# Fall 2022 Capstone Project
# Final Report

## Staying Ahead of Renewable Energy Curve
## And
## Analysis on Reusable Blades



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# Chapter 1. Introduction

## Project Overview

New York State is taking steps to combat climate change via comprehensive legislation. The historic Climate Leadership and Community Protection Act (Climate Act) requires New York State to achieve a 100% carbon-free electricity system by 2040 and to reduce greenhouse gas (GHG) emissions by 85%.

This would be possible by establishing a new standard for states and the nation to expedite the transition to a clean energy economy.

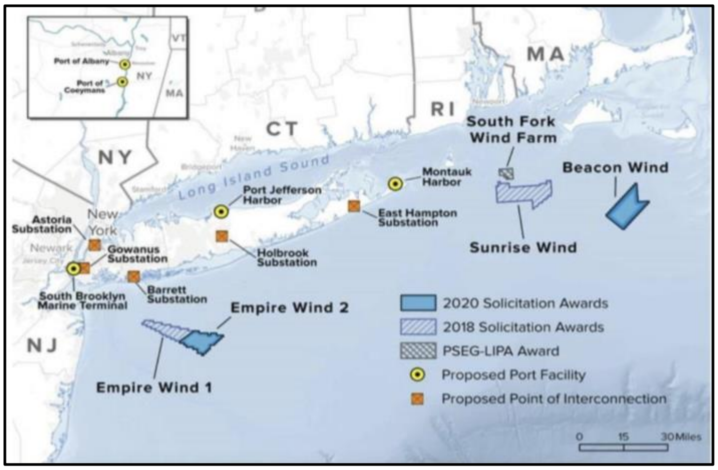



Fig.1. *NY State Offshore windmills planning and management mapping blueprint*

The law mandates that at least 70% of New York's electricity come from renewable energy sources by 2030 and calls for the development of 9,000 megawatts of offshore wind energy by 2035.

## Re-use of Wind Turbine Blade Research, NYC Town+Gown

Wind turbine blades are mainly composed of fiberglass, epoxy resin, balsa wood, and a handful of metals. Because of their composite structure and the high proportion of glass fiber reinforced polymer or carbon fiber reinforced polymer, the blades are among the most difficult components to reintegrate into material circularity. Therefore, our project is a proactive approach to finding more sustainable end-of-life alternatives compared to landfill and incineration. More specifically, we will focus on repurposing the blades.

## Project Scope and Goal

The project scope has two main pieces:

1) Identify turbine blade reuse options, while minimizing Greenhouse Gases (GHG) emissions
2) Develop a dynamic reporting dashboard for stakeholders

## Identify turbine blade reuse options

NYC Town+Gown has identified several locations that want to reuse wind turbine blades to improve their own facilities. While our direct stakeholder will be NYC Town+Gown, we will indirectly drive impact for the following by allocating retired turbine blades:

1) Public Parks
2) Modern Art Enthusiasts
3) Port Authorities
4) Fiberglass Manufacturers

We create two models to assist in finding reuse options:

1) Establishing Transportation Boundaries
2) Estimating Wind Blade Weights
3) Estimating GreenHouse Gases (GHG) Emissions

It is important to limit how far the wind blades are transported from its source, as transportation itself contributes to the overall GHG emissions emitted in decommissioning and reusing the wind blades. So, we use a greedy, exhaustive search on geographical data of landfills, finding the nearest landfill to each wind farm.

The weight of the blade is required to estimate the GHG emissions involved with transporting blades from project sites to stakeholders. It is difficult to find such data as no contractor makes it publicly available, so we will approximate the weight with approximations developed by other research papers.

Using that approximation, we feed data from The Wind Power into an XGBoost model that will predict rotor assembly weights for our NYC Turbine Data wind turbines, which the blade weight itself can be extracted from. Given our newfound boundaries and blade weights, we can use a known formula to model the GHG emissions.

## Develop a dynamic reporting dashboard for stakeholders

The dynamic dashboard will be developed in the second phase of our project. The dashboard, as suggested by NYC Town+Gown, would be used to report results descriptively and concisely.

We focus on using data descriptive analysis to develop this dashboard, utilizing various visualization techniques to track GHG emissions used for transportation of the decommissioned blades.

We develop heat maps, the primary data visualization technique to indicate the highly active greenhouse emitting regions in New York State and with their severity levels. As a result, we can identify the common areas that would be suitable for the stakeholders to focus on. Some potential uses for these wind blades can be recreational art pieces, benches, or small bridges in local parks, as mentioned above.

# Chapter 2. Data Collection

## 2.1. About the Dataset

Large-Scale Renewable Projects Reported by NYSERDA Beginning 2004

The dataset gives us all the existing and future wind farms in NY state starting in 2004 provided by New York State Energy Research and Development Authority (NYSERDA). The dataset has a well-defined structure with 33 columns and 228 rows. The dataset includes project names, geographic locations, different types of electricity quantity and capacity, contract duration, project status, year of delivery start date, etc. Our goal is to predict the decommission time of windmills with this dataset.

USGS Turbine Data

The dataset provides us with the location, project characteristics, and turbine characteristics of existing wind farms in the United States obtained directly from organizations, project developers and turbine manufacturers. The dataset has a well-defined structure with 27 columns and 72,357 rows. The dataset includes turbine manufacturer, turbine model, turbine capacity, etc. Our goal is to approximate greenhouse gas emissions to find the best repurposing location with low greenhouse gas emissions for transporting the blades with this dataset.

The Wind Power Data

This dataset is very similar to the USGS data, with the addition of rotor assembly weights. These features and ground truth rotor weights are used in the predictive model for rotor weight estimation in the USGS data.

New York Landfill Data

This dataset contains detailed information of landfills in New York. The locations of these landfills will be used to establish transportation boundaries for all wind farms in New York, explained in section 3.1.

New York State Park Data

This dataset contains detailed information of state park facilities in New York, which also includes historic sites, recreational trails, golf courses, boat launches, and etc. The locations of these sites will be used to identify potential reuse locations in New York, visualized in the interactive dashboard, explained in section 4.2.

## 2.2. Data Dictionary

*Large-Scale Renewable Projects Reported by NYSERDA Beginning 2004*

| Project Name | Renewable Technology | Project Status | Year of Delivery Start Date | Contract Duration | New Renewable Capacity (MW) | Bid Capacity (MW) | Bid Quantity (MWh) | Max Annual Contract Quantity (MWh) | Georeference |
|---|---|---|---|---|---|---|---|---|---|
| **Heritage Wind, LLC** | Land Based Wind | Under Development | 2023.0 | 20 | 147.0 | 147.0 | 393100.0 | 471720.0 | POINT (-78.208094 43.232126) |

| Column Name | Description | Data Type | Missing Value |
|---|---|---|---|
| **Renewable Technology** | The type of renewable energy technology for the project | String | 0 |
| **Project Status** | The phase the project is in as of the Data Through Date | String | 0 |
| **Year of Delivery Start Date** | Date NYSERDA's payments started or are expected to start | Float | 15 |
| **Contract Duration** | Number of years of performance under the Agreement | Integer | 0 |
| **Georeference** | Open Data/Socrata-generated geocoding information based on supplied address components | Point | 7 |

| Column Name | Description | Data Type | Non-missing Value |
|---|---|---|---|
| **case_id** | Unique uswtdb id | Long | 72357 |
| **t_state** | State where turbine is located | String | 72357 |
| **t_county** | County where turbine is located | String | 72357 |
| **p_name** | Project name | String | 72357 |
| **p_year** | Year project became operational | Integer | 71790 |
| **p_tnum** | Number of turbines in project | Integer | 72357 |
| **p_cap** | Project capacity (MW) | Double | 69270 |
| **t_manu** | Turbine original equipment manufacturer | String | 68111 |
| **t_model** | Turbine model | String | 67974 |
| **t_cap** | Turbine capacity (kW) | Integer | 68282 |
| **t_hh** | Turbine hub height (meters) | Double | 67785 |
| **t_rd** | Turbine rotor diameter (meters) | Double | 67844 |
| **t_rsa** | Turbine rotor swept area (meters$^2$) | Double | 67844 |

| Column Name | Description | Data Type | Non-missing Value |
|---|---|---|---|
| t_ttlh | Turbine total height - calculated (meters) | Double | 67785 |
| xlong | Longitude (decimal degrees - NAD 83 datum) | Double | 72357 |
| ylat | Latitude (decimal degrees - NAD 83 datum) | Double | 72357 |

We are only concerned about Renewable Technology with Land Based Wind and Offshore Wind.
We assume that the decommissioned year for turbine blades is the addition of the year of delivery start date and contract duration confirmed by NYSERDA. Therefore, we create a new column called decommission time, which is the combination of  the column year of delivery start date and the column contract duration.

*USGS Turbine Data*

| case_id | t_state | t_county | p_name | p_year | p_tnum | p_cap | t_manu | t_model | t_cap | t_hh | t_rd | t_rsa | t_ttlh | xlong | ylat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3075458 | NY | Chautauqua County | Arkwright Summit | 2018.0 | 36 | 78.4 | Vestas | V110-2.0 | 2200.0 | 95.0 | 110.0 | 9503.3 | 150.0 | -79.2097 | 42.382 |

We are only concerned about turbine blades located in New York State.


Fig.2. New York Wind Turbine Locations

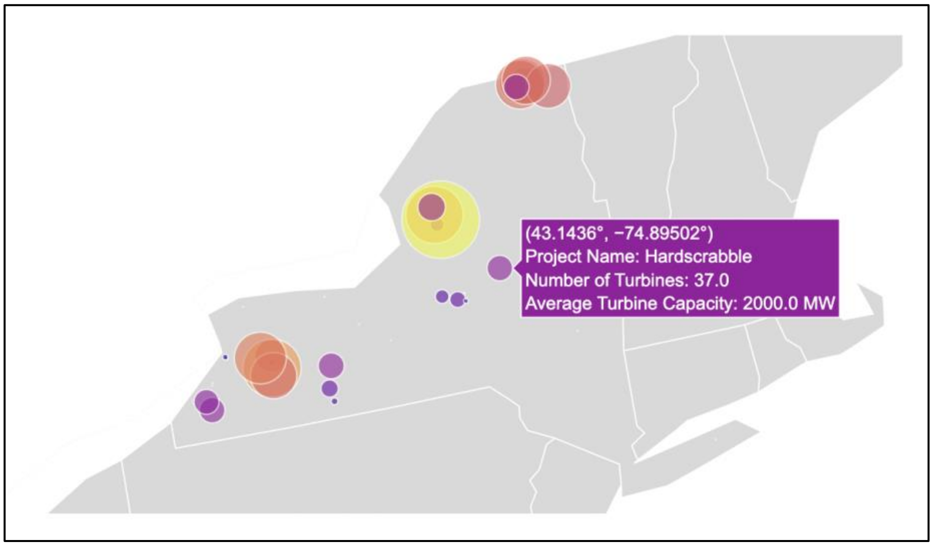



Fig.3. New York Wind Turbine Projects

*The Wind Power Data*

| Column Name | Description | Data Type |
|---|---|---|
| **Manufacturer** | Turbine original equipment manufacturer | String |
| **Rated power (kW)** | Turbine peak production power | Float |
| **Minimum hub height (m)** | Turbine minimum hub height | Float |
| **Maximum hub height (m)** | Turbine maximum hub height | Float |
| **Rotor diameter (m)** | Turbine rotor diameter | Float |
| **Swept area ($m^2$)** | Turbine area of rotor sweep during movement | Float |
| **Rotor weight (tons)** | Turbine rotor weight | Float |

Besides the rotor weight, each of these columns are also in the USGS data.

# Chapter 3. Modeling Approach

## 3.1 Establishing Transportation Boundaries

For each wind farm, we want to design a reuse plan for the turbine blades so that local and state government agencies can use them as resources to build public facilities, such as benches, bridges, and art statues.

Repurposing blades require minimum processing, so transporting them will contribute the most to the greenhouse gas (GHG) emissions. Additionally, the further the blades need to travel, the more GHG the reuse will emit. Since sustainability is our client's main concern, it is essential to establish a transportation boundary around each wind farm. If the GHG emissions from transporting the blades end up too large, it defeats our purpose to manage decommissioned blades in a sustainable manner.

Another key factor to consider is how decommissioned blades are processed currently. Since most of the blades have been grinded and sent to landfills, it is useful to incorporate landfill locations when identifying transportation boundaries.

Assuming that all landfills in New York state will accept turbine blades, we define the transportation boundary of a wind farm as the distance of its closest landfill. Leveraging a landfill facilities dataset, provided by New York State Open Data, we use a greedy, exhaustive search to find the landfill with the shortest driving distance from each wind farm.

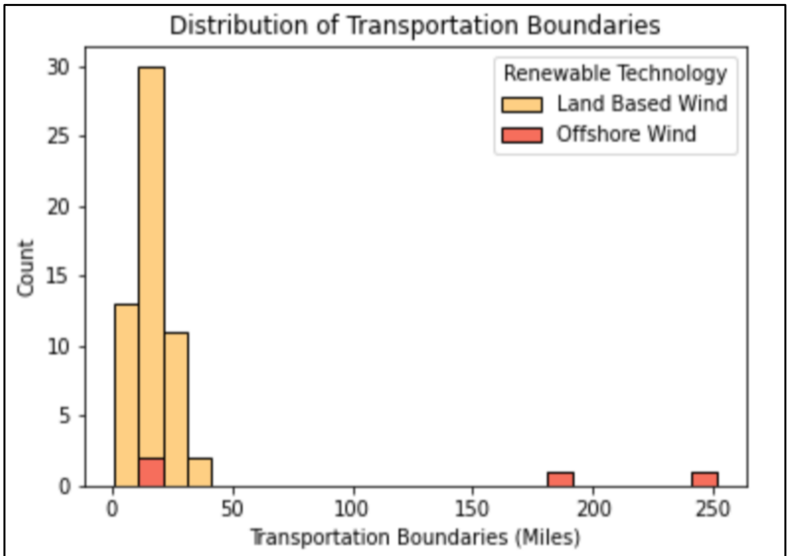



Fig.4. Distribution of transportation boundaries in miles

Fig.4. depicts the distribution of the transportation boundaries of all existing and future wind farms in New York. Offshore wind farms tend to have larger boundaries because they are located at the sea, far away from the landfills. Furthermore, all land based wind farms are less than 50 miles away from a landfill, reinforcing the idea to keep reuse of the blades local instead of sending them across the state.

## 3.2 Estimating Blade Weights

To estimate the greenhouse gas (GHG) emissions of transporting the blades from the wind farm to the repurposing location, the blade weights will be required in the GHG emission estimation formula. Unfortunately, blade weights are neither directly available in current datasets nor publicly shared by most manufacturers. Eggleston and Stoddard approximate that a singular turbine blade is about one-sixth of the weight of the entire rotor assembly. However, there is no public information on rotor assembly weight either.

We reached out to Michael Pierrot from The Wind Power, who gave us access to a database that has rotor assembly weights alongside other potential features. With the data from The Wind Power, we had enough information to make a regression model to predict rotor assembly weights for NYC turbine blades. This model will take in features such as the manufacturer, rated power, rotor diameter, or hub heights, and predict the rotor assembly weights, which will be used to approximate the blade weights with the metric discussed above. Features like this have a correlation to the rotor assembly weight. For instance, a larger hub height would indicate a larger rotor assembly weight. As a note, we can only use features that appear in both our USGS Turbine Data and The Wind Power databases (see Fig.5.).

We can only use columns that appear in the USGS data as predictors. Thus, we can use the following columns:

| The Wind Power Data | USGS Turbine Data |
|---|---|
| Manufucturer | t_manu |
| Rated power (kW) | t_cap (kW) |
| Minimum hub height (meters) ; Maximum hub height (meters) | t_hh (meters) |
| Rotor diameter (meters) | t_rd (meters) |
| Swept area (meters$^2$) | t_rsa (meters$^2$) |
| Minimum hub height (meters) ; Maximum hub height (meters) ; Rotor diameter (meters) | t_ttlh (meters) |
| Rotor weight (Tons) | **To be predicted** |

Fig.5. The Wind Power features matched to the USGS Turbine Data features

In creating our model, we had to be careful during the feature engineering stage. For instance, we had to be careful to only use the manufacturer as a predictor if the manufacturer appeared in both databases. If this feature was only available in one database, the manufacturer was marked as "Other." Since the data is available from over many years, we also had to be manually aware of mergers, such as Siemens and Gamesa merging into Siemens Gamesa.

We explored two different models, K-Nearest Neighbor and XGBoost to predict the rotor assembly weights in the USGS data. K-Nearest Neighbor was our baseline, as intuitively, it makes sense that we would want to match the NYC windmill to the closest similar windmill with an available rotor weight. However, this model did not perform as well as XGBoost. After some hyperparameter tuning, we found the optimal parameters of our XGBoost model to be 100 estimators, a learning rate of 0.1, a max depth of 3, and a max leaves of 0. We found the following metrics for final evaluation (see Fig.6.).

| | Metric (tons) | Train | Test |
|---|---|---|---|
| 0 | mean_absolute_error | 3.178986 | 4.890546 |
| 1 | mean_squared_error | 30.099500 | 75.422166 |
| 2 | median_absolute_error | 1.709862 | 2.475006 |

Fig.6. XGBoost metrics for train and test data

We chose to minimize the mean squared error as it is most important to penalize large misses, since these can have a more detrimental real-world impact. Mean absolute error is interpretable for users like NYSERDA and other non-technical audiences. Median absolute error reassures our mean absolute error, as it helps us see that the larger mean absolute error is pulled by some larger residuals. Fig.10 below depicts the distribution of predicted blade weights.

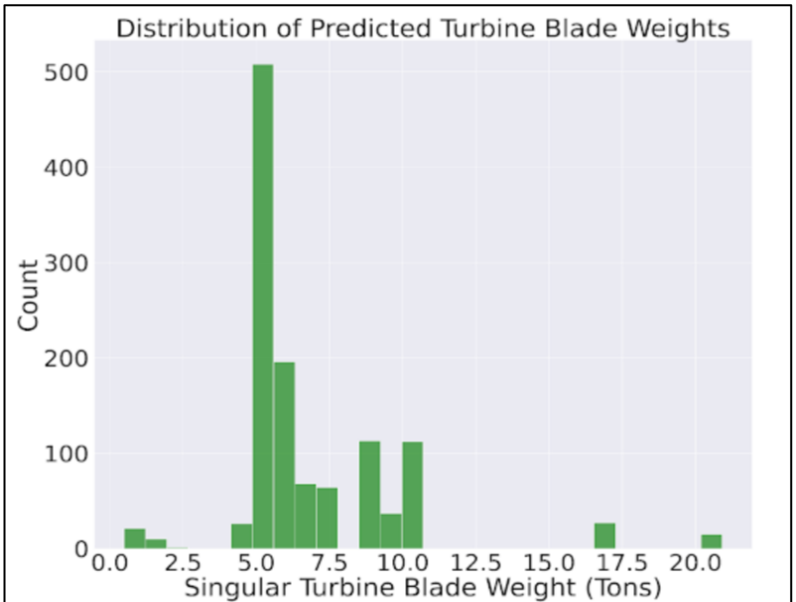



Fig.10. Distribution of transportation boundaries in miles

## 3.3 Estimating Transport Emissions

To help our client compare environmental costs between other end-of-life options and the reuse of turbine blades, we develop a model to estimate the greenhouse gas (GHG) emissions of reuse. As previously stated, given the size and the weight of these turbine blades, most of the environmental cost will come from transportation. Thus, we specifically model the GHG emissions from transporting a blade from its wind farm site to a potential reuse destination.

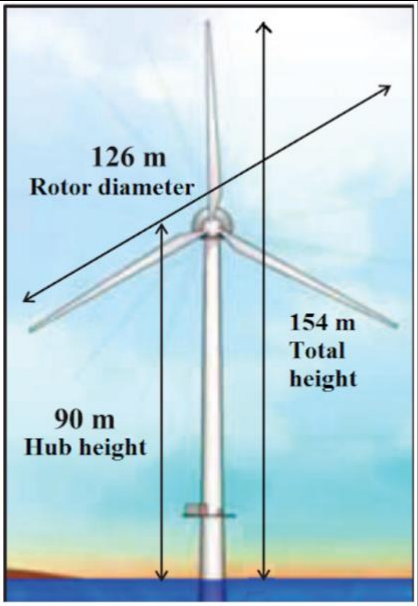


Fig.7. Wind turbine structure

We assume that any relevant origin and destination can be expressed in terms of latitude and longitude. Finding the travel distance between two locations is not a novel problem; several commercial and open source solutions already exist. Initially, we attempted to use open street maps, however, there were several issues. To keep our work self-contained, we attempted to download the relevant New York state data. Unfortunately, loading the data into Python led to memory issues. Thus, the next best option was to make REST API calls, so we only process the relevant data in each run. Open Street Maps gives free keys; however, when we share the code online, we would not want to share private API keys. Thus, we moved to another solution: Open Source Routing Machine (OSRM). This allows us to make API calls without using a private key. Using OSRM, we can estimate travel distance and driving time.

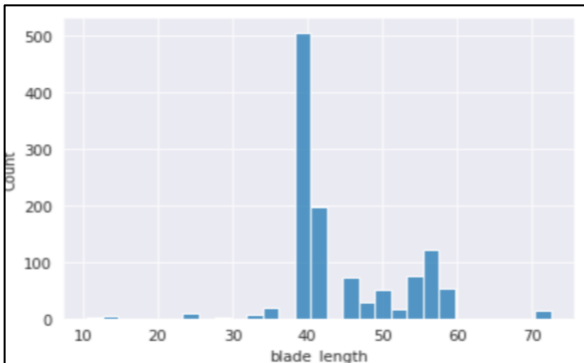


Fig.8. Distribution of approximated blade length

Next, we must consider the size and weights of the turbine blades. In section 3.3, we will discuss how we approximate the weights. Regarding blade size, the USGS dataset does not include any information about rotor length. However, we do have rotor diameter, hub height, and total height. Given these measurements, we can try to approximate turbine length in two ways. First, we can argue that the turbine length is half the rotor diameter as seen in Fig.7. Another valid option would be to subtract the hub height from the windmill total height. After experimenting with both methods, we found that the difference between the two were negligible. Ultimately, we chose the first method because it is slightly more intuitive than the latter.

After calculating the blade lengths, we analyzed the distribution and found it had a mean of **44.135**, with a significant number of blades being over 50 meters long. For the sake of the project, we can assume that the turbine blades will be cut when they are taken off the windmill on-site. As per a meeting with NYSERDA representatives, this is a fair assumption. It follows that we may need three to five flatbeds for transport. So, when calculating the emissions, we will have to consider one truck and then multiply by the number of necessary flatbeds.

Given all these details, we are finally ready to calculate GHG emissions using the emissions factor of a flatbed. The formula to calculate GHG emissions = *Distance * Weight * Emissions Factor*.

We have the distance from the windmill origin to its destination, calculated using ORSM API calls. Additionally, we have already estimated the weight of the blades in 4.1. An emission factor describes the rate at which a given activity releases greenhouse gas into the atmosphere. The emissions factor for the flatbed is 161.8. To decide how many flatbeds are necessary, we divide the blade length by the size of a flatbed, then multiply that by the number of windmill blades for transport. Inputting these variables into the above equation, we are able to estimate the GHG emissions.

Since there are no ground truth answers on what the real GHG emissions are, there are no available metrics to test its accuracy. We would rely on environmental scientists to verify if these are reasonable estimations. Below, there is a screenshot of the frontend result of our GHG emission predictor. In the backend, we have already predicted the blade weights from the farm. The frontend offers the user the choice to input a wind project and a landfill as well as an amount of flatbeds and dimensions. With this information, distance to travel and weight of the blades from the wind farm are calculated, so we can make an estimate of the GHG emissions, offered back to the user.

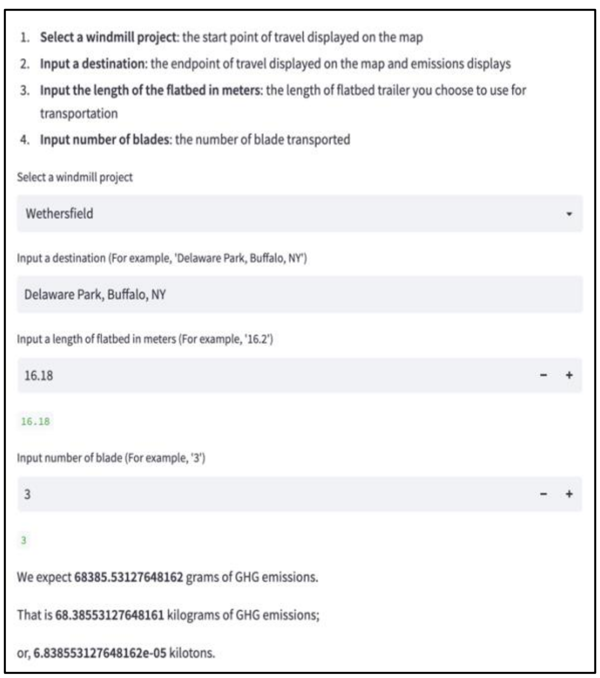



Fig.11. GHG Emissions Calculator

# Chapter 4. Interactive Geographical Dashboard

## 4.1 Develop Interactive Dashboard

To help nontechnical audiences visualize our work and results, we develop a dynamic geographical dashboard with folium packages. The dashboard contains three different maps, each carrying out a different function (see Fig.9.).

The first map plots the locations of windmill projects in New York, including existing projects from the USGS dataset and future under-development ones from the NYSERDA dataset.

The second map is powered by our GHG emissions calculator, previously explained in section 3.3. To compute the total GHG emissions to transport one blade, we use this following formula: Total GHG emissions = GHG emissions of one truck * number of trucks.

The GHG emissions of one truck can be further dissected into 3 factors multiplied together: distance, weight, and emission factor. The distance is between the wind farm location and the repurposing destination. Users of the dashboard can select the origin from a list of wind farm projects and enter the reuse destination. The blade weights are then estimated with the best performing XGboost model, described in section 2.2. Lastly, the emission factor of a flatbed is 161.8, as stated in section

The number of trucks needed are determined by turbine blade length, length of flatbed, and the number of turbine blades for transportation. Users can customize the number of blades and length of flatbed so our calculator will determine how many flatbeds are needed.

Lastly, the third map identifies potential reuse locations within the GHG radii described in section 2.1. We include New York State Parks for park facilities and NYS Thruway Authority for sound barriers as main reuse locations on the map. After selecting a specific windmill project, users can see potential reuse locations within the GHG radius, serving as a good starting point to design a repurposing plan.

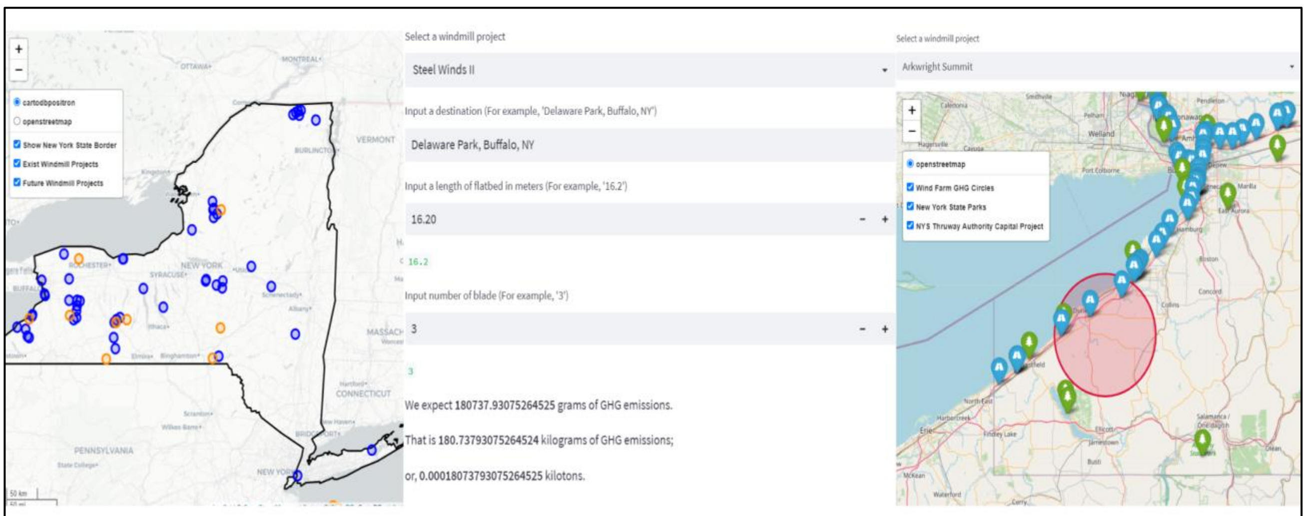



Fig.9. NY wind turbine map (left), GHG emissions calculator (middle), reuse locations within GHG circles (right)

## 4.2 Implement and host project web application

In addition to the interactive dashboard, we have implemented the project web application to summarize our findings and host links to the interactive dashboards, discussed in 4.1. In the future, it will be convenient for the client to showcase our research to a nontechnical audience.

Furthermore, recognizing the data security and our machine learning code vulnerability, we hosted the developed web application on Amazon Web Services. We used the Amazon S3 bucket for our cloud storage and Amazon Amplify service to build the CI/CD pipeline for the hosting and versioning of the web application.

Cloud Service Providers are determined to provide scalability, durability, and robustness while productionizing the web application. With the academic credit voucher provided by our academic mentor, we created and stored S3 objects across multiple systems.

To provide easy access to the web application, we published it to fit all screen devices. However, since it costs $3 per hour for the server to run, we temporarily rolled back the deployment on Amazon S3. Currently, we host our website on GitHub Pages under MIT License to save the cost.

The website is friendly to both tablet and laptop users, and Fig.12 are three screenshots of the website:

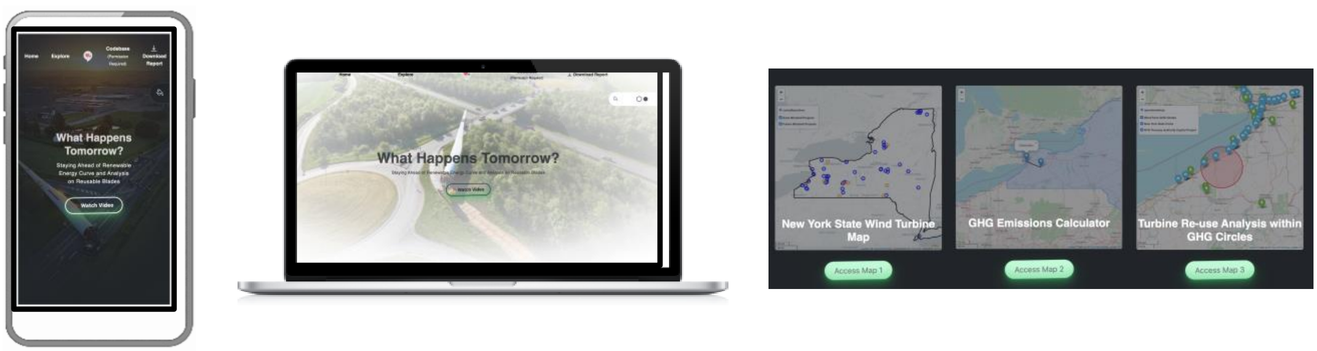



Fig.12. Web application screenshots

# Chapter 5. Discussing Ethics

Moving forward with this project, there are a few future ethical challenges to consider. The reuse of decommissioned blades requires some types of cutting and processing, which produces dust and particles in the air. It can be a potential environmental hazard if the dust is toxic to people and animals, and further research should be conducted.

Additionally, the reuse of decommissioned blades will create a new labor market. It is important to ensure that workers will be treated fairly. Furthermore, the issue of how this new labor market will impact existing workers in waste management facilities should also be addressed.

# Chapter 6. Conclusions and Future Improvements

In this project, we developed a plan to support future reuse of decommissioned blades, a much more sustainable end-of-life option to manage the blades. We also designed a geographical reuse model to minimize the additional GreenHouse Gas emissions from transporting the blades.

More specifically, we established transportation boundaries of decommissioned blades around wind farms, identified potential reuse locations within the transportation boundaries, and lastly estimated the GHG. To help non-technical audiences understand the results, we developed a geographical dashboard and web application.

During the modeling phase, we made a few assumptions, and it is important for future teams to revise the assumptions when more information is available. One of the assumptions is that all landfills will accept decommissioned turbine blades, which might not hold true as waste management policies evolve. We also assume a linear relationship between blade weight and rotor assembly mass. However, as new models of turbines roll out, the relationship will not hold exactly. Lastly, we assume all the decommissioned blades will be transported by trucks. Future offshore farms will require a more complicated transportation model when estimating GreenHouse Gas emissions.

In the future, it is key to inform stakeholders about the term “repurposing.” The distinction between decommissioning wind blades to landfills and reusing the wind blades in more eco-friendly options is crucial to getting these stakeholders on board with the repurposing of blades. Additionally, making this project accessible to the public will spread awareness of how important it is to reuse blades. Involving environmental and civil engineers in this will also progress this idea moving forward, as their understanding of the ideology behind transporting wind turbine blades will make them more inclined to prioritize this project. NYC Town+Gown can also hold workshops and events to raise awareness for wind blade reuse. Overall, we are looking for opportunities over current limitations, and with our work we have made a path for further progression in the reuse and repurposing of wind blades.

# Chapter 7. References

Below are all the resources the team has used and based their domain research on:


- URR 7 Recording: New Frontier for Construction Materials
- Material Composition of Wind Turbines
- Environmental Analysis of End-of-Life Alternatives for Wind Turbine Blades
- An Integrated Geospatial Approach for Repurposing Wind Turbine Blades
- New York State Energy Research and Development Authority
- NYSERDA: Offshore Wind
- Construction Begins on New York's First Offshore Wind Farm
- An integrated geospatial approach for repurposing wind turbine blades
- Wind Turbine Blade Material in the United States: 2 Quantities, Costs, and End-of-Life Options
- Wind turbine blade waste in 2050
- NYS Thruway Authority
- NYS Thruway Authority Noise Policy
- NYS Thruway Authority Capital Programs
- Wind Turbine Engineering Design


### Data Sources


- **Large-scale_Renewable_Projects_Reported_by_NYSERDA__Beginning_2004:**
  Large-scale Renewable Projects Reported by NYSERDA: Beginning 2004
- **USGS_data:**
  United States Wind Turbine Database
- **New York Landfill Facilities**
  NY Open Data: Landfill Facilities
- **New York State Park Facilities**
  NY Open Data: State Park Facilities
- **The Wind Power Project**
  The Wind Power

# Appendix

During the domain research project, the team had tried to implement their data science model and finding into the web-based application which can be accessed through any digital device (be it any mobile or personal computer) using the following two methods:

1) Scanning this QR code to access the web application

(Using Google Lens or Camera on your mobile will take you to web application)

2) Typing or clicking this link directly on any web browser

[https://virslaan.github.io/Wind-Turbine-Blades-CUCP/](https://virslaan.github.io/Wind-Turbine-Blades-CUCP/)

## Technologies used in our whole project :

**GitHub:** For Storing Python Scripts and Hosting Web Application

**Machine Learning and Data Science Implementation:** For Domain Research and Building Models

**Frameworks and Programming :** Python, HTML5, CSS, Bootstrap & Streamlit

## Exploring the Web Application:

In this appendix section we would walk through the basics of using our web application

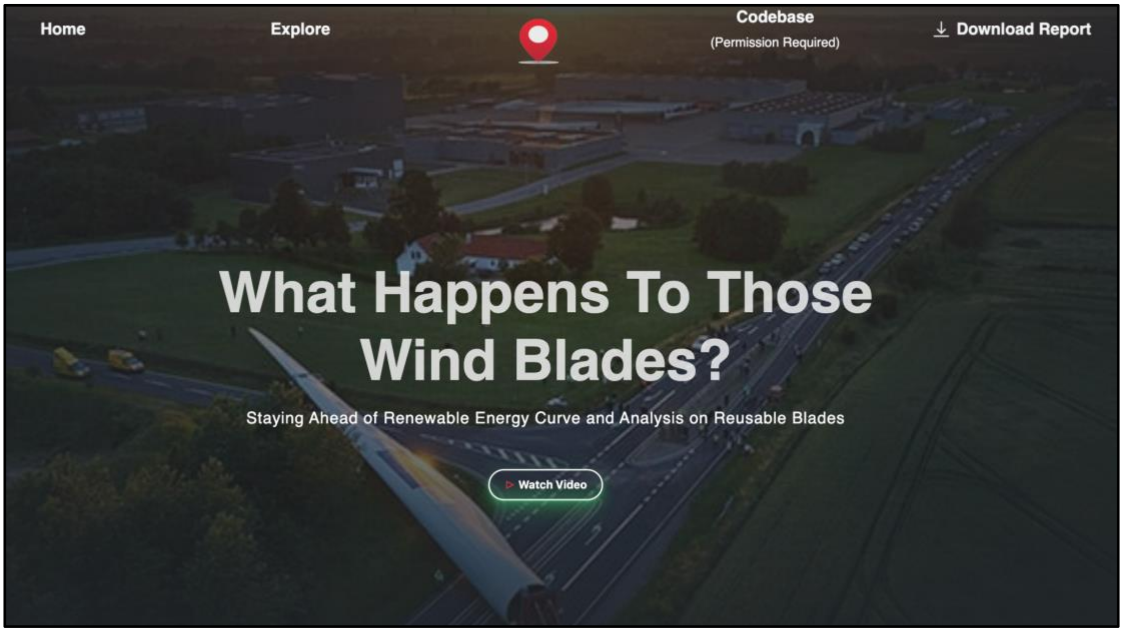



Figure a) Landing Page through personal computers

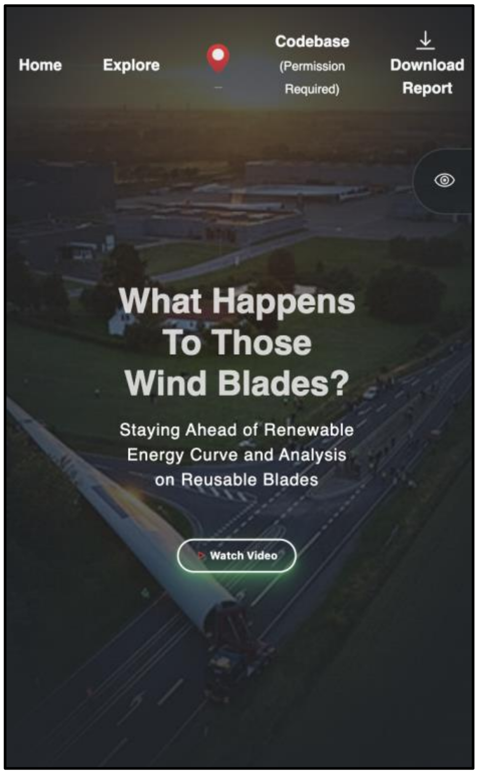
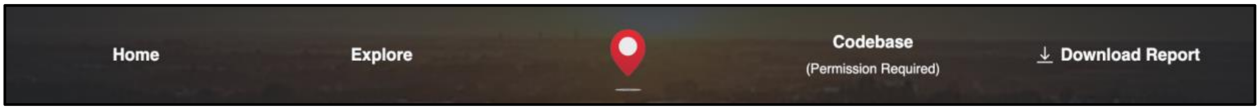



Figure b) Landing page through mobile devices




**Home Tab:** Takes the user to the landing if you are scrolling way down the application
**Explore Tab:** Indicates the tools that can be accessed by the team
**Icon:** Takes the user to interactive dashboard with tools made with data science and our domain research
**Codebase Tab:** This tab is exclusive and would not open anything until you have permission from our team to access the development code
**Download Report Tab:** This Tab directly exports a pdf version of files onto your device

Below are the figures indicating the type of screen the user would see as he scrolls through the web application:

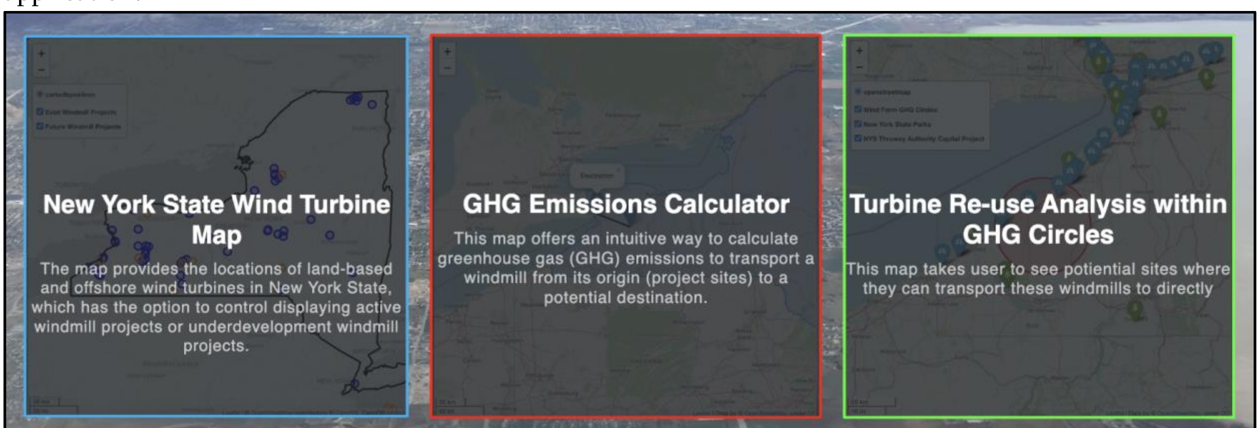



Figure c) Shows the tools section on web application that opens as the user clicks on Explore Tab

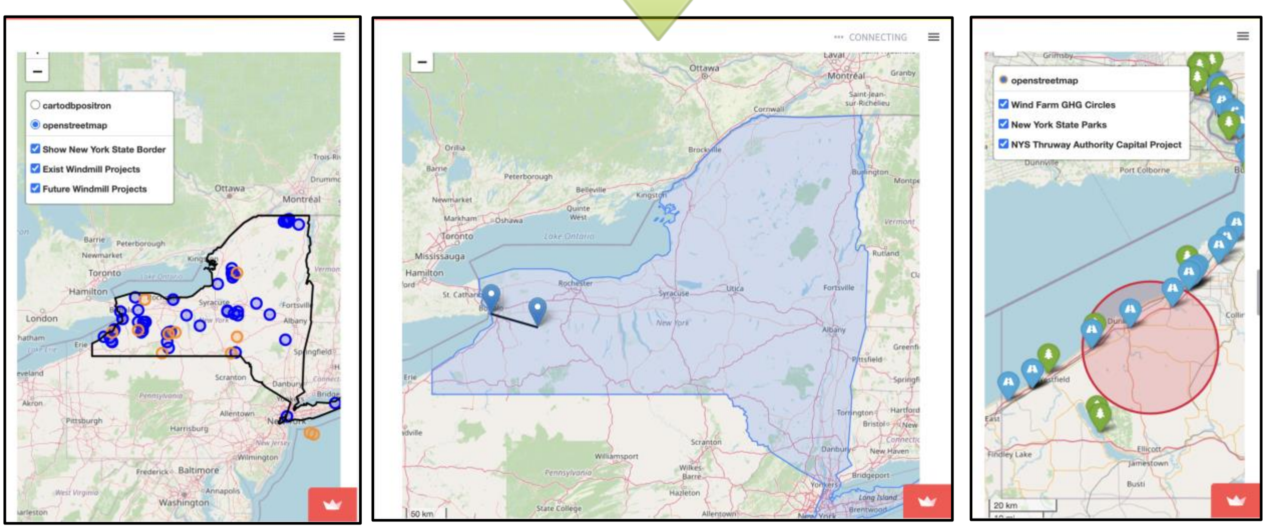



Figure d) Shows the tools section on web application that opens as the user clicks on Icon Tab