COMPARATIVE LIFE CYCLE ASSESSMENT OF SMALL VERTICAL-AXIS WIND TURBINES AND NATURAL GAS FACILITY AT AN URBAN UNIVERSITY

Mary Kate Ranii

Follow this and additional works at: https://dsc.duq.edu/etd

Part of the Sustainability Commons

Recommended Citation

This Immediate Access is brought to you for free and open access by Duquesne Scholarship Collection. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of Duquesne Scholarship Collection. For more information, please contact beharyr@duq.edu.
COMPARATIVE LIFE CYCLE ASSESSMENT OF SMALL VERTICAL-AXIS WIND TURBINES AND NATURAL GAS FACILITY AT AN URBAN UNIVERSITY

A Thesis
Submitted to the Bayer School of Natural and Environmental Sciences

Duquesne University

In partial fulfillment of the requirements for
the degree of Master of Science

By
Mary Kate Ranii

August 2023
ABSTRACT

COMPARATIVE LIFE CYCLE ASSESSMENT OF SMALL VERTICAL-AXIS WIND TURBINES AND NATURAL GAS FACILITY AT AN URBAN UNIVERSITY

By

Mary K Ranii

August 2023

Dissertation supervised by Professor David M. Kahler.

Fossil fuels generate the majority of the electricity in the United States and generate pollutants that negatively affect public and environmental health. Renewable energy projects serve as an opportunity for low-pollution and low-carbon electricity; small-scale projects, such as vertical axis wind turbines (VAWTs), provide opportunities for generation in urban areas close to consumers. Researchers collected wind speed and directional data from a potential turbine installation site at Duquesne University to better demonstrate the potential benefits in an urban university location. The data was used in a life cycle assessment framework and a social review to better understand the value of electricity produced by a small-scale VAWT as compared to that produced by natural gas. Results showed that energy produced by the VAWT using the Mellon Hall wind resources created fewer pollutants than that of the natural gas plant.
ACKNOWLEDGEMENT

I would like to thank Duquesne University, the faculty of the Center for Environmental Research & Education, and the Kahler lab for supporting this research and providing me with the knowledge and skills necessary to complete this project and extend my sustainability expertise.

Thank you to my thesis committee members, Dr. Robert Sroufe and Dr. Michael Huster, as well as my research advisor, Dr. David Kahler, for their time and guidance. Dr. Kahler, thank you for your endless patience with me and for explaining, yet again, how to push the code to Github. You have provided me with wonderful opportunities, and I am forever grateful.

I would like to acknowledge my personal and professional support network for their encouragement throughout this process. To my family and friends, who have listened to me complain and cry about this project for years and shown me nothing but support. To my wonderful husband(!!) Robert, who has also listened to me complain and cry about this project for years and shown me nothing but love. To the former and current students of CERE, who have shown me how to persevere and laugh throughout the process.
# TABLE OF CONTENTS

ABSTRACT .............................................................................................................................................. iv

ACKNOWLEDGEMENT .......................................................................................................................... v

LIST OF TABLES ..................................................................................................................................... viii

LIST OF FIGURES .................................................................................................................................. x

CHAPTER 0: PROJECT INTRODUCTION ............................................................................................. 1

CHAPTER 1: REGIONAL ENERGY MIX ............................................................................................... 1
   1.0.1 AIR POLLUTION .......................................................................................................................... 3
   1.0.2 CLIMATE CHANGE .................................................................................................................... 4

1.1 WIND AND TRENDS IN WIND ENERGY ....................................................................................... 6
   1.1.1 WIND TURBINE AND BIRDS .................................................................................................... 8

1.2 SMALL-SCALE WIND TURBINES ................................................................................................. 9

1.3 WIND STATISTICS & THE CONSEQUENTIAL POWER OF WIND ............................................ 12
   1.3.1 SITING MICRO- AND SMALL-SCALE WIND TURBINES ......................................................... 13

1.4 LIFE CYCLE ASSESSMENT .......................................................................................................... 14
   1.4.1 EXISTING LIFE CYCLE ASSESSMENTS ON SMALL-SCALE WIND TURBINES ................. 15
   1.4.2 NATURAL GAS LIFE CYCLE ASSESSMENT ......................................................................... 22

1.5 EXPANDED LIFE CYCLE ASSESSMENT AT UNIVERSITIES .................................................. 23
   1.5.1 DUQUESNE UNIVERSITY CASE STUDY: OPPORTUNITIES FOR HIGHER EDUCATION
   INSTITUTIONS .................................................................................................................................. 28

1.6 HYPOTHESIS .................................................................................................................................. 30

CHAPTER 2: MATERIALS AND METHODS ..................................................................................... 31

2.1 ENERGY OUTPUT FROM WIND .................................................................................................... 31

2.2 LIFE CYCLE ANALYSIS OF WIND TURBINE ........................................................................... 34
   2.2.1 SYSTEM DESCRIPTION: SMALL-SCALE WIND TURBINE ..................................................... 34
   2.2.2 SYSTEM DESCRIPTION: NATURAL GAS FACILITY .............................................................. 38

2.3 HEALTH IMPACTS AND ASSOCIATED FINANCIAL IMPACTS ............................................. 39

2.4 EXPANDED LIFE CYCLE ASSESSMENT .................................................................................... 40
   2.4.1 RECRUITMENT AND RETENTION ......................................................................................... 40
   2.4.2 EDUCATIONAL OPPORTUNITIES .......................................................................................... 41
   2.4.3 REPUTATION AND LEADERSHIP OPPORTUNITIES ............................................................ 41

CHAPTER 3: RESULTS AND DISCUSSION .................................................................................... 43

3.1 WIND SPEED AND DIRECTION ................................................................................................. 43

3.2 LIFE CYCLE ASSESSMENT ......................................................................................................... 47
3.2.1 GLOBAL WARMING POTENTIAL ................................................................. 48
3.2.2 PARTICULATE MATTER POLLUTION ...................................................... 51
3.2.3 FINANCIAL COSTS OF EMISSIONS ....................................................... 52

3.3 EXPANDED LIFE CYCLE ASSESSMENT ..................................................... 54
3.3.1 RECRUITMENT AND RETENTION ............................................................ 54
3.3.2 EDUCATIONAL AND LEADERSHIP OPPORTUNITIES ............................ 55
3.3.3 REPUTATION AND LEADERSHIP .......................................................... 56
3.3.4 FINANCIAL OPPORTUNITIES ................................................................. 58

CHAPTER 4: CONCLUSIONS .............................................................................. 62

4.1 IMPORTANCE OF SITING .......................................................................... 62
4.2 WIND IS A CLEAR CARBON WINNER ...................................................... 62
4.3 VALUES & SOCIAL COST OF CARBON ..................................................... 63
4.4 WATER USAGE ......................................................................................... 64
4.5 STUDY LIMITATIONS ............................................................................... 64
4.6 FUTURE DIRECTIONS ............................................................................... 65

CHAPTER 5: REFERENCES ................................................................................. 66
LIST OF TABLES

Table 1: Greenhouse gas carbon dioxide equivalents (IPCC, 2014). .................................................. 5

Table 2: Global Warming Potential from existing small-scale wind turbine life cycle assessments. ..................................................................................................................................................................... 16

Table 3: Materials and processes associated with the Nemi S Wind Turbine and based on region of data. RNA: Region: North America. GLO: Region Global. RoW: Rest of World. Cut-off, S refers to the cut-off system model, meaning that all the upstream impacts are included in a single inventory. Under this system all impacts of recycled content are attributed to the first user (Eastern Research Group, 2023). .................................................................................................................................................. 37

Table 4: Processes associated with the natural gas plant. ......................................................................... 39

Figure 13: A Weibull distribution of the frequency of average wind speeds in 15-minute intervals from November 2021 to April 2023 at Mellon Hall. Vertical line represents the arithmetic mean.

Table 5: Mean monthly wind speeds with standard deviations from November 2021 to April 2023 at Mellon Hall. .................................................................................................................................................. 43

Table 6: Average monthly wind speed and standard deviations from November 2021 to April 2023 at Towers Hall. .................................................................................................................................................. 44

Table 7: Wind speed and potential energy produced at existing weather stations in the Greater Pittsburgh Area. .................................................................................................................................................. 47

Table 8: Impacts of electricity produced by wind turbine and natural gas.............................................. 47

Table 9: Characterization factors of carbon dioxide equivalents in terms of Disability Adjusted Life Years (DALYs) per kg of pollutant emitted.................................................................................................................................................. 49

Table 10: Health and Economic Impacts of Electricity produced by the Wind Turbine and Natural Gas. .................................................................................................................................................. 50
Table 11: Cost of electricity produced by wind turbine and natural gas using various social cost of carbon values. ................................................................. 50
Table 12: Characterization factors of PM$_{2.5}$ in terms of Disability Adjusted Life Years (DALYs) per kg emitted. ........................................................................................................ 51
Table 13: Cost in Disability Adjusted Life Years (DALYs) of pollutants emitted from energy sources.................................................................................................................................... 52
Table 14: Costs of laboratory equipment........................................................................................................................................ 56
LIST OF FIGURES

Figure 1: Net energy sources for the United States (top) and Pennsylvania (bottom) from 2001-2021. ................................................................. 2

Figure 2: Wind Turbine Heights have been increasing for years and are predicted to continue increasing in size in the future. (Hartman, 2022). The accompanying picture was retrieved from the Department of Energy https://www.energy.gov/eere/articles/wind-turbines-bigger-better. .... 8


Figure 4: Global Warming Potential from existing small-scale wind turbine life cycle assessments. .......................................................................................................................... 17

Figure 5: Box and Whisker Plot of Global Warming Potentials from horizontal axis wind turbines (HAWTs), vertical axis wind turbines (VAWTs), and Natural Gas Facilities. This figure cuts off two outliers (2.247 and 2.92) from the VAWT. An outlier is a value that is outside 1.5 times the Interquartile Range from the 25th or 75th percentiles. .......................................................... 23

Figure 6: Weather Stations on the roof of Mellon Hall (left) and Towers Hall (right). Source: Google Earth. Retrieved 17 July 2023. ................................................................. 31

Figure 7: Wind roses representing wind speed and directions at Pittsburgh International Airport and Acrisure Stadium (formerly Heinz Field). ............................................................................... 32

Figure 9: Photograph by Mary K Ranii. (2022) Title: Weather Stations on the roof of Mellon Hall (left) and Towers Hall (right). ................................................................. 33
Figure 10: System boundary for Wind Turbine System. ................................................................. 35
Figure 11: System boundary for Natural Gas System. ................................................................. 35
Figure 12: Power curve associated with the Nemoi S Wind Turbine ........................................ 38
Figure 13: A Weibull distribution of the frequency of average wind speeds in 15-minute intervals from November 2021 to April 2023 at Mellon Hall. Vertical line represents the arithmetic mean.
Table 5: Mean monthly wind speeds with standard deviations from November 2021 to April 2023 at Mellon Hall. ................................................................................................................................. 43
Figure 14: A Weibull distribution of the frequency of average wind speeds in 15-minute intervals from December 2021 to April 2023 at Towers Hall. Vertical line represents the arithmetic mean. ........................................................................................................................................................................... 44
Figure 15: Power curve associated with the Nemoi S Wind Turbine ........................................ 45
Figure 16: Wind rose depicting the wind speed and direction at Mellon Hall from November 2021 to April 2023 ........................................................................................................................................................................ 46
Figure 17: Wind rose depicting the wind speed and direction at Towers Hall from December 2021 to April 2023 ........................................................................................................................................................................ 46
Figure 18: Global Warming Potential emissions from wind turbine material production. ........ 48
Figure 19: Particulate Matter emissions from wind turbine material production ....................... 49
Figure 20: Cost per kWh of energy produced by a natural gas facility and wind turbine in terms of price, costs from DALYs, and social cost of carbon. Left graph shows the low characterization factors for each factor, center graph shows the current/median characterization factors, and the right graph shows the high characterization factors for each factor .................................................................................................................................................................................. 53
Figure 21: Cost per kWh of energy produced by a natural gas facility and wind turbine in terms of price, and costs from DALYs and the social cost of carbon. Graph uses error bars to show the high and low characterization factors.
CHAPTER 0: PROJECT INTRODUCTION

Environmental, health, and climate imperatives demonstrate the need to reduce fossil fuel consumption. Institutions across sectors seek solutions that provide low-pollution and low-carbon electricity. Small-scale wind turbines, especially vertical axis wind turbines (VAWTs), offer opportunities for electrical energy generation close to many consumers, including urban areas. A life cycle assessment framework allows decision-makers to review and better understand the environmental, health, social, and financial impacts and opportunities of small-scale renewable energy generation.

As the world looks for renewable energy solutions, universities are uniquely positioned for on-site generation to provide additional educational and mission-driven opportunities to the campus community. Urban settings require additional study as wind resources can be extremely variable even between nearby sites. This study will investigate priorities in Pittsburgh, Pennsylvania and at Duquesne University, and will include feasibility assessments for small-scale vertical axis wind turbines and evaluations of organizational opportunities.

CHAPTER 1: REGIONAL ENERGY MIX

Currently, most electrical energy in the United States is generated by fossil fuels. In 2021, approximately 60% of electrical energy was generated from fossil fuels, namely natural gas (38.4%), coal (21.9%), and petroleum (0.5%). Renewables (19.9%), nuclear (18.9%), and other minor sources (3.4%) provided the rest (U.S. EIA, 2023b). In Pennsylvania, the majority of electrical energy is produced by natural gas and nuclear sources. Coal usage has decreased in recent years in both Pennsylvania and the United States as a whole. In 2001, coal provided 57% of Pennsylvania’s electricity, though by 2021, this number had shrunk to 12%. On the other hand, natural gas has increased from just 2% in 2001 to 52% in 2021. Nuclear energy
consistently provides between 30 and 40% of the Commonwealth’s electricity. Renewable electricity sources have increased slowly over the last twenty years. However, they are still a very small portion of the state’s electricity sources (3.6%), with biomass as the most significant source (U.S. EIA, 2023c). (Figure 1).

![Net energy sources for the United States (top) and Pennsylvania (bottom) from 2001-2021.](image)

Figure 1: Net energy sources for the United States (top) and Pennsylvania (bottom) from 2001-2021.
Electricity generation from fossil fuels results in negative human and environmental impacts. While fossil fuel combustion contributes the most emissions, the associated mining, drilling, and refining processes release even more pollutants (Dincă et al., 2010).

1.0.1 AIR POLLUTION

Fossil fuel combustion releases millions of tons of air pollutants including particulate matter, nitrogen oxides, sulfur oxides, carbon monoxide, ozone, lead, and mercury (U.S. EPA, 2023). These pollutants decrease visibility, affect cloud formation, contribute to acid rain, limit plant growth, damage existing vegetation (Stern, 1977), decrease wildlife populations, and increase wildlife disease, stress, and toxicity (Newman, 1979).

Many air pollutants are monitored by the U.S. Environmental Protection Agency (EPA) via the Air Quality System (AQS) (U.S. EPA, 2023). The AQS is a collection of ambient air quality data collected by the EPA as well as state, county, and tribal groups (U.S. EPA, 2023). The American Lung Association uses these AQS values to grade cities and counties nationwide in their annual State of the Air Report. In 2022, the American Lung Association awarded Allegheny County, the county in which Pittsburgh resides, an F grade in the ozone and the 24-hour particle pollution categories (American Lung Association, 2022). The primary source of pollution in Allegheny County is fossil fuel combustion. A major source of particulate matter pollution is coal combustion from a series of coal-fired power plants located along the Ohio River Valley as well as other regional industrial sources (Pekney et al., 2006).

In addition to environmental damage, air pollution harms human health. Exposure to short and long-term air pollution can lead to respiratory and cardiovascular diseases, neuropsychiatric complications, eye and skin irritation, cancer, and asthma (Ghorani-Azam et al.,
The World Health Organization estimates that air pollution exposure leads to seven million premature deaths annually (World Health Organization, 2021).

**Particulate Matter Pollution**

Of specific importance to Pittsburgh and all of Allegheny County is particulate matter pollution. While all particulate matter is damaging to lung health, particulate matter with an aerodynamic diameter \( \leq 2.5 \) micrometers (PM\(_{2.5}\)) is considered the most harmful (Commission of the European Communities, 2005). PM\(_{2.5}\) pollution is also associated with reduced cognitive function all age groups (Chandra et al., 2022). A review of deaths in 2012 found an estimated 10.2 million global excess deaths from PM\(_{2.5}\) pollution from fossil fuel combustion (Vohra et al., 2021). PM\(_{2.5}\) was ranked as the fifth highest mortality factor in 2015 (Cohen et al., 2017). PM\(_{2.5}\) was also responsible for 4.2 million deaths and 103.1 million disability adjusted life years (DALYs) in 2015 (Cohen et al., 2017). DALYs are “…a time-based measure that combines years of life lost to premature mortality and years of life lost due to time lived in states of less than full health…” (World Health Organization, 2023). DALYs represent the loss of human health and commensurate loss of economic productivity.

This study will review particulate matter 2.5 equivalents (PM\(_{2.5}\)-eq). Equivalents are used as a measure of comparison between a variety of emissions on the basis of respiratory effects. Different pollutants are converted to the equivalent of PM\(_{2.5}\) with the same amount of respiratory impact.

1.0.2 CLIMATE CHANGE

Fossil fuel combustion generated 72.6% of the United States’ total greenhouse gas emissions in 2020. The greenhouse gas emissions come from a variety of sectors: 37% from the transportation sector; 32% from electricity retail sales; 28% from industrial sources; 19% from
residential sources; and 16% from commercial sources in 2021 (U.S. EIA, 2022). Fossil fuel combustion and the resulting greenhouse gases contributes to global climate change (Wuebbles & Jain, 2001). Climate change is the change in long-term regional temperature and weather patterns (Lee et al., 2023). Changes in regular weather patterns lead to various effects, including but not limited to: rising sea levels; increased frequency and severity of natural disasters; local flooding events; disturbed agricultural systems; and increased spread of tropical diseases (Hitz & Smith, 2004). In addition, climate change has caused ecological, behavioral, physiological, and genetic changes in plant and animal species across the globe – these changes have led to species loss, increased interactions between species, and increased competition for limited resources (IUCN, 2019).

Climate change has also caused and exacerbated existing health crises and is likely to continue to do so in the future. Between 2030 and 2050, the World Health Organization (WHO) predicts an additional 250,000 deaths per year due to malnutrition, diarrhea, and heat stress associated with climate change (World Health Organization, 2021b). Other studies indicate that climate change will cause 83 million additional deaths by 2100 (Bressler, 2021).

The Intergovernmental Panel on Climate Change (IPCC) has determined that countries must transition away from fossil fuels in the next several years to mitigate the worst of the effects of climate change (Freund et al., 2018). This study will review global warming potential regarding carbon dioxide equivalents (CO₂-eq). Equivalents are used as a measure of comparison between a variety of emissions on the basis of global warming’s potential effects. Different pollutants are converted to the equivalent CO₂ with the same amount of global warming potential (Table 1).

Table 1: Greenhouse gas carbon dioxide equivalents (IPCC, 2014).
<table>
<thead>
<tr>
<th>Molecule</th>
<th>Chemical Nomenclature</th>
<th>Carbon Equivalents/Global Warming Potential using 100-Year Time Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>25</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>N₂O</td>
<td>265</td>
</tr>
<tr>
<td>CFC-11</td>
<td>CCl₃F</td>
<td>4,660</td>
</tr>
<tr>
<td>HFC-23</td>
<td>CHF₃</td>
<td>12,400</td>
</tr>
<tr>
<td>HFE-125</td>
<td>CHF₂OCF₃</td>
<td>12,400</td>
</tr>
</tbody>
</table>

**1.1 WIND AND TRENDS IN WIND ENERGY**

Wind energy provides a huge opportunity to transition to renewable energy sources — onshore U.S. wind potential alone is between 2.2 – 15.1 terawatts (Lopez et al., 2021). Wind is the motion of air driven by atmospheric pressure gradients caused primarily by the Sun’s uneven heating of the Earth (Mathew, 2006). Wind energy has been used for thousands of years to sail ships, grind grain, pump water, and, in more recent years, generate electricity (Letcher, 2023).

This project will review wind within the planetary boundary layer, the portion of atmosphere impacted by the surface. Understanding the regular cycles of this boundary layer can help understand wind speed and direction. Atmospheric mixing within the planetary boundary layer changes throughout the day, and its thickness ranges between approximately 100 meters to several kilometers (Stull, 1988). Overnight, the ground cools, leading to a stable layer of air near the ground with warmer air above it. This temperature inversion keeps the air in place, leading to slower and calmer winds. As the sun rises, the ground gains more heat from solar radiation, and the boundary layer rises. (This process can be likened to water bubbling up as it boils). The boundary layer expands and mixes with the above atmospheric layers – this mixing leads to gustier wind (Stull, 1988). As the sun sets and the ground cools, the boundary layer returns to the shallow stable state and the cycle begins again (Stull, 1988). In recent years, climate change has
been impacting ground temperature and affecting this diurnal cycle of atmospheric mixing (Seidel et al., 2012).

Wind speed and direction are also impacted by the Earth’s rotation as well as conduits formed by natural and human-made topography (i.e., mountains, valleys, and buildings) (Letcher, 2023). Air passing over the ground, ground cover, and other layers of air results in friction, which adds roughness and eddies. These eddies make predicting wind speed and direction difficult as they can decrease or increase velocity in different circumstances. However, higher above the ground, the impact of topography and ground cover on the air decreases, resulting in air that moves more smoothly and gathers more speed (Olsen & Preus, 2015).

Wind projects have typically worked to take advantage of the highest wind speed possible. Wind speed typically increases with increased height; thus, taller turbines are generally favored (Olsen & Preus, 2015). The average height of commercial wind turbines has been steadily increasing over the last several decades. The average hub height (height to the middle of the wind turbine’s rotor) was 90 meters in 2020, as compared to just 30 meters in 1999 (Hartman, 2022) (Figure 2). Wind turbines are likely to grow even taller in the future, though are limited in part by the ability to fit the turbine’s blades under highway overpasses as they are usually transported by truck (Lantz et al., 2019).
Figure 2: Wind Turbine Heights have been increasing for years and are predicted to continue increasing in size in the future (Hartman, 2022). The accompanying picture was retrieved from the Department of Energy https://www.energy.gov/eere/articles/wind-turbines-bigger-better.

1.1.1 WIND TURBINE AND BIRDS

In recent years, critics of wind power have noted turbines’ negative impact on birds. A review of avian mortality and operating performance in Europe and North America found that an estimated 0.3 bird fatalities were associated per gigawatt-hour of electricity produced by wind turbines. These deaths include bird collisions with turbines, support structures, or associated transmission and distribution lines (Sovacool, 2013). With 378.20 gigawatt-hours of wind electricity generated in the U.S. in 2021 (U.S. EIA, 2023b), we can estimate 113.50 bird deaths every year. However, the number of birds killed by wind turbines pales in comparison to those killed by the effects of fossil fuels and other human impacts. Fossil fuel electricity stations (primarily coal) were associated with 5.2 bird fatalities per gigawatt-hour of electricity. These include bird deaths during mining, collisions with power plant equipment, and fatalities related to acid rain and climate change (Sovacool, 2013). With 2,507.82 gigawatt-hours of fossil fuel electricity generated in the U.S. in 2021 (U.S. EIA, 2023b), we can estimate 13,040.66 bird deaths every year.
Beyond fossil fuels, other anthropogenic sources of bird mortality are much higher than those posed by wind turbines. For example, free-roaming domestic cats kill between 1.4 and 4.0 billion birds every year in the United States (Blancher, 2013; Loss et al., 2014). Furthermore, U.S. buildings are estimated to cause between 365 and 988 million bird deaths per year (Loss et al., 2014).

Though wind turbines do not kill many birds, companies should take steps to further reduce that loss of life. Developers should avoid building wind turbines along bird migration routes and assess locations for wildlife impacts before construction. Turbines should also be adapted to reduce the impact on wildlife; for example, painting one blade black enables wildlife to better see and avoid turbines (May et al., 2020). Turbine size and height can change how much impact a wind turbine has on birds, with larger blades associated with higher wildlife mortality (Miao et al., 2019). Therefore, small-scale wind turbines have the further benefit of less impact on wildlife simply due to their size.

1.2 SMALL-SCALE WIND TURBINES

Wind turbines harness the kinetic energy of moving air and convert it to electrical energy. Turbines are typically composed of blades or scoops around a central tower. The two major wind turbine categories are horizontal-axis and vertical-axis. Horizontal-axis wind turbines (HAWTs) turn on a horizontal axis. HAWTs must be rotated (or yawed) to the direction of the wind as they can only utilize wind from one direction. HAWTs are more efficient and generate more electricity than other wind turbines (Letcher, 2023). Conversely, vertical-axis wind turbines (VAWTs) turn on a vertical axis and can use wind from any direction (Figure 3). This ability makes them good options in areas with variable wind direction, such as urban environments.
In addition, VAWTs are often quieter and more easily maintained (Danao et al., 2014).

Figure 3: Darrieus Vertical Axis Wind Turbine, Horizontal Axis Wind Turbine, and Helical Darrieus Vertical Axis Wind Turbine as part of the Dept. of Energy’s Offshore Wind Projects (Advanced Research Projects Agency, 2019).


Though large-scale wind turbines have been studied extensively for decades, more research is needed regarding small-scale wind projects. According to the U.S. Department of Energy, small-scale wind turbines have an energy capacity between 1 and 100 kW (Olsen & Preus, 2015). The U.S. Office of Energy Efficiency & Renewable Energy defines micro-scale wind turbines as those that produce between 20 and 500 Watts (EERE, 2023). However, studies vary in definitions of turbine size – this study categorizes all turbines with a capacity of less than 5 kW as small-scale wind turbines.

Small-scale wind projects are a part of net zero emissions plans for many professional environmental groups, including Project Drawdown and the World Energy Outlook (Hawken,
Like large-scale wind projects, small-scale wind produces zero-carbon electricity during operation (Peacock et al., 2008).

Unlike large-scale turbines, small-scale wind projects can generate electricity close to the point of use (ex., a commercial office building). Reducing the distance between the point of generation and the point of use reduces electricity lost in distribution, further reducing the carbon intensity of the electricity (Drew et al., 2015). Small-scale wind turbines have been shown to be especially effective in rural and peri-rural areas. These areas are unable to otherwise be connected to grid electricity or must generate their own electricity, often using a diesel generator (Glassbrook et al., 2014). Two studies in Alberta, Canada found that small-scale wind turbines produce more electricity than do diesel generators (Fleck & Huot, 2009; Kabir et al., 2012). However, it should be noted that these studies both used wind data from 30-meter heights, which are not accessible to most small-scale wind turbines, which are typically installed 10 meters high or lower. Small-scale wind projects also allow for energy production in urban and suburban areas. As 65 percent of global energy is used in cities, providing nearby electricity sources can have significant impacts (Pellegrini et al., 2021). Small wind projects are also sources of distributed electrical energy. Distributed energy is loosely defined as small-scale electricity generation. Distributed energy increases reliability of electricity, improves electricity security, protects consumers from price fluctuations, and often supports renewable energy projects (Pepermans et al., 2005).

In most studies featuring small-scale wind turbines, cost and siting are the biggest concerns. Most studies found long periods of return on investments: 16 years (Bahaj et al., 2007), 26.8 years (Peacock et al., 2008), 15-86 years (Bahaj et al., 2007). Most of these studies
cited high up-front costs, both in terms of monetary cost and pollution from turbine manufacturing, were often the most significant portion of both burdens (Ayhan & Sağlam, 2012; Bukala et al., 2015; Pellegrini et al., 2021; Sunderland et al., 2016). However, with assistance from grants, foundations, or government programs for material procurement, small-scale wind turbines can be a financially viable option. At least one study also noted that goals outside of pure electricity generation added to the success of small-scale wind projects (Fields et al., 2016). Without proper siting, the wind turbines took even longer to succeed. These findings solidify that small-scale wind turbines can only succeed if placed in areas with access to high-speed wind.

1.3 WIND STATISTICS & THE CONSEQUENTIAL POWER OF WIND

The Intergovernmental Panel on Climate Change (IPCC) estimates that wind’s global technical energy potential is more than twice the global energy production (Wiser et al., 2011). Two principles are used to determine how much power the wind can exert. The first principle is the idealized power equation, which shows that the total power generated, \( P \), is proportional to the wind velocity cubed \( v^3 \) (Ramenah & Tanougast, 2016). Therefore, siting wind turbines to capture the highest velocity wind is critical to its success.

\[
P = \frac{1}{2} \times \rho \times A \times v^3
\]

(1)

Where \( P \) is Power, \( \rho \) is air density, \( A \) is cross-sectional area of the wind, and \( v \) is the wind velocity.

The second principle is the Betz Limit. A wind turbine cannot extract all of the energy from the wind – if a turbine were to capture 100% of the wind’s energy, the air molecules would completely stop after passing over the turbine. The Betz limit is the theoretical maximum energy,
59.3%, that a turbine can extract from the wind (Betz, 1920). This equation is the limit based on mechanical energy transfer. Realistically, wind turbines are able to capture less than the Betz Limit – usually between 20-40% (U.S. EPA, 2013).

1.3.1 SITING MICRO- AND SMALL-SCALE WIND TURBINES

Effectively siting wind projects is critical to their success. Large wind projects can use wind atlas data to identify sites with adequate wind resources for turbines. Wind atlases collect wind speed and directional data at heights of 30 meters and higher. Wind prediction models utilize atlas data to predict which sites will be suitable for turbines (Badger et al., 2023). Small-scale wind projects cannot utilize most wind atlas data, as most small-scale wind turbines are installed at heights lower than 30 meters. Therefore, the industry standard is on-site measurements (Ramenah & Tanougast, 2016). On-site measurements are especially vital in urban environments where wind resources can vary significantly within a matter of meters.

Typically, an experienced wind assessor is necessary to determine wind project feasibility, especially for small-scale wind turbines and/or urban environments. Currently, the industry standard includes an initial site visit from a wind assessor to find potential site locations (Olsen & Preus, 2015). Assessors identify terrain effects such as wind roughness from nearby obstacles (Sagrillo & Taivalkoski, 2010). Potential sites then collect on-site temperature, wind speed, and wind direction data for at least a year, ideally at two different heights (Olsen & Preus, 2015). The assessor then uses these data to create distribution functions to estimate future wind speed and availability (Olsen & Preus, 2015). Wind speed typically fits a Weibull distribution with a shape factor of approximately 2.0 or a Rayleigh distribution (Drew et al., 2015; Khraiwish Dalabeeh, 2017; Ramenah & Tanougast, 2016; Seguro & Lambert, 2000; Stevens & Smulders, 1979).
Jowder (2006) used wind speed data from Bahrain and found that the Weibull distribution fits wind speed variation better than the Rayleigh distribution. Assessors then use the calibrated Weibull distribution and the turbine’s power curve to predict annual energy production. The power curve gives power as a function of wind speed and is provided by the manufacturer or a third-party. The assessor will review the energy production to determine project feasibility (Olsen & Preus, 2015).

1.4 LIFE CYCLE ASSESSMENT

This study will evaluate two energy sources through the process of a life cycle assessment (LCA). LCA is a methodology used to assess and understand the potential environmental impacts associated with the various stages of a life cycle of a product, material, process, or activity. Life cycles can span from cradle to grave (raw material extraction to final disposal), cradle to gate (raw material extraction to the end of product production), or cradle to cradle (raw material extraction to end of life, which serves as raw material for another life cycle). The International Organization for Standardization (ISO) has two methodologies for conducting LCAs, including ISO 14040 and ISO 14044, that include standardized methodologies for conducting LCAs. We will utilize the methods outlined in ISO 14044.

According to ISO 14044, the LCA’s initial phase is defining the study’s goal and scope. This definition includes setting the level of detail, identifying the audience and stakeholders, stating the study’s intended use, outlining any assumptions or limitations, and identifying the functional unit and system boundary (ISO, 2006). The functional unit is the unit of comparison in an LCA; the system boundary outlines which portions of the system will be included in the LCA. The second phase of the process is a Life Cycle Inventory Analysis in which the assessor
collects data regarding inputs and outputs and relates it to the specific study. The data collection process includes data validation and allocation as well as specifies assumptions and limitations. The third phase of an LCA is the Impact Assessment, in which assessors review how the system’s inputs and outputs impact the environment and the significance of those impacts. These impacts are typically divided into different impact categories. ISO 14044 does not specify an Impact Assessment methodology. A common life cycle impact assessment methodology in the United States is TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), which categorizes all emissions nine groups so that stakeholders can better understand the total impacts (Bare, 2011). For example, all greenhouse gases are categorized as one value of Global Warming Potential. The fourth phase of an LCA is the Interpretation Phase, in which the assessor summarizes inventory analysis results and provides conclusions and recommendations (ISO, 2006).

The service under investigation is energy production by a Semtive Nemoi S wind turbine theoretically installed on Mellon Hall and Towers Hall roof on Duquesne University’s campus. The alternative service under investigation is energy produced by a natural gas facility. The primary function of both the wind turbine and the natural gas facility is to generate electrical energy. The functional unit for this LCA is 1 kWh of electrical energy produced. This study will focus on the Global Warming Potential and Respiratory Impact Categories under the TRACI characterization system.

1.4.1 EXISTING LIFE CYCLE ASSESSMENTS ON SMALL-SCALE WIND TURBINES

Most wind energy life cycle assessments (LCAs) are for large-scale systems, with only a handful conducted on small-scale wind projects and even fewer for vertical-axis turbines. Moreover, studies show variability in emission impact levels (Table 2, Figure 4). A literature
review included LCAs of wind projects with turbine capacity ≤ 6 kW and that used Global Warming Potential or an equivalent Impact Category. Only a portion of these LCAs include Respiratory Impacts, so we did not include them in this review.

Table 2: Global Warming Potential from existing small-scale wind turbine life cycle assessments.

<table>
<thead>
<tr>
<th>Author</th>
<th>Turbine Type/Size</th>
<th>Location</th>
<th>Global Warming Potential (kg CO₂-eq/kWh)</th>
<th>LCA Scope</th>
<th>Wind Data Source</th>
<th>Assumed Turbine Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rankine, Chick, &amp; Harrison, 2006</td>
<td>1.5kW HAWT</td>
<td>United Kingdom</td>
<td>0.0857</td>
<td>Cradle-to-Grave</td>
<td>Assumes wind speeds of 4-7.2 m/s</td>
<td>20 Years</td>
</tr>
<tr>
<td>Fleck &amp; Huot, 2007</td>
<td>400W HAWT</td>
<td>Canada</td>
<td>0.382</td>
<td>Cradle-to-Electricity Conversion</td>
<td>Collected data from 3 existing weather stations within 100 km – all at 30 m height</td>
<td>20 Years</td>
</tr>
<tr>
<td>Allen, Hammond &amp; McManus, 2008</td>
<td>600W HAWT</td>
<td>United Kingdom</td>
<td>0.102 - 0.020</td>
<td>Cradle-to-Point of Electricity Delivery (Excludes disposal)</td>
<td>16 years of wind data from 26 Met Weather stations – 10 meters high in both urban (2.3-5.2 m/s mean) and rural (2.8-7.8 m/s mean) areas</td>
<td>15 Years</td>
</tr>
<tr>
<td>Mithraratne, 2009</td>
<td>1.5kW HAWT</td>
<td>New Zealand</td>
<td>0.271</td>
<td>Cradle-to-Grave</td>
<td>Assumed wind speed of 5.5-6.3 m/s</td>
<td>20 Years</td>
</tr>
<tr>
<td>Tremeac &amp; Meunier, 2009</td>
<td>250W VAWT</td>
<td>France</td>
<td>0.046</td>
<td>Cradle-to-Grave</td>
<td>Not disclosed.</td>
<td>20 Years</td>
</tr>
<tr>
<td>Amor et al., 2010</td>
<td>1kW HAWT</td>
<td>Canada</td>
<td>&lt;Avg Wind: 0.56 Avg Wind: 0.16 &gt;Avg Wind: 0.0007</td>
<td>Cradle-to-Grave</td>
<td>Collected Data from Natural Resources Canada. Does not disclose how they determined the below-average, average, and above-average wind speeds.</td>
<td>20 Years Moving Parts 40 Years Fixed Parts</td>
</tr>
<tr>
<td>Kabir et al., 2012</td>
<td>5kW HAWT</td>
<td>Canada</td>
<td>0.0427</td>
<td>Cradle-to-Grave</td>
<td>Canadian Wind Energy Atlas (30 meters)</td>
<td>25 Years</td>
</tr>
<tr>
<td>Greening &amp; Azapagic, 2013</td>
<td>6kW HAWT</td>
<td>United Kingdom</td>
<td>0.0480</td>
<td>Cradle-to-Grave</td>
<td>Assumed average wind speed of 5 m/s</td>
<td>20 Years</td>
</tr>
<tr>
<td>Uddin &amp; Kumar, 2014</td>
<td>300W VAWT</td>
<td>Thailand</td>
<td>0.270</td>
<td>Cradle-to-Grave</td>
<td>Government Weather Stations &amp; Existing Study</td>
<td>20 Years</td>
</tr>
<tr>
<td>Uddin &amp; Kumar, 2014</td>
<td>500W HAWT</td>
<td>Thailand</td>
<td>0.009</td>
<td>Cradle-to-Grave</td>
<td>Government Weather Stations &amp; Existing Study</td>
<td>20 Years</td>
</tr>
<tr>
<td>Study Details</td>
<td>Turbine Size</td>
<td>Location</td>
<td>Capacity Factor</td>
<td>Life Cycle</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
<td>----------</td>
<td>----------------</td>
<td>------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Lombardi et al., 2018</td>
<td>1kW VAWT</td>
<td>Italy</td>
<td>0.225</td>
<td>Cradle-to-Grave</td>
<td>“…two different locations characterized by average wind speed equal to 3.5 m/s and 5.0 m/s respectively…” (p. 557)</td>
<td></td>
</tr>
<tr>
<td>Lombardi et al., 2018</td>
<td>3kW VAWT</td>
<td>Italy</td>
<td>0.177</td>
<td>Cradle-to-Grave</td>
<td>“…two different locations characterized by average wind speed equal to 3.5 m/s and 5.0 m/s respectively…” (p. 557)</td>
<td></td>
</tr>
<tr>
<td>Kouloumpis et al., 2020</td>
<td>5kW VAWT</td>
<td>Poland</td>
<td>0.0555 0.0713 0.126 0.162 2.27 2.92</td>
<td>Cradle-to-Grave</td>
<td>Researchers used electricity data from the wind turbine, as well as from the on-site anemometer and the nearby (15 km away) MERRA station data.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Global Warming Potential from existing small-scale wind turbine life cycle assessments.

Rankine et al. (2006) conducted an LCA regarding a hypothetical 1.5 kW horizontal axis Swift wind turbine installed at 10 meters in the United Kingdom with an assumed 20-year lifetime. Study boundaries included the manufacture of the turbine from raw materials, transportation, installation, operation and maintenance, and final disposal. Assessors used wind data from the European Wind Atlas and adjusted it to a 10-meter height and found the range of
wind speeds of 4.0-7.2 m/s. This study found the Global Warming Potential to be 0.0857 kg CO$_2$ per kWh when final disposal included recycling.

Allen et al. (2015) conducted an LCA regarding a hypothetical 600-Watt horizontal axis wind turbine across 26 urban and rural sites across the UK with an assumed 15-year lifetime. Study boundaries included the energy and raw material resources and extended to electricity delivery. Researchers used 16 years of hourly wind data from existing weather stations and determined the turbines could produce 2,835.6 to 14,178 kWh in urban environments over the course of 15 years. Therefore, the wind project would result in 0.102 to 0.020 kg CO$_2$-eq per kWh.

Tremeac and Meunier (2009) conducted an LCA of a hypothetical 250 W Windside WS-0.3 C vertical axis wind turbine in southern France. Study boundaries included turbine construction, transportation, operation, decommissioning, and final disposal. The study does not disclose how researchers determined wind speed or applied that information to their results. Tremeac and Meunier used the Impact 2002+ analysis method to categorize the environmental impacts of the turbines. This study found the Global Warming Potential to be 46.4 g CO$_2$ per kWh.

Mithraratne (2009) conducted an LCA of hypothetical 1.5 kW Swift horizontal axis wind turbines on rooftops in New Zealand. Study boundaries included turbine manufacturing from raw materials, transportation, installation, operation and maintenance, and final disposal. Mithraratne assumed an average wind speed of 5.5 m/s, as recommended by the WINEUR project (Wind Energy Integration in the Urban Environment). In addition, the author used energy and
greenhouse gas emissions intensity to determine environmental impacts and found Global Warming Potential to be 0.271 kg CO$_2$ per kWh.

Fleck and Huot (2009) conducted an LCA of a 400 W Air X horizontal axis wind turbine in Alberta, Canada. Study boundaries included material production and manufacturing, transportation, operation, power storage, and electricity conversion from DC to AC. The study used wind data from similar sites to calculate average wind speed and used the turbine’s power curve to determine estimated electrical output. The study found the Global Warming Potential to be 0.382 kg CO$_2$ per kWh.

Amor et al. (2010) conducted an LCA of a hypothetical 1 kW horizontal axis wind turbine on a 10-meter pole in Quebec, Canada. Study boundaries included turbine manufacturing from raw materials, transportation, installation, operation and maintenance, and final disposal. The study assumed all materials were produced in the United States and shipped to Quebec (1,500 kilometers). The study used data from the EcoInvent Database as well as the manufacturer, and collected wind data from Natural Resources Canada to determine below-average (3.5 m/s), average (5.6 m/s), and above-average (7 m/s) wind speeds for the region. Researchers used the IMPACT 2002+ analysis method to categorize the environmental impacts of the turbines. This study found the Global Warming Potential to be 0.56, 0.16, and 0.0007 kg CO$_2$ per kWh for the below-average, average, and above-average wind speeds, respectively.

Kabir et al. (2012) conducted an LCA of hypothetical 5 kW horizontal axis wind turbines in Alberta, Canada. Study boundaries included turbine manufacturing from raw materials, transportation, installation, operation and maintenance, and final disposal. The study used 30-meter wind data from the area from the Canadian Wind Atlas. In addition, Kabir et al. used
greenhouse gas emissions, acidification, and ozone depletion to determine environmental impacts. This study found the Global Warming Potential to 0.0427 kg CO$_2$ per kWh.

Greening and Azapagic (2013) conducted an LCA of a hypothetical Proven 11 6 kW horizontal axis wind turbine in the United Kingdom. Study boundaries included raw material extraction and processing, parts manufacturing, turbine assembly, transportation, turbine assembly, operation and maintenance, and decommissioning and final disposal. Greening and Azapagic assumed an average wind speed of 5 m/s. The study used data from the GaBi v.4.4 Database and the CML 2 Baseline 2001 method to categorize the environmental impacts of the turbine. They found the Global Warming Potential to be 0.048 kg CO$_2$ per kWh.

Uddin and Kumar (2014) conducted an LCA of a hypothetical 300 W vertical axis wind turbine and a 500W horizontal axis wind turbine at three sites in Thailand. Study boundaries included raw material extraction and production, parts manufacturing, transportation, turbine assembly and installation, and final disposal. Uddin and Kumar collected wind speeds at three locations, all roughly 30, and used that data and the company power curve to estimate electricity generation. Authors used the CML 2 Baseline 2001 analysis method to categorize the environmental impacts and found the Global Warming Potential to be 0.012 and 0.005 kg CO$_2$-eq per kWh for the 300 W turbine and the 500 W turbine, respectively (Uddin and Kumar 2014).

Lombardi et al., (2018) conducted an LCA of a hypothetical Skyline-10 1 kW and a Skyline-30 3 kW vertical axis wind turbine in Italy. Study boundaries included raw material production and manufacturing, transportation, operation and maintenance, and final disposal. Researchers assumed both turbines were sited in a location with 4 m/s average wind speeds with a distribution characterized by a shape factor of 1.4. Lombardi et al., used the CML-IA and the TEC-LC analysis method to categorize the environmental impacts of the turbines. Authors found
the Global Warming Potential to be 0.225 and 0.177 kg CO₂-eq per kWh for the Skyline-10 and the Skyline-30 turbines, respectively.

Kouloumpis et al. (2020) conducted an LCA of an existing Windkop 5 kW vertical axis wind turbine on a 15.6-meter mast at Bialystok University of Technology in Poland. Study boundaries included raw material acquisition and production, transportation, parts manufacturing, installation, operation and maintenance, and final disposal. This study used electricity data from the wind turbine, as well as from the on-site anemometer and the nearby (15 km away) MERRA station data. Kouloumpis et al. used different scenarios based on two different disposal practices as well as three different wind turbine capacity factors based on their on-site data (0.5%), the average of 5 similar studies (9%), and the maximum capacity in the literature (20.5%). The assessors used the CML2001 method to categorize the environmental impacts of the system. This study found that the Global Warming Potential (over 100 years) to be 2.92, 0.162, 0.0713, 2.27, 0.126, 0.0555 kg CO₂-eq per kWh for these scenarios.

As seen in these studies, only thirteen life cycle assessments of small-scale (6 kW or less) wind turbines have been conducted. In these existing studies, there is variability in the wind project impacts, ranging from 0.0007 to 2.92 kg of CO₂-eq per kWh. Only one study collected wind data from the site or at a potential height where a wind turbine would be installed. Many studies utilized wind atlas data at the height of 30 meters, which often provide very different wind data than at the height that a small-scale wind turbine would be installed (0-10 meters). Others used off-site wind data and still others assumed a wind speed without disclosing their methodology or reasoning.
This gap in the literature leaves room for a small-scale wind turbine LCA using measured wind speed data from potential installation sites. This study will be especially helpful at a higher education institution where researchers also have the opportunity to understand the educational, social, and community benefits of such a project beyond the financial elements.

1.4.2 NATURAL GAS LIFE CYCLE ASSESSMENT

Informed decisions regarding electrical generation require consideration its sources. For this study, the proposed wind turbine was compared to a natural gas combustion power plant, the most common electrical energy source in the United States and Pennsylvania (Figure 1). A review of recent LCAs of energy produced by natural gas combustion plants found a range of results in terms of Global Warming Potential (Figure 5). Almost all these impacts were higher than those produced by small-scale wind turbines.

O’Donoughue et al. (2014) reviewed hundreds of existing natural gas combustion facilities to determine a mean of 0.45 kg of CO$_2$-eq per kWh from a combined cycled system, which uses natural gas and steam to be more efficient than a traditional natural gas power plant. The review also determined a mean of 0.75 kg of CO$_2$-eq per kWh from traditional natural gas combustion turbines (O’Donoughue et al., 2014). Similarly, in a review of existing LCAs, Marashli et al. (2022) found that on average, natural gas facilities produce 0.502 kg CO$_2$-eq per kWh. Hertwich et al. (2015) found that natural gas power plants with combined cycle systems produce 0.247 kg CO$_2$-eq per kWh, while those without combined cycle systems produce 0.527 kg CO$_2$-eq per kWh. Hertwich et al. also found that natural gas facilities with combined cycle systems produce 0.000916 kg PM$_{10}$ per kWh while those without combined cycle systems produce 0.00757 kg PM$_{10}$ per kWh (Hertwich et al., 2015).
Figure 5: Box and Whisker Plot of Global Warming Potentials from horizontal axis wind turbines (HAWTs), vertical axis wind turbines (VAWTs), and Natural Gas Facilities. This figure cuts off two outliers (2.247 and 2.92) from the VAWT. An outlier is a value that is outside 1.5 times the Interquartile Range from the 25th or 75th percentiles.

1.5 EXPANDED LIFE CYCLE ASSESSMENT AT UNIVERSITIES

Life cycle assessments (LCAs) are meant to identify and analyze sources of emissions across a product’s life cycle, leaving room for further analysis of its social, educational, and reputational values. This study will use additional data to better understand these expanded benefits from a small-scale wind turbine at an urban university to help stakeholders judge project impacts more holistically. The National Renewable Energy Laboratory found that the most successful small-scale wind projects were those with goals beyond energy production (Fields et al., 2016). Filling this gap in the literature can help institutions across sectors achieve financial,
educational, and reputational goals, though these benefits most strongly align with those of universities.

Students and universities have often been the heart of social movements, with universities uniquely positioned to educate and lead young people to be future leaders. Young people have been critical to social movement formation and success ranging from rallying for civil rights, ending the use of sweatshops, divesting from institutions supporting apartheid, and supporting the Black Lives Matter movement (Earl et al., 2017). The environmental movement is no different. In 1990, 22 universities signed the Talloires Declaration, the first official statement by a coalition of universities, committing to sustainability in higher education – likely urged on by their students. Signatories agreed to a 10-point action plan to increase environmental education and literacy on campus. As of April 2023, over 500 universities have signed the Talloires Declaration (University Leaders for a Sustainable Future, 2015). In 1994, students at Yale University organized the Campus Earth Summit, which brought together students, faculty, and staff from campuses across the globe to work toward a sustainable future (Neves, 1994).

In 1997, the University of Kansas at Lawrence adopted the first university green fee ($1 per semester) to help fund campus environmental efforts (Bintliff, 2009). A green fee is a student fee that is collected regularly (e.g. per academic year, per semester). Funds are then awarded for campus environmental projects, such as renewable energy projects, energy-efficient light fixtures, or environmental speakers. As of April 2023, approximately 130 institutions in the United States have followed suit, charging small fees from students to further campus sustainability projects and goals (AASHE, 2023b).
More recently, university students have organized to demand that their universities divest from fossil fuels. Divesting fossil fuels is withdrawing one’s stocks from companies that extract fossil fuels or fund fossil fuel projects. Divestment is often paired with investments in renewable energy technology, companies, and stock (Global Fossil Fuel Divestment Commitments Database, 2021). According to the Global Fossil Fuel Divestment Commitments Database, 249 educational institutions have committed to divest from fossil fuels as of April 2023 (Global Fossil Fuel Divestment Database, 2023).

Higher educational institutions also respond to student demands for environmental action by publishing campus sustainability reports. In 2006, the Association for the Advancement of Sustainability in Higher Education (AASHE) created the Sustainability Tracking, Assessment, and Rating System (STARS) to better track university sustainability efforts. STARS is a self-reporting framework for universities, similar to private sector frameworks, such as the Global Reporting Initiative (GRI). As of April 2023, 1,148 higher education institutions have registered to use the STARS reporting tool, and 595 have earned a STARS rating. AASHE reviews and publishes the report and publicly awards the University a certificate based on performance; these results are posted on the AASHE STARS website, the Sierra Club’s Cool Schools List, and the Princeton Review’s Guide to Green Colleges. Other organizations rank universities and their programs on sustainability. Corporate Knights ranks business schools from around the globe on their sustainability work (Corporate Knights, 2022).

Leadership in social issues, research, community engagement, and other categories can give institutions a competitive edge in terms of attracting students as well as employees, as well as attracting funding opportunities. In addition, incoming, current, and past students increasingly
demand that their universities pursue sustainability and environmentally-friendly practices in their operations and curriculum (Menon & Suresh, 2020; Weiss & Barth, 2019). Therefore, universities have an opportunity to reduce emissions and improve their environmental practices to attract students and compete with other higher education institutions.

Universities can be considered a social entrepreneurship, “entrepreneurship with an embedded social purpose” (Christie & Honig, 2006; Peredo & Chrisman, 2006; Peredo & McLean, 2006). Social enterprises focus on the “social mission or the creation of social value” (Austin et al., 2006; Dorado, 2006; Nyssens, 2006; Peredo & McLean, 2006). Organizational identity is the shared perception of the organization’s central qualities and what the organization represents (Brickson, 2007; Dutton & Dukerich, 1991, 1994; Dyer & Whetten, 1991; Fiol, 1991, 2001, 2002; Foreman & Whetten, 2002). Social organization’s use both ideological and commercial elements to succeed (Miller & Wesley, 2010). Some institutions respond more to social and altruistic prompts, while others respond to more economic needs and profits (Foreman & Whetten, 2002). A 2010 review of over 100 successful social ventures found that all utilized both normative & utilitarian organizational missions (Moss et al., 2010). Triple bottom line theory offers expanded business metrics to include social, environmental, and economic well-being and has evolved into the integrated bottom line theory. Priorities are often referred to as the three P’s, people, planet, and prosperity, and are all connected. Institutions which only focus on economic prosperity do not account for their full costs to people and planet, and therefore will fail in the long-term (Elkington, 1994). In recent years, the triple bottom line has expanded into the integrated bottom line, which includes more innovation and systems-level thinking. Integrated bottom line theory quantifies how sustainability initiatives will drive productivity and
return on investment as well as incorporates sustainability into all business-level decisions (Sroufe, 2018).

Sustainability and green practices have been increasing across sectors in popularity for years. A number of meta-analyses of existing literature have shown a positive relationship between corporate environmental performance (CEP) and corporate financial performance (CFP) (Dixon-Fowler et al., 2013; Entrikat et al., 2014). Some studies determined that environmental efficiency is a “proxy” for operational efficiency; pollution represents wasted resources and unnecessary costs (Porter & Van Der Linde, 2017). Therefore, enhanced environmental performance represents innovation and efficiency (Aragón-Correa, 1998; Judge & Douglas, 1998; Klassen & Whybark, 1999; Russo & Fouts, 1997; Shrivastava, 1995). Other studies viewed environmental performance as a representation of managerial capabilities able to focus on both short- and long-term goals and strategy and therefore avoid risk (Aragón-Correa, 1998; Russo & Fouts, 1997; Sharma, 2000; Sharma & Vredenburg, 1998; Shrivastava, 1995). Other studies found that environmental performance enhances the organization’s reputation and could lead to increased sales and better employee recruitment (Russo & Fouts, 1997; Turban & Greening, 1997). LEED Certification, a green building certification, improves employee morale and retention, especially for female employees (Leland et al., 2015; von Paumgarten, 2003). Improved employee satisfaction can reduce absenteeism, turnover, tardiness, and grievances (Mirvis & Lawler, 1976). One study found that increasing job satisfaction by 0.5 standard deviation at a bank lead to direct-cost savings of $17,664 in absenteeism, turnover, and performance (Mirvis & Lawler, 1976). Additionally, green certifications like LEED can increase building’s property value. Certified facilities have higher rent prices while maintaining higher occupancy rates (Eichholtz et al., 2010; Sandoval & Prakash, 2016). Similarly, customers are
willing to pay higher prices for goods and services certified as environmentally friendly (Ward et al., 2011).

Universities, therefore, have a lot to gain by implementing sustainability plans and projects, integrating energy generation and environmental impacts into curriculum, investing in high-performance green buildings, and projects such as small-scale wind and other renewable energy. Demonstrating leadership in the green sector can amount to actual financial savings and gains, especially as universities tie sustainable investments to student, community, and religious missions. As universities continue to struggle with enrollment declines, sources of income, like tuition, grants, and major gifts, are more critical than ever (Berg et al., 2023).

1.5.1 DUQUESNE UNIVERSITY CASE STUDY: OPPORTUNITIES FOR HIGHER EDUCATION INSTITUTIONS

Universities and other higher education institutions contribute approximately 2% of the United States’ greenhouse gas emissions (Sinha et al., 2010). These higher education institutions function essentially as small cities and typically use energy mixes that reflect that of the region. However, with the majority of U.S. energy produced by fossil fuels, universities have much room for improvement.

Similarly, the majority of energy in Pennsylvania and Duquesne University is produced by combusting natural gas. Duquesne University used 45,115,964 kWh of electricity in the Fiscal Year 2021 (July 1, 2020, to June 30, 2021) generated primarily (29,593,643 kWh) by Clearway Energy Inc.’s Tri Generation on-site natural gas facility (Zuccolotto & Marks, 2022). Like many universities, Duquesne takes proactive steps to increase energy efficiency and reduce emissions. The natural gas facility is a cogeneration facility, using waste heat and energy from burning
natural gas for electricity to produce byproduct steam and hot/chilled water. The Tri Generation Facility has also earned the EPA’s Energy Star Combined Heat and Power Award for efficiency (Zuccolotto & Marks, 2022).

Furthermore, the University has a Power Purchase Agreement with Direct Energy Business, LLC, which purchases 16,590,500 kWh of Green-e certified renewable energy credits (RECs) per year (Zuccolotto & Marks, 2022). Renewable energy credits are a market-based instrument representing the rights to an environmental attribute of renewable energy generation (U.S. EPA, 2022). With a REC, the electricity is generated off-site, so an institution can claim the benefits of using renewable electricity without having physical energy projects on-site. These RECs lower Duquesne University’s ecological footprint; however, the Tri Generation facility still produced 41,562 Metric Tons of CO₂ equivalents (MT CO₂-eq) in Fiscal Year 2021 (Zuccolotto & Marks, 2022).

Duquesne University has an opportunity to transition to renewable energy to reduce emissions and honor its public commitments. In 2015, Duquesne University joined the Pittsburgh 2030 District, a collaboration of property owners, facility managers, and developers committed to reducing energy use, water use, and transportation emissions by 50% by 2030 as compared to national baselines (Green Building Alliance, 2023). In Duquesne’s most recent Institutional Master Plan, the University highlights 14.02% reductions in regard to energy reductions. No comments were made regarding water use and transportation emissions (Duquesne University, 2021). Duquesne University must take significant actions to meet all the committed goals by 2030.
1.6 HYPOTHESIS

This study aims to compare the energy produced by small-scale VAWTs in an urban environment to energy produced by a natural gas energy plant using the TRACI Impact Categories, though researchers will evaluate: global warming potential and particulate matter pollution (respiratory impacts). Researchers also propose a measure for a higher education institution's educational, leadership, and social benefits.

Researchers hypothesize that the life cycle assessment will show that energy produced by the small-scale wind turbine is associated with lower global warming potential and particulate matter pollution, and that energy produced by natural gas will be associated with lower economic cost. Researchers also hypothesize that the expanded life cycle assessment will show that energy produced by the small-scale wind turbine is associated with less health damage and provide social, educational, and leadership benefits.
CHAPTER 2: MATERIALS AND METHODS

2.1 ENERGY OUTPUT FROM WIND

To understand how much electricity the Nemi S turbine will produce at Duquesne University, researchers must understand the campus wind resources. For this project, two weather monitoring stations were installed at potential turbine installation sites on Bluff Street. The historic record shows that the majority of wind in this region comes from the south and west (Figure 6, 7) which is the direction the Bluff Street faces. Furthermore, elongated ridges perpendicular to dominant wind flow, like that of Bluff Street, optimizes accelerated wind flow (Olsen & Preus, 2015).

Figure 6: Weather Stations on the roof of Mellon Hall (left) and Towers Hall (right). Source: Google Earth.

Stations were established on the roof of Mellon Hall and the roof of Towers Hall (Figure 6, 8). The former monitored wind speed and direction (RM Young, Pittsburgh, PA USA), precipitation (Texas Electronics, Dallas, TX, USA), temperature and relative humidity (Campbell Scientific, Logan, UT, USA). The station was equipped with a Data Logger (Campbell Scientific, Logan, UT, USA) and solar panel (Campbell Scientific, Logan, UT, USA) with network capabilities. The latter monitored wind speed and direction, temperature, precipitation, relative humidity, vapor pressure, barometric pressure wind gust, solar radiation, lightning strike counter, and lightning strike distance. (ATMOS 41 All-In-One, Pullman, WA, USA) The Mellon and Towers stations were installed November 2021 and December 2021, respectively. Researchers collected data from the weather monitors between November 2021 and May 2023 (with a gap in the RM Young wind speed data from May – November 2022 due to a technical error). The following data was collected from both sites: temperature, wind speed, wind
direction, precipitation, and relative humidity. For this study, researchers focused on wind speed and direction.

![Weather Stations](image1.png) ![Weather Stations](image2.png)

Figure 8: Photograph by Mary K Ranii. (2022) Title: Weather Stations on the roof of Mellon Hall (left) and Towers Hall (right).

Researchers used the R programming language to create a directional wind rose and created a wind speed Weibull curve; typical parameters were reported to have a shape factor of approximately 1 and a scale factor of approximately 2 (Drew et al., 2015; Jowder, 2006; Khraiwish Dalabeeh, 2017; Ramenah & Tanougast, 2016; Seguro & Lambert, 2000; Stevens & Smulders, 1979). We then parameterized the Weibull Distribution by the Mellon and Towers datasets. The manufacturer power curve interpolation determined expected energy from the turbine over one year. Researchers also reviewed the average wind speeds from other weather stations in the area, and used the turbine’s power curve to determine energy output. These values were compared to the Mellon Hall and Towers Hall data as a sensitivity test.
2.2 LIFE CYCLE ANALYSIS OF WIND TURBINE

This study will utilize SimaPro software to conduct a life cycle assessment (LCA) of electricity produced by a 600-Watt Semtive Nemoi S vertical axis wind turbine using wind resources available at two locations at Duquesne University. These results will be compared to an LCA of electricity produced by a natural gas facility. This LCA will utilize the ISO 14044:2006 methodology for the LCA, which outlines specific requirements and guidelines for an LCA. This LCA will use the TRACI methodology for the life cycle impact assessment (LCIA) phase of the LCA as ISO 14044:2006 does not specify which methodology must be used for the LCIA. Study data will come from USLCI and EcoInvent v. 3 databases.

The boundaries of this LCA include material extraction, transportation, production, operation, and final disposal, with the specific boundaries outlined below. The functional unit for the study is 1 kWh of electrical energy produced.

2.2.1 SYSTEM DESCRIPTION: SMALL-SCALE WIND TURBINE

The first system will be a cradle-to-grave review of a hypothetical Nemoi S wind turbine installed on Mellon or Towers Hall at Duquesne University in Pittsburgh, Pennsylvania (Figure 9). This turbine is primarily comprised of aluminum, with small amounts of copper, and accompanied by cabling and an inverter (Semtive USA, 2022, 2023). This system includes a mast and foundation for the turbine. The expected life cycle of this wind turbine is 20 years in accordance with existing small-scale wind turbine LCAs (Table 2). This system will omit electricity transmission infrastructure to the end user as the turbine will be connected directly to point of use.
System boundaries for the wind turbine will include the following unit processes:

extraction, processing, and transportation of aluminum, copper, steel, concrete, cables, and a
transformer, turbine parts manufacturing, transportation to assembly site, transportation to installation site, operation, and final disposal.

The foreground data relating to the Nemoi S system include the weight and material makeup of the turbine, the location of turbine assembly, and the transportation distances and type (U.S. EPA, 2006). Foreground data relates to the specific LCA system and are identified by the LCA analyst based on the study scope and goal.

According to Semtive literature, the majority of the 45-kilogram turbine is aluminum with a small portion comprised of copper. Therefore, this study assumed the turbine is made of 44 kg of aluminum and 1 kg of copper. The blades of the turbine are formed of aluminum sheets, while the other components are formed from extruded aluminum. Researchers assumed the blades were comprised of 25 kilograms of aluminum, the other components were comprised of 19 kilograms of aluminum and 1 kilogram of copper components. This study utilized aluminum industry recycled content averages: aluminum sheets are comprised of 23.8% primary aluminum and 76.2% secondary aluminum (The Aluminum Association, 2022b, 2022a), while extruded aluminum is 40% primary and 60% is secondary. All copper was assumed to be primary (Table 3).

Raw materials are assumed to be shipped from the port of Houston to Semtive’s Austin, Texas facility via combination truck (275 kilometers). The turbine is assembled in Austin and then shipped to Duquesne University via combination truck (2,400 kilometers). The materials weigh approximately 75 kilograms and were converted into ton kilometers to allocate their impacts via mass (Table 3). Information regarding the turbine parts manufacturing were not available. As a replacement, this study will use the assumed electricity used by facilities to create such parts from a similar life cycle assessment of a small-scale wind turbine (158 MJ) (Wang &
Teah, 2017). This electricity is assumed to be produced by natural gas, the primary electricity source in the United States (U.S. EIA, 2023b).

Table 3: Materials and processes associated with the Nemoi S Wind Turbine and based on region of data. RNA: Region: North America. GLO: Region Global. RoW: Rest of World. Cut-off, S refers to the cut-off system model, meaning that all the upstream impacts are included in a single inventory. Under this system all impacts of recycled content are attributed to the first user (Eastern Research Group, 2023).

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
<th>Unit</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum, Cold rolling at plant/kg/RNA</td>
<td>5.95</td>
<td>kg</td>
<td>USLCI</td>
</tr>
<tr>
<td>Aluminum, secondary, rolled/RNA</td>
<td>19.05</td>
<td>kg</td>
<td>USLCI</td>
</tr>
<tr>
<td>Aluminum, primary, ingot, at plant/RNA</td>
<td>7.6</td>
<td>kg</td>
<td>USLCI</td>
</tr>
<tr>
<td>Aluminum, secondary, extruded/RNA</td>
<td>11.4</td>
<td>kg</td>
<td>USLCI</td>
</tr>
<tr>
<td>Copper {GLO}</td>
<td>market for</td>
<td>cut-off, S</td>
<td>1</td>
</tr>
<tr>
<td>Coll rolled sheet, steel, at plant/RNA</td>
<td>5</td>
<td>kg</td>
<td>USLCI</td>
</tr>
<tr>
<td>Concrete block {RoW}</td>
<td>market for concrete block</td>
<td>Cut-off, S</td>
<td>10</td>
</tr>
<tr>
<td>Cable, unspecified {GLO}</td>
<td>market for</td>
<td>Cut-off, S</td>
<td>5</td>
</tr>
<tr>
<td>Transformer, low voltage use {GLO}</td>
<td>market for</td>
<td>Cut-off, S</td>
<td>10</td>
</tr>
<tr>
<td>Assembly</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport, combination truck, average fuel mix</td>
<td>22.74</td>
<td>tkm</td>
<td>USLCI</td>
</tr>
<tr>
<td>Transport, combination truck, average fuel mix</td>
<td>198.42</td>
<td>tkm</td>
<td>USLCI</td>
</tr>
<tr>
<td>Electricity</td>
<td>158</td>
<td>MJ</td>
<td>USLCI</td>
</tr>
<tr>
<td>Durable goods, (waste scenario)</td>
<td>n/a</td>
<td>n/a</td>
<td>EcolInvent3</td>
</tr>
</tbody>
</table>

Wind data and the turbine’s power curve were used to determine the total energy output. Researchers combined Mellon and Towers wind data with the Nemoi S power curve to determine the amount of electrical energy generated over the course of a year. Semtive does not provide a detailed power curve, so we digitized the available power curve (Automeris) to provide power as a function of wind speed (Figure 11). We used a linear interpolation of the power curve to find the power output from the wind speed data. The turbine’s total impacts were then divided from the estimated energy production over 20 years to calculate the impact of 1 kWh (the functional unit). This system will not include electricity transmission infrastructure to the end user as the energy generation will be on campus.
Background data for this system includes unit process level data for extraction, processing, and transportation of all materials until they reach the Port of Houston. Background data references the industry as a whole and is made up of generalized data and is selected and customized by the LCA analyst (U.S. EPA, 2006). Background data also includes the unit process data for natural gas extraction, processing, transportation, and combustion at a North American natural gas facility for the 158 MJ of electricity required to manufacture turbine parts. The unit process data of disposal of durable goods in North America was used for all materials associated for this project. These data were available through the EcoInvent v. 3 and USLCI databases.

2.2.2 SYSTEM DESCRIPTION: NATURAL GAS FACILITY

The second LCA system will be a cradle-to-grave review of a natural gas facility using Marcellus Shale gas. This system includes natural gas extraction and processing, transportation via pipeline, and combustion. This system represents the most common electrical energy source in Pennsylvania and the United States (Figure 10). This system will not include electricity
transmission infrastructure to the end user as the energy generation will be on campus. This system will not include the construction of the natural gas facility, as those impacts are negligible relative to the study functional unit of 1 kWh (Scientific Applications International Corporation (SAIC), 2006). System boundaries include the following unit processes: Marcellus Shale natural gas extraction; transport via pipeline; and combustion for electricity. The input of concern for the facility is natural gas and the outputs of concern are CO$_2$-eq and PM$_{2.5}$-eq. The foreground data for the natural gas facility in the study is that the natural gas is from the Marcellus Shale, the most likely source of natural gas in the Pittsburgh region, as well as the gas’ transportation via pipeline, which is how Duquesne University receives its natural gas (M. Johnson, personal communication, December 18, 2022). The background data includes natural gas extraction, processing, transportation, and combustion at a natural gas facility match the North American averages for producing 1 kWh of electricity. All of these values are included in the USLCI values (Table 4).

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Amount</th>
<th>Unit</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas, Marcellus Shale</td>
<td>1</td>
<td>kWh</td>
<td>USLCI</td>
</tr>
</tbody>
</table>

2.3 HEALTH IMPACTS AND ASSOCIATED FINANCIAL IMPACTS

To determine the health impacts of the wind turbine and a natural gas facility to produce electricity, the researchers used the CO$_2$-eq and PM$_{2.5}$-eq emitted from each system per functional unit. We conducted a meta-analysis of health impacts from carbon dioxide and particulate matter pollution to determine the damage to human health in Disability Adjusted Life Years (DALYs) per functional unit, also known as the characterization factor. Researchers multiplied the pollutants by the range of categorization factors in the meta-analysis to find a
range of DALYs per kilogram of pollutant emitted by each electricity source. We then used Daroudi et al.’s (2021) values of the average cost per DALY averted in health care costs in a highly developed country - $649,999 per DALY averted. Researchers then multiplied the DALYs by the economic cost per DALY to determine the cost of each electricity source.

Researchers also used the social cost of carbon to further assess the financial effect on society. The social cost of carbon represents the costs of emitting one ton of carbon dioxide, ranging from floods to air pollution to climate change-related illness and deaths. Currently, the U.S. EPA has valued the social cost of carbon at $51 per ton of carbon dioxide emitted, however those numbers have changed several times over the recent years (Table 11). In 2022, the U.S. EPA has proposed increasing that number up to between $120 and $640 per ton of carbon dioxide emitted (U.S. EPA, 2022).

2.4 EXPANDED LIFE CYCLE ASSESSMENT

LCA methodology provides a number of useful impact levels; however, it does not include social, educational, economic, and reputational evaluation. In this project researchers investigated several aspects to understand and analyze those potential benefits.

2.4.1 RECRUITMENT AND RETENTION

A small-scale wind turbine can improve recruitment and retention for universities like Duquesne. Green certifications and rankings assist with student recruitment and retention. Specifically, a wind turbine would contribute to the most common certification and ranking systems, namely LEED and AASHE STARS. Minutolo and Ivanova (2020) found that each one-point increase on a higher education institution’s STARS sustainability report resulted in enrollment increases of 0.016 students per employee ± 0.0057. Researchers assumed that adding
an urban small-scale wind turbine would add 0.5 points to an AASHE STARS score as an Innovation Credit, as the best category for a new renewable energy project.

2.4.2 EDUCATIONAL OPPORTUNITIES

Researchers considered an on-campus wind turbine as a potential piece of laboratory equipment. We reviewed costs for common university laboratory equipment and compared these costs to the Nemoi S wind turbine. The common laboratory equipment reviewed included: a YSI Water Quality Testing Meter; a Deionized Water System; a Thermocycler for a PCR (polymerase chain reaction tests), and a Micropipette set of three.

2.4.3 REPUTATION AND LEADERSHIP OPPORTUNITIES

Sustainability projects such as renewable energy sources can improve institution’s reputation. Higher education is well positioned to take leadership roles in the investigation of novel technologies due to their research focus and can be early adopters if appropriate. Researchers conducted a meta-analysis to determine the variety of ways that a wind turbine could benefit a higher education institution like Duquesne University. This meta-analysis covered research and studies regarding the value of mission adherence, especially for religious institutions, and the value of honoring existing environmental commitments. For Catholic institutions such as Duquesne University, this adherence exists most specifically through Laudato Si’, Pope Francis’ 2015 encyclical which calls for the care of the natural environment and all people (Pope Francis, 2015). The wind turbine is used as a visible symbol of taking steps towards a more sustainable future, responding to campus and community needs, and honoring institutional commitments.
2.3.4 FINANCIAL OPPORTUNITIES
Researchers reviewed potential revenue to the higher education institution from increased enrollment and recruitment and green fees and comparison to other STEM lab equipment.

Researchers reviewed the Association for the Advancement of Sustainability in Higher Education (AASHE)'s Campus Sustainability Hub to determine the number of universities that utilize green fees and the amounts. Researchers used the tags “green fee” and “student fees” and reviewed all the submissions to find almost 140 universities in the United States that have implemented a student-funded green fee. Researchers used those with specific student fee values to calculate the average student green fee for an academic year. Researchers further broke down the higher education institutions with green fees into public and private categories.
CHAPTER 3: RESULTS AND DISCUSSION

3.1 WIND SPEED AND DIRECTION

Wind speed at Mellon Hall ranged from $2.00 \times 10^{-3}$ to 10.7 meters per second (m/s) and the mean wind speed was 2.26 m/s (Figure 12, Table 5) (November 2021 – May 2023). February had the highest monthly average wind speed in both 2022 and 2023, while December 2021 had the lowest monthly averages (Table 5). At Towers Hall, the wind speed ranged from $2.60 \times 10^{-1}$ to 11.3 m/s and the average monthly wind speed was 1.78 m/s (Figure 13, Table 6). February had the highest monthly average wind speed in both 2022 and 2023, while August had the lowest monthly averages (Table 6).

![Figure 12: A Weibull distribution of the frequency of average wind speeds in 15-minute intervals from November 2021 to April 2023 at Mellon Hall. Vertical line represents the arithmetic mean.](image)

Table 5: Mean monthly wind speeds with standard deviations from November 2021 to April 2023 at Mellon Hall.

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2021</td>
<td>n/a</td>
</tr>
<tr>
<td>December 2021</td>
<td>2.17 ± 1.40</td>
</tr>
<tr>
<td>January 2022</td>
<td>2.43 ± 1.43</td>
</tr>
<tr>
<td>February 2022</td>
<td>2.43 ± 1.31</td>
</tr>
<tr>
<td>March 2022</td>
<td>2.42 ± 1.68</td>
</tr>
<tr>
<td>April 2022</td>
<td>2.30 ± 1.42</td>
</tr>
<tr>
<td>Month</td>
<td>Average Wind Speed (m/s)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>December 2021</td>
<td>1.62 ± 0.91</td>
</tr>
<tr>
<td>January 2022</td>
<td>2.09 ± 1.40</td>
</tr>
<tr>
<td>February 2022</td>
<td>2.18 ± 1.25</td>
</tr>
<tr>
<td>March 2022</td>
<td>2.15 ± 1.45</td>
</tr>
<tr>
<td>April 2022</td>
<td>2.00 ± 1.19</td>
</tr>
<tr>
<td>May 2022</td>
<td>1.35 ± 0.66</td>
</tr>
<tr>
<td>June 2022</td>
<td>1.40 ± 0.70</td>
</tr>
<tr>
<td>July 2022</td>
<td>1.26 ± 0.64</td>
</tr>
<tr>
<td>August 2022</td>
<td>1.15 ± 0.56</td>
</tr>
<tr>
<td>September 2022</td>
<td>1.34 ± 0.79</td>
</tr>
<tr>
<td>October 2022</td>
<td>1.48 ± 0.94</td>
</tr>
<tr>
<td>November 2022</td>
<td>1.94 ± 1.30</td>
</tr>
<tr>
<td>December 2022</td>
<td>1.78 ± 1.15</td>
</tr>
<tr>
<td>January 2023</td>
<td>1.99 ± 1.16</td>
</tr>
</tbody>
</table>

Figure 13: A Weibull distribution of the frequency of average wind speeds in 15-minute intervals from December 2021 to April 2023 at Towers Hall. Vertical line represents the arithmetic mean.

Table 6: Average monthly wind speed and standard deviations from November 2021 to April 2023 at Towers Hall.
The 15-minute mean wind speed data was used to estimate the electrical energy output with the numerical power output curve from the manufacturer (Figure 14). Given the recorded wind speeds at Mellon Hall, the wind turbine will produce between 8.80 and 15.5 kWh monthly, with an average of 12.0 kWh per month. Over its 20-year lifetime, this wind turbine is expected to generate $2.88 \times 10^3$ kWh.

Given the recorded wind speeds at Towers Hall, the wind turbine will produce between 0.380 and 2.74 kWh per month, with an average of 1.29 kWh per month. The turbine will therefore produce 15.5 kWh each year and generate 310 kWh over the turbine’s expected 20-year lifetime.

Most of the wind originated from the west and southeast, though wind from all directions were recorded at Mellon Hall (Figure 15). This variable directionality supports the use of a vertical axis wind turbine at Mellon Hall to capture wind from all directions. At Towers Hall, the
wind originated from the northwest with small amounts originating from the east (Figure 16). The Towers Hall site includes a building to the north of the weather station, which is likely impacting the wind direction data. The constant wind directionality supports the use of a horizontal axis wind turbine so as to more efficiently capture the wind from its primary direction. The directions were different than other sites throughout the region such as Acrisure Stadium and the Pittsburgh International Airport (Figure 7), which both show primarily southern winds. These results further support the need for individualized on-site wind measurements before installing a small-scale wind turbine.

Figure 15: Wind rose depicting the wind speed and direction at Mellon Hall from November 2021 to April 2023.

Figure 16: Wind rose depicting the wind speed and direction at Towers Hall from December 2021 to April 2023.
Mean wind speeds at weather stations in the Greater Pittsburgh Area ranged from 0.565 m/s to 3.77 and would therefore produce between 0 and 18,300 kWh over a turbine’s life time (Table 7).

Table 7: Wind speed and potential energy produced at existing weather stations in the Greater Pittsburgh Area.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Wind Speed (m/s)</th>
<th>Energy Produced – 1 Month (kWh)</th>
<th>Energy Produced – 1 Year (kWh)</th>
<th>Energy Produced – 20 Years (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathedral of Learning</td>
<td>1.58</td>
<td>4.05</td>
<td>48.7</td>
<td>973</td>
</tr>
<tr>
<td>Acrisure Stadium (Heinz)</td>
<td>1.48</td>
<td>3.33</td>
<td>39.9</td>
<td>799</td>
</tr>
<tr>
<td>Falk School</td>
<td>1.05</td>
<td>1.35</td>
<td>16.2</td>
<td>323</td>
</tr>
<tr>
<td>Environmental Charter School</td>
<td>0.565</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Penn State Allegheny</td>
<td>1.10</td>
<td>1.41</td>
<td>17.0</td>
<td>339</td>
</tr>
<tr>
<td>Pittsburgh Airport</td>
<td>3.77</td>
<td>76.3</td>
<td>916</td>
<td>$1.83 \times 10^4$</td>
</tr>
<tr>
<td>Allegheny County Airport</td>
<td>3.74</td>
<td>72.1</td>
<td>866</td>
<td>$1.73 \times 10^4$</td>
</tr>
<tr>
<td>Liberty</td>
<td>2.38</td>
<td>14.5</td>
<td>174</td>
<td>$3.49 \times 10^5$</td>
</tr>
<tr>
<td>Lawrenceville</td>
<td>2.26</td>
<td>11.6</td>
<td>139</td>
<td>$2.79 \times 10^7$</td>
</tr>
<tr>
<td>North Braddock</td>
<td>1.59</td>
<td>4.08</td>
<td>49.0</td>
<td>979</td>
</tr>
<tr>
<td>Parkway East 1</td>
<td>1.63</td>
<td>4.18</td>
<td>50.2</td>
<td>$1.00 \times 10^3$</td>
</tr>
<tr>
<td>Parkway East 2</td>
<td>2.07</td>
<td>8.64</td>
<td>104</td>
<td>$2.07 \times 10^7$</td>
</tr>
</tbody>
</table>

3.2 LIFE CYCLE ASSESSMENT

Researchers collected life cycle assessment results in a number of categories, though will be focusing on Global Warming Potential (CO$_2$-eq) and Respiratory Effects (PM$_{2.5}$-eq).

Table 8: Impacts of electricity produced by wind turbine and natural gas.

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Unit</th>
<th>VAWT (Total)</th>
<th>VAWT/kWh (Mellon)</th>
<th>VAWT/kWh (Towers)</th>
<th>Nat. Gas/1 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone Depletion</td>
<td>kg CFC-11 eq</td>
<td>$4.71 \times 10^{-6}$</td>
<td>$1.64 \times 10^{-9}$</td>
<td>$1.52 \times 10^{-8}$</td>
<td>$5.15 \times 10^{-13}$</td>
</tr>
<tr>
<td>Global Warming</td>
<td>kg CO$_2$ eq</td>
<td>304</td>
<td>0.106</td>
<td>0.979</td>
<td>0.720</td>
</tr>
<tr>
<td>Smog</td>
<td>kg O$_3$ eq</td>
<td>35.7</td>
<td>$1.24 \times 10^{-2}$</td>
<td>0.115</td>
<td>$1.53 \times 10^{-2}$</td>
</tr>
<tr>
<td>Acidification</td>
<td>kg SO$_2$ eq</td>
<td>5.24</td>
<td>$1.82 \times 10^{-3}$</td>
<td>$1.69 \times 10^{-2}$</td>
<td>$6.13 \times 10^{-3}$</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>3.94</td>
<td>$1.37 \times 10^{-3}$</td>
<td>$1.27 \times 10^{-2}$</td>
<td>$5.97 \times 10^{-5}$</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>CTUH</td>
<td>$1.30 \times 10^{-4}$</td>
<td>$4.52 \times 10^{-8}$</td>
<td>$4.19 \times 10^{-7}$</td>
<td>$3.01 \times 10^{-9}$</td>
</tr>
<tr>
<td>Non Carcinogens</td>
<td>CTUH</td>
<td>$1.16 \times 10^{-3}$</td>
<td>$4.03 \times 10^{-7}$</td>
<td>$3.74 \times 10^{-6}$</td>
<td>$3.91 \times 10^{-8}$</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM$_{2.5}$ eq</td>
<td>0.582</td>
<td>$2.02 \times 10^{-4}$</td>
<td>$1.88 \times 10^{-3}$</td>
<td>$3.62 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
3.2.1 GLOBAL WARMING POTENTIAL

The wind turbine produced 0.126 kg of carbon dioxide equivalents (CO₂-eq) per kWh with Mellon Hall’s wind resources, while the natural gas plant produced 0.720 kg of CO₂-eq per kWh. The largest source of the turbine’s emissions was the materials, specifically the various types of aluminum and the associated electronics (i.e., the transformer and the cables) (Figures 17, 18).

Figure 17: Global Warming Potential emissions from wind turbine material production.
The literature varies regarding the impacts of carbon dioxide on human health (Table 9). The wind turbine at Mellon Hall will result in $1.17 \times 10^{-9}$ to $5.47 \times 10^{-3}$ DALYs per 1 kWh, while natural gas facility will result in $7.92 \times 10^{-9}$ to $1.30 \times 10^{-5}$ DALYs per functional unit. Each DALY represents negative impacts to human wellbeing and the economy. Every DALY represents $649,999$ lost due to health care expenditures and lost economic productivity in highly developed nations such as the United States (Daroudi et al., 2021). Per functional unit the wind turbine will cost between $7.60 \times 10^{-4}$ and $1.24$ while the natural gas facility will cost society between $5.15 \times 10^{-3}$ and $8.45$. While this is a significant increase for the natural gas, the large range of values does not allow the CO$_2$-eq DALYs to be a directly useful metric for comparison.

Table 9: Characterization factors of carbon dioxide equivalents in terms of Disability Adjusted Life Years (DALYs) per kg of pollutant emitted.

<table>
<thead>
<tr>
<th>Study</th>
<th>Characterization Factor (DALYs/kg CO$_2$ emitted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Schryver et al., 2009</td>
<td>$1.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Beyond healthcare costs, researchers used the social cost of carbon to determine the societal costs of the CO₂-eq emissions from the wind turbine and the natural gas facility. Using the April 2023 value of the social cost of carbon ($51 per ton of CO₂-eq), the wind turbine will cost $5.96 x 10⁻³ compared to the $3.63 x 10⁻² from the natural gas facility. As seen in Table 11, the federal government’s value of the social cost of carbon has changed over the last several years and is projected to change dramatically in the near future. Given the proposed values of $120, $190, and $640 per ton of carbon dioxide emitted, the financial benefit of the wind turbine could be as continues to grow (Table 11).

Overall, the small-scale vertical-axis wind turbine results in fewer CO₂-eq emissions than the natural gas facility. These reduced effects will mean fewer humans harmed as well as fewer financial resources lost on healthcare expenditures and other costs to society.
3.2.2 PARTICULATE MATTER POLLUTION

The vertical axis wind turbine will result in $2.02 \times 10^{-4}$ kg of PM$_{2.5}$ per kWh, while the natural gas facility will result in $3.62 \times 10^{-4}$ kg per functional unit. The largest source of these emissions were the materials were the turbine’s materials, with the largest sources of pollution being the associated electronics (i.e. the transformer and the cables).

Similar to CO$_2$-eq, the wind turbine produced fewer emissions than the natural gas facility. The literature varies regarding the impacts of PM$_{2.5}$ on human health (Table 12). The wind turbine will generate $1.24 \times 10^{-8}$ to $8.84 \times 10^{-7}$ DALYs per kWh while the natural gas facility will generate $2.21 \times 10^{-8}$ to $1.75 \times 10^{-6}$. Per functional unit the wind turbine will cost between $8.07 \times 10^{-3}$ to $0.64$ while the natural gas facility will cost society between $1.43 \times 10^{-2}$ to $1.14$.

Table 12: Characterization factors of PM$_{2.5}$ in terms of Disability Adjusted Life Years (DALYs) per kg emitted.

<table>
<thead>
<tr>
<th>Study</th>
<th>Characterization Factor (DALYs/kg PM$_{2.5}$ emitted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pop Density - Frischknecht et al., 2016</td>
<td>$4.87 \times 10^{-3}$</td>
</tr>
<tr>
<td>Low Pop Density - Frischknecht et al., 2016</td>
<td>$2.32 \times 10^{-4}$</td>
</tr>
<tr>
<td>van Zelm et al., 2016</td>
<td>$9.70 \times 10^{-5}$</td>
</tr>
<tr>
<td>Oberschelp et al., 2020</td>
<td>$6.50 \times 10^{-4}$</td>
</tr>
<tr>
<td>High Pop Density - Fantke et al., 2019</td>
<td>$9.85 \times 10^{-4}$</td>
</tr>
<tr>
<td>Low Pop Density - Fantke et al., 2019</td>
<td>$6.15 \times 10^{-5}$</td>
</tr>
<tr>
<td>Eckelman et al., 2018</td>
<td>$7.00 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Researchers found that energy produced by the small-scale vertical-axis wind turbine will results in fewer particulate matter emissions than energy produced by a natural gas facility.

These reduced impacts will mean fewer humans harmed as well as fewer financial resources lost on healthcare expenditures and lost economic productivity. These results are especially
meaningful in a region like Pittsburgh, where particulate pollution continues to pose a problem (American Lung Association, 2023).

Table 13: Cost in Disability Adjusted Life Years (DALYs) of pollutants emitted from energy sources.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>PM$_{2.5}$-eq Pollution</th>
<th>DALYs (Low)</th>
<th>DALYs (High)</th>
<th>Economic Cost (Low)</th>
<th>Economic Cost (High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine (Total)</td>
<td>0.582 kg PM$_{2.5}$</td>
<td>6.15 x 10$^{-5}$ (Characterization Factor)</td>
<td>4.87 x 10$^{-3}$ (Characterization Factor)</td>
<td>$649,999</td>
<td>$649,999</td>
</tr>
<tr>
<td>Turbine (Per Functional Unit)</td>
<td>2.02 x 10$^{-4}$ kg PM$_{2.5}$</td>
<td>3.58 x 10$^{-5}$</td>
<td>2.84 x 10$^{-3}$</td>
<td>$24.30</td>
<td>$1,850</td>
</tr>
<tr>
<td>Natural Gas Facility (Per Functional Unit)</td>
<td>3.62 x 10$^{-4}$ kg PM$_{2.5}$</td>
<td>2.21 x 10$^{-8}$</td>
<td>1.75 x 10$^{-6}$</td>
<td>$1.43 x 10^{-2}$</td>
<td>$1.14</td>
</tr>
</tbody>
</table>

3.2.3 FINANCIAL COSTS OF EMISSIONS

This study then compared the cost per kWh of energy from both the wind turbine, using resources from Mellon Hall, and a natural gas facility. The cost per kWh for the wind turbine is $1.25, while the average cost per kWh for the natural gas facility in Pennsylvania is $0.1273. When simply comparing the market cost of both of these electricity sources, the payback period for the wind turbine is 197 years. Given the initial cost of the turbine ($3,600), the lifetime electrical production of the turbine (2,877.16 kWh), and the cost per kWh of electricity in Pennsylvania ($0.1273), the return on investment (ROI) is 0.102.

Researchers found the cost per kWh for both energy sources and combined those with the current/median, high, and low costs of DALYs and the social cost of carbon from the emissions (Figures 19, 20). Wind electricity costs much more that produced by the natural gas facility. However, the natural gas electricity has higher associated health and societal costs. When using the higher characterization factor, the natural gas electricity can cost a lot more than the wind
electricity. These results support my hypothesis that electricity from the wind turbine is associated with lower health impacts.

![Figure 19](image1.png)

Figure 19: Cost per kWh of energy produced by a natural gas facility and wind turbine in terms of price, costs from DALYs, and social cost of carbon. Left graph shows the low characterization factors for each factor, center graph shows the current/median characterization factors, and the right graph shows the high characterization factors for each factor.

![Figure 20](image2.png)

Figure 20: Cost per kWh of energy produced by a natural gas facility and wind turbine in terms of price, and costs from DALYs and the social cost of carbon. Graph uses error bars to show the high and low characterization factors.
3.3 EXPANDED LIFE CYCLE ASSESSMENT

3.3.1 RECRUITMENT AND RETENTION

Sustainability initiatives and green projects, like wind turbines, can assist with student recruitment and retention goals. For years, university students have demanded environmental initiatives and commitments from their institutions. Even small sustainability projects can contribute to green certifications and speak to a university’s awareness of issues that matter to students.

A small-scale wind turbine can contribute towards green certifications and ranking systems. The Sierra Club and the Princeton Review use the Association for the Advancement of Sustainability in Higher Education (AASHE)’s Sustainability Tracking, Assessment, & Reporting System (STARS) campus sustainability report annually to rank universities. As of May 2023, 1,153 institutions have registered for STARS, though only 596 have received a rating of Reporter, Bronze, Silver, Gold, or Platinum (AASHE, 2023a). A recent review of higher education institutions showed a positive relationship between increased STARS campus sustainability report scores and endowments, enrollment, and environmental performance (Minutolo et al., 2020).

A small-scale wind turbine could result in up to 0.5 direct points for a STARS report through the Innovation & Leadership section and therefore result in 19.3 students ± 6.88 to Duquesne University’s campus enrollment. This increase represents between $565,752 and $1,225,125 in tuition (using Fall 2023 tuition cost at $47,146 and a Fall 2021 count of 2,414 employees). Larger institutions could stand to gain even more new students. Though additional students require additional campus resources, it is likely that they would provide more revenue than costs, especially at tuition-driven institutions like Duquesne University.
Once students matriculate, institutions must adequately serve their needs and demands to retain them, including offering campus green initiatives. The majority of undergraduate students typically support sustainability; in 2022, the Princeton Review surveyed 14,148 individuals as part of their annual College Hopes and Worries Survey (10,398 were college applicants and 3,750 were applicant parents). Most respondents (74%) said that an institution’s sustainability efforts would factor into their decision to apply to a school (Princeton Review, 2022).

Several specialties and majors, including medical, nursing, and business, specifically have demonstrated the demand for more environmental practices and education (Hampshire et al., 2021) found that the majority U.S. medical school students believe the “…climate change and its health effects should be included in the core medical school curriculum” (2021). The National League of Nursing has identified the need to educate all nursing students about environmental health (National League of Nursing, 2010). Some nursing organizations have already committed to addressing climate change and its impacts on human health (Mcdermott-Levy et al., 2019). Yale Center for Business and the Environment’s “Global Survey of Business Students” revealed that majority of students want: “more experiential learning focused on sustainability”, “more case studies highlighting sustainability issues”, and “better career services focused on sustainability jobs” (Cort et al., 2022). Having access to small-scale renewable projects, like an on-site wind turbine offers students the ability to learn about the public health, business, and environmental needs for distributed renewable energy projects. These hands-on and topical learning experiences can help recruit, retain, and serve more students.

### 3.3.2 EDUCATIONAL AND LEADERSHIP OPPORTUNITIES

Opportunities for laboratory and field experiences are expected by university students and their families. While the equipment to enable these experiences can be expensive, higher
education institutions consistently invest in these supplies as they see the value of applied education and research (Table 14). The Nemoi S wind turbine can function as laboratory equipment, able to provide students with educational opportunities regarding sustainability, renewable energy, return on investments, fluid mechanics, and more. Universities can use this installation as an example of how they will prepare students for a future that demands green energy.

Sustainability and renewable energy training are especially marketable in the current economy. The International Energy Agency (IEA) projects the world’s renewable energy capacity to expand by 2,400 gigawatts between 2022 and 2027 (U.S. EIA, 2023a). Globally, renewable energy jobs were approximately 12.7 million in 2021, an increase of 700,000 from 2020 – these numbers are projected to grow more in future years (International Renewable Energy Agency, 2022). By offering students the ability to study renewable energy projects they will be able to take advantage of this growing industry.

Table 14: Costs of laboratory equipment.

<table>
<thead>
<tr>
<th>Laboratory Equipment</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micropipette Set of 3</td>
<td>$1227.00</td>
</tr>
<tr>
<td>YSI Water Quality Testing Meter with Quatro Cable and Starter Probes</td>
<td>$1345.00</td>
</tr>
<tr>
<td>Medifuge Centrifuge</td>
<td>$3,110</td>
</tr>
<tr>
<td>Nemoi S Vertical Axis Wind Turbine</td>
<td>$3,600</td>
</tr>
<tr>
<td>Deionized Water System</td>
<td>$5055.00</td>
</tr>
<tr>
<td>Thermocycler for a PCR</td>
<td>$5960.00</td>
</tr>
<tr>
<td>Inductively Coupled Mass Plasma Spectrometer</td>
<td>$100,000</td>
</tr>
</tbody>
</table>

3.3.3 REPUTATION AND LEADERSHIP
Environmental projects, like renewable energy installations, can boost an institution’s reputation. Demonstrating leadership can be very important for a university’s many different stakeholders, including current and prospective students and families, boards, funding sources, alumni, accrediting bodies, and the local and global community. These stakeholders are concerned with sustainability and environmental issues, marking a need for universities to pursue green initiatives (Woodrow, 2006).

An institution’s mission statement communicates organizational values and priorities, and should “…motivate them to collaborate towards a cause and provides them with the opportunity to make a difference in the world” (Woodrow, 2006, p. 314). Institutional missions should also reflect the values of employees, and in the case of universities, students. As a social enterprise, higher education institutions have dual responsibilities to respond to workforce needs and market trends (Miller & Wesley, 2010; Moss et al., 2010). These dual missions can be beneficial to the organization’s bottom line. A 2010 review of over 100 successful social ventures found that all utilized both normative (altruism) and utilitarian (economic needs) organizational missions (Foreman & Whetten, 2002; Moss et al., 2010). Higher education institutions should therefore lean into a more social and ideological side of their missions.

Serving students and those outside the institution can help employees feel like they are contributing to and connecting with society at large (Clawson, 2021). Taking steps to invest in students and the community can motivate employees and improve workplace satisfaction. Improved employee satisfaction can reduce absenteeism, turnover, tardiness, and grievances, thus saving financial resources (Mirvis & Lawler, 1976).
Small-scale wind turbines or other environmentally friendly projects can be a step to honor existing environmental and social commitments. With 747 higher education institutions signing on to at least a portion of the University Presidents’ Climate Leadership Commitments as of April 2023, many institutions must take steps to honor at least some environmental commitments (Second Nature, 2023). Many institutions have also signed on to local commitments; for example, Duquesne University signed on to the Pittsburgh 2030 District, a collaboration of property owners, facility managers, and developers committed to reducing energy use, water use, and transportation emissions by 50 percent by 2030 (as compared to national baselines) (Green Building Alliance, 2023). In Duquesne University’s most recent Institutional Master Plan, the University highlights 14.0 percent reductions in regard to energy reductions, though no comments were made regarding water use and transportation emissions (Duquesne University, 2021) Renewable energy projects like a wind turbine, can signal that the University is invested in their future and health and is able to meet deliverables and goals.

3.3.4 FINANCIAL OPPORTUNITIES

Green practices have been increasing in popularity for years and show enormous opportunity for financial growth. Positive environmental performance can enhance an institution’s reputation, leading to increased sales (in the case of universities, fundraising) and improved employee recruitment (Russo & Fouts, 1997; Turban & Greening, 1997). Positive environmental performance has a positive and significant effect on corporate social responsibility, which both have a positive and significant effect on the firm’s value (Ratri & Dewi, 2017).

Meta-analyses of existing literature have shown a positive relationship between corporate environmental performance (CEP) and corporate financial performance (CFP) (Dixon-Fowler et
Environmental efficiency can be used as a “proxy” for operational efficiency; pollution represents wasted resources and unnecessary costs (Porter & Van Der Linde, 2017). Enhanced environmental performance therefore represents innovation and efficiency at an institution (Aragón-Correa, 1998; Judge & Douglas, 1998; Klassen & Whybark, 1999; Russo & Fouts, 1997; Shrivastava, 1995). Companies that use integrated bottom line theory are able to understand how sustainability initiatives like a renewable energy project can offer financial returns to a company (Sroufe, 2018). Environmental performance can also be viewed as a representation of managerial capabilities able to focus on short- and long-term goals and strategy (Aragón-Correa, 1998; Hart, 1995; Russo & Fouts, 1997; Sharma, 2000; Sharma & Vredenburg, 1998; Shrivastava, 1995). Higher education institutions can use even small environmental installations to demonstrate their foresight and business acumen.

Small-scale wind projects can be applied to an institution’s green certifications such as LEED Green Buildings, WELL certified buildings, AASHE STARS campus sustainability reports, and B Corp green business certifications (§ 3.1.1). In the private sector LEED certification has led to positive market reactions (Ivanova & Minutolo, 2018; Klassen & Whybark, 1999; von Paumgartten, 2003), and can increase building’s property value. Certified facilities have higher rent prices while maintaining higher occupancy rates (Eichholtz et al., 2010) and customers are willing to pay higher prices for environmentally certified goods and services (Ward et al., 2011). LEED Certifications also improves employee morale and retention, especially for female employees (Leland et al., 2015; von Paumgartten, 2003). Increasing job satisfaction can lead to thousands of dollars of direct-cost savings in absenteeism, turnover, and performance (Mirvis & Lawler, 1976).
These findings suggest universities with green certifications can increase tuition or fees while maintaining or even increasing enrollment. Projects like a small-scale wind turbine can lead to other financial and engagement opportunities. At many institutions, students and campus community members have demonstrated their willingness to pay for sustainable projects, like renewable energy installations, by self-imposing fees specifically for environmental initiatives.

Many universities harness the passion of their student body to further environmental campus projects through a green fee. A green fee is a regular fee charged to enrolled students that fund environmental projects on campus. Over 130 institutions have initiated a student green fee, ranging between $1 per year (University of Oregon, Eastern Mennonite University, and the University of Pittsburgh) to $100 per year (Prescott College) (AASHE, 2023b). A recent study at a small New York City private college, students were open to paying between $10 and $18 per semester (González-Ramírez et al., 2021).

Researchers reviewed all institutions with a green fee or fund on the AASHE website home and found 133 higher education institutions in the United States that collect a green fee on a regular basis from their student body. In academic year 2020-2021 there were 5,916 postsecondary Title IV institutions in the United States (National Center for Education Statistics, 2022). Some institutions did not disclose how much they charged their students. Of those that did the average of all institutions, excluding outliers, was $13.72 ± $10.17 with a median of $10. (Outliers were observations more than 1.5 times the Interquartile Range ($14) above the third quartile ($20).) The majority of the institutions that collected green fees were public universities (103) with the remaining being private higher education institutions (30). The states with the most institutions that collected green fees were: California (12), Colorado (9), Tennessee (7), and
Wisconsin (7). At Duquesne University, should students voted to initiate an annual green fee of $1, $10, or $15, the University would collect $8,128, $81,280, and $121,980, respectively.

Most green fees were enacted by the students through a ballot initiative through the university student government. Furthermore, most of these green fees are controlled by students, either in the form of the existing student government or a university sustainability committee which features students. Campus community members, including students, are then invited to apply for these funds to implement projects. These projects, such as renewable energy projects or efficiency projects, often have the benefit of shouldering the upfront cost of environmental installations, which often have long-term cost-savings, which the university is then able to enjoy. Students and other campus community members can be involved with real projects, fostering engagement and awareness of environmental issues and solutions.

At the University of Northern Colorado, students used funding from green fees to install a solar flower which will serve to generate electricity and educate the campus community about renewable energy (Corder, 2019). At Southern Illinois University, students used funding from green fees to install solar charging stations and explore wind turbine potential on campus (Southern Illinois University, 2023). At the College of William & Mary, students used funding from green fees to install a number of campus solar projects to generate renewable energy and educate students (College of William & Mary, 2023). Students are motivated to think creatively and strategically to improve the campus community and prepare them for a future that includes environmental awareness and protection.
CHAPTER 4: CONCLUSIONS

This LCA supported researchers’ hypothesis that energy produced by the small-scale vertical axis wind turbine was associated with lower global warming potential and particulate matter pollution than energy produced by a natural gas facility. The results also supported the hypothesis that renewable energy projects like a small-scale wind turbine are associated with improved enrollment and retention, valuable educational opportunities, leadership and adherence to organizational mission.

4.1 IMPORTANCE OF SITING

This study further supported the need for individual on-site wind speed and direction data to predict LCA and electricity generation accurately. Researchers saw very different wind speed and direction data at the Mellon Hall and Towers Hall Site, which are approximately 0.1 miles apart. These different wind resources resulted in different electricity generating potential and therefore different Global Warming Potential and Respiratory Effects per functional unit. This finding was further supported in the review of wind speeds and potential electricity production at the various weather stations in the Greater Pittsburgh Area. The wind speeds varied greatly from site to site, even those that are close together. As can be seen in § 1.4.1 Existing Wind LCAs, most studies used generalized wind data or wind data from several kilometers away. These results should be reviewed with caution, as they may not reflect actual wind resources.

4.2 WIND IS A CLEAR CARBON WINNER

Even with the lower wind speeds, the electrical energy produced from a small-scale wind turbine produced fewer CO₂-eq per unit than did the natural gas facility. The wind turbine with Mellon Hall’s wind resources produced fewer Respiratory Effects, Smog Forming Potential, and
Acidification Forming Potential than the natural gas facility. In all other categories, the natural
gas facility produced fewer pollutants and emissions. These results are not surprising as the wind
resources at Mellon Hall were not very high, with a mean of 2.26 m/s. Should future wind
turbines be installed on campus in areas with even slightly better wind resources, the wind
turbine would be a winner in more categories. Even so, few projects using the life cycle
assessment technique provide clear-cut winners and losers. Therefore, it is important to
understand the most important issues facing the region where the project is installed and the
values of the institution conducting the LCA.

4.3 VALUES & SOCIAL COST OF CARBON

The results of LCAs are intrinsically subjective; LCAs rely on interpretation from
assessors as well as the goals and values of an institution. These values can include regional
needs, such as Pittsburgh’s history with particulate matter air pollution or Baltimore’s attention
to eutrophication prevention. These values can also reflect an institution’s priorities, such as
becoming carbon-neutral by 2050. However, no decision exists in a vacuum, and assessors must
understand their audience.

The social cost of carbon has been changing for years and continues to be a source of
ethical debate. These debates stem from existential questions about the value a human life and
how society places different values on different human lives. This can be demonstrated in the
cost per DALY used in this study, which valued human health and lost earnings on the economic
prosperity of each country. Future studies should work to assess the social cost of carbon in a
more equitable way to better understand how different individuals and communities will be
harmed by the effects of climate change and pollution.
4.4 WATER USAGE

Future studies should also assess water use and pollution from both energy sources. Fossil fuel extraction and combustion as well as material extraction and processing use millions of gallons of water every year. For example, the average Marcellus Shale hydraulic fracturing gas well in Pennsylvania requires 2.9 million gallons of (Carter et al., 2011). There are over 13,774 unconventional wells in Pennsylvania alone (FracTracker, 2023). In the United States, thermoelectric plants were the largest source of water withdrawals at 133,000 million gallons per day in 2015 (Harris & Deihl, 2021). Most of this water was from freshwater surface sources (Dieter et al., 2018). Mining, refining, and other production uses large amounts of water as well. (Buxmann et al., 2016) found 18.2 m³ H₂O-eq per ton of global primary aluminum, and 9.6 m³ H₂O-eq per ton of global primary aluminum excluding China. Both processes have the potential to use a lot of water, which may be issues in water-scare areas.

Water scarcity can lead to both health and environmental issues. The World Health Organization (WHO) and the United Nations International Children’s Emergency Fund (UNICEF) report that 4 billion people experience severe water scarcity for at least part of the year (UNICEF, 2023). Water scarcity and the resulting impacts disproportionately face developing nations (Pfister et al., 2009). Water scarcity results in the degradation of environmental health, damaging ecosystems, reducing biodiversity, and leading to species loss.

4.5 STUDY LIMITATIONS

This project faced a number of limitations. Due to a technical error, researchers were not able to gather wind speed and direction data at Mellon Hall between June and October 2022. Therefore, we do not have a full calendar year of data at that site. Most of the existing wind
siting literature suggests assessing a potential site’s wind speed for at least one year. Ideally, this study would continue through October 2023 to gather at least a full calendar year’s data to better assess the site’s wind resources.

Another limitation was site availability. As this study was conducted on Duquesne University’s campus, researchers had to obtain permission to install weather stations. Researchers obtained permission to install the weather stations only at the Mellon Hall and Towers site. These locations are likely not those with the best campus wind resources.

4.6 FUTURE DIRECTIONS

Future research can build off of this study. As addressed in § 4.5, some study limitations should be addressed. Future research should collect wind data for at least one year to better assess the wind resources, as well as review other sites on campus. Potential locations include light and flag poles along Bluff Street and Rooney Field or closer to the Bluff Street side of Mellon Hall. However, future researchers should place weather stations where a wind turbine could potentially be installed. Future projects should review other Impact Categories as well as include the water intensity of both systems. Finally, researchers support the installation of small-scale wind turbines to truly understand electricity production as well as educational, leadership, and reputational benefits.
AASHE. (2023a). Sustainability Tracking, Assessment & Rating System: STARS Participants & Reports.


https://doi.org/10.1038/s41467-021-24487-w


https://doi.org/10.1016/J.JWEIA.2015.06.017

https://doi.org/10.1007/s11367-015-0997-1


https://doi.org/10.2139/ssrn.1281839


https://www.wm.edu/offices/sustainability/funding_opportunities/greenfee/index.php


Corporate Knights. (2022). Top 40 MBAs double down on commitments to sustainability.
https://www.corporateknights.com/education/top-40-mbas-double-down-on-commitments-to-sustainability/


Fantke, P., McKone, T. E., Tainio, M., Jolliet, O., Apte, J. S., Stylianou, K. S., Illner, N.,


https://doi.org/10.1016/J.RENENE.2009.06.016


https://doi.org/10.2307/256982

https://doi.org/10.1016/J.JCLEPRO.2019.119520


https://doi.org/10.1177/0891242415587526


https://nces.ed.gov/fastfacts/display.asp?id=1122

National League of Nursing. (2010). Outcomes and Competencies for Graduates of Practical/Vocational, Diploma, Associate Degree, Baccalaureate, Master’s Practice Doctorate, and Research Doctorate Programs in Nursing.

https://ydnhistorical.library.yale.edu/?a=d&d=YDN19940222-01.2.2&e=-------en-20--1--txt-txIN-------


https://doi.org/10.1021/acs.est.0c05691

https://doi.org/10.1111/jiec.12084
https://www.nrel.gov/docs/fy15osti/63696.pdf

https://doi.org/10.1016/J.ENBUILD.2007.12.004


https://doi.org/10.1016/J.ENPOL.2003.10.004


https://doi.org/10.2307/257052


https://doi.org/10.1002/eet.1724

https://nepis.epa.gov/Exe/ZyNET.exe/P1000L86.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2006+Thru+2010&Docs=&Query=&Time=&EndTime=&SearchMethod=1&ToggleRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C06thru10%5CTxt%5C00000002%5CP1000L86.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C- &MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL


https://doi.org/10.1029/2012JD018143


https://doi.org/10.2307/1556361


U.S. EIA. (2023c, April 27). Historical State Data.


Regionalized life cycle impact assessment of air pollution on the global scale: Damage to human health and vegetation. Atmospheric Environment, 134.
https://doi.org/10.1016/j.atmosenv.2016.03.044

Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. Environmental Research, 195, 110754.
https://doi.org/10.1016/J.ENVRES.2021.110754

https://doi.org/10.1108/14725960410808096

https://doi.org/10.1016/J.JCLEPRO.2016.09.128

https://doi.org/10.1016/J.ENECO.2011.02.003


Zuccolotto, G., & Marks, B. (2022). One Step at a Time: Duquesne University’s Ninth Greenhouse Gas Inventory. https://dsc.duq.edu/ghg-reports/1