Integrating Wind Energy into the Design of Tall Buildings – A Case Study of the Houston Discovery Tower

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Harvesting Wind Power from Tall Buildings

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Abstract
Integrating wind energy systems into building design is a small but growing trend, and high rises with their elevated wind speeds seem particularly suited to the technology. Designs that incorporate wind turbines are increasingly being seen on the drawing boards for skyscrapers across the globe. Leading the development of this fledgling field, wind engineers at CPP have evaluated the potential for wind turbine integrated buildings in both the U.S. and China. This paper will focus on a project conducted for the Discovery Tower in downtown Houston, TX, which is slated to break ground in early 2008.

Keywords: Small wind turbines, tall buildings, wind resource assessment

Introduction

Tall building designers are showing an increasing interest in reducing the environmental impact of the construction and operation of their buildings. One of the approaches currently used, is the incorporation of on-site power generation. This is primarily achieved by integrating solar and wind devices into the design of the building. One such example is the Discovery Tower, which is currently under construction in Houston, TX.

The requirements for optimizing the performance on wind generators in an urban environment are quite different from those pertaining to wind farms in open sites. This entails the use of different design approaches to assess the optimum placement of wind turbines within the building envelope, the most suitable generator types for the building environment, and to estimate annual energy production for the wind turbines.

This paper will examine aspects involved in wind power generation on tall buildings, and how those were specifically addressed for the Discovery Tower.

Wind climate

When contemplating the incorporation of wind power generation into a tall building design, the first consideration must be the local wind climate of the area. Bluntly, if there is not sufficient wind resource in the area, then the potential for successful use of turbines will be very limited.

Wind conditions in urban environments tend to be very different. The effect of urban environments on a boundary-layer is shown in Figure 1. This shows how buildings slow the wind near the ground, and increases turbulence. Turbines work most efficiently in low-turbulence environments; therefore care needs to be taken in specifying turbine types that will cope with both existing turbulence levels and potential future changes as a result of urban development.

Urban development is likely to pose one of the greatest challenges to increasing use of turbines on tall buildings. In city center locations, height restrictions often mean that many tall buildings are of similar heights. Even if a building is very tall, if all the surrounding buildings are of similar height then the potential for efficient turbine installation is significantly reduced.

Unlike rural wind farms, where the nearest anemometer may be located many miles away, most cities have reasonable lengths of records from nearby airports. This is not, however, to say these are necessarily good records. It is not uncommon to see anomalous directionality characteristics due to poor anemometer siting close to buildings. Wherever possible, records from multiple stations should be used. A rule of thumb is to use a minimum of 10 years of records to ensure statistical robustness. Trends are also sometimes apparent that don’t reflect climate changes, but are more often indicative of changing urban development close to the anemometer site.

In all cases, the first stage is to correct the data back to the equivalent of open-country exposure to simulate the readings that would be experienced in the absence of any development. There are a number of methods for doing this, and the approach codified by ESDU (1993a and 1993b) and based on the work of Deaves and Harris is among the most common.

In areas where available anemometer records are suitable to describe the local wind environment, a simple wind speed transfer approach can be utilized, as illustrated in Figure 1. In this approach, the wind speeds at the anemometer are extended to a gradient height (200 m to 600 m above grade), where the local terrain has little or no impact on the wind speeds, using a power law relationship. That same wind speed is then assumed to exist at the gradient height (which may not be at the same height above grade) above the site. The wind speeds are then transferred down to the site using either the power law with a site specific exponent, or by measuring the vertical velocity profile in an atmospheric boundary layer wind tunnel.

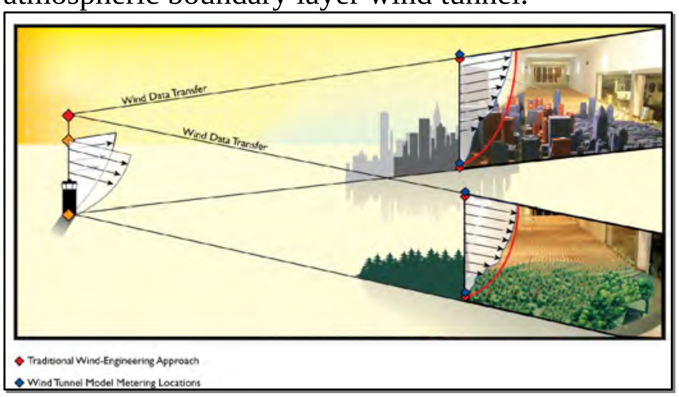

Figure 1: Transfer of Wind Speed from Hobby Airport to the Discovery Tower site

When there are no reliable anemometer records within a reasonable distance of the site, meso-scale modeling can be used to determine the wind climate of the area. This uses input from historical meteorological records from, maybe, hundreds of kilometers away to regenerate the weather systems affecting the site. This is an approach that is commonly used for rural turbine locations.

The directionality of the wind is also important. The incorporation of turbines into tall buildings tends to favor limited wind directions, perhaps within a 45 degree sector, depending upon the building configuration and the location of the wind turbines on the building.

Figure 2 shows the wind frequency distribution at the Hobby Airport in Houston, TX, while Figure 3 shows the alignment of the Discovery Tower. The wind turbines are located along the southwest side of the roof. The wind rose indicates that the predominant winds in Houston are from the SSE through S. The discovery tower is aligned such that the broad sides of the structure are along a SE to NW axis. As a result, the roof-top turbines are likely to be somewhat sheltered from the predominant winds, whereas the most favorable wind conditions for the turbines (winds from the SW) are fairly infrequent. As shown later on, this mismatch will significantly impact the wind energy potential for the roof top wind turbines.

Basic tall building aerodynamics

As discussed in the previous sections, it is desirable to locate turbines in regions of high wind speed and low turbulence. Describing the wind flow around a tall buildings can be quite complex and has been studied in depth for many years (Cermak, 1975 and 1976). A simplified sketch of the mean flow is shown in Figure 4. There will be positive pressure on the windward face and negative pressure on the side and leeward faces. As air naturally flows from areas of high pressure to areas of low pressure, the most effective locations for wind turbines will be either in the accelerated shear layers around the edge and top of the building, or in specially developed passages linking the areas of positive and negative pressure. Note that wind speeds close to the center of a flat roof may be low as this area is often in a region of separated flow. Whereas with a pitched or tiered roof, the center may be the location of the greatest wind resource.

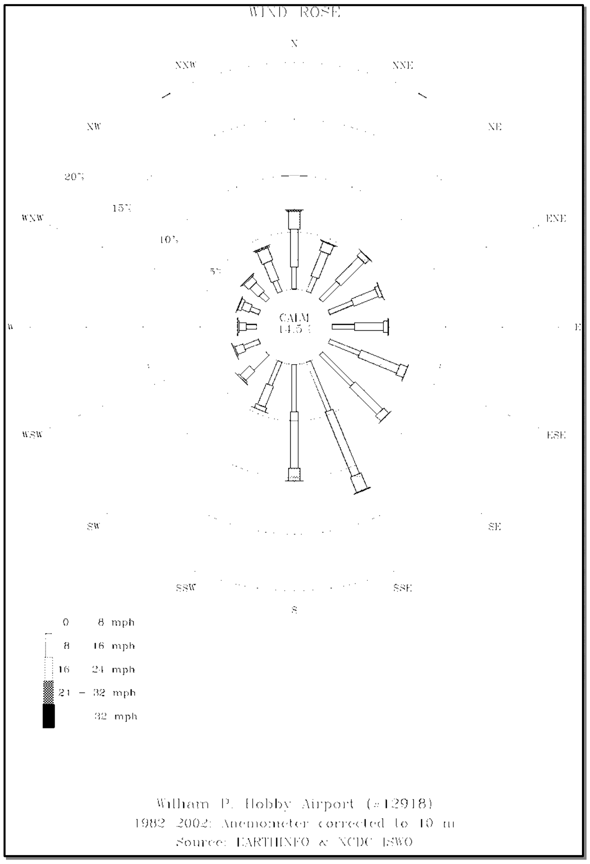

Figure 2: Wind frequency distribution at Hobby Airport, Houston TX.

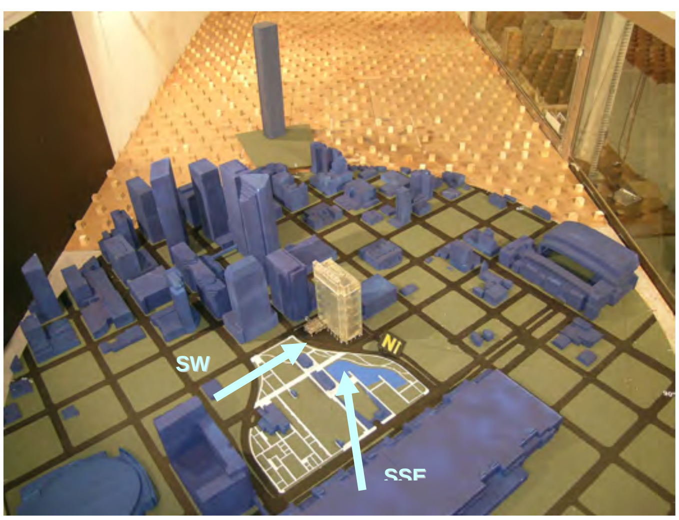

Figure 3: Alignment of the Discovery Tower in Houston, TX.

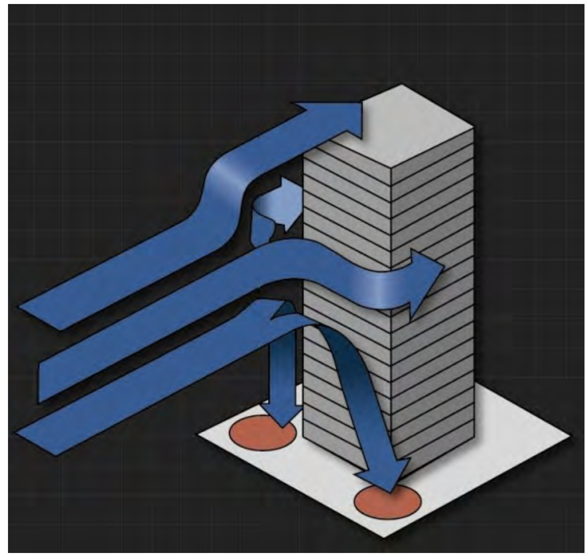

Figure 4: Wind flow around a tall building.

Shaping of tall buildings to increase efficiency of wind turbines

Shaping of tall buildings can be used effectively to enhance the performance of wind turbines. Two examples of this are the Bahrain World Trade Center (Figure 5) and the Pearl River Tower in China (Figure 6). The Bahrain World Trade Centre Tower is formed to create a Venturi effect, placing the horizontal axis turbines between two wings of the building. This approach clearly works for only a limited number of wind directions, but may be useful in a location with a very dominant prevailing wind direction. Restricting the orientation of horizontal axis turbines, however, severely limits the efficiencies gained from using this type of turbine. In the Pearl River Tower, slots through the tower are used to relieve the pressure between the front and rear faces of the tower with these slots being aerodynamically shaped to increase flow through them. Again, this approach is most efficient for only a few wind directions, but has the advantages accelerating the flow while likely reducing the turbulence approaching the turbines.

Wind Energy Potential

A physical model of the Discovery Tower and surroundings within a 450 m radius, shown in

Figure 3, was placed in an atmospheric boundary layer wind tunnel. The wind tunnel was used to characterize the wind environment on the tower roof, including any shielding or acceleration. The analysis included vertical wind profiles at four locations along the southwest end of the tower for 16 approach wind directions. Each profile was collected using a five-hole probe, shown in Figure 8, which is capable of measuring the mean wind vector and turbulence intensity values. The mean wind speeds were combined with the wind frequency distributions to determine the wind resource at each measurement location. The velocity vector and turbulence intensity values were used to determine the appropriateness of various wind turbine designs.

Figure 5: Bahrain World Train Center (Image courtesy of www.bahrainwtc.com)

Figure 6: Pearl River Tower (Image courtesy

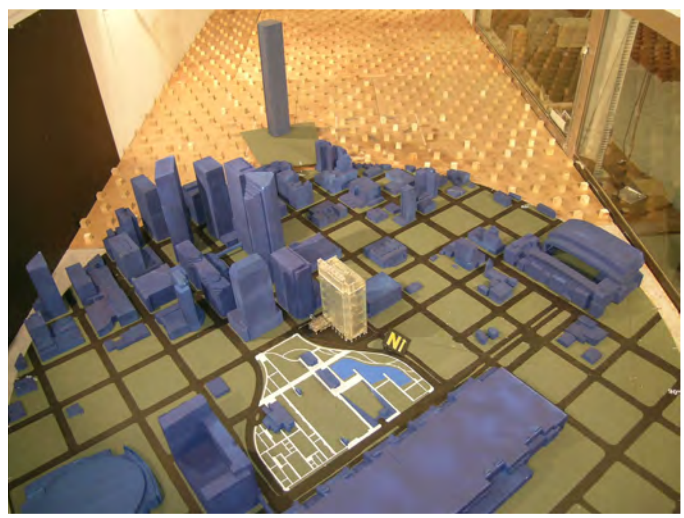

Figure 7 Photograph of the 1:300 scale model installed in an atmospheric boundary layer wind.

The mean velocity vector within each profile was used as the transfer value between the reference velocity at 152 m above grade (upwind and outside of the effects of the local buildings) and the local wind speed. For profiles with little or no local shear, the average value accurately represents the wind environment across the entire turbine rotor. In areas with high shear, this value may be less valid. A more accurate wind speed is obtained by integrating the wind speed vertical distribution. However, since information on the impact of the vertical shear is not available from most turbine manufacturers, the average wind speed was used to characterize each profile. Figure 9 shows the distribution of the normalized mean wind speeds (the ratio of the local wind speed with (U_{mean}) and without (U_{ref}) the presence of the building) at each of the four measurement locations as a function of the approach wind speed.

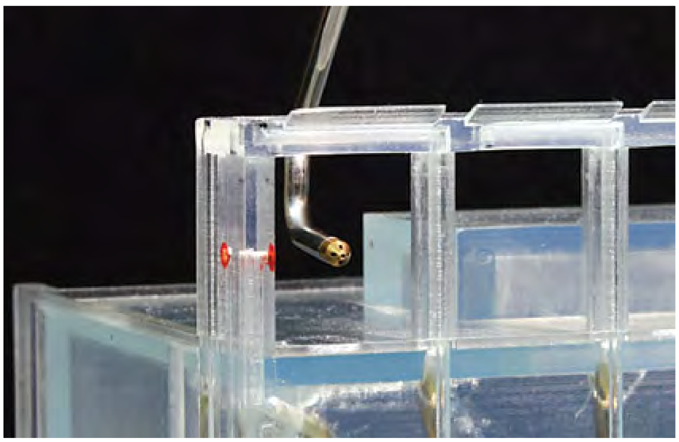

Figure 8: Close-up of the roof showing the 5-hole probe used to measure local wind velocities.

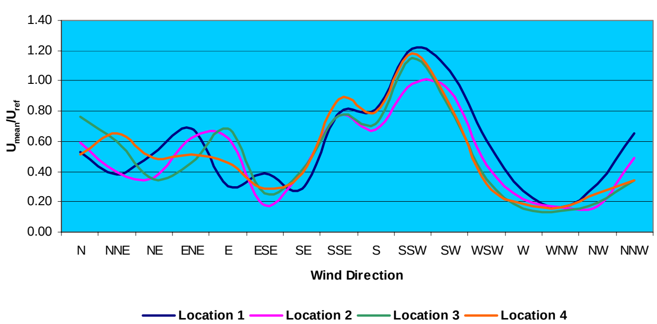

Figure 9: Mean longitudinal wind speed distribution vs. approach wind direction

The results indicated that there is accelerated flow (U_{mean}/U_{ref} greater than unity) on the roof of the Discovery Tower at the proposed wind turbine locations for wind directions from the SSW through SW. For these wind directions the local wind speeds are as much as 20 percent greater than the reference wind speed. The results also indicate that there is considerable sheltering of the air flow for winds from E through SE and from W through NW.

WIND POWER DENSITY

In order to estimate how much energy a specific turbine will be expected to produce at a given location, the wind resource at that location must be identified. A wind turbine works by extracting kinetic energy out of the wind and converting it to mechanical and then electrical energy. The power that is available in the wind to be converted to electrical energy is defined in the following relationships:

$$P_w = \frac{1}{2}\rho U^3 A \qquad \text{Equation 1}$$

and

$$PD = P_w / A \qquad \text{Equation 2}$$

or

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

Where:

- PD -Power density, W/m^2;
- P_W- Power available in the wind, W;
- ρ - Air density, kg/m^3;
- U - Wind speed approaching the wind turbine, m/s; and
- A- Projected area of the turbine perpendicular to the approaching wind, m^2.

Since the potential power production is proportional to the wind speed cubed, the annual average wind power density cannot be defined by strictly using the mean annual wind speed. Rather some knowledge of the distribution of wind speeds must be known to accurately estimate the annual average wind power density (*PD*). This can be achieved by applying Equation 3 to the hourly recorded wind speed measurements obtained throughout the year and then taking the average of the hourly values, where U is the local mean wind speed derived from the airport anemometer and the normalized wind speed distributions for each measurement location, using the techniques described above.

The results of this analysis are shown below in Table 1. The table indicates that the wind power density at the site in the absence of the Discovery Tower and surrounding buildings is 472 W/m^2. When the impact of the Discovery Tower and surrounding buildings is taken into account, the wind power density values are reduced by approximately 1/3rd and range from 114 W/m^2 to 153 W/m^2.

Table 1
Average wind speed and wind power density

Location	Annual Average Wind Speed (m/s)	Annual Wind Power Density (W/m^2)
Reference[1]	6.89	472
1	4.26	153
2	3.93	114
3	4.11	141
4	4.18	148

1) 152 m above local grade, outside of the influence of nearby structures.

To determine the feasibility of wind power at a site, the wind power density is often compared to various classifications developed to describe a site's wind power potential. Table 2 lists the classifications as a function of the predicted wind power density and mean annual wind speed.

The Discovery site falls into Class 4. The resource potential in a Class 4 environment is considered "Good". In the U.S. much effort has been undertaken in the last few years to develop wind turbines that are economically feasible in a Class 3 environment, since this is the most common wind class found in the U.S. Therefore, these results suggest that the wind resource at the Discovery Tower site is sufficient to be considered feasible for modern wind turbines. However, as currently configured, the wind turbines on the roof of the Discovery Tower will only experience a Class 1 to Class 2 wind environment. In this environment it may be economically difficult to justify wind turbine installations.

Table 2
Wind Power Classifications

Wind Power Class	Resource Potential	Wind Power Density* (W/m^2)	Annual Average Mean Wind Speed (m/s)
2	Marginal	200 - 300	5.6 - 6.40
3	Fair	300 - 400	6.4 - 7.00
4	Good	400 - 500	7.0 - 7.50
5	Excellent	500 - 600	7.5 - 8.00
6	Outstanding	600 - 800	8.0 - 8.80
7	Superb	800 - 1600	8.8 - 11.1

* - Wind classifications are typically base on the wind power density at 50m above grade

Wind Environment Characterization

In order to determine the appropriateness of installing wind turbines at the site, it is not only important to evaluate the wind power density, but also to characterize the wind environment in terms of flow vectors, gradients, and turbulence intensities. The local wind speeds on the roof of the Discovery Tower were measured using the Aeroprobe 5-hole probe, described above. The 5-hole probe provides measurements of wind speed in each of the three coordinates, longitudinal (U), lateral (V), and vertical (W) and can provide both mean and fluctuating wind speeds. For this analysis, each of the three components of the local wind velocity were normalized by the mean reference wind speed measured upwind of the turntable in unobstructed flow at a full-scale height of 152 m above the local grade. This results in normalized wind speed values of U_{mean}/U_{ref}; V_{mean}/U_{ref}; and W_{mean}/U_{ref}. The local turbulence intensity values were calculated by normalizing the fluctuating component of the wind speed by the mean longitudinal wind speed (U_{rms}/U_{mean}; V_{rms}/U_{mean}; and W_{rms}/U_{mean}). The lateral (θ_Y) and vertical (θ_z) angles of attack were calculated as the inverse tangent of the lateral to longitudinal (V_{mean}/U_{mean}) and vertical to longitudinal (W_{mean}/U_{mean}) velocity ratios. Finally, the magnitude of the local velocity vector was calculated as the square root of the sum of the squares of the three velocity components.

Figure 10 and Figure 11 show the vertical distributions above roof level of mean velocity and turbulence intensity at Location 2 for approach wind direction of 135 degrees (the prominent wind direction) and 202.5 (perpendicular to the broad side of the Discovery Tower). The plot on the right side of each figure shows the normalized mean velocity as a function of the height above the local roof. The plot on the left side shows the distributions of longitudinal turbulence intensity as a function of the height above the local roof.

Turbulence Intensity. Turbulence intensity is the ratio of the fluctuating velocity to the mean velocity and is a measurement of the gustiness of the wind. Although all three components of turbulence intensity are calculated, typically only the longitudinal turbulence is relevant because it is most readily available from field measurements. Therefore, for the purpose of this analysis, the focus was placed on the longitudinal turbulence intensity, even though the lateral and vertical turbulence intensity values can be significant

In an unobstructed open field environment turbulence intensity values are typically in the range of 10% to 15% at 30 m above grade and decrease at higher elevations. Utility scale wind turbines are typically designed for maximum turbulence intensity values around 17% to 18%. Smaller turbines, particularly those designed to be integrated into buildings, must be able to withstand much higher turbulence intensities.

Figure 10 indicates that the turbulence intensity values at Location 2 for a southeast wind direction are consistently above 60% throughout the entire profile. This is likely due to vortex shedding occurring at the upwind corner of the Discovery Tower for this wind direction. The turbulence intensity values for a southwest wind direction, shown in Figure 11 are substantially lower, particularly at 5 m above the roof and higher. In this region, the turbulence intensity values are within the range that one would expect to find in an open field environment.

Wind Shear. The wind shear is a description of the rate of change in wind speed along the vertical profile. It is defined by the exponent, *n*, in the power law equation. Wind shear is important, particularly on large turbines, because it can create unequal wind loading along the vertical axis of the wind turbine. In an unobstructed open environment the power law exponent typically ranges between 0.1 and 0.2. Utility scale wind turbines are typically limited to operating in environments with wind shear values less than 0.2 to 0.23. Once again, building integrated wind turbines must be designed to handle the higher wind shear values that are commonly present on and around physical structures.

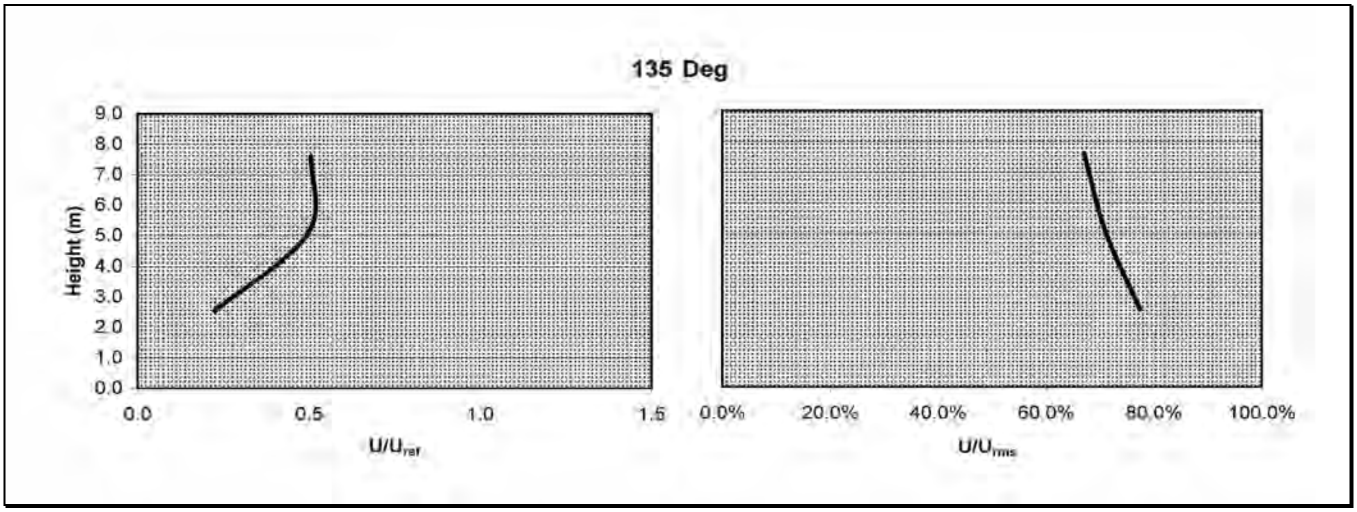

Figure 10: Wind shear and turbulence intensity ratios (in the plane of the rotor) for a wind direction of 135 degrees (SE).

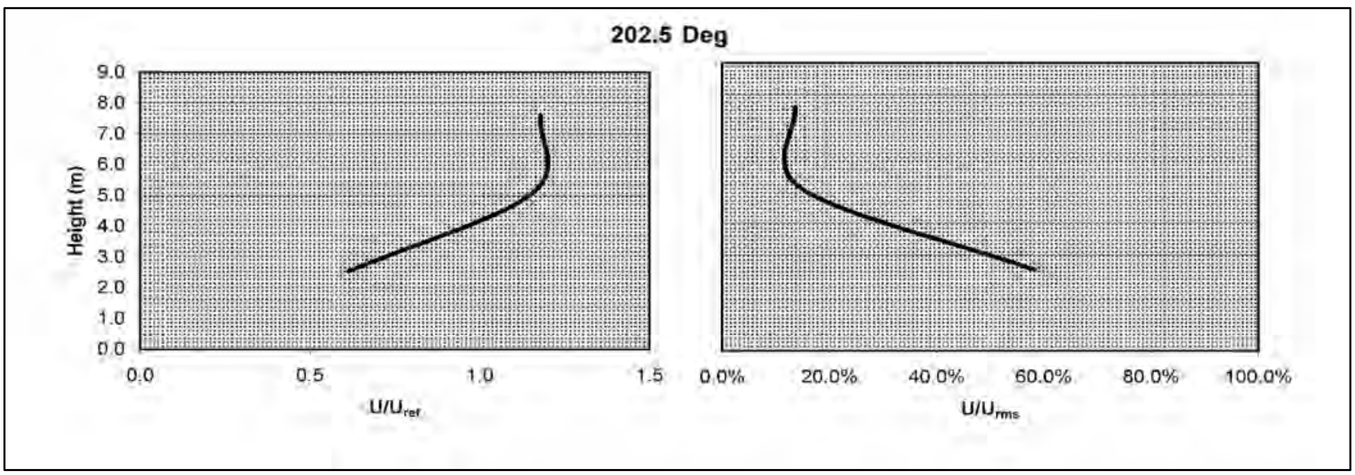

Figure 11: Wind shear and turbulence intensity ratios (in the plane of the rotor) for a wind direction of 202.5 degrees (SW).

Wind shear values on the Discovery Tower roof tend to follow the same trends as the turbulence intensity values. They are often low in areas of accelerated flow, whereas, they are typically higher in areas exposed to either vortex shedding or flow separation near the roof top. In areas where sheltering exists, the wind shear values tend of be fairly low throughout the profile.

Angle of Attack. The angle of attack of the local wind vector was defined in two components, the lateral angle of attack, θ_y, and the vertical angle of attack, θ_z. The lateral angle of attack is only important if it varies significantly with height. If the angle is consistent over the height of the entire rotor, the wind turbine will respond to it as a change in the mean wind direction. A lateral angle of attack that varies within the profile can be more troublesome, particularly to horizontal axis wind turbines (HAWT). If a HAWT rotor experiences different wind directions across its span, some portion of the rotor will always be exposed to wind forces that are not perpendicular to its plane. This will, at best, result in inefficient power production because portions of the blades will not be creating lift. At worst, it could destroy the blade due to excessive loading. Because most vertical axis wind turbines (VAWT) are omni-directional, the lateral angle of attack will likely have little or no influence on the turbine behavior, even if the angle of attack is varying along the axis of the turbine. It may alter the torque profile of the turbine through the rotation as different portions of the rotor enter and exit the maximum power production at different segments of the rotation. A large vertical angle of attack can also be responsible for decrease in turbine performance due to less than optimum lift on the blades and can create destructive loads if the turbines are not designed to sufficiently handle the vertical component of the velocity.

Wind Turbine Selection Process

The wind power density calculations described above were combined with manufacturer published power production curves for four different wind turbines to determine annual energy production (AEP) values. All four of the turbine evaluated can be described as vertical axis Darrieus wind turbines. VAWTs are expected to have a better chance of withstanding the strong wind shear predicted to exist on the roof of the Discovery Tower.

The first wind turbine evaluated, shown in Figure 12, is the UK Quiet Revolution, QR5. The QR5 turbine is 5 m tall and 3.1 m in diameter, and it is rated at 10kW at 11 m/s. Based on the manufacturer's supplied power curve, ten of these turbines placed on the Discovery Tower roof are predicted to produce approximately 77 MWh per year.

Figure 12: Quiet Revolution twisted Darrieus wind turbine

The second turbine evaluated is the PAC Wind Delta II 10kW H-Darrieus, shown in Figure 13. Eight of the 10 kW units are expected to have an AEP of approximately 70 MWh. (It is the Author's opinion that this value is inflated due to the manufacturer overstating their turbine performance, which indicates efficiencies in excess of 40%.)

Figure 13: PAC Wind H-Darrieus wind turbine

The third arrangement evaluated consisted of fifteen 2.5 kW Turby twisted Darrieus wind turbines (Figure 14). The calculated AEP for the fifteen units is 35 MWh per year.

Figure 14: Turby twisted Darrieus wind turbine

The last turbine evaluated is the 3 kW Eurowind H-Darrieus. Twelve of the 2.2 m tall by 2.5 m wide turbines are expected to have an AEP of 52 MWh per year.

Figure 15: Eurowind H-Darrieus Wind Turbine

It should be noted that at the time of this publication, none of these turbines have undergone testing to show their performance and/or reliability in a wind environment similar to that found on the roof of the Discovery Tower.

Conclusions

When assessing the merit of building integrated wind turbines, it is important to consider that wind conditions near the building surface will be very different from the general wind conditions in the region, due to both the influence of neighboring structures and the effects of the building itself. The winds will typically be more gusty (turbulence intensity) and uneven across the turbine blades (wind shear), which can significantly affect the turbine's performance. Improperly located, a wind turbine in this environment may be subjected to an inadequate wind resource, resulting in less than optimum power production, and/or an environment that the turbine is not designed to withstand.

Through the use of an atmospheric boundary layer wind tunnel, the building design team is able to identify the wind resource and wind flow characteristics at the proposed turbine location(s) during the design process so that an accurate assessment can be made of the potential power performance and survivability of the wind turbine before the building is constructed.

Table 3
Estimated Annual Average Energy Production

Wind Turbine	Height (m)	Rotor Width (m)	Area (m^2)	Potential Number of Turbines	Estimated Annual Average Energy Production (kW hrs/yr) (assumes 100% availablity) Location 1	Location 2	Location 3	Location 4	Total
Pacwind Delta II	4.3	4.0	7.4	8.0	9,196	8,013	8,770	8,925	**69,808**
Turby	2.9	2.0	5.7	15.0	2,509	2,130	2,383	2,419	**35,404**
QR5	5.0	3.1	15.5	10.0	8,189	6,976	7,782	7,973	**77,300**
Eurowind 3 kW	2.2	2.5	5.5	12.0	4,645	3,881	4,389	4,511	**52,278**

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