of the system is less than the expected replacement period of the system.

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