New York State Energy Research and Development Authority

Case Study of the Performance of the Erastus Corning Tower Small Wind Turbine and Building-Mounted Wind Recommendations

Final Report

December 2011

No. 12-01

nyserda
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Prepared for the

New York State Energy Research and Development Authority

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NYSERDA Report 12-01 NYSERDA 9998 December 2011

NOTICE

ACKNOWLEDGEMENTS – This report was written by Peter Johnson and Dan Ryan. Contributing authors/editors were Julien Bouget, Marie Schnitzer, and Janine Freeman. Results and figures from the computational fluid dynamics analysis discussed in this report were provided by Cyclopic Energy in Report CE20094073-1: *Modeling of the Wind around Erastus Corning Tower for Wind Energy Application*.

ABSTRACT AND KEY WORDS

AWS Truepower assessed the performance of a SWIFT 1.5 kW small wind turbine installed on the roof of the Erastus Corning Tower in downtown Albany, NY. Energy production data was obtained for the turbine and compared to results from a computational fluid dynamics model completed by Cyclopic Energy. Based on the CFD model results, AWS Truepower presented general observations regarding building-mounted small wind turbines that may occur for building-mounted turbine installations on other rooftops. AWST presented both benefits and challenges associated with building-mounted wind, concluding with recommendations for best practices for building-mounted wind turbine installations.

KEY WORDS – building-mounted wind, Corning Tower, SWIFT 1.5 kW turbine, NYSERDA, AWS Truepower, Cyclopic Energy.

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SUMMARY

The New York State Energy Research and Development Authority (NYSERDA) commissioned AWS Truepower (AWST) to conduct a monitoring campaign for a building-mounted small wind installation on the roof of the 180 m (590 ft) tall Erastus Corning Tower, located in downtown Albany, NY. The SWIFT 1.5 kW turbine was intended to serve as a case study to evaluate the effectiveness of building-mounted wind systems and to develop general best siting practices. AWST was also requested to provide general information on building-mounted wind, including a discussion of factors affecting system performance.

As part of the Corning Tower case study, AWST contracted Cyclopic Energy (Cyclopic) to perform a computational fluid dynamics (CFD) simulation of 49 distinct wind conditions that occur atop the Corning Tower. Using modeled data as an input, the CFD analysis characterized how flow conditions across the roof are influenced by roof geometry and determined locations on the tower's rooftop where energy production is expected to be greatest. Results from the CFD simulation were compared to production data from the SWIFT turbine and to expected production from other small wind options.

Results from this case study show that the turbine's location on the Corning Tower is subject to a variety of complex flow conditions, including recirculation, inclined flow, turbulence intensity, and the effect of ventilation. These flow conditions resulted in a net annual energy production estimate of 500 kWh at the installed site, corresponding to 14.1 percent of the AWEA rated annual energy. Energy production data from the turbine confirmed this estimate, with an availability-adjusted annual energy production of 467 kWh, corresponding to 13.1 percent of the AWEA rated annual energy. The cost of energy generated by the Corning Tower's turbine was estimated to be over a dollar per kWh. The expected annual energy production for the best practical location on the roof was estimated to be 1,000 kWh, corresponding to 28.1 percent of the AWEA rated annual energy. While somewhat greater energy production may be possible to achieve at other locations on the roof, practical siting constraints make these locations unfeasible for installation.

Based on the case study results, general observations were drawn regarding building-mounted wind systems. Although some benefits may exist, including the potential for distributed renewable energy generation in urban environments, the more complex wind conditions over building rooftops present many challenges, including the difficulty in characterizing the wind resource and expected energy production prior to system installation. Other challenges include safety risks and the potential for premature turbine failures due to increased fatigue loading from more turbulent wind conditions. These considerations may detract from the technical and economic feasibility of building-mounted wind systems.

Based on the performance of the Corning Tower wind turbine and AWST's experience, an ideal siting location for a building-mounted turbine is on a tall building and as high as possible above the roof to

minimize the effect of surroundings and the flow effects immediately above the roof. A location on the windward side of the rooftop is preferred. The turbine is recommended to be sited upwind of and as far as possible from obstacles that may wake wind flow and increase turbulence. Following these siting practices will help to minimize avoidable energy losses for building-mounted wind systems.

The energy production of the Corning Tower wind turbine and the complex conditions characterized by the CFD simulation illustrate how complex flow conditions over a rooftop may affect energy output from a building-mounted wind turbine. This implies that careful siting is necessary to minimize the effect of complex flow; however, due to the complexity and uniqueness of flow conditions over rooftops, characterizing ideal siting locations can be expensive, requiring anemometry at multiple rooftop locations and/or CFD analysis. These prospecting costs may be significant when compared to the overall value of the energy obtained from a building-mounted wind turbine.

1. INTRODUCTION

1.1. BUSINESS CASE

As renewable energy generation technologies have progressed over the last decade, it has become apparent that a combination of renewable energy solutions will be required in order to meet overall goals; and technologies such as wind, solar, geothermal, biomass, and possibly tidal energy will all play a part in addressing the global energy crisis. Not only will multiple technologies be involved, but a variety of applications and size scales will likely contribute to the long-term energy solution.

Because of this, the question has been raised as to how upcoming technologies such as building-mounted wind might be implemented to further renewable energy advancement in the United States and abroad. While utility-scale wind projects generate renewable energy in large quantities, these projects have some limitations, including their distance from primary energy load centers such as cities, as higher wind speeds are often more prevalent in rural environments. Transmitting electricity from utility-scale wind projects to urban load centers requires the construction and/or maintenance of expensive infrastructure and is associated with energy lost along the way due to transmission inefficiencies. It has been thought that these limitations could possibly be addressed by installing turbines directly in the urban environment. Locations where building-mounted wind turbines might be installed are the very locations where large scale wind generation is limited because of siting and transmission constraints. Although much smaller in capacity than utility-scale machines, building-mounted wind turbines can be distributed over the rooftops of urban environments, generating energy from directly within the load center and avoiding transmission over long distances. Additionally, customer sited wind installations can offset retail energy purchases, while energy produced from large scale projects is often purchased at a lower, wholesale rate. This can improve the economics of a building-mounted wind project.

The potential for widespread distributed renewable energy generation throughout urban environments has caused increased attention to be given to building-mounted wind turbines in New York State and New York City. At the National Clean Energy Summit in 2008, New York City Mayor Michael Bloomberg suggested that building-mounted wind may be one of the technologies that will contribute to the city's renewable energy goals.[1] At a session of the Public Service Commission (PSC) on March 25, 2010, the City of New York indicated that it would like small wind incentives to "specifically include building-mounted systems in urban areas."[2] The PSC requested that the "City of New York work with the New York State Energy Research and Development Authority (NYSERDA) to identify whether there are building-mounted systems that are efficient enough that they could be supported."

[1] LaMonica, Martin, CNET Green Tech. *Mayor Bloomberg Floats New York City Wind Plan* (August 20, 2008). Retrieved September 2010 from CNET News Web site http://news.cnet.com/8301-11128_3-10020875-54.html/

[2] State of New York Public Service Commission Order, Case 03-E-0188, Issued and Effective April 2, 2010. Pages 11 and 14. Available from PSC Web site http://documents.dps.state.ny.us/public/Common/ViewDoc.aspx?DocRefId={5BD8A99E-3762-4650-8FC2-D35D9CB12C7C}.

1.2. PROBLEM STATEMENT

Although interest in building-mounted wind is growing, the current level of knowledge and technical understanding on the subject is somewhat limited. The information in this report will support the growing level of interest by providing policy makers and individuals with the knowledge necessary to make educated decisions about building-mounted wind. Specific areas where research is needed include:

(1) an understanding of wind conditions immediately above a building's rooftop,

(2) how system performance and reliability are affected by these conditions,

(3) best siting practices for optimal system performance, and

(4) technical and financial risks associated with building-mounted wind.

Wind conditions over a rooftop in an urban setting tend to be far more complex than those encountered by a tower mounted turbine in a more rural environment. Wind flow patterns around a building are specific to the particular building design, location, surroundings, shape, and position of the turbine on the roof, making it difficult to accurately estimate the energy production and loading on a potential wind turbine. Despite these challenges, characterizing the wind's flow is critical for assessing system energy production and reliability and for optimal turbine siting. However, cost-effective techniques to accurately assess rooftop wind conditions are limited due to the complexity of flow over rooftops and in urban environments, as described in more detail in Section 4.2.

Increasing numbers of small wind turbines are being manufactured specifically for building-mounted applications, but little is known about how these turbines will perform in wind conditions encountered on a building's rooftop.

If building-mounted wind is to be implemented as a distributed renewable energy solution, appropriate turbine siting will be critical for optimizing performance and to minimize avoidable energy losses. The development of best siting practices will inform installers about where to site a turbine to maximize potential output, increasing the value of building-mounted wind systems to customers.

1.3. GOAL STATEMENT AND SPECIFIC OBJECTIVE

In support of NYSERDA's effort to evaluate the effectiveness of building-mounted wind as a distributed renewable energy generation option, AWS Truepower (AWST) has investigated a building-mounted small wind turbine installed on top of the Corning Tower in Albany, NY as a case study. Based on the results from the analysis and AWST's general knowledge of wind energy, the preliminary answers are provided to the four areas of research described in the problem statement:

- characterization of the wind resource
- evaluation of factors affecting performance and reliability

- the development of ideal configuration and siting practices, and
- an assessment of potential risks.

The wind resource was characterized using computational fluid dynamics (CFD) modeling. Performance was assessed on the basis of annual energy production. Wind conditions characterized by the CFD model were used to discuss system reliability. Best siting practices were defined based on CFD results and AWST's general knowledge. Financial risks were evaluated through a cost of energy assessment for the Corning Tower turbine and a discussion of the uncertainty associated with preconstruction energy estimation for building-mounted systems. Technical risks were presented through a general discussion of potential benefits and challenges of building-mounted wind systems.

1.4. PROJECT SCOPE

Under the scope of work agreed upon by NYSERDA and AWST, AWST was requested to conduct a monitoring and performance evaluation campaign for roof-mounted small wind installations selected by NYSERDA. AWST evaluated the performance of a SWIFT 1.5 kW wind turbine on the roof of the Corning Tower as a case study. The turbine's placement was limited by existing uses of the rooftop and the final placement was determined based on these constraints. A research plan was developed that included using AWST's ***windTrends*** modeled data set as in input into a CFD modeling to predict wind conditions and expected energy production across the roof of the Corning Tower. Actual energy production data from the turbine was compared to an expected annual energy output derived according to the research plan.

AWST was requested to review and evaluate the data to identify trends, lessons learned, and best practices for building-mounted wind. Based on the results of the case study and wind behavior illustrated by the CFD model, AWST presented general observations for building-mounted wind systems, including benefits and challenges associated with building-mounted wind. General siting considerations for building-mounted wind systems were outlined, and an overall assessment as to the effectiveness of building-mounted wind was provided.

1.5. INTRODUCTION TO TERMS

A fundamental background on fluid dynamics, wind energy technology, and wind industry terminology is useful for understanding how these factors interact and affect building-mounted wind systems. This section outlines the definitions of several wind flow and industry terms that will be used throughout the remainder of the report.

1.5.1. Ideal Wind Conditions

Ideal wind conditions are defined as the wind conditions that result in maximum power output from wind turbines. Most wind turbines are designed to produce the most energy when exposed to constant strong horizontal winds. These conditions are likely to result in optimal performance and the longest turbine lifetime. A similar term is laminar flow, which is characterized by smooth parallel movement of wind (see Figure 1.1).

1.5.2. Complex Wind Conditions

Complex wind conditions are defined by wind conditions that are less likely to result in optimal power output. Instead of following smooth movements like ideal flow, complex flow is often chaotic, and is characterized by some or all of the following phenomena.

1.5.2.1. Turbulence. Turbulence is defined as a rapidly changing wind resource. In highly turbulent environments, wind may frequently change speed and/or direction. Mathematically, the turbulence intensity (TI) is calculated throughout the wind industry by dividing the standard deviation of the wind speed by the average wind speed, usually over a ten-minute period, and is expressed as a percent. A TI of 20 percent or greater is considered to be a relatively turbulent environment and a TI of 30 percent or greater is considered to be a highly turbulent environment for wind turbine exposure.

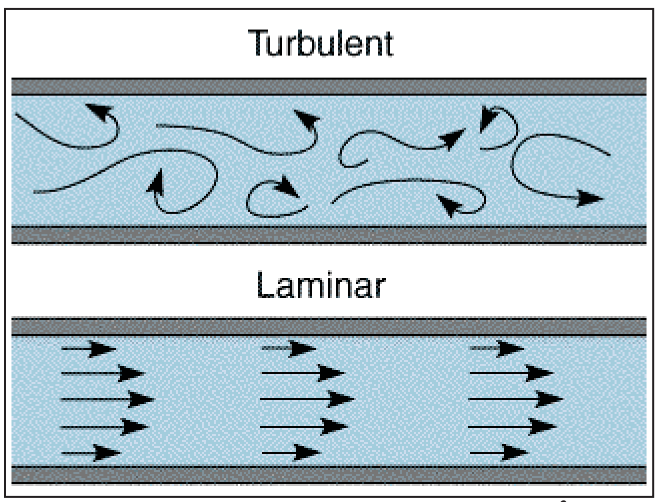

Figure 1.1: Turbulent and Laminar Flow[3]

1.5.2.2. Waked Flow. Wind flow may be deflected from its path when it encounters an obstacle. Wind flows around the obstacle, speeding up as it passes around the sides and over the top of the obstacle, while creating a slower and more turbulent wind area that continues for a distance behind the obstacle (see Figure 1.2 and Figure 1.3). This area of disturbed flow is known as waked flow. As the flow continues downstream of the obstacle, it eventually reformulates into a more laminar flow at a distance multiple times the obstacle's height (see Figure 1.2).

[3] Source: University of Cambridge. Hydrodynamic Voltammetry (2010). Retrieved August 2010 from University of Cambridge Web site http://www.ceb.cam.ac.uk/pages/hydrodynamic-voltammetry.html. Used with permission.

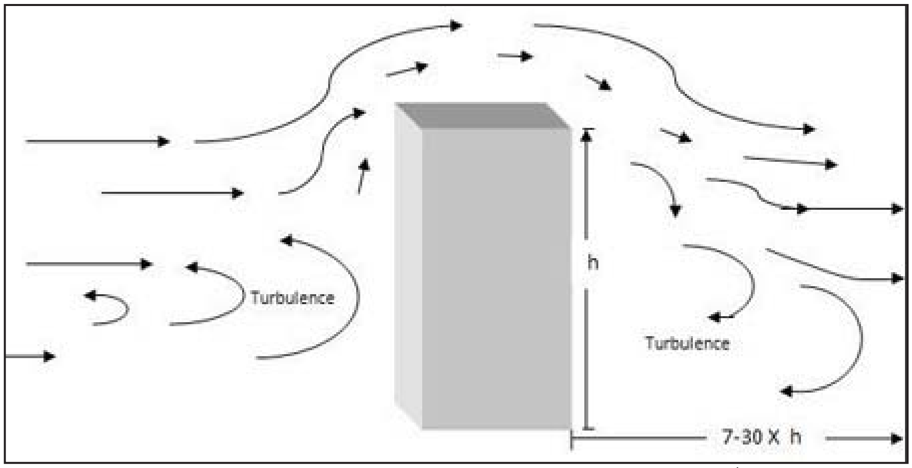

Figure 1.2: Waked Flow downstream of Obstacle[4]

1.5.2.3. <u>Recirculation.</u> As wind passes around an obstacle, a recirculation zone is created directly behind the obstacle (see Figure 1.3). In this zone, the wind swirls in a circular motion creating reverse current patterns known as eddies. Recirculation zones are highly turbulent areas where the wind's direction and speed is changing constantly.

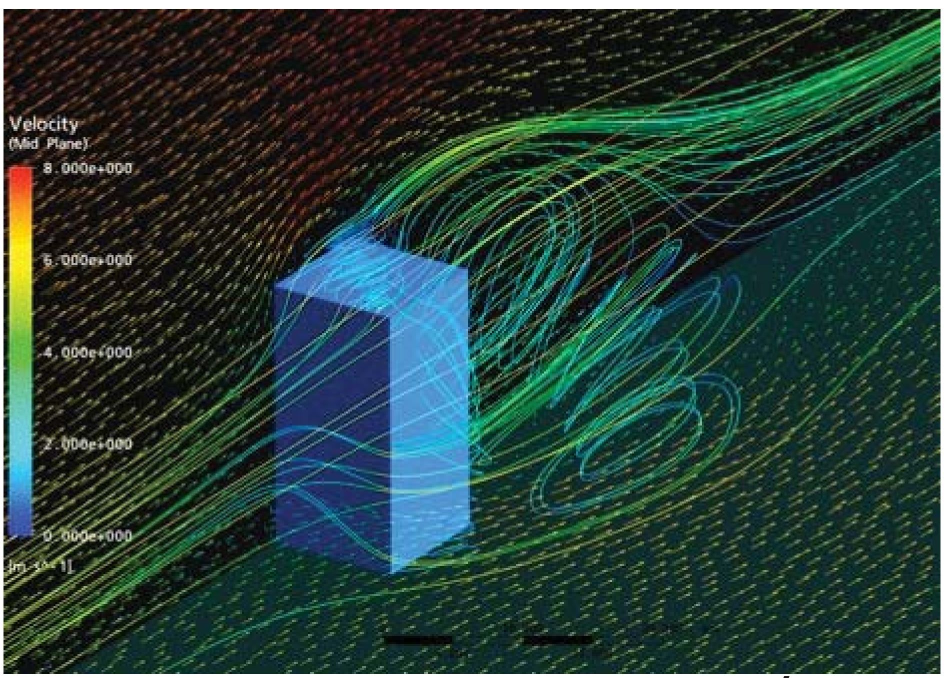

Figure 1.3: Recirculation Zone downstream of Obstacle[5]

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[4] Source: Belfort Instrument. *Surface Wind Modifiers/Buildings and Structures* (2009). Retrieved August 2010 from Belfort Instrument Web site http://blog.belfortinstrument.com/2009/08/wind-instruments/surface-wind-modifiersbuildings-and-structures/. Used with permission.

[5] Source: Cleanfield Energy. Used with permission.

1.5.2.4. Inclined Flow. Wind usually flows parallel to the earth's surface. When wind flow encounters complex terrain such as mountains, hills, and valleys, the wind tends to follow the shape of the terrain, causing flow to deviate from the horizontal. Another name for inclined flow is off-horizontal flow. Inclined flow is also generated as wind passes over and around an obstacle in its path. This is apparent in Figure 1.3. In urban environments, the flow angle is often influenced by the effects of city buildings.

1.5.2.5. Shear Gradient. The change in wind speed or direction with increasing height above ground is known as the shear gradient. Wind speeds usually show a slight increase with height above the ground as the effect of friction from the earth's surface decreases with increasing height. This is modeled throughout the wind industry using the wind shear formula,[6] shown below:

$$U = U_{ref} \times \left(\frac{h}{h_{ref}}\right)^{\alpha}$$

where U and U_{ref} represent the wind speed at height h and the reference height, respectively, h and h_{ref} represent the height of interest and the reference height, respectively, and α represents the site/condition-specific shear exponent. In conditions with a mild shear gradient (i.e., wind shear exponent of $\alpha = 0.1$ or less), wind conditions are generally uniform across a turbine's rotor plane. In conditions with a sharp shear gradient (i.e., wind shear exponent of $\alpha = 0.3$ or more), conditions experienced at the bottom of the rotor plane may be quite different from those experienced at the top.

In urban environments, the presence of rough surface elements such as tall buildings contribute to greater ground friction, leading to even higher and non-uniform shear gradients. Local shear gradients can also be generated above a roof's surface as flow passes over the building, leaving a low wind speed region immediately above the roof that transitions steeply to a higher wind speed zone as the wind accelerates to flow around the building (see Figure 1.4). In these cases, the formula above may not be applicable to model the wind shear at the site.

[6] A description of this formula is provided by the National Oceanic and Atmospheric Association at http://www.esrl.noaa.gov/csd/projects/lamar/windshearformula.html/.

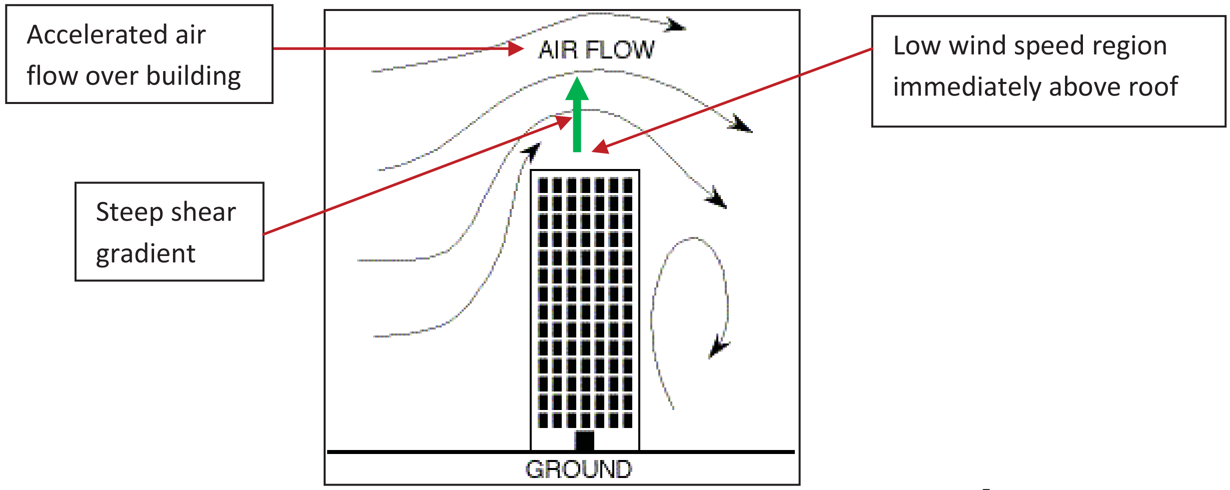

Figure 1.4: Air Accelerating over Building, Creating Steep Shear Gradient[7]

1.5.3. Turbine Performance

Expected turbine performance is demonstrated by the manufacturer's power curve. The manufacturer's power curve is typically derived from test data in ideal wind conditions. Data from non-ideal wind conditions is filtered out of the analysis so that results demonstrate the turbine's performance when subjected to unwaked horizontal non-turbulent flow at sea-level air density. Although some installation sites may be close to ideal conditions, many others, particularly those in urban environments, will exhibit less-than-ideal conditions. This manifests in lower power production at these locations, indicated by a drop in the manufacturer's power curve. Figure 1.5 presents an example power curve and demonstrates how energy production may be lower in non-ideal wind conditions. Therefore, expected energy production at turbine locations requires adjustment to reflect performance based on the real conditions experienced at the site.

Another consideration for turbine performance is a uniform standard for manufacturer power curves. Until recently, no standard for small wind turbines was adhered to in order to provide a uniform testing basis for small wind turbine power curves. In December of 2009, the American Wind Energy Association (AWEA) developed a small wind turbine-specific standard known as the AWEA Small Wind Turbine Performance and Safety Standard, which adjusts the requirements of IEC 61400-12-1, the standard for utility-scale wind turbines, to apply for turbines with a rotor diameter of 200 m^2 or less. This provides the small wind industry with a baseline by which to uniformly test and evaluate small wind turbines. Although an increasing number of wind turbines are undergoing testing according to the AWEA Standard, power curves for some small wind turbines have either been derived theoretically, measured in laboratory settings, or have been measured in field conditions that deviate from the uniform conditions specified by the standard. This is a significant contributor of uncertainty to the small wind energy estimation process.

[7] Source: modified from Van Milligan, Tim. Using Rocket Gliders in Education (2006). Retrieved August 2010 from Apogee Components Web site http://www.apogeerockets.com/.

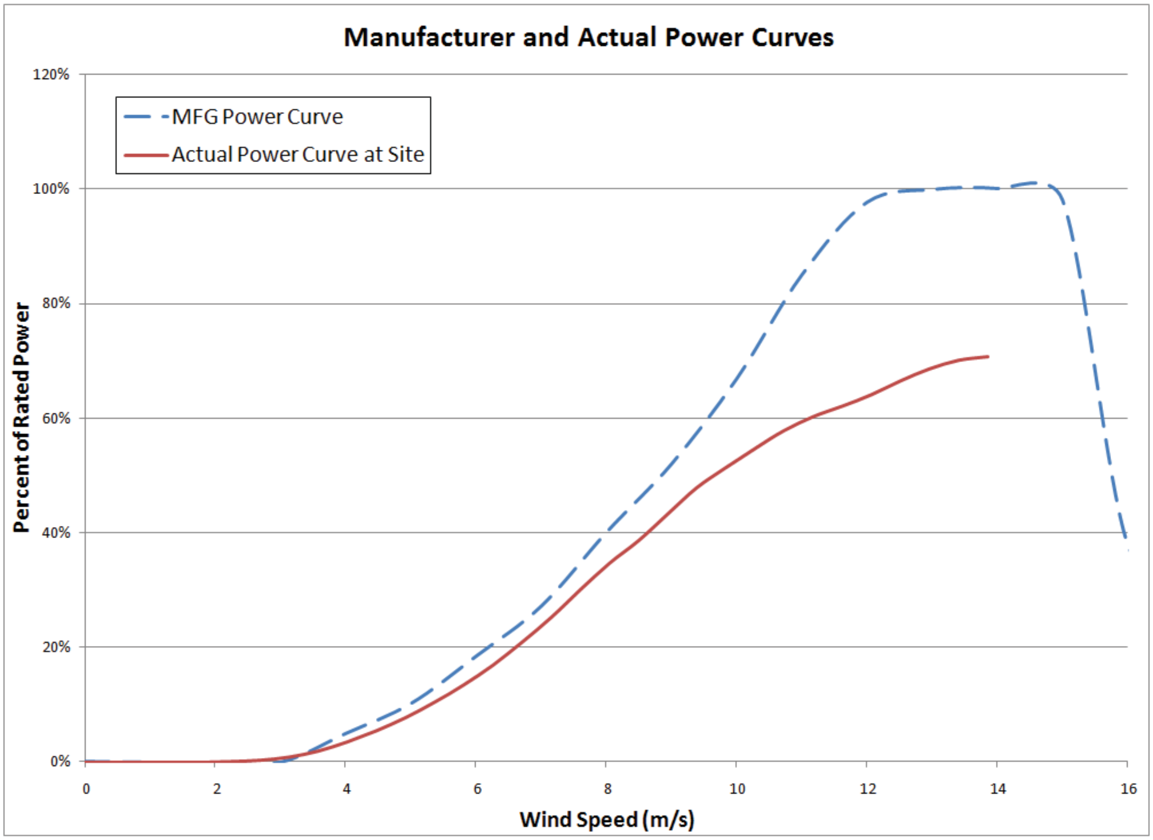

Figure 1.5: Manufacturer and Actual Power Curve Comparison (Simulation) [8]

1.5.4. Annual Energy Production

Annual energy production (AEP) is the amount of energy that is generated by a wind turbine in a given year. Site-specific wind resource characteristics, site surroundings, and wind turbine parameters such as the power curve are all inputs to an AEP estimate. Gross AEP is the amount of energy that could be produced if no real-world losses are taken into account. Net AEP is the annual production after adjusting gross AEP for losses associated with system availability, grid availability, turbulence, and other complex flow conditions. Estimated AEP may differ from actual AEP because of differences between modeled assumptions and the actual impact of conditions at the site.

1.5.5. AWEA Rated Annual Energy

Another measure of a wind turbine's performance is the percent of AWEA rated annual energy. The AWEA rated annual energy is a measure of the gross annual energy production expected from the turbine in specific wind conditions that serve as a reference for the industry. The AWEA rated annual energy is defined in section 1.5.2.2 of the *Small Wind Turbine Performance and Safety Standard*, published in

[8] Source: AWS Truepower, LLC.

December 2009, which states the following definition: “the calculated total energy that would be produced during a one-year period at an average wind speed of 5 m/s (11.2 mph), assuming a Rayleigh wind speed distribution, 100 percent availability, and the power curve derived from IEC 61400-12-1 (sea level normalized).” The energy value calculated from these conditions is considered to be a reference value for the particular turbine: by dividing annual energy output by the AWEA rated annual energy (i.e., percent of AWEA Rated Annual Energy), energy output is normalized to account for the turbine power curve. The advantage of using the percent of AWEA rated annual energy is the ability to compare performance using a uniform definition across all turbine types.

According to the AWEA *Small Wind Turbine Performance and Safety Standard*, the AWEA rated annual energy must be calculated using a power curve derived according to the standard test conditions described in IEC 61400-12-1. Small wind turbine manufacturers do not always indicate whether power curves were derived according to IEC 61400-12-1; in these cases, there is some uncertainty in calculating the AWEA rated annual energy, since the power curve used in the calculation may not reflect performance under standard test conditions.

It should be noted that percent of AWEA rated annual energy is not to be interpreted as a measure of system performance on a 100-point scale. Rather, it is a relative comparison of energy output normalized for the turbine power curve and wind conditions. A value over 100 percent does not mean that the turbine is performing better than expected: it only means that energy output at the site was greater than the reference scenario. Similarly, a value under 100 percent does not mean that the turbine is underperforming: it only means that energy output at the site was less than the reference scenario.

2. CASE STUDY DESIGN: BUILDING-MOUNTED WIND SYSTEM ON CORNING TOWER

2.1. OVERVIEW OF APPROACH

AWST assessed the performance of a SWIFT 1.5 kW small wind turbine installed on the roof of the Erastus Corning Tower. The building is approximately 180 m (590 ft) tall and is located in the Empire State Plaza in downtown Albany, NY. A three dimensional model of the Corning Tower and wind resource data was prepared by AWST was used as input to a CFD model completed by Cyclopic. Energy production data was obtained for the turbine and compared to results from the CFD analysis as well as the theoretical energy production from various alternate installation locations.

2.2. INSTALLATION SITE DESCRIPTION

The SWIFT 1.5 kW small wind turbine was installed on the south side of the hexagonal roof of the Erastus Corning Tower on January 22, 2009. At 180 m (590 ft) tall, the building is the tallest structure in Albany and is likely to experience unobstructed winds, making it a candidate for a building-mounted wind turbine. The turbine's location on the building's roof is illustrated in Figure 2.1. The turbine was mounted on a pole approximately 6.6 m (22 ft) above the rooftop's surface and attached to a penthouse structure, as shown in Figure 2.2. A 2.1 m (6.9 ft) parapet wall surrounds the roof area, making the turbine's height 4.5 m (15 ft) above the rooftop's edge. The roof area includes the penthouse, window cleaning machinery and tracks, high speed exhaust fans expelling 500,000 cubic feet of air per minute, and various small antennas and instrumentation.

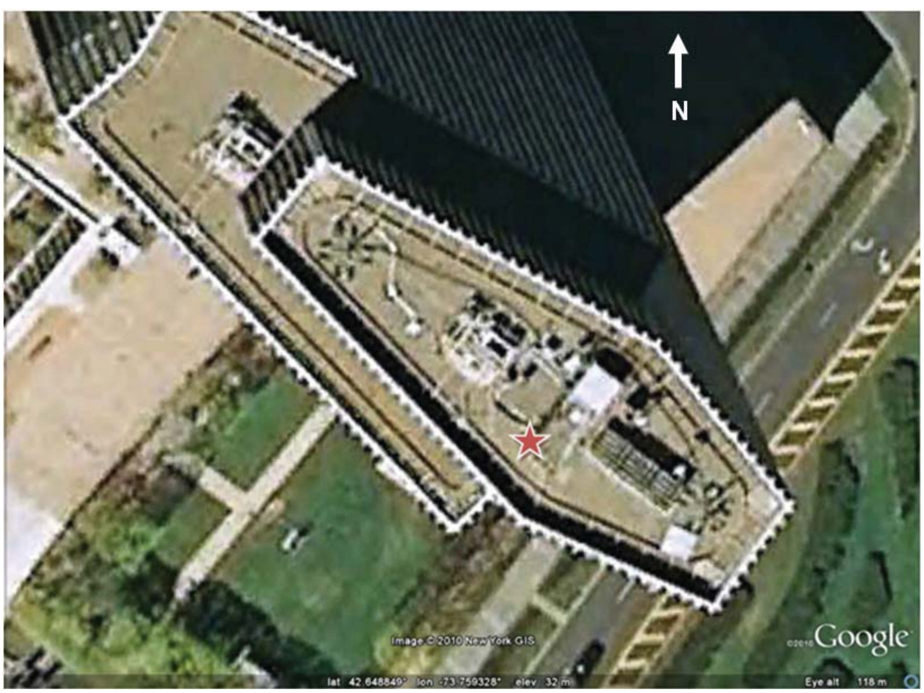

Figure 2.1: SWIFT 1.5 kW Turbine's Location on the Corning Tower Marked with Star[9]

[9] Source: Google Earth Pro. Image © 2010 New York GIS.

Figure 2.2: SWIFT 1.5 kW Turbine's Mounted on 6.6 m (22 ft) Pole[10]

Although the Corning tower is significantly taller than any other building in Albany, flow effects from the shorter buildings in the Albany skyline and turbulence associated with wind flow over the urban ground cover may still influence wind conditions at the turbine's location. The buildings in the area that may have the greatest effect on wind conditions are the four agency buildings northwest of the proposed site, each at a height of 95 m (312 ft), and the Alfred E. Smith Building to the north of the Corning Tower at a height of 118 m (388 ft). The parapet wall and other roof structures make the surrounding environment very complex and difficult to estimate the wind flow that the rotor plane of the wind turbine experiences.

2.3. WIND RESOURCE DATA

Hourly modeled wind data at the turbine's location was obtained from the windTrends data set created by AWST. The windTrends data set provides a database of weather conditions for the continental United States, southern Canada and India spanning the years 1997 to the present. It provides a weather snapshot every hour at multiple heights above ground every 20 km (12.4 mi): a total of nearly 100,000 data records for each height and point. Included in each record are wind speed, direction, temperature, pressure, and turbulence intensity. The annual average wind speed from windTrends was adjusted to the height of the

[10] Source: Green Buildings NYC. Retrieved October 2010 from gbNYC Web site http://www.greenbuildingsnyc.com/2009/02/11/wind-power-corning-tower-albany/.

Corning Tower (590 ft), using the wind shear equation presented in Section 1.5.2.5.[11] The annual average wind speed at the top of the Corning Tower was estimated to be approximately 8.6 m/s. The predominant wind directions were from the northwest and south-southwest, as shown in Figure 2.3.

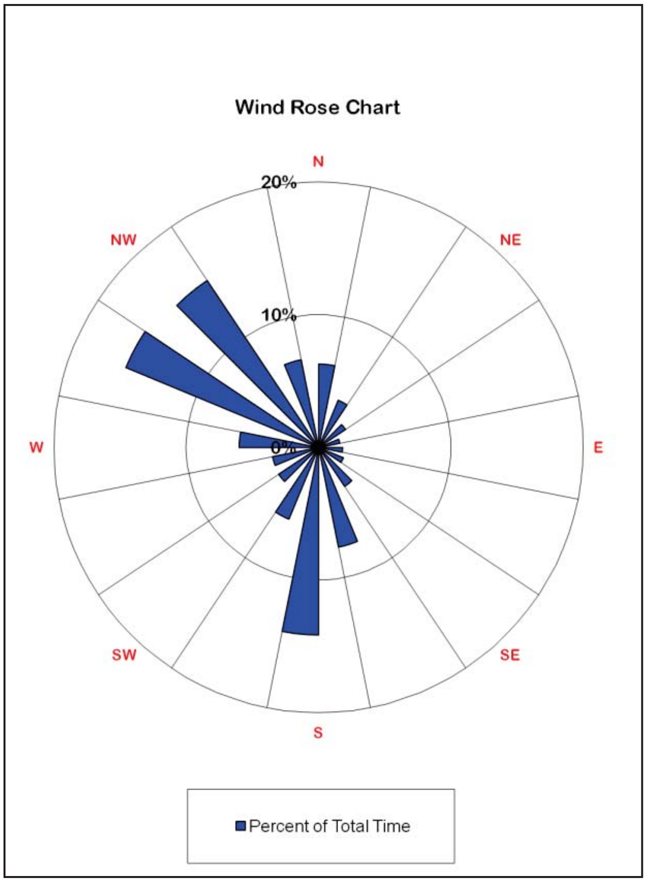

Figure 2.3: Wind Rose Chart for the Corning Tower Location[12]

2.4. COMPUTATIONAL FLUID DYNAMICS MODELING

CFD modeling was conducted to assess wind conditions and estimate system energy output atop the Corning Tower, accounting for the specific geometry of and obstacles on the Corning Tower. Prevalent wind states at the location were defined from the windTrends data set, and site geometry was modeled using Computer Aided Design (CAD). Wind conditions were then projected onto the modeled geometry to estimate the flow conditions resulting from the interaction between the wind and onsite structures. A detailed explanation is presented below.

[11] A wind shear exponent of 0.27 was used to shear the windTrends data to 590 ft. This exponent was determined from the 100-m and 120-m windTrends time series data set.
[12] Source: AWS Truepower, LLC.

2.4.1. Definition of Wind States

In order to conduct the CFD analysis for a variety of wind conditions experienced at the Corning Tower, the wind resource data was divided into 48 discrete categories. [13] Cyclopic clustered the data set into various wind speed and direction groupings that reflect each wind state's probability.

The CFD model included a total of 49 simulations [14] to represent distinct wind conditions that occur atop the Corning Tower. The wind conditions modeled by the first 48 simulations are defined in Table 2.1. For these 48 simulations, it was assumed that the building's exhaust fans would be operating, influencing the wind conditions on the tower's roof. For the most frequent wind state (state 1), a forty-ninth simulation was performed to represent wind flow when the exhaust fans on the roof were turned off. Simulation results were reported using color-coded three-dimensional contour maps that demonstrated the wind flow over the rooftop for the scenarios assessed.

[13] Note from Cyclopic report: "A clustering algorithm was used to discretize the 2-dimensional probability density function into 48 clusters. The wind state at the centroid of each cluster is defined by a wind speed and direction, which is applied as the reference inlet conditions for corresponding flow simulations. This method increases computational resolution around the most statistically relevant wind conditions."

[14] Simulations were conducted using a steady-state Reynolds-Averaged Navier Stokes solver with a k-ω SST turbulence model. Inlet conditions assumed a standard log-law model for the atmospheric boundary layer with a reference inlet velocity at 689 ft, according to Palma, Castro, Ribeiro, Rodrigues and Pinto, *Linear and nonlinear models in wind resource assessment and wind turbine micro-siting in complex terrain,* Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 2308-2326.

Table 2.1: Wind States Analyzed in CFD Analysis. [15]

Wind state ID	Frequency (%)	Wind direction (degrees)	Wind speed (m/s)	Power density (W/m^2)	Contribution to wind resource (%)
1	4.69	293.12	8.39	354.35	2.20
2	4.27	315.53	7.27	230.54	1.30
3	4.16	292.46	5.62	106.50	0.59
4	4.13	317.75	3.32	21.96	0.12
5	3.93	273.05	3.52	26.17	0.14
6	3.8	268.34	7.45	248.10	1.25
7	3.57	335.06	5.3	89.33	0.42
8	3.54	308.16	9.91	583.95	2.74
9	3.31	225.49	3.24	20.41	0.09
10	3.29	292.06	12.28	1111.08	4.84
11	3.14	277.47	10.19	634.85	2.64
12	3.11	171.48	3.46	24.85	0.10
13	3.09	247.25	6.15	139.57	0.57
14	2.76	306.46	13.04	1330.41	4.86
15	2.67	324.19	11.47	905.40	3.21
16	2.59	211.09	6.71	181.27	0.62
17	2.51	45.88	3.23	20.22	0.07
18	2.42	252.27	10.13	623.71	2.00
19	2.28	115.83	3.7	30.39	0.09
20	2.21	227.48	9.15	459.64	1.34
21	2.05	202.64	11.02	802.96	2.18
22	2.02	339.78	8.49	367.18	0.98
23	2.00	186.82	6.82	190.33	0.51
24	2.00	282.24	15.06	2049.40	5.44
25	1.87	216.3	13.79	1573.42	3.90
26	1.82	152.76	6.22	144.39	0.35
27	1.78	297.75	16.73	2809.56	6.61
28	1.69	175.15	9.91	583.95	1.31
29	1.68	234.89	12.19	1086.83	2.42
30	1.62	265.37	13.2	1379.98	2.96
31	1.6	318.19	15.88	2402.72	5.08
32	1.43	250.15	14.76	1929.35	3.65
33	1.36	22.99	6.58	170.93	0.31
34	1.32	198.91	16.63	2759.48	4.82
35	1.16	179.22	13.85	1594.04	2.46
36	1.04	143.58	10.21	638.60	0.88
37	0.98	218.17	20.56	5214.59	6.80
38	0.96	56.86	7.01	206.68	0.26
39	0.92	344.29	13.03	1327.35	1.62
40	0.83	232.24	17.05	2973.89	3.26
41	0.82	103.87	9.77	559.54	0.60
42	0.67	155.91	15.23	2119.59	1.89
43	0.67	14.29	10.93	783.45	0.70
44	0.62	118.37	14.47	1817.84	1.50
45	0.55	200.61	23.08	7376.64	5.39
46	0.37	93.56	16.57	2729.72	1.35
47	0.35	179.14	21.87	6276.21	2.89
48	0.34	53.04	13.55	1492.69	0.66

2.4.2. Model Description

[15] Blue highlight indicates most frequent wind states, green indicates highest contribution to the wind resource, and orange indicates states with the highest power density. All states represent conditions with the exhaust fans in operation. Source: Cyclopic Energy. Used with permission.

AWST prepared the three dimensional model of the Corning Tower shown in Figure 2.4 and generated modeled wind data for the building's location as input to the CFD model that was completed by Cyclopic, based out of Adelaide, SA Australia.

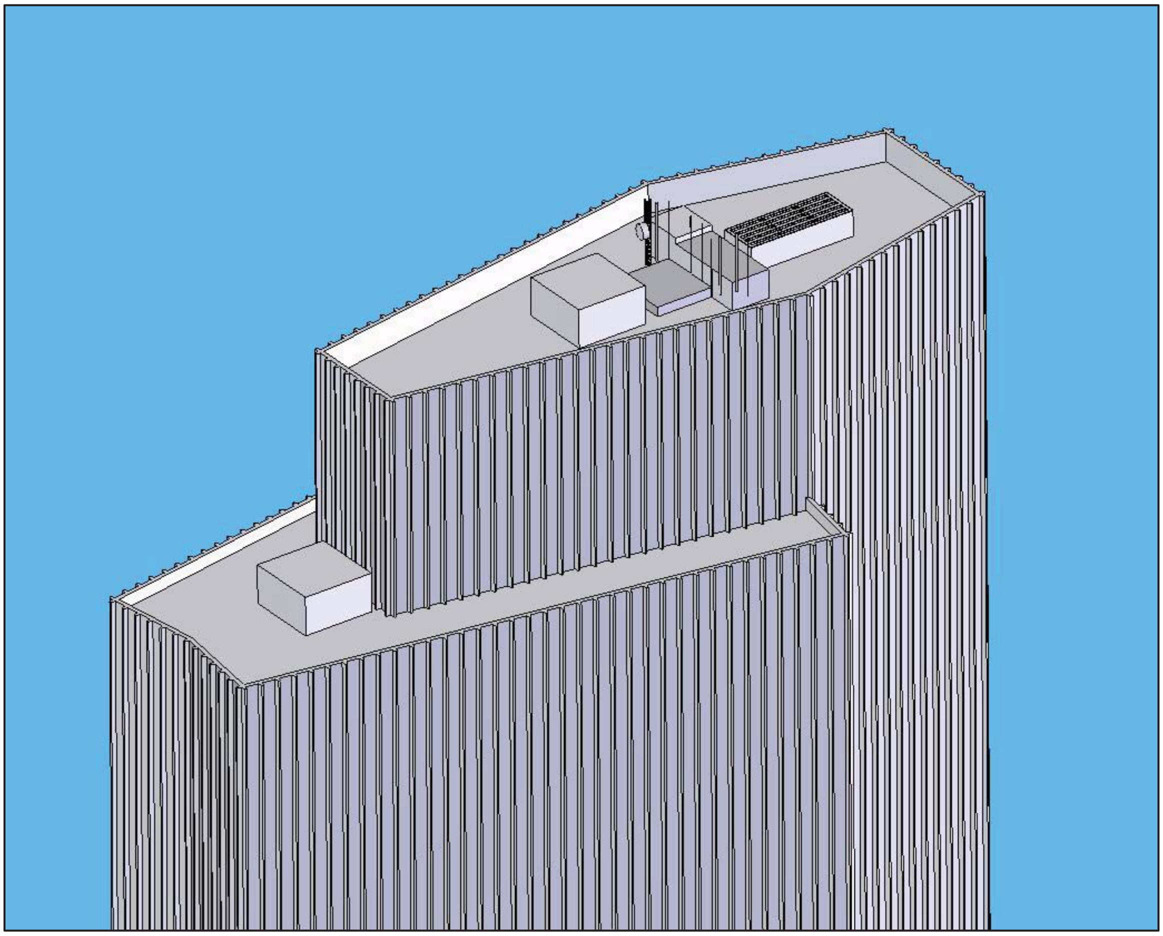

Figure 2.4: Three-Dimensional Model of Corning Tower Generated by AWST [16]

The predominant buildings of the Albany skyline were initially included in the analysis to assess their effect on wind conditions at the top of the building. Figure 2.5 shows the Corning Tower CAD model along with the surrounding buildings in the Plaza. Using the CFD model, it was determined that other buildings were unlikely to significantly affect wind conditions above the height of Corning Tower, with the exception of the Alfred E. Smith Building, located to the north of the Corning Tower. Since only a small portion of wind's energy comes from the north at this site, the influence of the Alfred E. Smith building on overall wind conditions at the Corning Tower the is likely minimal. Therefore, the effects of all other buildings were considered to be negligible and were excluded from the detailed CFD modeling simulations.

[16] Source: AWS Truepower, LLC.

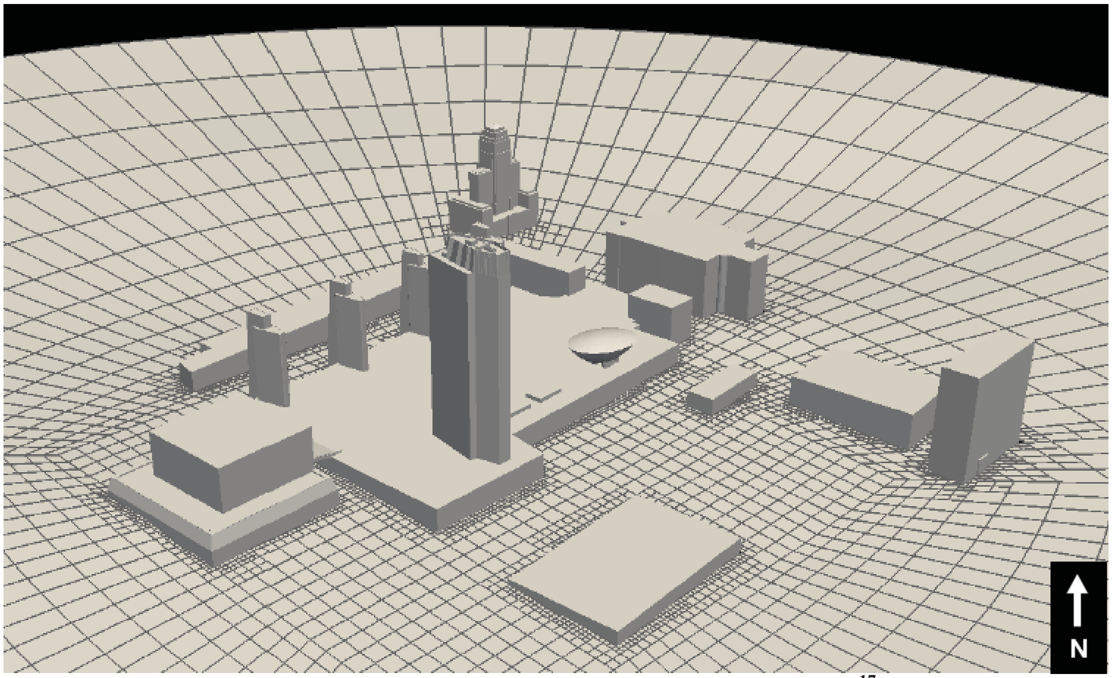

Figure 2.5: Corning Tower and Surrounding Buildings [17]

The CFD model featured a mesh of 4.5 million cells with a maximum cell resolution of 0.2 m in the volume around and immediately above the Corning Tower. The final mesh used at the top of the building is illustrated in Figure 2.6.

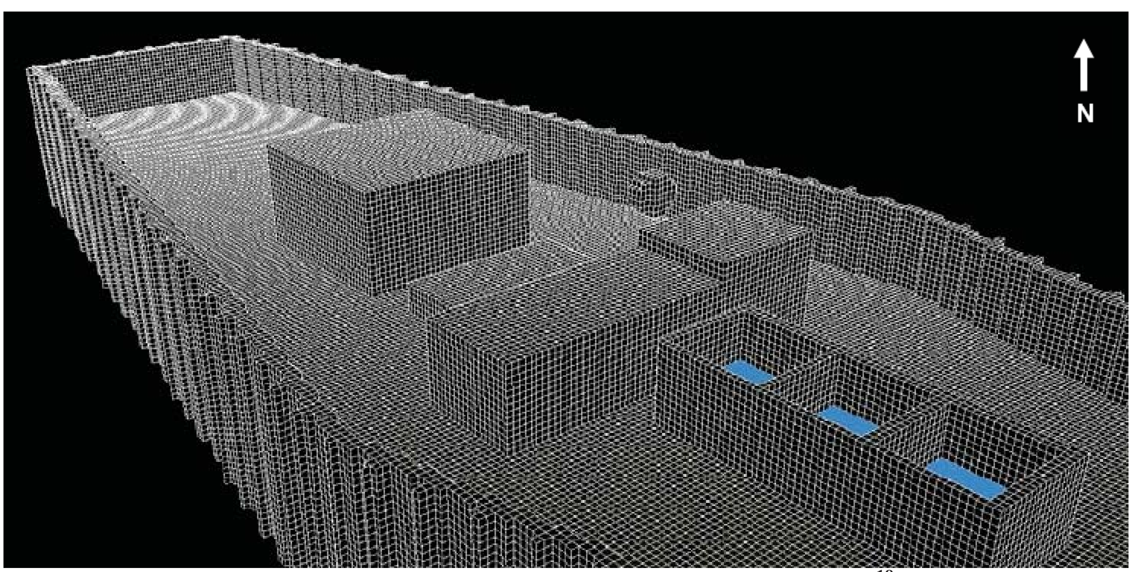

Figure 2.6: Wireframe Visualization of Mesh Resolution [18]

[17] Source: Cyclopic Energy. Used with permission.
[18] Source: Cyclopic Energy. Used with permission.

For each of the 48 wind conditions described in Table 2.1 and for the forty-ninth scenario with the exhaust fans operating, a separate simulation was conducted to demonstrate how wind flow is affected by the geometry of the rooftop. Contour plots were generated for each state to describe how horizontal wind speed, turbulence intensity, inflow angle, and recirculation vary across the rooftop and in the region immediately above the roof. Similar plots were generated for the aggregate of all 48 wind states to depict the overall conditions that are experienced in the region above the Corning Tower's rooftop. The aggregate plots are included in Section 3.1 of the report to demonstrate overall wind conditions at the site.

3. CASE STUDY RESULTS: BUILDING-MOUNTED WIND SYSTEM ON CORNING TOWER

3.1. FLOW CONDITIONS

Using the aggregate of all 48 wind conditions, the CFD model was used to determine the magnitude of complex flow conditions across the rooftop. The CFD results demonstrate how the wind flow is deflected over and around the building. The deflection effect is greater when the wind direction is perpendicular to the wide face of the building. This deflection creates inclined off-horizontal wind flow over the top of the building. Wind recirculation results in eddies immediately above the roof, leading to high turbulence levels and low wind speeds. Recirculation immediately above the roof is increased further by the exhaust fans on the building's roof. As height increases above the roof, wind speeds increase rapidly, creating a large shear gradient. Inclined flow, recirculation eddies, high wind shear, high turbulence, and low wind speed all contribute to lower energy production and higher fatigue loading than what would be expected in ideal conditions.

3.1.1. <u>Recirculation</u>

Recirculation is associated with lower wind speeds and higher turbulence levels, which contribute to decreased production and increased fatigue loading on the turbine; therefore, the ideal location for a building-mounted turbine would be out of the areas of greatest recirculation. The amount and shape of recirculation is influenced by the geometry of the rooftop, the height of the building, the wind speed, and the prevailing wind direction.

A region of high wind speed flow forms over the top of the Corning Tower as wind is deflected over and around the building. Free-stream wind flows over the face of the building, causing increased pressure and vertical wind velocity as the air flow is deflected. The magnitude of deflection is directly proportional to the face width that is perpendicular to the flow: when wind flow is perpendicular to the wider face of the building, the vertical deflection effect is greater than when wind flow is perpendicular to the narrower face of the building.

A low speed region exists immediately above the roof and below the high wind speed region. At the interface of the high wind speed flow and the low wind speed region, a steep shear layer exists. This results in increased turbulence intensity. A turbine sited in this zone would experience high levels of cyclic loading, contributing to component fatigue and a shorter turbine lifetime and lower energy production.

As illustrated in Figure 3.1, air flow is caught between the upwind and downwind parapets, creating a recirculation zone. Reversed recirculation flow and higher turbulence levels are present in this region. The exhaust fans contribute to further low-speed, high-turbulence recirculation.

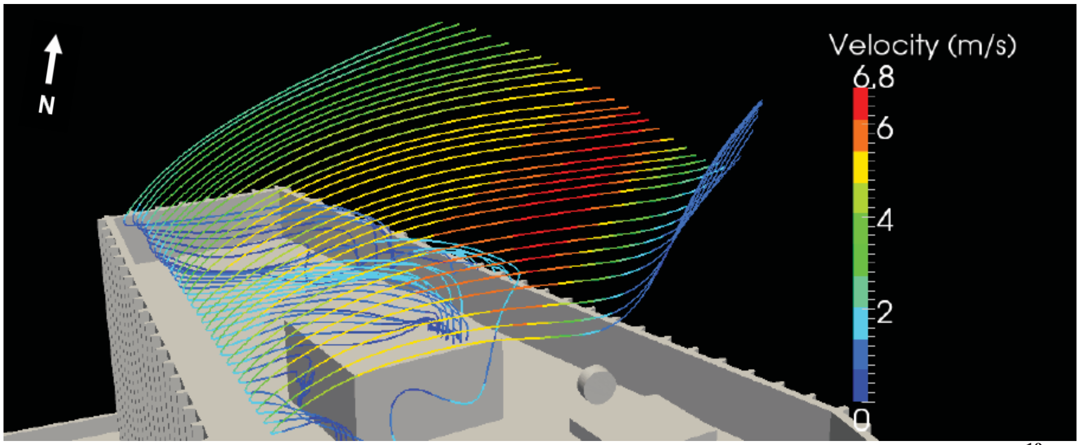

Figure 3.1: Example Simulation Run Depicting Flow Recirculation from Wind State 23 [19]

In order to quantify the amount of recirculation across the Corning Tower's rooftop, the required height (m) above the roof in order to be out of the recirculation zone for 80 percent of the time is presented in Figure 3.2. The plot is an aerial view of the rooftop, and results are based on an aggregate of the 48 wind conditions with ventilation, with red zones representing areas of greatest recirculation and blue zones representing areas of least recirculation. As illustrated in Figure 3.2, recirculation is greatest on the downwind side of the building and in the area near the exhaust fans. Recirculation is greatest in the area directly above the roof's surface and within the parapet walls and decreases with increasing height above the roof's surface. At the current location of the turbine indicated by the star in Figure 3.2, the tower would have to be approximately 10 – 12 m (33 – 39 ft) above the roof surface to avoid the recirculation zone 80 percent of the time, compared to its installed height of 6.6 m above the roof surface. The ideal siting locations with respect to recirculation are indicated by the cooler colors in the plot, which shows the required height above the roof to avoid the recirculation zone 80 percent of the time; however, other factors such as wind speed, turbulence, and inflow angle must also be considered when siting a small wind turbine.

[19] Source: Cyclopic Energy. Used with permission.

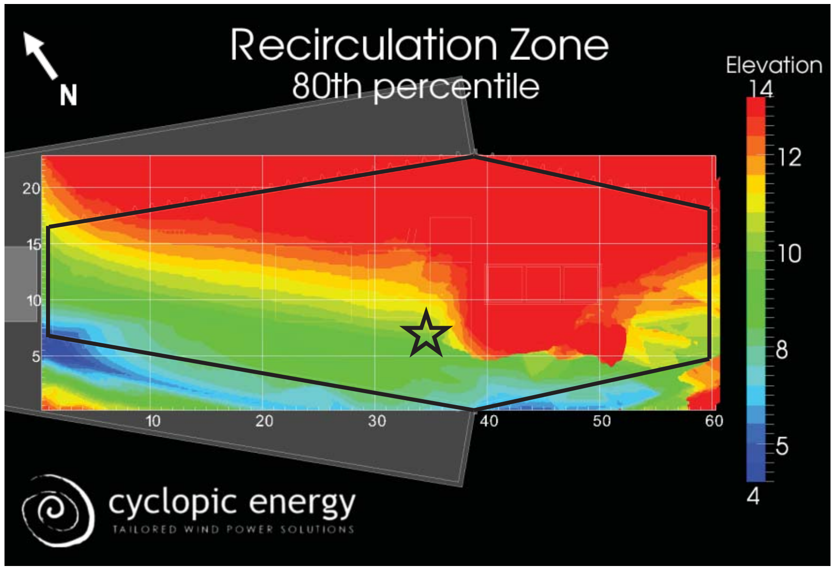

Figure 3.2: Required Height (m) above Roof to Avoid Recirculation Zone 80% of the Time [20]

[20] Source: modified from Cyclopic Energy. Used with permission.

3.1.2. **Inclined Flow**

Inclined flow occurs when wind passes through the turbine's rotor plane at an angle. The inflow angle is defined as the angle with respect to the horizontal direction that wind is flowing when it passes through the rotor plane of the turbine. Most wind turbines are designed to produce power in response to a horizontal wind flow. Greater inflow angles result in decreased performance, since only a component of the wind's energy is in the horizontal direction in cases of non-horizontal flow. When wind passes through a turbine's rotor at an angle, the wind turbine is only able to convert the horizontal component of the wind's power into electricity. Performance is decreased by the uneven loading on the turbine rotor from the angled flow. Fatigue loading is greater in wind conditions with a large inflow angle.

The aerial view in Figure 3.3 depicts the elevation (m) across the Corning Tower roof at which the inflow angle is less than 30 degrees for 80 percent of the time. Note that the inflow angle tends to be greater around the exhaust vents and at the upwind edge of the roof. Ideal locations for siting a small wind turbine with respect to inflow angle would be those where the inflow angle is less than 30 degrees at low heights illustrated as blue and green colored areas. As currently positioned, the bottom of the turbine's rotor plane would need to be approximately 7 – 11 m (23 – 36 ft) above the roof surface to avoid inflow angles greater than 30 degrees.

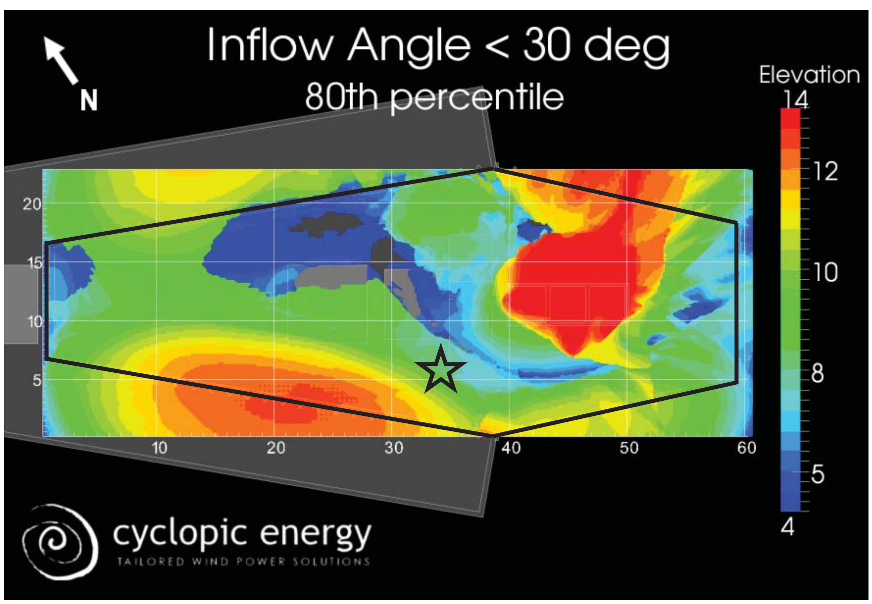

Figure 3.3: Required Height (m) above Roof to Avoid 30° Inflow Angle 80% of the Time [21]

[21] Source: modified from Cyclopic Energy. Used with permission.

3.1.3. Turbulence Intensity

Turbulence intensity is a term used to describe the amount of variation in the wind's speed; it is defined as the standard deviation of the wind speed divided by the average wind speed. Higher turbulence intensity is associated with decreased energy production and increased fatigue loading on turbine components. Figure 3.4 shows the heights across the roof where the turbulence intensity is less than 30 percent for 80 percent of the time (80th percentile). The figure indicates that turbulence is greater on the downwind side of the building than the upwind side and that additional turbulence is created by the exhaust fans. The best place to site a turbine with respect to turbulence intensity would be in the blue and green colored areas in Figure 3.4, where the required height above the roof to avoid the recirculation zone 80 percent of the time is lower. At the current location of the turbine, the bottom of the turbine's rotor plane would have to be approximately 9 – 10 m (30 – 33 ft) above the roof surface to avoid turbulence intensity greater than 30 percent.

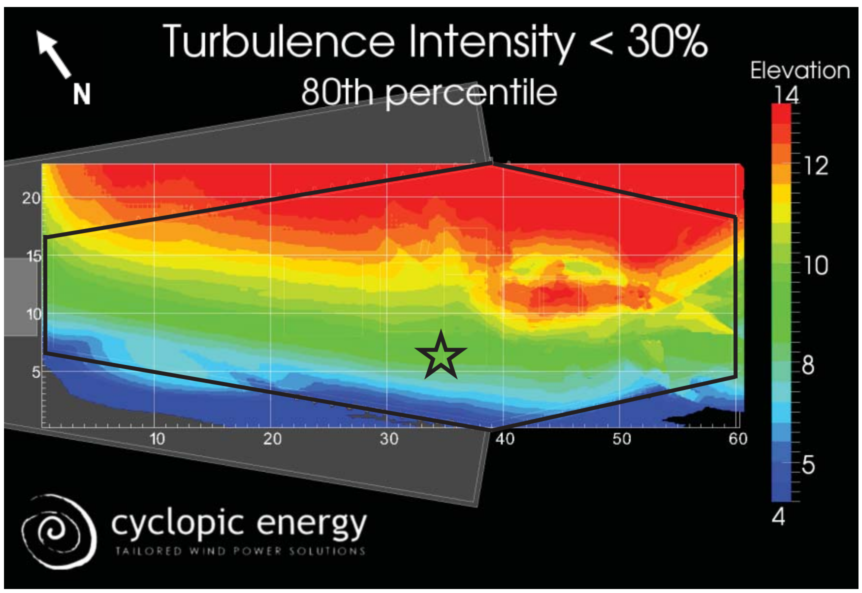

Figure 3.4: Required Height (m) above Roof to Avoid 30% Turbulence Intensity 80% of the Time [22]

[22] Source: modified from Cyclopic Energy. Used with permission.

3.1.4. Combined Effects

In order to determine the best location and height for a building-mounted wind turbine, the above considerations can be used in conjunction: recirculation zone, inflow angle, and turbulence intensity. Figure 3.5 shows the heights required to avoid the combined effects for 80 percent of the time. Green colored areas represent locations where complex flow effects drop off a few meters above the rooftop. These are contrasted with the red and orange areas, where complex flow conditions persist at higher heights. At the current turbine location, the rotor plane must be approximately 10 – 12 m (33 – 39 ft) above the roof surface to avoid all of these factors for 80 percent of the time. If the turbine was located on the northwest portion of the roof, the required height is decreased to approximately 8 – 10 m (26 – 33 ft). All locations on the roof require a tower height that is greater than the installed tower height.

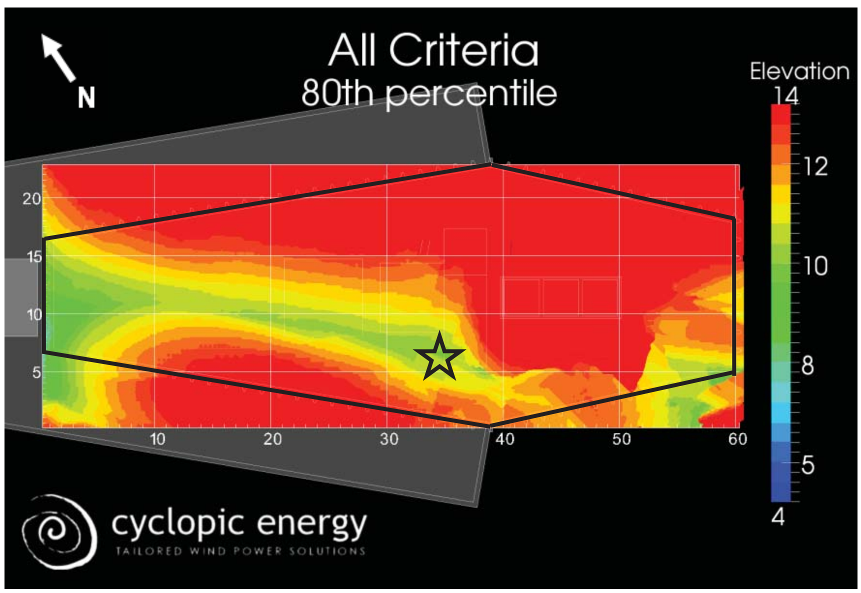

Figure 3.5: Required Height (m) above Roof to Avoid Combined Effects of Recirculation, Inflow, TI[23]

3.1.5. Effect of Ventilation

Ventilation shafts and other sources of forced air flow on a building's roof will affect turbulence and the recirculation zone, as illustrated by the previously discussed CFD model. On the Corning Tower, forced air flow from the building's ventilation system slightly increased the height of the recirculation zone above the building and decreased laminar wind speed on the rooftop. This implies that forced air flow has the potential to increase the amount of turbulence experienced by the turbine and to lower the wind speed at the turbine location, negatively affecting turbine performance. Nevertheless, these results are specific to the wind conditions, system configuration, and forced air flow at the Corning Tower, and may not apply to

[23] Source: modified from Cyclopic Energy. Used with permission.

other buildings. The effect of ventilation may have an impact on wind conditions and energy production, impacting turbine siting.

3.2. COMPARISON TO AEP AT OTHER LOCATIONS

As part of the case study, alternative scenarios were evaluated for comparison to the installed location of the SWIFT wind turbine to demonstrate how the same turbine technology may perform in different environments. Both practical scenarios and hypothetical scenarios were assessed for comparison. Based on AEP, the cost of energy was estimated for each scenario.

For comparison to the AEP at the installed location, AEP was estimated for the ideal location on the rooftop as indicated from the CFD results. This assessment ignored physical constraints that might preclude installation at this optimal location. A more practical scenario was also evaluated for the best location on the roof at which installation of the turbine would be physically feasible considering the current geometry and uses of the roof.

Flow effects from the building geometry contribute significantly to energy losses. In order to quantify the effect of distorted flow on energy production, AWST simulated a hypothetical scenario without the building effects, only accounting for typical urban turbulence losses at the Corning Tower location.

3.3. ANNUAL ENERGY PRODUCTION (AEP)

3.3.1. Power Density

The CFD model generated by Cyclopic was used to determine the mean wind power density over the rooftop of the Corning Tower at different heights. Mean wind power density (*PD*), measured in W/m^2 is defined by the following formula:

$$PD = \frac{1}{2}\rho U^3$$

where ρ is the air density and U is the wind speed. Mean wind power density is a normalized measure of wind power. Figure 3.6 indicates that mean wind power density is greatest on the upwind side of the building in the northwestern corner. This is close to the location that was determined to be ideal with respect to inflow angle, turbulence intensity, and recirculation zones, and represents the location on the roof of the Corning Tower that is most likely to produce the highest energy output.

3.3.2. AWEA Rated Annual Energy for SWIFT 1.5 kW Turbine

For comparison, the AWEA rated annual energy was calculated for the SWIFT wind turbine using the manufacturer's power curve, dated June 2005, the most up-to-date publicly available power curve at the time of the analysis. There was no indication that this manufacturer's power curve or other power curves also found for the SWIFT wind turbine were derived according to the standard test conditions outlined in IEC 61400-12-1, which is necessary to ensure a uniform definition for calculating the AWEA rated annual energy. Because of this, there is some uncertainty in the calculated AWEA rated annual energy. Correspondence with the manufacturer revealed that the SWIFT turbine is currently undergoing power curve testing according to the specifications outlined in IEC 61400-12-1. When this power curve is released, there will be greater certainty in energy estimates for the SWIFT wind turbine and in the corresponding AWEA rated annual energy.

Using the 2005 power curve and assuming a Rayleigh distribution with a wind speed of 5.0 m/s (11.2 mph), the AWEA rated annual energy was determined to be 3553 kWh.

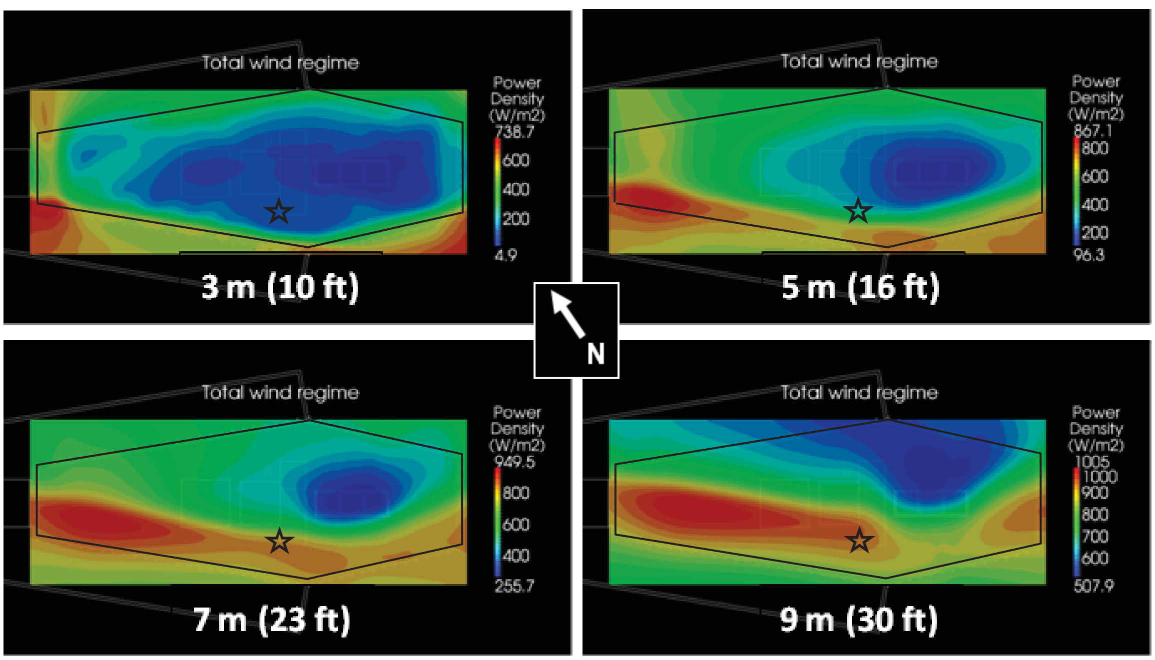

Figure 3.6: Mean Wind Power Density at 3 m (10 ft), 5 m (16 ft), 7 m (23 ft), and 9 m (30 ft) above the Rooftop [24]

[24] Source: modified from Cyclopic Energy. Used with permission.

3.3.3. Existing Location: Expected AEP

Based on the results of the CFD analysis, Cyclopic estimated the annual energy output from the turbine for the rooftop of the Corning Tower. Annual energy production estimates were computed using the SWIFT 1.5 kW turbine's power curve. The estimated annual energy production for two vertical cross sections of the CFD model are shown in Figure 3.7 and Figure 3.8. These cross-sections are from the perspective of a horizontal view across the roof's surface along the long and wide axes of the building, respectively. The turbine's location and rotor diameter are illustrated by the gray circle in the figures.

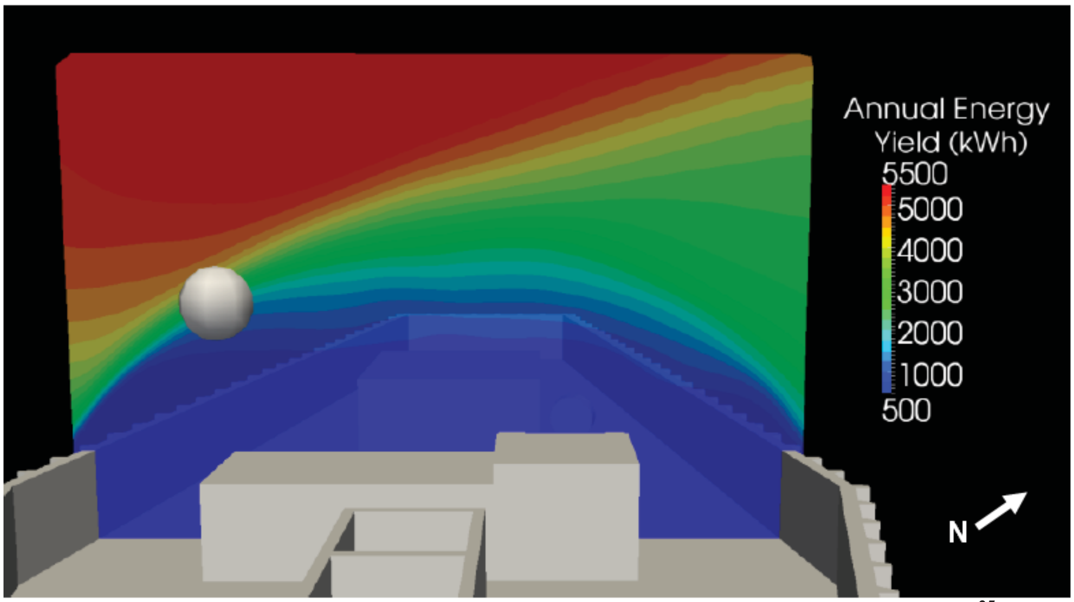

Figure 3.7: Estimated Annual Energy Yield for the Corning Tower Rooftop (1) [25]

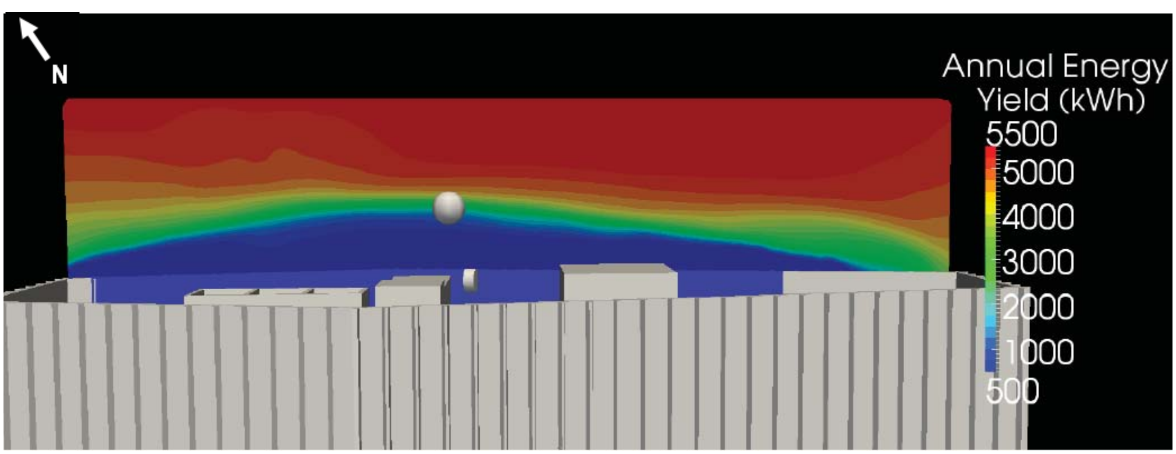

Figure 3.8: Estimated Annual Energy Yield for the Corning Tower Rooftop (2) [26]

[25] Source: Cyclopic Energy. Used with permission.
[26] Source: Cyclopic Energy. Used with permission.

As illustrated in Figure 3.7, the turbine's rotor diameter spans a large range of annual energy yield values, implying that the turbine is sited directly within the region of greatest wind shear. Due to variations in the wind speed across the rotor plane, the energy production is more likely to be represented by the contours at the lower portion of the rotor diameter. Using the manufacturer's power curve, which is valid for ideal conditions at the existing location, the SWIFT 1.5 kW wind turbine's gross annual energy estimate is approximately 1,000 kWh per year, corresponding to 28.1 percent of the AWEA rated annual energy. Because this energy estimate does not account for complex wind conditions on the rooftop such as increased turbulence, greater shear gradient, and inclined flow, this value is greater than the energy that could practically be expected at the site. The magnitude of the effect of complex flow on energy production is difficult to estimate. Data from building-mounted wind installations is limited, and complex flow is likely to vary significantly from site to site and across a rooftop depending on wind resource characteristics, building geometry, and location on the rooftop. This is discussed in more detail in Chapter 5 of the report. As a rough estimate, AWST considers that these effects may result in an energy decrease of 30 to 70 percent. A middle value of 50 percent was applied to account for the effect of complex flow on turbine performance. The adjusted energy production estimate results in an approximate annual energy estimate of 500 kWh, corresponding to 14.1 percent of the AWEA rated annual energy.

3.3.4. Existing Location: Availability-Corrected AEP

Actual production data from the turbine was collected to compare with results from the CFD model. Data provided from the New York State Office of General Services indicates that 397 kWh were generated between April 30, 2009 and April 29, 2010. During this period, there were 54 days of system downtime, corresponding to an availability of 85 percent. After correcting to 100 percent availability, the turbine's equivalent annual energy production would be 467 kWh per year, corresponding to 13.1 percent of the AWEA rated annual energy for this period of record. This is close to the above annual average energy estimate of 500 kWh per year from the CFD model.

This comparison does not consider how inter-annual variability in the wind conditions may have affected the installed system's energy production during the period of data collection. Wind conditions such as average speed, direction, and frequency distribution during the period of data collection may differ from the historical average wind conditions at the site. Using the windTrends data set, the wind speed during the turbine's operational period was approximately 1.1 percent lower than the long-term estimate, indicating that variability in the wind speed was not a significant factor affecting actual production when comparing to the coarse resolution of the presented energy production estimate.

3.3.5. Optimal Locations on Corning Tower

Results from the CFD analysis reveal the locations on the Corning Tower's roof that are likely to be optimal for a building-mounted wind installation. From Figure 3.7 and Figure 3.8, AWST estimated annual production at two additional locations on the Corning Tower's roof: (1) the best practical location based on the current geometry and uses of the roof, and (2) the ideal location, which ignored physical constraints.

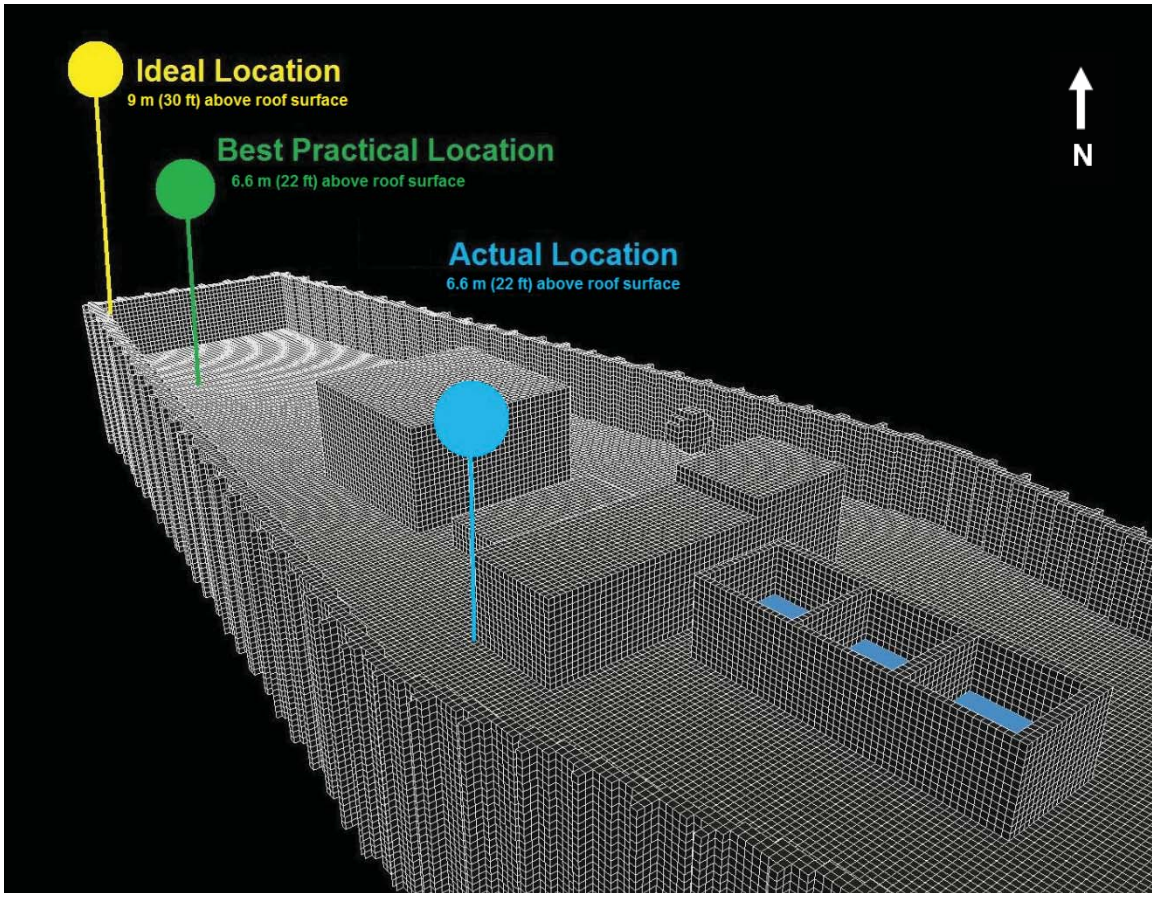

Figure 3.9: Ideal, Best Practical, and Actual Locations for Building-Mounted Turbine Installation [27]

3.3.6. Best Practical Location: Expected AEP

Considering physical constraints and current uses of the roof, the best practical location for siting a building-mounted wind turbine would be as close to the ideal location as possible. The track for window cleaning 1 – 2 m (3 – 6 ft) from the edge of the wall and the additional equipment adjacent to the westernmost portion of track limit these areas for turbine installation. The best practical location is likely in the same general area on the west side of the building and as close to the window cleaning track as possible on the south side of the building, as illustrated in Figure 3.9.

[27] Source: modified from Cyclopic Energy. Used with permission.

Although more research may be necessary to determine how city ordinances and engineering constraints might limit the tower height, AWST assumed that the tower would be 6.6 m (22 ft) above the rooftop's surface, consistent with the existing design. Based on the CFD analysis, gross energy production for this location would be approximately 2,500 kWh per year. Applying a 50 percent loss factor, the middle value as discussed in Section 2.3.2.2., the net energy production estimate for this location would be roughly 1,250 kWh per year, corresponding to 35.2 percent of the AWEA rated annual energy. This is more than twice the expected energy production of the turbine at the existing location.

3.3.7. Ideal Location: Hypothetical AEP

Based on the contours in Figure 3.7 and Figure 3.8, it was determined that the ideal location for a small wind turbine installation would be the western corner of the building as illustrated in Figure 3.9. Ideally, the turbine would be sited high enough for most of the recirculation, turbulence, shear, and inclined flow effects to be minimized, approximately 9 m (30 ft) above the rooftop's surface (this is approximately 2.5 m/8 ft higher than the installed height of 6.7 m/22 ft). At this location, the gross energy production would be approximately 5,000 kWh per year. Since complex flow conditions are expected to be less extreme at the ideal location than at the actual location, AWST applied a 40 percent loss factor, which is the low-end value of the 30 to 70 percent range. After applying this loss factor, net energy production would be approximately 3,000 kWh corresponding to 84.4 percent of the AWEA rated annual energy.

This hypothetical site ignores physical constraints. A track for window cleaning runs around the perimeter of the rooftop, limiting the ability to site a permanent tower in the westernmost corner of the building. Installing a 9 m (30 ft) tower above the roof may not be structurally feasible and may conflict with city ordinances for roof-mounted structure heights.

3.3.8. Existing Location: Hypothetical AEP with Building Effects Removed

Flow effects from the building geometry contribute significantly to energy losses. In order to quantify the effect of distorted flow on energy production, AWST simulated a scenario without the building effects, only accounting for typical urban turbulence losses at the Corning Tower location. The simulation approximated wind conditions at the turbine height of 184 m (604 ft) by using the log law to extrapolate the modeled windTrends data to the hub height, resulting in an annual average wind speed of 8.4 m/s (18.8 mph). Although some uncertainty exists in shearing the wind speeds to this height,[28] it provides a reasonable estimate for unobstructed wind speeds. The estimate assumed that the turbine was tower-mounted instead of building-mounted, removing flow distortion effects from the analysis. Gross annual energy for this scenario was projected to range from 5,700 to 6,300 kWh (middle value of 6,000 kWh), corresponding to a range of 160.4 to 177.3 percent of the AWEA rated annual energy (middle value of

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[28] Some uncertainty exists when shearing to 184 m due to the changing height of the planetary boundary layer. These changes create instances where shear conditions may not follow the power-law assumption.

168.9 percent). After applying a loss factor of 30 percent to account for turbulence in an urban environment, the range is 3,990 to 4,410 kWh (middle value of 4,200 kWh), corresponding to a range of 112.3 to 124.1 percent of the AWEA rated annual energy (middle value of 118.2 percent).

To provide a relative comparison in performance, the gross and net energy estimates (middle values) were compared for the Cyclopic contour plot scenario that accounts for building effects and the hypothetical scenario without building effects (see Table 3.1). The gross energy comparison reflects the hypothetical difference in wind conditions for the two scenarios. The net energy comparison reflects additional losses for turbulence intensity and inflow angle due to building effects.

Table 3.1: AEP with and without Building Effects

Scenario	With Building Effects	Without Building Effects
Description	Energy at as-built location from Cyclopic Contour Plot	Hypothetical energy without building effects
Gross AEP (kWh)	1,000	6,000
Overall Loss (%)	50%	30%
Net AEP (kWh)	500	4,200

The gross energy production estimates in Table 3.1 indicate that wind flow and consequently potential energy production is significantly affected by building effects from the Corning Tower. The decrease in gross energy for the building-mounted scenario is a result of decreased average annual wind speeds. The results imply that 80 to 90 percent of the energy available at the site may be lost due to building effects.

Annual Energy Production (AEP) values for the hypothetical and actual scenarios described above are summarized in Figure 3.10. Hypothetical scenarios are shown in Figure 3.10 as purple bars.

3.3.9. Energy Comparison

The AEP for the five scenarios described in this chapter are compared in Figure 3.10. Hypothetical AEP at the ideal location on the Corning Tower and at the installed location without building effects is many times greater than the estimated AEP and actual AEP at the installed location. Although a sufficient wind resource may be available above the rooftop to reach a hypothetical AEP of over 4,000 kWh, practical siting constraints and losses associated with complex flow from building geometry limits the actual energy that can be harvested from a building-mounted wind turbine, with actual AEP anticipated to be less than 1,300 kWh. These results draw attention to the risks associated with a building-mounted wind project and highlight the importance of conducting a thorough site evaluation, including on-site measurements and/or CFD analysis, to determine the feasibility of the project prior to development.

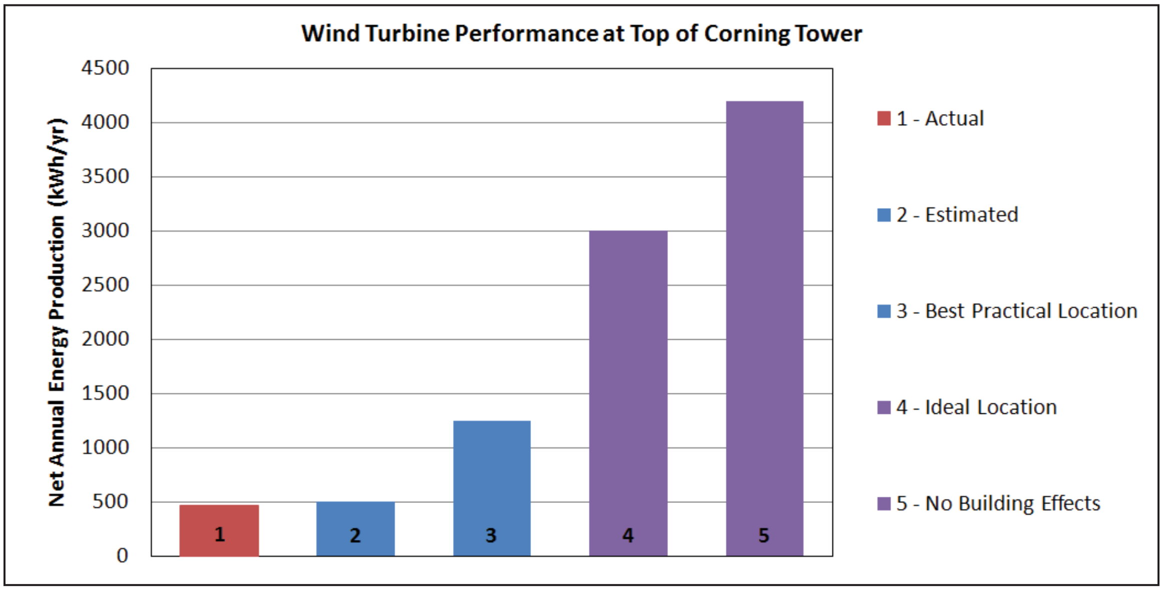

Figure 3.10: Summary of Annual Energy Production Statistics for Multiple Scenarios [29]

For comparison purposes, a high-level cost of energy (COE) analysis was conducted. The COE was computed assuming no government incentives, [30] an installed system cost of \$10,000, a system lifetime of 20 years, and an O&M cost of \$0.02 per kWh generated. [31] It was assumed that there would not be performance degradation over time and that energy production would continue to at the values in Figure 3.10 over the 20-year system life. This is a generous assumption, considering that performance degradation is likely, especially in an environment with a large degree of complex flow. The LCOE calculation is presented below:

$$\mathrm{COE} = \frac{\$10{,}000}{20\ years\ \times AEP\ kWh\ per\ year} + \$0.02/kWh$$

As shown in Table 3.2, results from the COE analysis indicate that the cost of energy from building-mounted wind installations may be greater than \$0.40 per kWh. This is much greater than electricity retail rates in New York State, which are approximately \$0.15 to \$0.20 per kWh.

[29] Source: AWS Truepower, LLC.
[30] Government incentives affect economics by reducing the system's cost, lowering the cost of energy for the turbine owner.
[31] An estimated system cost of \$10,000 is based on a review of internet data for the SWIFT 1.5 kW turbine. The O&M cost assumption is based on AWST's experience.

Table 3.2: Net AEP and Cost of Energy

Location/Scenario	Net AEP (kWh/yr)	COE ($/kWh)
1 - Actual	467	$1.09
2 - Estimated	500	$1.02
3 - Best Practical Location	1,250	$0.42

3.4. RESULTS FROM RECENT BUILDING-MOUNTED WIND STUDIES

Recent building-mounted wind studies conducted in the United States and the United Kingdom provide a useful comparison to the results of the Corning Tower wind turbine case study. Summaries of three recent studies are provided below to bring to light common observations for building-mounted wind turbines.

3.4.1. Results from Warwick Wind Trials Project.

During 2007 and 2008, Encraft Ltd. (Encraft) conducted a performance assessment on 26 building-mounted wind turbines installed throughout the United Kingdom.[32] This study, known as the Warwick Wind Trials Project, was intended to assess the performance of a range of building-mounted wind technologies installed on a variety of building types. Average wind speed and energy output data were collected every ten minutes at the 26 sites and downloaded manually. Following the period of data collection, Encraft assessed the results to determine if measured wind speed and energy production matched the expected values, and to quantify operational metrics such as capacity factor and energy consumptions for the turbines.

As a fleet, the building-mounted wind turbines in the Warwick study exhibited less-than-expected performance. The two major contributors to this were determined to be "the accuracy of wind speed predictions in an urban environment and the accuracy of manufacturer supplied power curves." The average availability-corrected energy production was of a similar order of magnitude as that for the Corning Tower wind turbine. These results show that the performance of the Corning Tower's wind turbine is generally consistent with the experience of other building-mounted wind turbines.

Turbines in the Warwick study were evaluated for reliability. Some turbines experienced minor reliability problems with inverters, control boxes, and moisture ingress into the turbines. The most serious failures were those that had the potential to create a public safety risk: two of the 26 turbines in the study had blade failures, and one exhibited a tail failure.

As a result of the Warwick study, Encraft determined the following:

[32] Encraft's final report is publicly available at http://www.warwickwindtrials.org.uk/resources/Warwick+Wind+Trials+Final+Report+.pdf.

- Careful siting of building-mounted wind turbines is required
- Research is necessary to more accurately characterize the wind resource in urban environments
- Adherence to a uniform standard is needed when deriving power curves for building-mounted wind turbines.

The results of the Warwick study align with AWS Truepower's expectation based on the Corning Tower wind turbine case study, and in-house experience. Wind speeds in urban environments have the potential to be lower than those predicted by modeled data sources (i.e., wind maps) due to constant disruptions to the wind's flow from buildings in the urban setting. These flow disruptions also contribute to complex flow. As most wind turbines and manufacturer power curves are designed for ideal flow conditions, less-than-expected performance is not surprising. Complex flow also induces greater fatigue loads on wind turbine blades, which may result in premature component failures, such as blade and/or tail failures.

3.4.2. Results from Boston Museum of Science Study

A building-mounted wind study conducted by the Museum of Science in Cambridge and Boston, Massachusetts confirmed that energy output is strongly tied to appropriate turbine siting. In 2009, the Boston Museum of Science installed nine building-mounted wind turbines from five different manufacturers on the roof of the museum, ranging from 1 to 6 kW in size.[33] Although the installations were primarily intended to serve as a museum exhibit to stimulate public interest in renewable energy, the Museum of Science also collected power generation data and analyzed the energy output of each turbine. Prior to installation, the Museum of Science conducted a feasibility study, which included a year's worth of wind speed data from six anemometers sited at various locations on the museum roof. The anemometer data was correlated to data from the nearby Logan International Airport to estimate long-term wind conditions and was used to select the types of turbines that would be installed.[34] In the following months, ten-minute wind speed and power data were collected for each turbine. These ten-minute data were compared to the manufacturer-published power curves to assess turbine performance.

The results of this study showed that actual energy production was less than the preconstruction estimates. Between October 2009 and October 2010, the Museum of Science stated that the turbines collectively produced only 30 percent of the expected energy.[35] The difference between expected and actual energy output was attributed to the variability of wind patterns over the building, and equipment failures. According to Wind Turbine Lab Analyst Marian Tomusiak, four of the five turbine models experienced

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[33] Source: *Guide to the Museum of Science Wind Turbine Lab* (June 2010). Retrieved July 2011 from Museum of Science website http://www.mos.org/media/docs/MOS_Wind_Lab_Overview.pdf

[34] Source: Museum of Science and Boreal Renewable Energy Development. *Feasibility Study for Wind Turbine Installations at Museum of Science* (October 2006). Retrieved July 2011 from Museum of Science website http://www.mos.org/media/docs/MOS_Boreal_Renewable_Wind_Study.pdf.

[35] Source: boston.com. *Wind Turbines at Boston's Museum of Science Produce less Electricity than Expected* (February 9, 2011). Retrieved July 2011 from boston.com website http://www.boston.com/yourtown/news/downtown/2011/02/wind_turbines_at_bostons_museu.html.

reliability issues, including a broken tail shroud on one turbine, mechanical problems at others, and multiple inverter issues. None of the observed reliability issues created a public safety risk.

Although each of the five models produced less energy than expected, some turbines performed better than others. Two models correlated well with the manufacturer-published power curves, and one of these achieved 92 percent of its rated power at 12 m/s (27 mph). The other three models performed much lower than expected, with actual power output significantly lower than the manufacturer-published power curves, affecting the total performance of the group. For one of the underperforming turbines, a CFD analysis was conducted to evaluate wind flow conditions over the roof at the installed location. This revealed that this turbine was located within a recirculation zone, which most likely contributed to the difference between expected and actual energy production for this turbine. The CFD analysis showed that energy output likely would have been greater if the turbine had been installed three feet higher and 15 feet closer to the edge of the building on the prevailing wind side. The results of this study confirm that building-mounted wind turbine performance is highly dependent on turbine reliability and the selected location on the building.

3.4.3. Results from BRE Trust Laboratory Study

A study was conducted by the BRE Trust Laboratory in Watford, United Kingdom to assess wind flow conditions over rooftops in order to support optimal building-mounted wind turbine siting. Using wind tunnel tests and subscale models, the study simulated wind conditions over flat-roofed buildings ranging from 15 to 80 m (49 to 263 ft) in height. Wind conditions were simulated for a variety of incident angles. Wind speed data over the surface of the building models were collected by strategically located hot wire anemometers. The results of the wind tunnel simulations were applied to devise general best siting practices for building-mounted wind turbines. The study was summarized in the publication *Building Mounted Micro-Wind Turbines on High-Rise and Commercial Buildings* (Paul Blackmore, BRE, 2010).

The study confirmed that wind conditions close to the roof's surface tend to be turbulent. Since smooth flow conditions almost never occur within built environments, the study sought to characterize the locations over roofs where turbulent wind conditions would be less prevalent. These were expected to be the optimal siting locations for building-mounted wind turbines because it was assumed that the level of complex wind flow corresponded to reduced energy output.

The study concluded that the building height influenced how wind flowed around and over the building. While wind flow was forced to accelerate by up to 20 percent over the roof of the shortest building model (15 m/49 ft), this effect was almost unnoticeable for taller building models, presumably where wind was more likely to travel around the sides of the structure. For both taller and shorter buildings, the turbulence intensity was largely unaffected at the leading edge of the building, but increased significantly across the roof downwind from this location. This was especially the case for taller buildings.

Building dimensions were also shown to have an influence on the height and length of the region of recirculation. The building's height appeared to be the most significant parameter: the recirculation zone tended to be lower on an absolute (m) basis for shorter buildings. Conversely, the free-stream wind speed is expected to be greater at the height of taller buildings due to the effect of surface roughness-induced wind shear, which may imply a greater energy production potential, assuming the recirculation zone can be avoided.

The ideal siting locations were determined to be those with a high mean wind speed and low turbulence intensity, therefore necessarily outside of the recirculation zone. When wind flow was orthogonal to the building's leading edge, the center of the roof experienced the highest levels of turbulence and the lowest wind speeds, implying that the center of the roof is generally a poor location to site a turbine in these wind conditions. For skewed wind directions (i.e., 45 degrees offset from orthogonal), the center of the roof seemed to have relatively higher mean wind speeds and lower turbulence, implying that siting a turbine here would be more favorable in skewed wind conditions.

The study assumed that the acceptable height to mount a turbine was the height at which the mean wind speed and turbulence intensity had recovered to within 10 percent of their free-stream values.[36] Although this height varied somewhat with building height and wind direction, wind speeds generally reached 90 percent of the free-stream wind speed at a height of 7-to-9 percent of the building's height, while turbulence intensity typically reached 110 percent of the free-stream turbulence intensity at a height of 12-to-17 percent of the building's height. Therefore, the study suggested that wind turbines should be sited at a minimum height of 10 percent of the building's height, with a recommended height of 15 percent of the building's height, taking the rotor diameter into consideration for turbines with a rotor diameter greater than 2 m (7 ft).[37]

The report commented that "inappropriate siting of the turbines can lead to installations that do not realize their full potential, resulting in severely limited power generation possibilities." The results of this study, combined with the experience of the Warwick study, the Boston Museum of Science study, and the Corning Tower wind turbine, reinforce that careful siting is critical to achieving maximum energy output from building-mounted wind turbines and should be carefully evaluated prior to installation.

[36] Given the cubic relationship between wind speed and power output, a 10 percent reduction in wind speed corresponds to approximately a 27 percent reduction in power output.
[37] For example, a 20 m (66 ft) building would result in a minimum height of 2 m (7 ft) and a recommended height of 3 m (10 ft) above the roof.

4. BENEFITS AND CHALLENGES OF BUILDING-MOUNTED WIND

This section discusses benefits and challenges associated with building-mounted wind turbines. Based on the results from the CFD model for this case study and general industry knowledge, some general observations for building-mounted wind are discussed. In order to properly site building-mounted wind turbines and maximize energy production, the following observations can be applied to evaluate potential installations.

4.1. BENEFITS OF BUILDING-MOUNTED WIND

Building-mounted wind offers some unique advantages as a renewable energy technology. As a form of distributed generation, building-mounted wind turbines can be installed at the consumption point, eliminating the need to transport energy from the generation point to the end user. The opportunity to install building-mounted wind turbines is great, as there are many buildings in urban environments that may be suitable for installation from an architectural standpoint. Building-mounted wind presents a solution to the need for distributed renewable energy generation in urban environments. The benefit of a building-mounted wind turbine depends on effective system performance, which is supported by careful turbine siting. Building-mounted wind will offer the greatest benefit if losses from complex flow conditions can be minimized. Marginal energy output minimizes the contribution of building-mounted wind to meeting the need for distributed renewable energy generation.

4.2. CHALLENGES OF BUILDING-MOUNTED WIND

Despite the potential benefits, there are some considerable challenges that will need to be overcome for building-mounted wind to be considered a feasible renewable energy generation option. These are characterized in the following list:

- Wind resource assessment – as wind conditions on rooftops are generally very turbulent, there is a great degree of variation in wind conditions even across the rooftop of a single building. This makes it difficult to characterize expected wind flow using traditional approaches. For example, on-site monitoring with traditional anemometry may not adequately characterize the complex flow over a rooftop, as these sensors are generally designed to measure horizontal wind speed. CFD modeling can help to characterize wind flow at the top of a building; however, this analysis is often too costly to consider for most building-mounted small wind turbine applications since the expense may represent a significant fraction of the cost of the turbine itself. There is uncertainty associated with estimating rooftop wind conditions by adjusting higher atmospheric wind data to typical hub heights for building-mounted wind systems.
- Energy estimation – wind turbines are generally designed to operate most efficiently in ideal wind conditions. Since conditions over building rooftops typically are associated with increased turbulence, shear, and inclined flow, it is difficult to quantify actual energy production of a wind turbine in this environment. This, along with the difficulty in characterizing the wind resource at

rooftop sites, results in a greater degree of uncertainty when making preconstruction energy estimates.

- Performance and reliability in complex wind conditions – the high degree of turbulence, recirculation, inclined flow, and shear associated with building-mounted wind sites may limit energy production and may contribute to premature failure of turbine components due to increased fatigue loading.
- Safety – multiple safety considerations exist for building-mounted turbine installations, as the turbines are usually sited in an urban environment. The likelihood of failure is increased by the greater amount of turbulence at building-mounted sites. In order to reduce the effects from turbulence, inflow angle, and the recirculation zone, the tower height must be increased or sited closer to the edge, which results in increased safety concerns. Engineering analysis is necessary to make sure that the building's rooftop is capable of supporting the combination of static and dynamic loads induced by the building-mounted wind turbine over its lifetime. Other health and safety considerations may include noise and vibration from building-mounted wind turbines.
- Permitting requirements – in order for a building-mounted wind turbine to be sited above the most significant portion of the recirculation zone, it must be mounted at a hub height that may not be in conformance with city permitting requirements and may limit the height of roof structures. Other city requirements such as noise restrictions and safety concerns such as structural loading and vibrations (particularly for larger systems) may also pose a siting concern.
- Economics – Uncertainty in estimation of AEP makes investment in a building-mounted wind system a financially risky undertaking for the consumer. Although this uncertainty can be reduced by the collection of wind resource data and CFD modeling, the costs of these activities may be greater than would be warranted when compared to the cost of a building-mounted wind system. Because of complex flow conditions, building-mounted wind systems may exhibit lower energy production than expected, contributing to a higher cost of energy than estimated prior to construction.
- Untested technologies – although there are numerous building-mounted small wind turbine manufacturers, many of the building-mounted wind systems have not yet demonstrated adequate performance and reliability in field-tested applications. Many building-mounted wind technologies are new to the market and have not yet received industry acceptance as high-quality equipment.

4.3. SUMMARY

The performance and safety risks associated with building-mounted wind turbines, such as difficulty determining wind resource conditions and estimated production, the difference between expected and actual energy production, and premature turbine failure due to high levels of turbulence are significant and must not be ignored. These considerations may detract from the technical and economic feasibility of building-mounted wind systems.

5. GENERAL SITING CONSIDERATIONS FOR BUILDING-MOUNTED WIND

Based on the results of the Corning Tower wind turbine case study, the results of industry studies on building mounted wind, and experience with wind turbine feasibility, general siting considerations are outlined in this section. These factors are recommended for consideration when siting a building-mounted wind turbine in order to minimize the effects of non-ideal wind conditions and to maximize energy production potential.

5.1. WIND RESOURCE ASSESSMENT CAMPAIGN

Wind resource assessments can provide insight into wind conditions on the top of a building before a small wind turbine is installed. In some cases, a year of data from sonic and/or cup anemometers placed at strategic locations on the rooftop may help to quantify the wind resource and to assist in characterizing the flow on top of the building. Wind flow can be further characterized by implementing CFD modeling techniques to predict wind conditions at the site. However, both onsite monitoring with anemometers and CFD modeling may be too costly compared to the overall cost of the building-mounted wind system to be economically feasible. Regardless of the level of assessment undertaken, building-mounted wind projects represent a major investment risk, since wind conditions at a proposed site are usually very unpredictable, but the cost of quantifying these conditions is not trivial and still does not mitigate all risk of underperformance.

5.2. SURROUNDING ENVIRONMENT

The environment surrounding the building-mounted wind turbine affects the performance of the system. Trees, foliage, and other nearby buildings can contribute to decreased wind speeds and turbulent winds at the turbine location. The region of turbulent flow is approximately twice the obstacle height and persists horizontally for roughly twenty obstacle heights. Wind flow through urban and suburban environments is significantly more turbulent than flow through rural environments that have uniform surface roughness (see Figure 5.1). The magnitude of this effect will be mostly dependent on the height of the building-mounted wind turbine relative to the surrounding trees and buildings. An ideal building-mounted wind turbine location is recommended to be clear of upwind buildings or structures in the predominant wind directions.

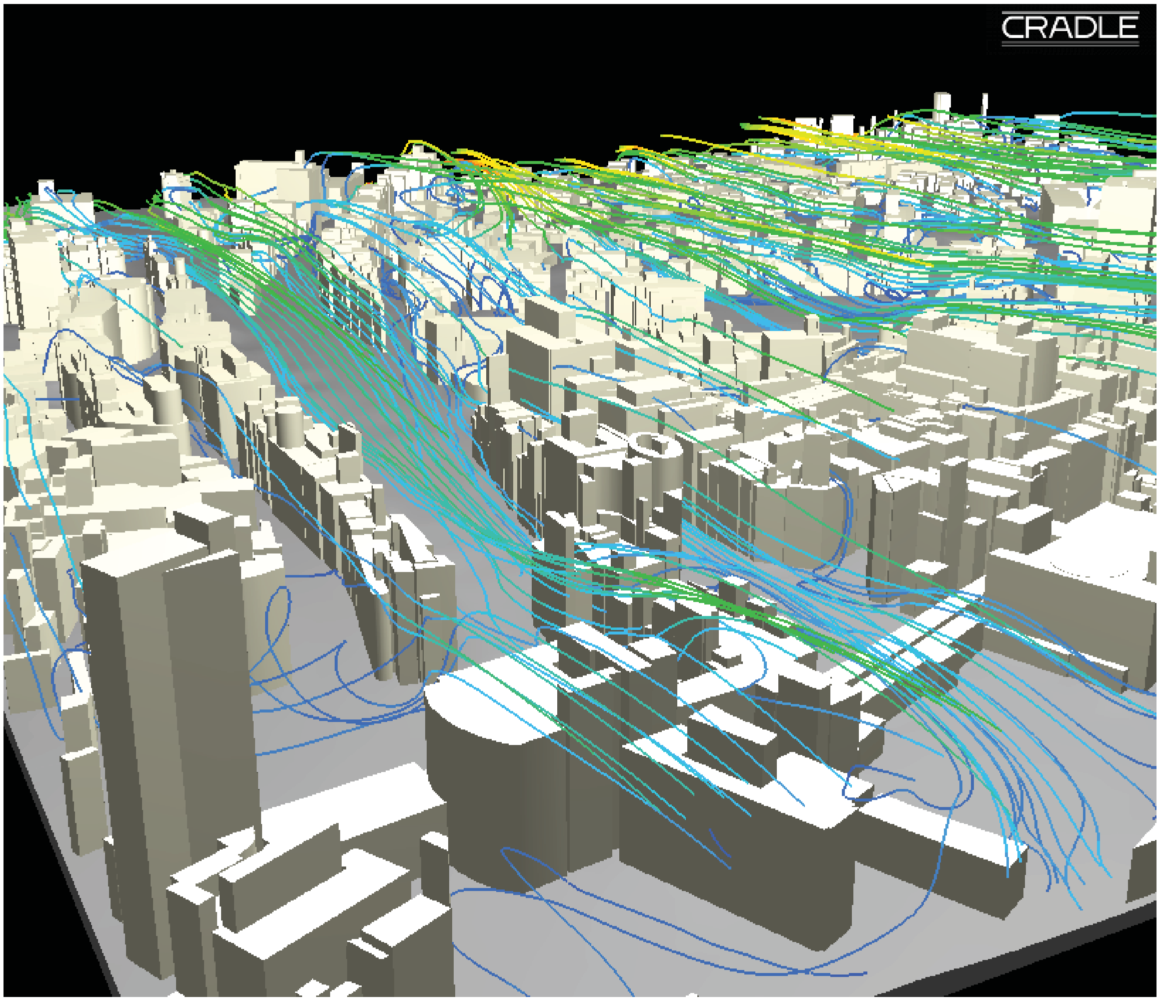

Figure 5.1. Simulated Wind Flow through Urban Environment [38]

5.3. BUILDING SIZE

Building height influences the amount of turbulence the building-mounted small wind turbine experiences from the surrounding environment. As discussed above, turbines mounted on taller buildings are less likely to experience waked flow resulting from shorter buildings. Wind speeds tend to be greater at heights farther above the ground due to surface roughness-induced wind shear. An ideal building will be tall enough to avoid the region of turbulent flow from nearby structures and to access higher wind speeds. Conversely, the height of the recirculation zone may be greater for taller buildings, as indicated from the results of a 2010 study conducted by the BRE Trust Laboratory. This is described in more detail in section 3.4.3.

The width of the building influences the amount of turbulence experienced by building-mounted wind turbines. Air flow around and atop wider buildings creates proportionally greater recirculation areas around

[38] Source: Software Cradle Co., Ltd. Simulated using STREAM software. Used with permission.

and above the structure. The tower height may need to be increased for wide buildings to avoid off-horizontal flow and increased turbulence in the recirculation zone.

5.4. ROOF GEOMETRY

Roof shape and roughness will influence the wind's flow across the building. Complex roof geometry will increase the turbulence experienced by the building-mounted wind turbine. Flat roofs are likely prone to a greater recirculation effect than an angled roof. Angled roofs may guide the wind flow along the contour of the roof's shape and into the rotor plane, but may also cause wind to pass over the turbine depending on the wind's direction and the turbine's placement. The shape and orientation of the leading edge of the building with respect to the prevailing wind direction will influence the wind flow patterns over the roof.

Obstacles on the roof such as chimneys, smokestacks, walls, pillars, small towers, and communications equipment/antennas may further disrupt laminar wind flow, increasing turbulence experienced by the small wind turbine. Ideally, turbines are sited as far away from obstacles as possible, as is recommended for traditional tower mounted turbines. Obstacle size and geometric shape (e. g., round face vs. flat face) impact turbulence. While any obstacles on the roof have the potential to increase turbulence in the roof area and impact performance, obstacles of particular concern include those directly in front of or directly behind the turbine in the predominant wind directions, as the impact of these features is likely to be more significant.

5.5. LOCATION ON ROOFTOP

The location of the wind turbine on the rooftop will affect performance, as its location will determine the wind speed, inflow angle, and turbulence intensity experienced by the turbine. At the Corning Tower, for example, the expected energy at the best practical location was more than double the expected energy at the installed location. As eddies tend to be more prevalent on the leeward side of buildings, the leeward side is more likely to experience greater flow recirculation and turbulence, negatively affecting performance and turbine lifetime. Therefore, it is generally recommended that building-mounted turbines be sited on the windward side of the roof. The windward side of the building is determined from the prevailing wind direction over the course of the year. A second consideration would be to site the turbine far away from any roof features such as chimneys, smokestacks, walls, pillars, small towers, and communications equipment/antennas that would expose the turbine to wakes from these features when the wind is coming from the primary direction.

5.6. TURBINE TECHNOLOGY

Differing types of small wind turbine technologies may perform differently in building-mounted applications. Horizontal-axis wind turbines (HAWTs) are designed to convert horizontally flowing wind into electrical power. Since wind flow at the top of a building tends to be non-laminar and is not always horizontal, HAWTs may not be ideally suited for many building-mounted applications. Vertical-axis wind turbines (VAWTs) may be more capable of generating power from turbulent, recirculating air flows.

5.7. RECOMMENDED SITING PRACTICES FOR BUILDING-MOUNTED WIND TURBINES

AWST recommends the following siting practices for building-mounted small wind turbines:

- Conduct engineering and structural analysis to evaluate the capability of the building and rooftop to support the combination of static and dynamic loads induced by the building-mounted wind turbine over its lifetime
- Site turbines on the roof of buildings that are significantly taller than other buildings and foliage in the area
- Site turbines on rooftops with no or few obstacles that may cause waked wind flow and increased turbulence
- Site turbines as far away from any existing obstacles as possible, especially obstacles immediately in front of or behind the turbine when considering the prevailing wind direction
- Site turbines at a hub height that is greater than the height of the most significant portion of the recirculation zone above the rooftop
- Site turbines on the windward side of the building when considering the prevailing wind direction.
- Consider the effect of forced air flow if ventilation shafts exist on the roof
- Investigate the performance of differing types of building-mounted wind turbine technologies to determine which technologies perform the best in the complex wind conditions of a rooftop environment.

6. SUMMARY OF RESULTS

As building-mounted wind systems are receiving increased interest, NYSERDA commissioned AWST to conduct a case study for a building-mounted wind turbine in downtown Albany, NY. This case study analysis evaluated the performance of a building-mounted wind system in a real world environment.

The installed turbine, a SWIFT 1.5 kW machine, was sited on the south side of the hexagonal roof of the Corning Tower at a height of 6.6 m (22 ft) above the roof's surface. The results of a CFD analysis indicated that the wind turbine experiences complex flow conditions on the rooftop, including recirculation of airflow between the tower top's parapet edge, inclined wind flow as wind flow traverses over the top of the tower, steep shear gradients, and high levels of turbulence, along with disturbances from out-flowing air from the building's ventilation system. In AWST's experience, these conditions are likely to decrease system energy output and increase fatigue loading on the turbine, possibly decreasing the turbine's lifetime. This was confirmed by operational energy production data collected at the site, which totaled to an AEP of 467 kWh after adjusting for availability, implying that significant energy losses were associated with these complex flow conditions. Energy generated by the SWIFT turbine was estimated to cost more than a dollar per kWh. Furthermore, the results of the CFD energy simulation indicated that, although higher wind speeds may be present at the top of the Corning Tower, siting a building-mounted wind turbine in a practical location that is out of the zone affected by complex flow may be a challenge.

Based on the Corning Tower turbine case study, benefits and challenges associated with building-mounted wind were apparent. Benefits include the potential for distributed generation on many buildings in urban environments, where other sources of renewables may be less accessible. Challenges include the difficulty of characterizing wind resource and preconstruction energy estimates due to (1) the unique and site-specific nature of wind flow over a rooftop and (2) the difficulty assessing a turbine's response to these unique wind conditions. The uncertainty associated with characterizing the wind resource and preconstruction expected energy output above a rooftop may increase the investment risk and detract from the economic feasibility of building-mounted wind systems. While this risk may be mitigated by the deployment of anemometry at multiple rooftop locations and/or CFD analysis prior to installation, these prospecting costs may be significant when compared to the overall value of the energy obtained from a building-mounted wind turbine. From a technical perspective, most building-mounted wind technologies have yet to be field tested for performance and reliability, and have not yet received industry acceptance as high-quality equipment. Another challenge includes safety risks and the potential for premature turbine failures due to increased fatigue loading in the highly-turbulent urban building-mounted environment. Siting a turbine high enough to avoid the recirculation zone while still complying with city permitting requirements is an additional challenge that may be encountered.

As the surrounding environment and structural geometries may affect performance, general siting considerations for building-mounted wind systems were recommended. Following these siting practices will help to minimize avoidable energy losses for building-mounted wind systems. These are summarized below:

- A year or more of onsite data collection from strategically placed anemometers and/or CFD simulations prior to system installation will help to characterize the unique wind conditions over the roof and provide valuable information that can help with optimal turbine siting; however, when compared to the cost of the building-mounted wind system, these techniques may be too expensive to be economically feasible
- Roughness in the surrounding environment in the form of trees, foliage, and other nearby buildings will contribute to increased turbulence experienced by the building-mounted wind system. An ideal siting location for a building-mounted small wind system is upwind of and at a distance from these features
- Flow conditions vary significantly from rooftop to rooftop and at different locations across the same rooftop depending on building size and roof geometry. Exposure to complex wind conditions immediately above the roof can generally be minimized by siting the turbine as high as possible above the surface of the roof. A location on the windward side of the rooftop upwind of and as far as possible from features that may wake wind flow and increase turbulence is preferred
- Some wind turbine designs, such as vertical-axis wind turbines, may be more capable of converting more turbulent non-linear flow into electrical power. Since flow over most rooftops is inherent with non-laminar flow conditions, these may be preferable to other horizontal-axis wind turbines that are designed to convert horizontal flow into electrical power.

Although careful siting may help to minimize avoidable energy losses, both the Corning Tower case study and general industry knowledge imply that building-mounted wind has the potential for low energy output, safety and reliability concerns, and great financial and technical risk. These considerations may detract from the technical and economic feasibility of building-mounted wind systems. Pre-construction prospecting with onsite anemometry and/or CFD analysis, careful siting, and technological development will all contribute to optimal building-mounted wind turbine performance and to realistic expectations for building-mounted energy production.

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Case Study of the Performance of the Erastus Corning Tower Small Wind Turbine and Building-Mounted Wind Recommendations

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