Title: **Harvesting Wind Power from Tall Buildings**

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Subject: Wind Engineering

Keywords: Renewable Energy
Wind

Publication Date: 2008

Original Publication: CTBUH 2008 8th World Congress, Dubai

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Dr. Roy Denoon is Principal-in-Charge for international projects at CPP Wind Engineering and Air Quality Consultants in Fort Collins, Colorado where he has been responsible for the wind engineering design of numerous signature tall buildings throughout the world. These include Pentominium, D1 Tower, and Burj Al Alam in Dubai as well as numerous other super-tall buildings throughout the region. Key projects where he and his co-authors have conducted studies on integration of wind power on tall buildings include DIFC Lighthouse in Dubai and China Merchants Bank in Shanghai. The team has also conducted numerous studies on the efficiency of different turbine types in various environments using analytical approaches, wind-tunnel testing and full-scale installations. Roy maintains active research interests in improving the design of tall buildings to resist wind loads and work in harmony with the local wind climate. He has many published papers in the field of wind engineering and is a regular speaker at international conferences.

Graeme Wood

Dr. Graeme Wood was educated at the University of Edinburgh and is a Director of CPP, based in Sydney. Over the last 10 years he has conducted numerous consultancy and research projects spanning many areas of wind engineering. His research areas include the distribution of wind loads on large span structures, full-scale dynamic measurements and wind induced dynamic response of tall buildings, thunderstorm winds, and development of wind turbines. Graeme has performed consultancy services throughout Australasia, Asia, and the Middle East. Graeme is a Member of the Institution of Engineers, Australia, Treasurer of the Australasian Wind Engineering Society, sits on the Standards Australia committee for structural wind actions, and was a member of the organizing committee for the 2007 International Conference on Wind Engineering.

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Abstract

The incorporation of wind turbines into tall buildings is becoming increasingly common as a method of both reducing carbon footprint and making a very public statement about a building's green credentials. There are, however, a number of considerations that should be assessed in determining the long-term environmental benefits of these incorporations. This paper will discuss some of the practical aspects of assessing the benefits of incorporating wind turbines, methods of assessing efficiency and optimizing design, and a discussion of key issues in introducing wind turbines to the urban environment.

Keywords: Wind turbines, tall buildings, wind energy

Introduction

Tall building designers are showing an increasing interest in reducing the environmental impact of the construction of their buildings. One of the approaches being used, and investigated more frequently, is the incorporation of power-generation, primarily solar and wind devices, into the design of the building. The requirements for optimizing the performance on wind generators in an urban environment are quite different from the considerations of the open sites that have traditionally been the domain of wind farms. This requires the use of different design approaches to assess the most suitable generator types, develop building forms that will enhance their efficiency, and predict expected power outputs.

This paper will examine considerations for introducing wind power generation on tall buildings and assist designers in assessing the value of them to any project.

Figure 1: Bergey Excel Horizontal Axis 3-Bladed Propeller Wind Turbine

Figure 2: Turby Vertical Axis Twisted H-Darrieus Wind Turbine

Common types of wind turbine

There are three basic types of wind turbine in common use today: the horizontal axial propeller, and the vertical axial Darrieus and Savonius turbines. Examples of each are illustrated in Figures 1 to 3 respectively. There are many variants of each design as well, as a number of other devices under development, such as the Dutch four are, H-rotor, giromill, and twisted Savonius. However, these are the three main types available for general commercial application from a number of suppliers. The propeller type turbine is most commonly used in large-scale applications while the vertical axis turbines are more commonly implemented in medium and small-scale installations.

Figure 3: TMA Vertical Axis Ducted Savonius Wind Turbine

Basic equation of wind power generation

The fundamental equation that governs the power output of a wind generator is:

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

Where:

P_t	-	Power produced by the wind turbine, W;
ρ	-	Air density, kg/m^3;
U	-	Wind speed approaching the wind turbine, m/s;
λ	-	Wind turbine efficiency; and
A	-	Projected area of the turbine perpendicular to the approaching wind, m^2.

The first point to note is that power is generally expressed as a function of wind speed cubed. Therefore, even a small increase in wind speed will result in a large gain in power output.

The second notable point is the inter-relationship between area and efficiency. The key issue here is the definition of the projected area. For a horizontal propeller wind turbine the projected area is fairly straight forward; it is the swept area of the rotor blades. For vertical axis turbines the definition is not as well defined. For example, the manufacturer of a Darrieus-type turbine may define efficiency in their product marketing based on the actual area of the blades rather than the swept-area of the entire turbine assembly. Similarly, a ducted turbine may use the projected area of the rotor and disregard the area of the duct. These definitions can result in turbines with rated efficiencies greater than 100 %; therefore great care needs to be taken in evaluating each manufacturer's stated efficiencies before comparing the performance of different turbines.

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 no wind to start with then the potential for successful use of turbines will be very limited!

The most common statistic that is quoted when assessing wind power potential is average wind speed. This is the average wind speed throughout each day throughout the year. Due to the cubic relationship between wind and wind power, this is on its own is not a particularly useful statistic as it does not reveal anything about the characteristics of the underlying wind climate. For instance, many locations around the world experience seasonal trade winds that mean that while high wind speeds will be experienced at some times of year, much calmer conditions, with limited power generation potential, will be experienced for other larger parts of the year. Similarly, many locations experience large diurnal effects with wind speed varying greatly throughout the day, for example as a result of afternoon sea breezes. A better metric for determining the power potential is the annual average wind power density of a site. The wind power density is the average amount of power that is in the wind on a yearly basis, which takes into account not only the mean wind speed for a site, but also the frequency distribution of wind speeds.

The directionality of the wind is also important. As will be discussed later, the incorporation of turbines into tall buildings tends to favour limited wind directions, perhaps within a 45° sector, depending upon the building configuration and the location of the wind turbines on the building.

Modification of the wind climate by the urban environment

Most commercial wind farms are located in very open rural environments, often taking advantage of local topographic features to accelerate the flow as shown in Figure 4.

Wind conditions in urban environments tend to be very different. The effect of urban environments on a boundary-layer is shown in Figure 5. This shows how buildings slow the wind near to the ground, and increase the turbulence in the wind. Turbines work most efficiently in low-turbulence environments so care needs to be taken in specifying turbine types that will cope with both existing turbulence and likely future changes in turbulence as a result of urban development.

Figure 4: Wind farm in southern Wyoming aligned along a bluff.

Urban development is likely to pose one of the greatest challenges to increasing use of turbines on tall buildings. In city centre 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 seeing suitable conditions for efficient turbine installation is significantly reduced.

Basic tall building aerodynamics

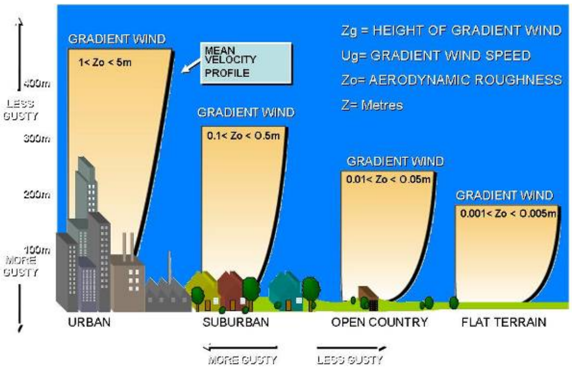

Figure 5: Mean Velocity Profiles for Various Types of Environments

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, 1971, 1975 and 1976). A simplified sketched of the mean flow phenomenon is shown in Figure 6. There will be positive pressure on the windward face and negative pressure on the side and leeward faces. As air, or any fluid, will naturally flow from areas of high pressure to low pressure this implies that 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 centre of the roof may be low as this area is often in a region of separated flow.

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 7) and the Pearl River Tower in China (Figure 8). 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 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 of not only accelerating the flow but by the compressing nature, decreasing turbulence.

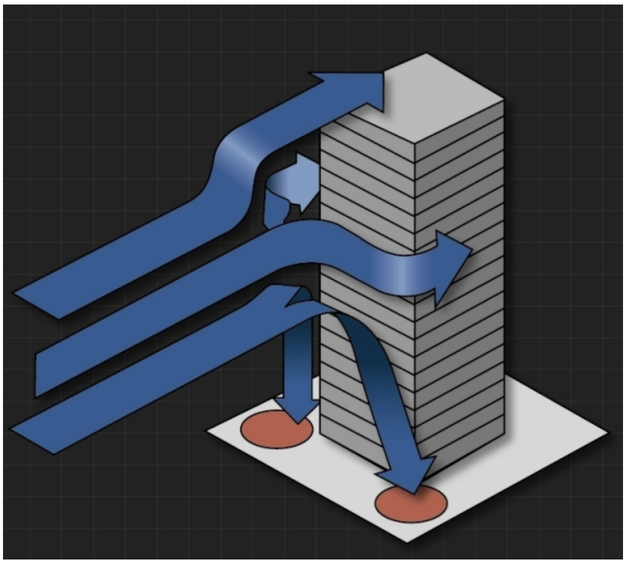

Figure 6: Wind flow around a tall building.

Tools for predicting wind power generation – wind climate analysis

Figure 7: Bahrain World Train Center (Image courtesy of www.bahrainwtc.com)

Figure 8: Pearl River Tower (Image courtesy of SOM)

The first part of assessing the suitability of a tall building for wind power incorporation is to understand the local wind climate. 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 or reliable records. It is not at all uncommon to see obscure directionality characteristics due to poor anemometer siting close to buildings. Wherever possible, records from multiple stations should be used as a check. 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) based on the work of Deaves and Harris is among the most common. This same approach can then be used to transfer the data to the proposed building site. This will then show the wind speeds and turbulence intensities that can be expected in the general area. It does not, however, give detailed information on the effects of individual neighbouring buildings. This must be investigated in the wind tunnel.

When there are no reliable anemometer records within a reasonable distance of the site, meso-scale modelling can be used to determine the wind climate of the area. This uses input from historical meteorological records from, maybe, hundreds of kilometres away to regenerate the weather systems current at the time. When these events have been recreated, the effects at other locations can be examined. This is an approach that is commonly used for rural turbine locations. An example of the output of this type of work as conducted by CPP is shown in Figure 9.

Tools for predicting wind power generation – computational fluid dynamics

Computational fluid dynamics (or CFD) is a vital part of the toolbox of the designer wanting to efficiently incorporate wind turbines into a building. It is, however, a developmental tool that is of most use in progressing a design to the stage of experimental testing.

The first role that CFD can play is in developing novel turbine forms to best suit the installation environment. For tall buildings which can, by necessity of space, only incorporate a limited number of turbines it may not be often that a budget will warrant special turbine designs. CFD is, however, a useful tool in predicting the comparative efficiency of different designs or the efficacy of design modifications. A comparison is shown in Figure 10 of CFD predictions and wind tunnel measurements of turbine efficiency.

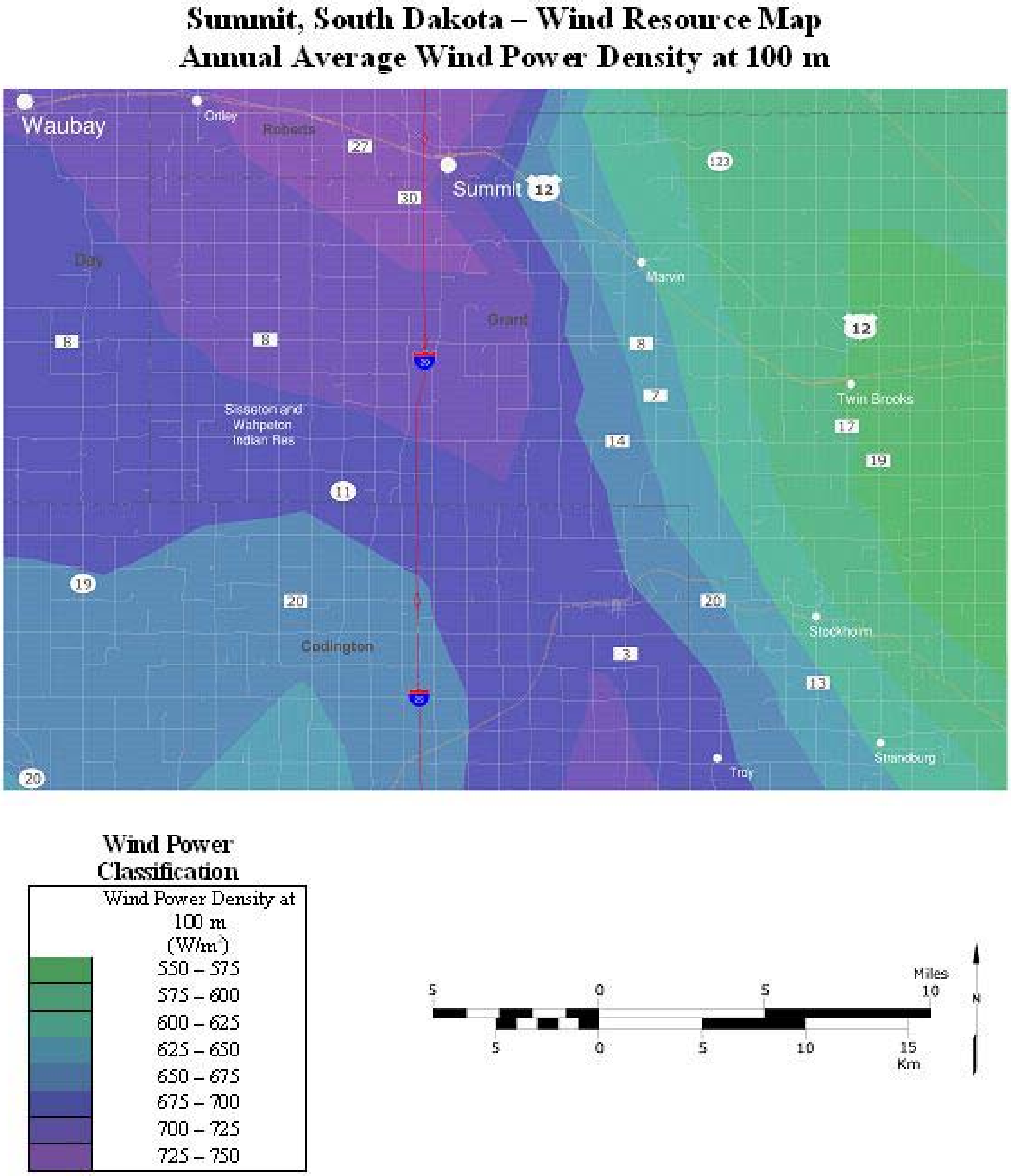

Figure 9: Meso-scale modeling used to determine the wind power density over large areas.

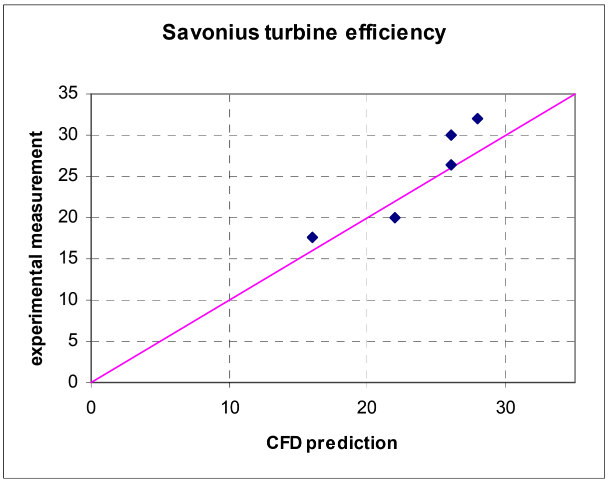

Figure 10: Experimentally measured efficiencies for various Savonius turbine blades shapes compared to efficiencies predicted using CFD.

When alternative building shapes are being considered to enhance the efficiency of turbines, CFD can also be a useful tool in investigating the general benefits of different forms. This can be a very useful visual tool in identifying flow patterns and aspects of the design leading to them. It offers a relatively quick way to make and test a substantial number of design options.

The one area where CFD is weakest is in the prediction of flows in very dense urban environments. At the moment, there is simply not sufficient computational power to accurately model the effects of turbulence in the built environment. As turbulence is one of the key items affecting how wind flows around buildings this makes CFD an unsuitable tool for use beyond a general comparison of alternative designs. It certainly can't accurately account for the effects of surrounding buildings or give outright quantitative advice on expected power outputs. For those tasks, a combined analysis using both CFD and the wind tunnel is needed.

Tools for predicting wind power generation – wind tunnel measurements

Wind tunnel measurements are used first as a design tool in the development of turbines. It is common to test a number of different design modifications during a test. It is, however, difficult to accurately model the full effects of turbulence in the wind tunnel; as the scale of turbulence that can be generated is limited by the physical size of the tunnel.

The wind tunnel can also be used to determine the effects of surrounding buildings and terrain on conditions at a proposed site (Derickson & Peterka, 2004). A terrain model, at a scale of 1:986, is shown for a rural site in Figure 11. This is used to determine the effects of large-scale topography and where there is a large site to determine the best locations on the site for the installation of turbines. Figure 12 shows a typical wind tunnel turntable in use during measurements to determine wind conditions above a tall building in Shanghai. This model is at a scale of 1:300. The blocks, trip board, and spires upwind of the model are used to generate the expected wind characteristics from far-field buildings and terrain. The effects of individual buildings within about 400 m of the test site are accounted for by their inclusion on this surround model. A directional pressure probe is used to measure wind speed, change in direction, and turbulence at the proposed turbine locations, Figure 13. Note that in this case, measurements were made at a series of locations over the roof to determine both the best locations for siting turbines, and the turbine types most suited for installation. The measurements were then used in an analysis to predict power output from a number of types of turbines.

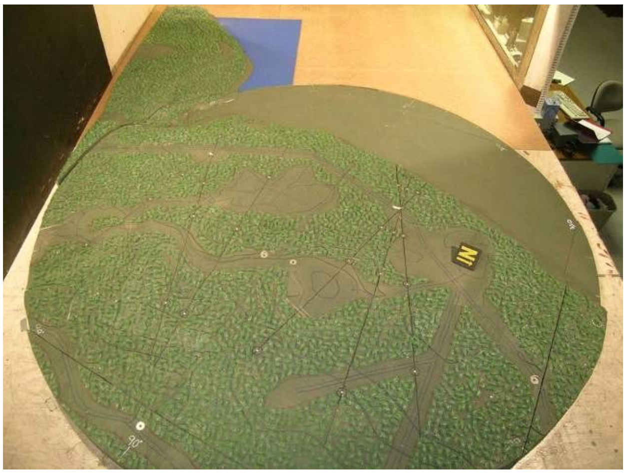

Figure 11: A 1986 scale model of terrain installed in a boundary layer wind tunnel to evaluate the optimum placement of wind turbines.

Figure 12: Photograph of a scale model installed in an atmospheric boundary layer wind tunnel to evaluate the potential for building integrated wind turbines.

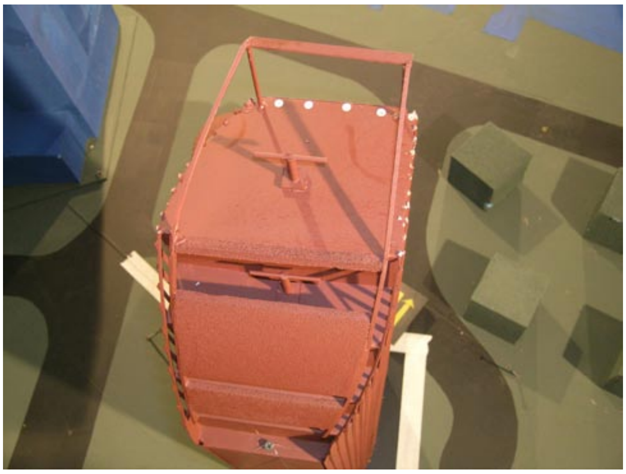

Figure 13: Close-up of the roof showing potential locations for wind turbines.

Tools for predicting wind power generation – field measurements

As well as CFD and wind tunnel predictions, it is common to field-test new turbine designs before large-scale production or installation. This gives added information on full-scale long-term performance. An example of an installation on the CPP field testing site is shown in Figure 14. Here, a turbine is instrumented and installed in a suitable windy environment next to a reference anemometer mast giving information on real-time site wind conditions. From this the efficiency of the turbine can be calculated in accordance with Eqn 1.

Why include wind turbines into the design of tall buildings?

The previous sections have discussed the practice of designing wind turbine installations for tall buildings. But, is it a worthwhile exercise? Certainly, it makes an environmental statement about a building but how practical is it?

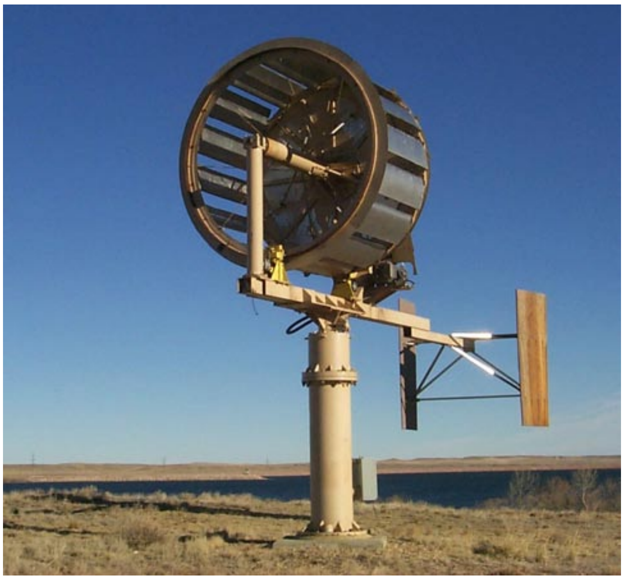

Figure 14: Field Testing of a Horizontal Axis Wind Turbine

In recent studies by CPP, predicted power outputs in the range of 1.5 - 90 MWh per year per small vertical axis turbine have been observed; small turbines are less than 15 m high. These are mounted on buildings that have not been specifically designed around wind turbines, but have had some design modifications to optimise the turbine additions. The power outputs are around 1 to 2% of the power output of a single large (70 m diameter horizontal axis) turbine located in a nearby rural environment. The cost of the turbines in one case made up roughly 2/3 of the 'green features' budget of the building yet generates only 10% of the power requirements of the building. In this case, the highly visual statement of the turbines took precedence. Although integrated turbines have the advantage of not needing large power distribution networks, would the money have been better spent on an investment on a better-located wind farm? A careful assessment of the site specific wind power potential and a detailed socio-economic feasibility study can help provide the answer.

Conclusion

When assessing the merit of building-mounted 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 both the influence of neighbouring structures and the effects of the building itself. The winds will typically be more gusty, hence uneven across the turbine blades, which can significantly affect the turbine performance. A range of tools are available to assess both the turbine performance and the local wind environment, including wind tunnel simulations, computer simulations, and full scale testing.

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