IN-CITY WIND: MAPPING WIND ENERGY POTENTIAL WITHIN THE FIVE BOROUGHS

ABSTRACT

At least three well-documented in-city wind turbine projects have been installed in NYC. Distinct from the large offshore wind instillations now under development near NYC, these involve comparatively smaller equipment that harness the wind resource available within the built environment. Yet an analysis of local windspeeds and of candidate locations for turbines on building rooftops and waterfront lots indicates that there is limited potential for large-scale deployment of this technology to contribute to NYC's energy transition. Under optimistic assumptions, it is estimated that roof-mounted turbines on tall buildings could achieve satisfactory performance and could meet up to 0.57% of NYC's current annual electricity demand. However, when the analysis accounted for the possibility that actual windspeeds across the city are lower than the windspeeds initially assumed, as observed at a Manhattan weather station, it found that the rooftop turbine potential is greatly reduced. The analysis found that turbines on shorter waterfront buildings likely could not achieve satisfactory performance even under optimistic assumptions, and they could meet at most 0.05% of NYC's electricity demand. Additionally, the model calculated that ground-mounted turbines in waterfront lots could achieve reasonable performance if appropriately sited, but the number of candidate-lots is limited. Results found that ground-mounted turbines could only provide up to 0.11% of NYC demand, and most lots would be able to generate more electricity if they installed solar PV instead.

RESEARCH AREA OVERVIEW AND OBJECTIVE

Local Law 104 of 2018 (LL104) requires the Mayor's Office to perform an assessment of wind energy as a part of long-term sustainability plans. The Law directs the Mayor's Office to identify and map areas of the city where wind energy could be effectively utilized. There are a handful of NYC buildings with roof-mounted turbines, and there is one example of a commercial-scale ground-mounted turbine operating in the city at the Sims Material Recovery Facility in Sunset Park, Brooklyn.

However, the urban environment is recognized as the most challenging context in which to make wind generation work.[i] In particular, the wind conditions over rooftops are more complex, and this makes accurate predictions of the wind resource and energy production potentials all the more difficult.[ii]

The presence of buildings and other adjacent obstacles can cause the wind resource to become turbulent, unstable and weak[iii]. Simulations have shown that rooftop turbine performance is highly sensitive to building height, the shape of the building and roof, and the height and specific location of the turbine installation. By contrast, wind turbines perform best with strong winds flowing in a consistent direction like those located offshore versus in-city turbines. Roof-mounted turbines are also more expensive than conventional installations, due to higher costs of engineering and the need for structural steel supports[iv]. Existing design standards and testing protocols for turbines were not developed for the urban environment, which presents unique safety concerns around falling ice or broken equipment in populated areas. The ideal location for a building-mounted turbine would be on the windward side of a tall building, as far away as possible from obstacles that would create turbulence These factors would need to be considered and addressed before pursuing a citywide wind initiative.

Globally, some in-city turbines have been a documented success. In 2002, for example, a three-blade horizontal axis 750 kW turbine was installed in Toronto, Canada on the waterfront of Lake Ontario. It was the first urban wind turbine in North America, and the first for-profit, cooperatively owned wind turbine in Canada[v]. Although it was out of service for two years following storm-related damage, the turbine is still operating and producing enough electricity for 250 homes.

The broader record for urban turbines is, at best, mixed. The Strata skyscraper in London, UK installed three 19 kW vertical-axis turbines on its roof in 2010 that were to provide 8% of the building's electricity, but the turbines were reportedly turned off following noise complaints from residents on higher floors.[vi] The Museum of Science in Boston installed nine roof-mounted turbines of varying size and manufacture in 2009; the turbines only generated 20% of what had been originally expected, while installation and maintenance costs have been greater than anticipated. Also in 2009, a Portland, Oregon building installed four Skystream 3.7 turbines mounted on 45 ft poles, but they provided only 61% of the expected generation and are estimated to have a payback period of 40 years. NASA installed four Eddy GT turbines on the roof of its facilities in Houston in 2014, and while the system had been expected to generate 1,250 kWh per year, it only produced 0.11692 kWh during the first month of operation.[vii]

A measure of a wind turbine's productivity is its capacity factor, which divides the actual energy produced over a period by its nameplate capacity. According to NYSERDA, utility-scale wind turbines in New York may achieve capacity factors between 20% and 50%.[viii] In contrast, turbines in urban environments struggle to approach these higher capacity factors. An assessment performed for NYSERDA of a SWIFT 1.5 kW wind turbine installed on the roof of the 590ft tall Erastus Corning Tower in downtown Albany, NY found the unit achieved a capacity factor of just 3.6%, with its cost of energy exceeding $1 per kWhii. An air flow simulation of the turbine's position underscored the importance and complexity of roof location. Simulations suggest the capacity factor for the best practical location on the roof was 7.6%.

Building-mounted turbines face challenging operating conditions. A study of 26 building mounted turbines across the UK found an average capacity factor of just 0.9%, although this increases to 4.2% by limiting the calculation to times when turbines were in usei. While turbines mounted on high rise buildings performed far better than any other installations in the study, achieving in-use capacity factors as high as 16.5%, these same turbines were turned off for most of the time due to noise complaints from building residents. The worst performing turbines could notcover the power demands of their own electronics.

Small-scale turbines struggle under the lower wind speeds that are more typical of the urban environment. In one study, six micro turbines rated between 0.6 kW to 5.8 kW were field tested for a site with a low average wind speed of 3.7 m/s (8.3 mph).[ix] The manufacturers had reported peak power coefficients — a measure of how efficiently a design converts the wind power flowing into the turbine — of between 0.2 and 0.6. By contrast, the study found power coefficients of between 0.1 and 0.3, concluding that the turbines were significantly less efficient under real world conditions.

In-city Wind Case Studies:

In 2008, the Brooklyn Navy Yard installed six AeroVironment AVX 1000 turbines, each with a 1 kW capacityvii. Over the first 192 days, the system generated only 126.92 kWh, just 2% of the anticipated generation of 6,269 kWh and equivalent to a capacity factor of 0.46%. The developers had reportedly decided to prioritize project visibility over resource utilization, and they did not have accurate pre-construction energy estimation tools. As a result, the turbines were not optimally located, and performance was greatly diminished. The necessary wind speeds were only achieved for a few minutes a day, and due to the high maintenance costs, the system has not been kept in working order.

Pearson Court Square, a large residential building in Long Island City, installed three roof-mounted VisionAIR5 turbines in 2014. Performance data is not available, but the system did need to be adjusted to correct vibration and noise issuesvii. Total project costs reached $185,000, in part because instillation required a crane and significant steal support. Even if the system were to generate 6,000 kWh annually for 20 years, the upfront investments would imply a cost of over $1.50 per kWh, nearly ten times the typical residential rate in NY.

In 2015, the Sims Municipal Recycling facility in Sunset Park installed NYC's first commercial-scale wind turbine, a 160 ft tall, 100 kW ground mounted system[x]. Sims is located on a manmade peninsula that extends into the East River, and the turbine was installed on a hillock near the water's edge as far from neighboring buildings as possible,[xi] so this is likely among the best turbine locations that could be achieved in the city. The turbine has shown some success, although it has not fully met initial expectations. Its annual capacity factor has ranged from 12.8% to 17.3% according to the study calculations using SIMS provided data. Yet the turbine has served as a valuable pilot for the city and provides a demonstration to student tour groups and the public more generally.

The objective of this study was to determine where and how NYC might accommodate wind turbines within the five boroughs, and to offer a view of how the technology might perform under available conditions.

METHODOLOGY

The methodological framework based in part on a published assessment of urban wind energy potential in the Netherlands[xii], which took the following approach:

1. Assess the available building stock;
2. Characterize the available wind resource;
3. Collect the manufacturer provided specifications for leading turbines; and
4. Combine the above data sources to estimate the city-wide wind generation potential

This assessment drew largely on publicly available data from both the City and Federal government. The research was also strengthened by data generously shared by private data holders.

Building and Lot Data

The study accessed the NYC Building Footprint dataset to obtain the roof height of buildings, calculated as the height of the roof above the ground elevation.[xiii] Measurements are reported according to Building Identification Number, and each entry includes the Borough, Block, and Lot (BBL) number corresponding to the building's location. The data was downloaded as a Shapefile that included geographic information.

Additional building data from the PLUTO dataset was used, which includes extensive land use and geographic data at the tax lot level, with more than seventy fields derived from data maintained by City agencies.[xiv] This dataset was used to access zoning information, tax status, and lot area.

Wind Data

Wind data was taken from the Wind Integration National Dataset (WIND) Toolkit, maintained by the National Renewable Energy Laboratory (NREL).[xv] The Toolkit provides information on the average wind speed (in m/s) from 2007-2013 across the United States at a 2 km resolution at 10, 40, 60, 80, 100, 120, 140, 160, and 200 meters above the surface level. The measurements were created using the Weather Research and Forecasting Model run on a 2-km grid over the continental United States at a 5-min resolution.

Additional data was collected from the Iowa Environmental Mesonet, which collects data from global airports. This Automated Surface Observing System (ASOS) data set has hourly wind speed and gust information from four points within New York City from September 2021 to September 2022.[xvi]

Additionally, hourly data for a weather monitoring station maintained by the New York State Mesonet system on the rooftop of a 300 ft building in Midtown Manhattan was retrieved through a data request process;[xvii] thank you to the Mesonet team for helpfully extending access to the dataset for the Mayor's Office.1

Wind Turbine Specifications

Leading wind turbine manufacturers provide specifications about the design and performance of their turbine models, and this information is reported online. A set of twenty representative turbines was selected, ranging in nameplate capacity from 1 kW to 200 kW. Manufacturer specifications were retrieved from the following resources:

- wind-turbine-models.com
- SolarStore.co
- Small Wind Certification[xviii]
- Aeolos Wind Turbine Company[xix]
- Voltacon[xx]
- Atlantis Solar Environmental Products[xxi]
- NPS 100[xxii]

For each of the twenty turbine models considered, the study collected the following points of information from the manufacturer's specifications:

[1] This research is made possible by the New York State (NYS) Mesonet. Original funding for the NYS Mesonet was provided by Federal Emergency Management Agency grant FEMA-4085-DR-NY, with the continued support of the NYS Division of Homeland Security & Emergency Services; the State of New York; the Research Foundation for the State University of New York (SUNY); the University at Albany; the Atmospheric Sciences Research Center (ASRC) at the University at Albany; and the Department of Atmospheric and Environmental Sciences (DAES) at the University at Albany.

- Rated power (kW)
- The cut-in wind speed, the rated wind speed, and the cut-out wind speed (m/s)
- The turbine design features, including the design (horizontal or vertical axis), hub height, blade count, and rotor diameter
- The turbine's power curve, which reports the machine's electrical output in kW as a function of wind speed (mph)

The analysis was conducted with a combination of Python-based GIS techniques (with the GeoPandas package) and Excel. Data was processed and reorganized in Python, calculations and analysis were performed in Excel, and the mapping of results was completed in Python. The analysis followed the steps described below:

Identification of Candidate Buildings for Rooftop Turbines

1. Building specific data from the Building Footprint dataset was merged with the lot specific data from PLUTO. This allowed zoning and tax lot features to be attributed to each building entry.
2. The NYC buildings were filtered by height to identify which buildings, regardless of location, were 100 ft or taller.
3. The NYC buildings were also filtered to identify which buildings are shorter than 100 ft but are located on waterfront property according to tax lot status.
4. Buildings satisfying either condition were separated out as candidates for rooftop wind turbine instillations based on current zoning standards.
5. Buildings sharing a lot with a taller building were removed from the list of candidates because roof-mounted turbines should not be located within the vicinity of taller buildings that would obstruct the wind. Even if zoning regulations would theoretically allow for an instillation, the physical conditions were assumed to not support reliable turbine performance.

Estimation of Wind Resource

6. The WIND Toolkit data was merged with a map of the five boroughs to identify the wind speed datapoints reported in NYC. There are some 162 observations that fall within the city. Each observation includes average wind speeds for nine heights ranging from 10 m to 200 m above surface level.
7. The map of candidate buildings was combined with the wind speed data. For each building, it was determined which set of wind observations was located closest to the building based on the building's coordinates, and the wind conditions at the site of the building were assumed to be identical. This was a broad assumption that does not account for the complex ways that the built environment alters wind conditions, but it was the best estimation possible for a city-wide assessment given available data.
8. For each building, the average annual wind speed at roof height was estimated by linearly interpolating between the wind measurements at available heights.
9. The average wind speed was extended to estimate a complete annual distribution of wind speeds for each candidate site. This was achieved with the Weibull distribution, which is commonly used to represent the probability density of wind speeds, with probability from 0 to 1 plotted against the possible range of wind speeds, and with the area under the curve necessarily summing to 1. A Weibull distribution is defined by two parameters; the scale parameter c determines which wind speeds the distribution is centered around, and the shape parameter k reflects the breadth of the distribution of windspeeds. For each candidate site, c was calculated based on the assumed average wind speed, and k was set according to the distribution observed in hourly ASOS data for NYC. A sample of Weibull distributions for different rooftop locations is presented in Figure X.

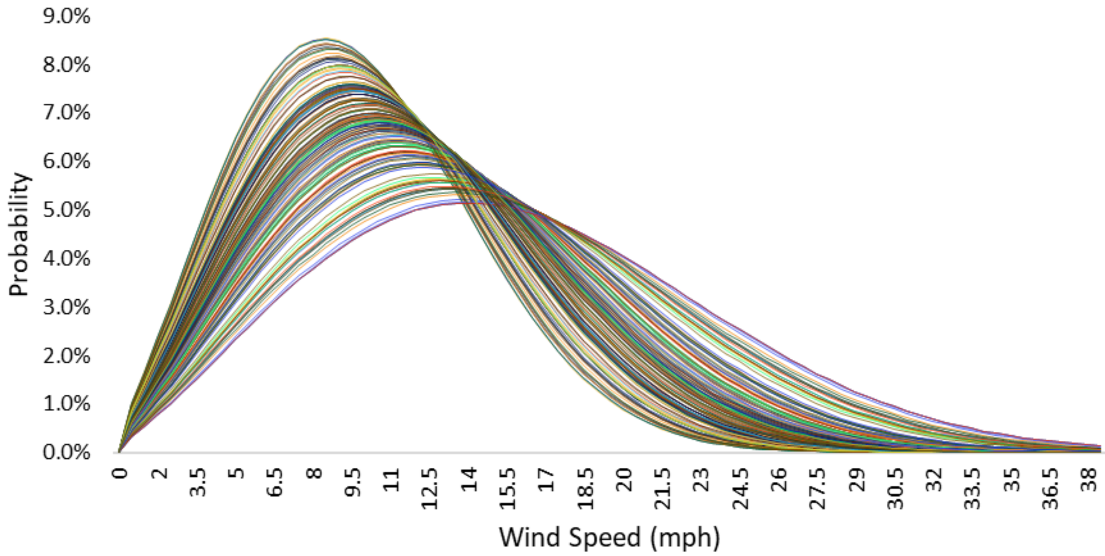

Figure X: Weibull distribution of 200 buildings in mph.

Estimating Wind Turbine Performance

10. Manufacturers provide power curves in a graphical format as part of published specifications. Data points were transcribed from these graphics for inclusion in the assessment. The potential range of wind speeds (from 3.5 mph to 60 mph) were broken into ten intervals, with increased granularity around the wind speeds most common to NYC. For each interval, the average power output from the corresponding segment on the power curve was recorded. This process was repeated for all 20 turbine models.
11. For each candidate building, a turbine model was tested under the available wind conditions. First the wind distributions from steps 7 and 8 were recalculated at the combined height of the building's rooftop and the turbine hub height. Then for each interval in the power curve determined in step 9, the probability of wind speeds at a turbine location falling within the given interval was calculated and multiplied by the corresponding power output. Then summing this product across all intervals of the power curve and dividing by the turbine's nameplate capacity returned the capacity factor that the turbine would achieve under the modeled wind conditions. This can be expressed as:
12. $CF = \frac{\sum_{i=0}^{n} P_i*((1-e^{\left(\frac{-V_l}{c}\right)^k})-(1-e^{\left(\frac{-V_h}{c}\right)^k}))}{P_R}$

Where:

- $i = Range\ in\ the\ power\ curve$
- $P_i = Power\ for\ a\ range\ in\ the\ power\ curve$
- $V_l\ and\ V_h = low\ and\ high\ wind\ speeds\ that\ define\ a\ range\ within\ the\ power\ curve$
- $P_R = Rated\ Power$
- n = number of ranges in the power curve

Finally, the capacity factor was then multiplied by the rated power and the number of hours in a year (8,760) to estimate the annual energy generation. This can be expressed as:

$$MWh = \frac{CF * 8760 * P_R}{1000}$$

The maximum number of turbines that could theoretically fit on a building's rooftop was estimated by taking the length of the building's footprint and calculating how many turbines could fit along this length if spaced at a distance of seven times the turbine model's rotor diameter. This was necessarily an over-estimation, as it did not account for the area difference between the building's footprint and rooftop, it did not account for the limitations in available space that may result from roof-mounted equipment or other obstacles, and it was not able to confirm whether the length of the roof corresponds to the windward side of the roof where turbines would most likely be installed. Despite these limitations, the approach offered an informed upper estimate of potential installed capacity.

Step 10 was repeated for different turbine models, and the optimal turbine model was selected for each building based on maximizing potential generation.

Ground-mounted Turbine Assessment

13. To identify candidate sites where ground-mounted turbines could be installed, all waterfront lots were identified according to tax lot status. Next, lots that were zoned for either manufacturing or commercial use were separated out for further consideration.
14. Remaining lots were evaluated to determine if they could potentially have enough open area to accommodate a ground-mounted turbine installation. The combined footprint of buildings on the lot was subtracted from the total lot area to find the open area. This is necessarily an over-estimation of the area available for turbine development, as it assumes the open area is collected in one expanse with access to winds off of the water without any meaningful obstructions from buildings. A general heuristic was used to estimate the spacing requirement for a larger turbine. Specifically, it was assumed that a turbine would require clearance equal to seven times its rotor diameter in one direction, and a clearance equal to one times its rotor diameter in the other direction. Lots with open area greater or equal to this minimum requirement were assumed to have enough area for a turbine. A more detailed assessment would require site-specific evaluations.
15. For each of the candidate lots, step 10 was adapted for the ground turbine assessment. The elevation of the turbine base above the surface level was assumed to be zero, and larger-scale turbines were considered.
16. The maximum number of turbines each lot could accommodate was estimated by taking the lot length and assuming turbines would need to be spaced seven times their rotor diameter apart.

Validation and Comparison with External Data

17. Hourly wind speed measurements from the Mesonet monitoring station on a Midtown Manhattan skyscraper were analyzed. Due to data confidentiality, specific numbers are not reported here, but it was found that the annual average wind speeds actually observed on the rooftop were approximately 50% of what had been estimated from the NREL WIND Toolkit. This substantial difference reflects the expected disruptions to the wind flow caused by the built environment, as well as the highly local dynamics in wind speeds that cannot be captured by a high-level dataset. The actual hourly wind speeds were paired with power curve data, and it was estimated that a 10-kW turbine could achieve only a 10% capacity factor under real world conditions, compared to the 40% capacity factor estimated using WIND Toolkit data.
18. Given the significant difference between modeled and observed wind speeds for the one rooftop, a sensitivity analysis was performed to estimate the impact if similar reductions in windspeed were observed across all candidate rooftops. The previously calculated annual average wind speeds were scaled down by the ratio of measured to modeled annual average wind speeds for the Mesonet location, and the corresponding wind speed distributions and turbine performances were recalculated.
19. While the exact wind conditions at the site of the Sims Municipal Recycling Facility turbine are not known, the facility team generously shared information about the turbine's power output. From this, it was calculated that the turbine's annual capacity factor varied between 12% and 17%. Using the nearest WIND Toolkit data, and the manufacturer provided power curve for the same turbine model, it was estimated that the turbine would achieve a 13% annual capacity factor. This is within the experienced range of performance, and so the procedure was taken to offer a reasonable estimation of ground-mounted, waterfront turbine performance. No additional sensitivity tests were performed.

Comparison with Solar PV

20. The potential performance of wind turbines was placed in context by estimating the solar potential for the same candidate sites.

21. It was assumed that 34% of a given building's footprint was eligible for rooftop solar. It was also assumed that 1 kW of solar PV could be installed for every 100 ft2 of open, unshaded rooftop. According to NYISO, a solar instillation in New York can expect to achieve a capacity factor of 13%. These assumptions were combined to estimate the annual electricity generation that could be achieved on each rooftop. Each building's solar potential was compared with its wind potential to determine which technology would offer more annual generation.
22. A similar process was performed for waterfront lots. To avoid shadows from adjacent buildings disrupting panel performance, ground-mounted solar instillations are generally located at least 50 ft away from built structures. Such a determination would necessarily be highly site specific, but to make an informed estimation, 100 ft were taken off both the assumed length and depth of the open lot area to determine the area theoretically available for a solar instillation. The name plate capacity area requirements and annual capacity factor were applied to calculate the potential annual solar generation.

Summary and Results

23. Candidate locations were grouped together, and total potential generation and average capacity factors were calculated. These calculations were performed for the entire city and by individual borough, as well as by type of building and lot.
24. Maps were generated using GeoPandas, plotting the location of candidate sites with color coded attributes, including building height, estimated wind speeds, capacity factors, and annual generation.

KEY FINDINGS

According to the most recent data published by the city, there are some 1,084,619 buildings in NYC.[xxiii] Out of this stock, there are 8,859 buildings (0.82%) that are 100 ft or taller, and 6,509 of these taller buildings are located in Manhattan. Drawing on tax lot data, there are at least an additional 2,019 buildings that are less than 100 ft tall but are located on waterfront blocks and so could be eligible for a roof-mounted turbine. A portion of these buildings are located near taller buildings, which would obstruct wind flow and limit turbine performance. Excluding these buildings from consideration reduces the count of eligible buildings to 7,587 buildings over 100ft tall and 1,427 waterfront buildings. (Figure 2)

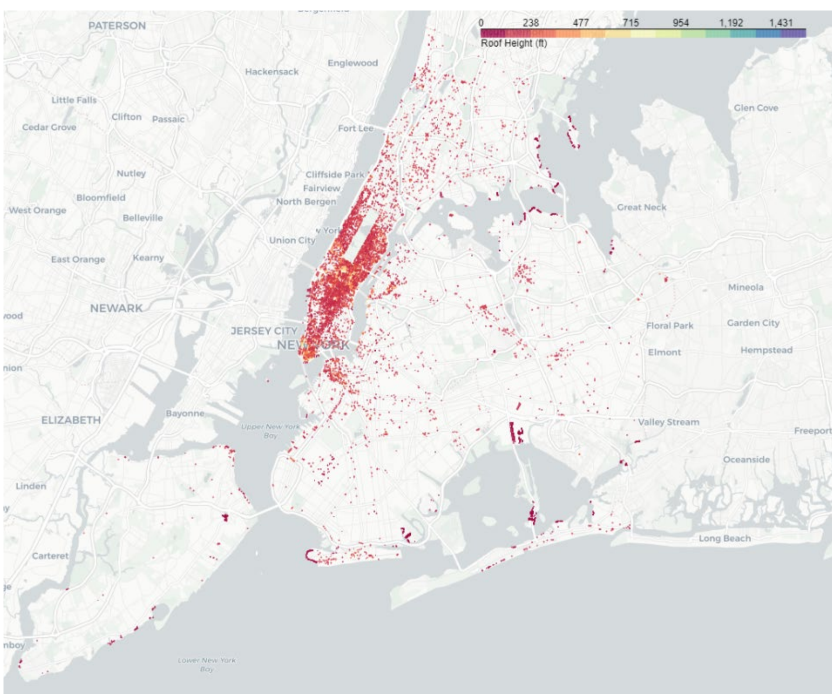

Figure 2: A map of building heights across the five boroughs for buildings that were identified as candidates for rooftop wind turbines.

Based on WIND Toolkit data, it is estimated that the average wind speed available on the roof of tall buildings is 11.7 mph (Figure 3). Optimizing turbine selection for maximum electricity generation, the model suggests that turbines on tall buildings would achieve on average a capacity factor of 34.6%, which would represent a satisfactory level of performance. If all tall building rooftops could be fully utilized, with multiple turbines installed where possible, it is calculated that 299,401 MWh could be generated annually city-wide, representing 0.57% of NYC's current annual electricity demand (Figure 4). Only on 176 buildings is it calculated that a solar PV installation could generate more electricity (Figure 5).

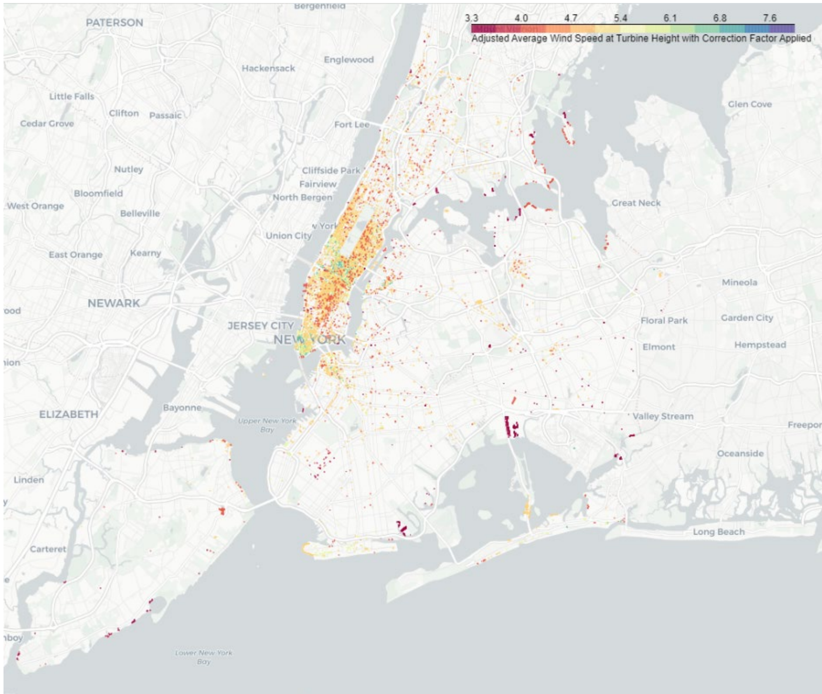

Figure 3: A map of estimated annual average windspeeds in mph at the roof height of tall buildings and other waterfront buildings throughout the five boroughs.

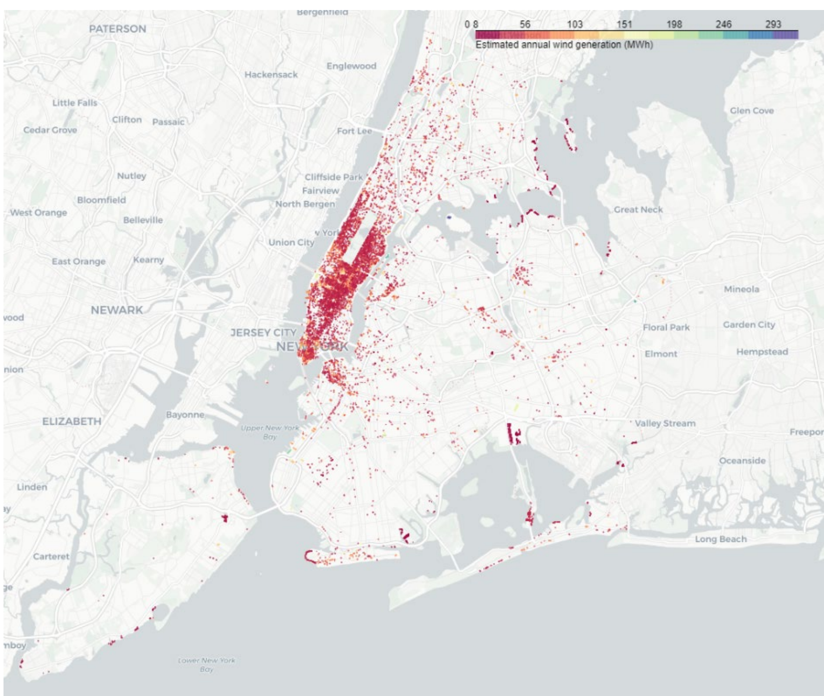

Figure 4: An estimate of annual generation from candidate buildings across the five boroughs if a maximum number of turbines could be installed on each rooftop.

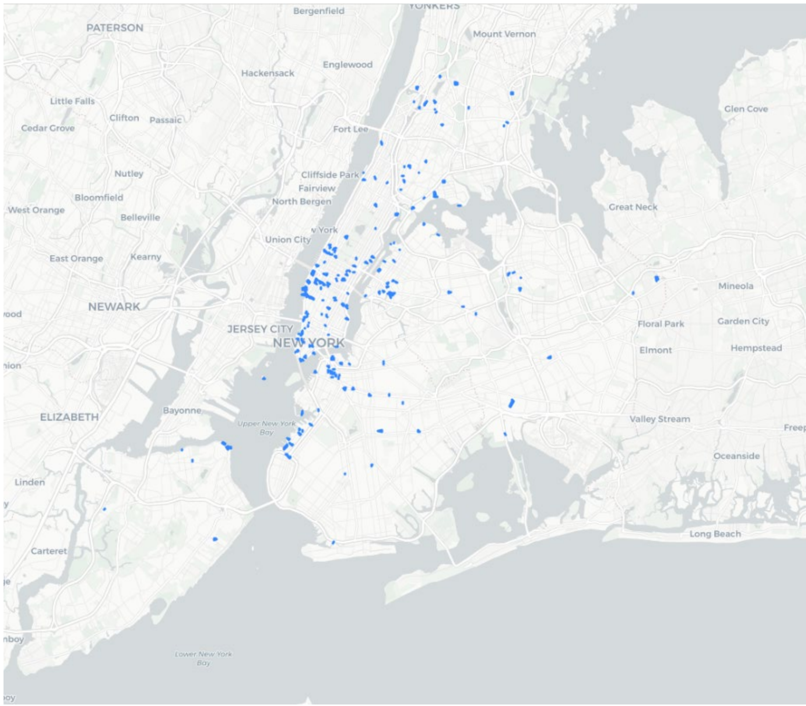

Figure 5: A map of the buildings where rooftop solar is estimated to offer greater generation potential than wind under initial assumptions.

It is estimated that the average wind speed available at the roof of shorter waterfront buildings is only 8.8 mph (Figure 3). Optimizing turbine selection for maximum electricity generation, the model suggests that turbines on shorter waterfront buildings would achieve on average a capacity factor of 19.3%, which would represent an unsatisfactory level of performance. If all shorter waterfront building rooftops could be fully utilized, with multiple turbines installed where possible, it is calculated that 25,167 MWh could be generated annually city-wide, representing 0.05% of NYC's current annual electricity demand (Figure 4). Only on 30 buildings is it calculated that a solar PV instillation could generate more electricity (Figure 5).

Mesonet station data collected from a Midtown building indicates that the estimates of in-city wind resources are inflated. This result is in keeping with the documented experiences of wind turbines in NYC and in other cities. A sensitivity analysis was performed whereby modeled rooftop wind speeds citywide were reduced proportionally to the reduction between modeled and observed wind speeds at the Midtown building. Under this sensitivity scenario, the average wind speed available on the roof of tall buildings was 5.3 mph (Figure 6), and only 148 buildings could access average between 7.5 and 8.0 mph, which would still be less than desirable for turbine operations (Figure 7). Turbines on tall buildings would achieve on average a capacity factor of just 6.0%. Under these conditions, if all tall building rooftops were fully utilized, 52,690 MWh could be generated annually citywide, representing 0.10% of NYC's current annual electricity demand. Under the sensitivity scenario, the average wind speed available at the roof of shorter waterfront buildings was 4.2 mph (Figure 6), leading turbines to achieve on average a capacity factor of just 2.9%. Under these conditions, if all shorter waterfront building rooftops were fully utilized, 3,801 MWh could be generated annually citywide, representing 0.01% of NYC's current annual electricity demand. For both building categories, turbine performance is far below what would be considered an effective or economic utilization. On 6,657 taller buildings and 368 shorter waterfront buildings, installing solar PV could generate more electricity annually.

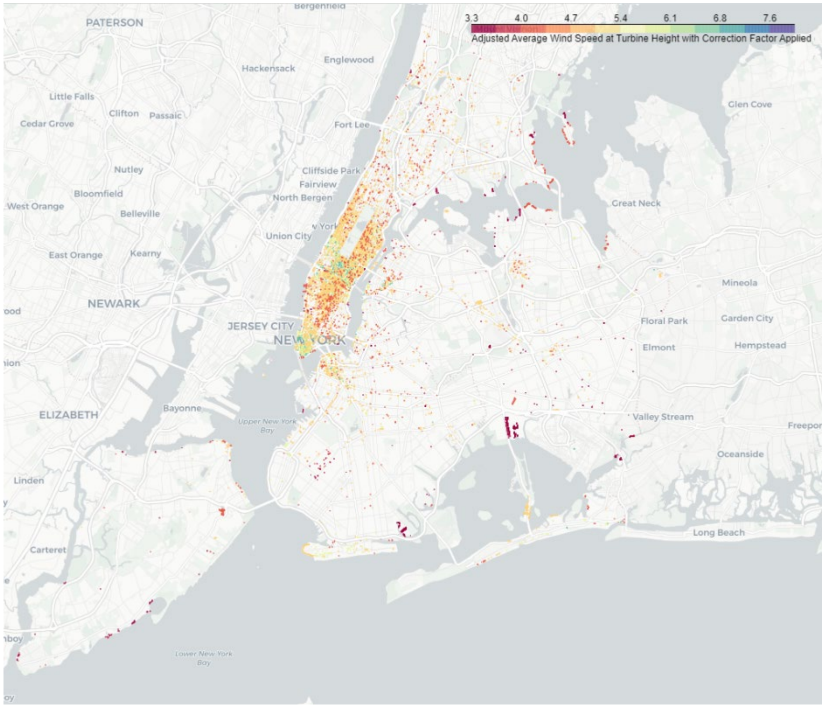

Figure 6: A map of rooftop wind speeds under a sensitivity scenario with speeds scaled down to reflect the recorded conditions at an existing monitoring site in Manhattan.

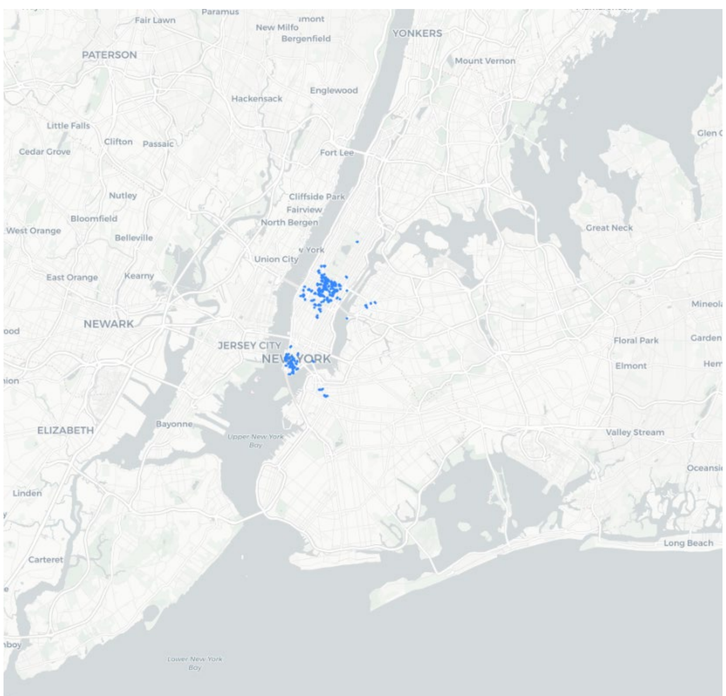

Figure 7: A map of the buildings that could still access comparatively higher wind speeds (between 7.5 and 8.0 mph) under a sensitivity scenario with reduced wind speeds reflecting the recorded conditions at an existing monitoring site in Manhattan.

It is estimated that there are 69 waterfront lots in commercial or manufacturing districts that have enough open area to accommodate commercial-scale turbines. Most of these lots (36) are in Manhattan (Figure 8). Using WIND Toolkit data and optimizing for maximum generation, the model suggests that ground-mounted turbines on waterfront lots would achieve on average a capacity factor of 20.0%, which would be on the cusp of satisfactory performance. If all appropriate waterfront lots could be fully utilized, with multiple turbines installed where possible, it is calculated that 59,162 MWh could be generated annually city-wide, representing 0.11% of NYC's current annual electricity demand (Figure 9). Yet it is estimated that 35 of these lots, mostly the lots with the greatest amount of open space, would be able to generate more electricity annually if they instead installed solar PV (Figure 10); out of the 34 lots where wind is estimated to offer greater annual generation potential than solar, 12 are in Manhattan, 9 on Statin Island, 7 in the Bronx, and 3 in both Brooklyn and Queens. A separate analysis confirmed that the model was able to predict the performance of the existing Sims turbine, installed in Brooklyn, with reasonable accuracy, so a sensitivity analysis for ground-mounted wind turbines was not performed.

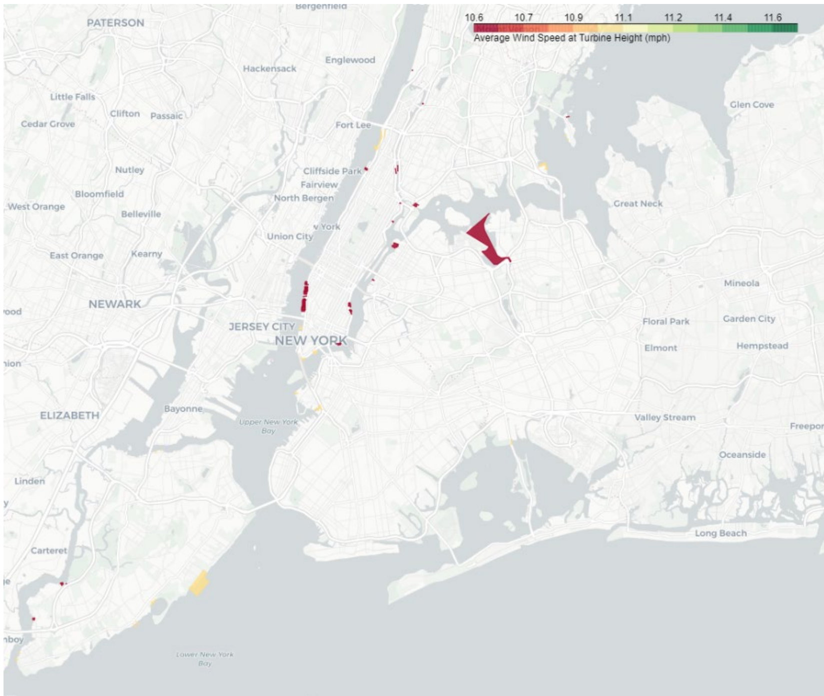

Figure 8: A map of estimated annual average wind speeds in mph at waterfront lots throughout the five boroughs identified as being potentially large enough to accommodate larger scale, ground-mounted turbines.

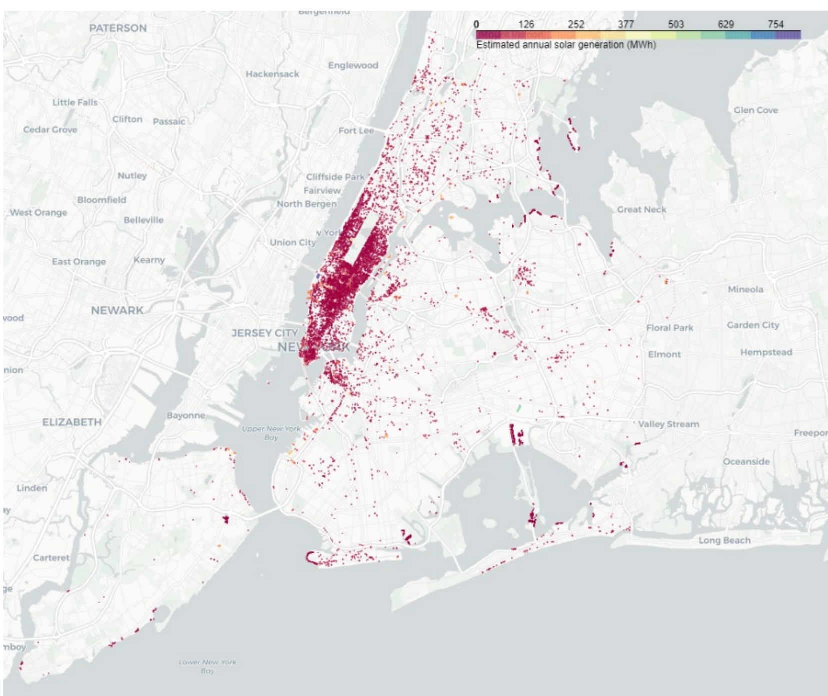

Figure 9: A map of the estimated annual generation potential from ground mounted wind at candidate waterfront sites across the five boroughs.

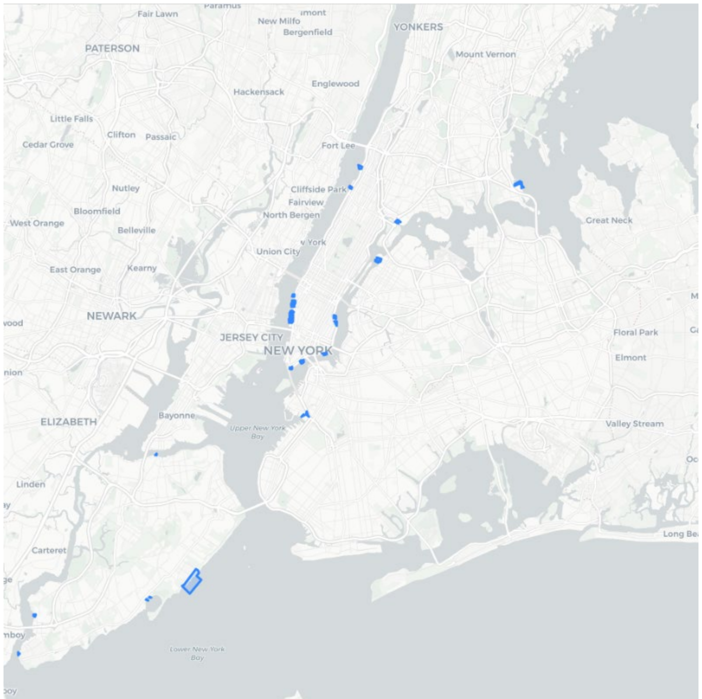

Figure 10: A map of the candidate waterfront lots where large-scale solar might offer greater generation potential than a wind instillation.

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[i] Source: "Warwick Wind Trials Report." Encraft
[ii] Source: "Case Study of the Performance of the Erastus Corning Tower Small Wind Turbine and Building Mounted Wind Recommendations." NYSERDA
[iii] Source: "Performance and Safety of Rooftop Wind Turbines: Use of CFD to Gain Insight into Inflow Conditions." Renewable Energy
[iv] Source: "Small Wind Site Assessment Guidelines." National Renewable Energy Laboratory
[v] Source: Windshare
[vi] Source: Brixton Buzz
[vii] Source: "Deployment of Wind Turbines in the Built Environment: Risks, Lessons, and Recommended Practices." National Renewable Energy Laboratory
[viii] Source: New York State Energy Research and Development Authority
[ix] Source: "Comparison of Energy Yield of Small Wind Turbines in Low Wind Speed Areas." IEEE Transactions on Sustainable Energy
[x] Source: Politico
[xi] E3 conducted an interview with SIMS recycling facility staff on September 8, 2022. Staff provided context about the turbine project and shared performance data in a subsequent email exchange.
[xii] Source: "A Framework for Preliminary Large-Scale Urban Wind Energy Potential Assessment: Roof-Mounted Wind Turbines." Energy Conservation and Management
[xiii] Source: City of New York
[xiv] Source: New York City Department of City Planning
[xv] Source: National Renewable Energy Laboratory
[xvi] Source: Iowa State University: Iowa Environmental Mesonet
[xvii] Source: New York State Mesonet
[xviii] Source: Small Wind Certification Council
[xix] Source: Aeolos Wind Turbine
[xx] Source: Voltacon
[xxi] Source: Atlantis Solar
[xxii] Source: Northern Power Systems
[xxiii] Source: City of New York