Built-Environment Wind Turbine Roadmap

J. Smith, T. Forsyth, K. Sinclair, and F. Oteri

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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Abbreviations and Acronyms

BWT	built-environment wind turbine
CFD	computational fluid dynamics
HAWT	horizontal-axis wind turbine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
kW	kilowatts
MCP	measure-correlate-predict
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Center
SWT	small wind turbine
TKE	turbulent kinetic energy
VAWT	vertical-axis wind turbine
WINEUR	Wind Energy Integration in the Urban Environment

Executive Summary

For the United States to generate 20% of its electricity requirements from wind technology by 2030, strong support from the general public will be needed. The majority of this production will come from large commercial wind projects installed throughout the United States, both land-based and offshore. To date, many of the easily developable sites have already been utilized, and future sites could face a range of potential barriers, including resistance from the general public.

Although only a small contributor to total electricity production needs, built-environment wind turbines (BWTs) nonetheless have the potential to influence the public's perception of renewable energy, and wind energy in particular. Higher population concentrations in urban environments offer greater opportunities for project visibility and an opportunity to acquaint large numbers of people to the advantages of wind projects. However, turbine failures will be equally visible. High-profile installations, many of which have failed to produce electricity as advertised, could have a negative effect on public safety and perception of wind technology because the general public cannot differentiate between emerging technology and proven technology used in the commercial wind industry.

The market currently encourages BWT deployment before the technology is ready for full-scale commercialization. To address this issue, industry stakeholders convened a Rooftop and Built-Environment Wind Turbine Workshop on August 11 - 12, 2010, at the National Wind Technology Center, located at the U.S. Department of Energy's National Renewable Energy Laboratory in Boulder, Colorado. Workshop attendees adopted the following vision statement:

> "To provide current, state-of-the-science recommendations for optimization (reliable and safe) of wind turbine design and placement in the built environment, assessment of potential challenges unique to the built environment, a list of barriers, and priorities for addressing those knowledge gaps with data/observations and modeling tools."

Workshop attendees identified barriers to BWT deployment in five key areas.

- *Safety* is considered the most critical issue for BWTs. Sub-areas include fatigue resistance, braking redundancy, fail-safe mechanisms, and ice- and part-shedding containment.

- Understanding the *wind resource* (including annual averages, turbulence, and extremes) and developing better wind resource maps are also considered high priorities to support BWTs.

- Improvements to the *turbine technology*, such as using control strategies to reduce vibration and noise, understanding loads measurements and yaw rates, and developing design and testing standards, will move the BWT industry toward stronger customer acceptance.

- At the same time, in terms of building-mounted systems, understanding *building interactions* will be pivotal. Concerns exist regarding resonance frequencies, and an understanding of how the building-turbine vibrations are coupled is needed. BWT system designs must comply with building codes as well as integrate with the building's mechanical and electrical systems.

- *Non-technical obstacles*, such as concerns regarding safety hazards during installation, operations and maintenance, and inspections must be understood. Consumer outreach and education, along with overcoming economic barriers, must also be addressed.

The BWT roadmap also outlines stakeholder actions to overcome the barriers identified. The actions are categorized as near-term (0 - 3 years), medium-term (4 - 7 years), and both near- and medium-term. The BWT industry is evolving rapidly, so long-term actions cannot be projected.

Workshop attendees developed a strategic approach to accomplish these actions that identifies two focus areas: understanding the built-environment wind resource and developing testing and design standards. In this report, the authors summarize the expertise and resources needed in these areas. A wide variety of domestic and international stakeholders are currently engaged with BWTs. Existing wind tunnels, wind measurement data, and models could be utilized and enhanced to expedite the development and deployment of BWTs.

This roadmap identifies key barriers to the development and deployment of BWTs and outlines a strategic approach to addressing these barriers.

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Introduction

What are built-environment wind turbines (BWTs)? In this roadmap, BWTs are defined as wind turbines located in an urban or suburban environment (built environment). Most BWTs are also classified as small wind turbines (SWTs), which are 100 kilowatts (kW) or less. While the terms "BWT" and "SWT" are interchangeable in many cases, this roadmap uses the term "SWT" when referring to turbines 100 kilowatts and less and the term "BWT" when referring to SWTs in the built environment. "SWT" refers to a category of turbines, and "BWT" refers to a specific application or market niche. See Appendix I for a detailed description of BWTs.

To date, most wind turbines installed in the built environment have been sited with limited understanding of or regard for the unique challenges of BWTs (Encraft 2009). Most SWTs were designed for rural areas, not the built environment with its high turbulence, lower average wind speed, more frequent wind direction changes, and potentially higher vertical inflow. Nor were turbines designed to be in close proximity to people, businesses, and other property. Poor siting and improper use of BWTs could lead to turbine failure, possibly resulting in injury, property damage, and potential liabilities. These liabilities extend to not only BWT owners but also to the industry, which would suffer from general negative perceptions of wind technology.

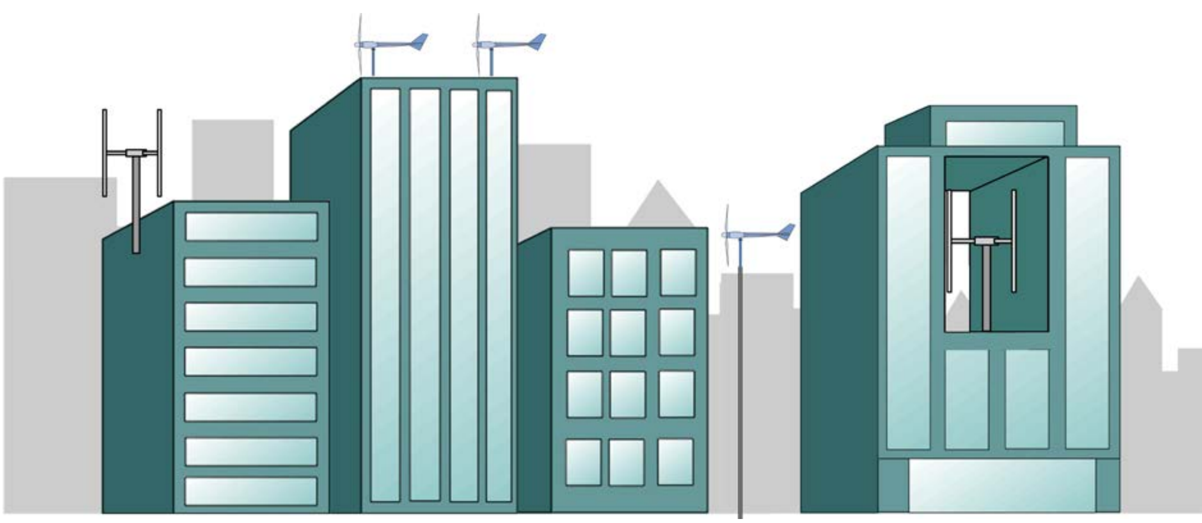

Figure 1. Examples of various BWT installations. Left to right: Side mounted to building, roof mounted, ground mounted in the built environment, building integrated

Recent research on wind energy in urban areas demonstrates that there are promising opportunities to extend the use of wind energy in the built environment. However, developers must pay careful attention to the micro or local wind conditions produced by the stochastic wind interactions with localized structures. Turbine efficiency is highly sensitive to the rapid variations in wind conditions that prevail in the built environments (Kooiman and Tullis 2010). Other difficulties include transfer of vibration and loads to a building structure, potentially causing noise and structural failures (Encraft 2009).

Understanding the loads, dynamics, yaw rate, and other technical specifications is critical in designing or modifying existing commercial products.

The number of BWT installations is increasing as consumers have easier access to relatively inexpensive SWTs (James et al. 2010). In 2010, BWT units experienced substantial sales growth to more than 1,700 kW, or 7% of 2010 U.S. SWT capacity sales. This represents a remarkable 430% growth from 2009. In terms of units, 1,074 roof-top units were sold (American Wind Energy Association 2011). Many people are motivated by a desire to be environmentally responsible, and they want clean, renewable energy to help power their homes or businesses. While the increased visibility of a BWT can be used to enhance a "green" image, a poorly sited turbine will not produce much electricity and may not even spin, which implies that "turbines don't work." Moreover, poor siting will likely increase fatigue issues and may drastically shorten a turbine's life span. This perception of BWT underperformance introduces a risk that the public will become disillusioned with the greater wind energy industry (Encraft 2009).

By developing the "Built-Environment Wind Turbine Roadmap," representatives from industry, government, academics, and those with an interest in BWTs have produced a document that addresses the critical needs of safety, technology, and non-technical obstacles in the built environment. Although this is a U.S.-centric document, it includes contributions from international stakeholders. Further, this work will be coordinated through the International Energy Agency (IEA) so that a variety of international entities can pursue this research area. This work is intended to aid in the crafting of public and business BWT policy by providing current, state-of-the-science recommendations.

This roadmap delves into the background of BWTs, including the current state of the BWT industry and the current state of BWT technology. Furthermore, this document describes the five categories of BWT industry barriers: safety, wind resource, turbine technology, building interactions, and non-technical obstacles. An action section addresses these barriers. One action may address more than one barrier, so these actions are grouped into three categories defined by their urgency: near-term (0-3 years), medium-term (4-7 years), and both. Because BWTs are a new wind technology and are evolving rapidly, long-term actions cannot be projected for the current BWT industry. The document concludes with a strategy section that identifies resources to help carry out the actions and provides a plan to remove BWT barriers.

This document is based on presentations and the ensuing discussions from the Rooftop and Built-Environment Wind Turbine Workshop hosted at the National Wind Technology Center (NWTC) at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) on August 11-12, 2010. Workshop participants are experienced in SWT modeling and data collection. Some of the key points from the workshop include:

- Approximate correlations exist between wind tunnel measurements and computational fluid dynamics (CFD) models for specific sites.

- More sophisticated CFD wind resource modeling tools exist, and there is a substantial body of existing work pertaining to other wind propagation models.

- Countries of focus on the topic of built-environment wind turbines (see www.urbanwind.net) exist, and the International Energy Agency Task 27 recently proposed new work.

- As a result, novel approaches to wind energy harvesting may emerge as important players in the effort to increase wind energy use in urban areas.

During the workshop, the participants agreed to the following vision statement:

> "To provide current, state-of-the-science recommendations for optimization (reliable and safe) of wind turbine design and placement in the built environment, assessment of potential challenges unique to the built environment, a list of barriers, and priorities for addressing those knowledge gaps both with data/observations and modeling tools."

This roadmap is a step toward that vision.

State of the BWT Industry

This section describes the state of the BWT industry in Europe and the United States. The Built-Environment Workshop team could not identify experts in this topic area from other regions of the world; therefore, this report focuses on Europe and the United States.

Europe

The European Union has moved forward with the development and deployment of BWTs through several programs supported by the European Commission. The United Kingdom, the Netherlands, and France participated in a large multi-country activity called Wind Energy Integration in the Urban Environment (WINEUR). Most of this work was completed in 2006 and 2007.

This program began by building the European Cities Urban Wind Network, a network of cities in which turbines were installed in the urban environment. Other activities followed, including the United Kingdom's Warwick Wind Trials[1]. Units were installed in The Hague, and researchers conducted a structured test program in Zeeland.

United States

The market for BWTs in the United States is expected to grow and develop in the coming years. SWTs appeal to consumers wishing to generate renewable energy and display environmental responsibility. "Urban turbines" experienced a 430% sales growth between 2009 and 2010, which resulted in 1,700 kW of installed capacity (American Wind Energy Association 2011).

Figure 2. Students at the University of California - Davis work on a roof-mounted Bergey wind turbine. ***Photo from University of California – Davis, NREL/PIX 17997***

Historically, specialized distributors and installers provided the link between the SWT manufacturer and consumer, but increasingly SWT manufacturers market directly to consumers.[2] Easier consumer access to SWTs appears to have increased sales, but without professional installation services, site suitability and installation quality will suffer.

The poor quality of SWT installations completed without professional consultation is particularly apparent in BWT installations (Encraft 2009). These installations are often located in areas where the wind is blocked or diverted by

[1] http://www.warwickwindtrials.org.uk/

[2] Lowes Home Improvement Centers sell Bergey 10-kW wind turbines, and Home Depot sells the Southwest Windpower Air-X 400-Watt wind turbine.

upstream obstacles and may present issues related to safety, turbine durability, effects on the building, and energy production.

Although people may intuitively believe that the wind resource on their roofs is adequate for SWT installations, in fact it may not be. Underperformance is widely reported for many BWT installations. Although the causes are diverse, and some are not well understood, a poor understanding of the wind resource is a consistent issue. An example of this situation is a turbine at the Boston Museum of Science, which was installed inside a roof re-circulation eddy. Completion of a CFD analysis revealed that the winds flow on the bottom part of the turbine in opposition to the prevailing winds and the wind through the top part of the turbine (Viti et al. 2010).

In some documented cases, few or no studies were conducted before a BWT installation (Encraft 2009). In another case, the structural analysis and public safety concerns were considered in addition to the wind resource, and the final BWT placement was a compromise among all three (Museum of Science et al. 2006).

Besides the intangible "green" value, BWTs have economic value. The economic value, however, is diminished due to poor turbine production and the likely additional costs for custom-designed and fabricated mounting systems (when compared to conventional ground-mounted SWTs with open access to the wind).

It is also worth noting that the economics of BWTs are not limited to electricity production. Some people simply want to make a statement, and in certain cases a good economic argument exists even when the electricity generated does not create revenue (Beller 2011). A recent BWT installation on the roof of a Portland apartment building is a good example of this scenario. The turbines serve as a message to the community about environmental consciousness and, as a result, the building has become quite popular.

State of BWT Technology

SWTs can be safe and reliable; installing them on towers tall enough to place them well above any nearby obstacles increases production and reduces turbulence-induced loads. In the built environment, the wind resource is more turbulent than conventional locations, which can lead to increased loads. Placing an SWT into a built environment may exceed the design limitations of the SWT and present issues related to safety, durability, and performance.

Figure 3. Quiet Revolution vertical-axis wind turbines at Cleveleys Promenade, United Kingdom. ***Photo from Quiet Revolution, NREL/PIX 18054***

The current International Electrotechnical Commission (IEC) design standard designates a maximum occurrence of turbulence intensity of 18% (IEC 2006) for siting an SWT, but this is well below a documented incident of a turbulence intensity of 41% measured at a 10-m height over complex terrain in a forest (Carpman 2010). Scale effects cause small turbines to be affected by turbulence in a different way than large turbines. Turbulent vortices can fully engulf a small turbine, whereas similar vortices impacting larger turbines are distributed across the large turbine and therefore have a less significant effect.

The most common sizes of BWTs are between 1 and 3 kW of rated output, which correspond to a rotor diameter of approximately 2 to 4 m (7 to 13 ft) for horizontal-axis wind turbines (HAWTs). SWTs of this size may employ a variety of governing mechanisms to control rotor speed. One of the most common governing mechanisms is passive overspeed control, such as furling, mechanical, and electrical control through design stall and braking. Due to differing response and recovery time, some methods of governing will prove more effective in the higher turbulence and rapidly changing wind directions of the built environment.

The HAWTs in this size range are free-yaw machines, employing a tail or blade coning to orient to the wind without the aid of a yaw motor. Due to the vertical orientation of vertical-axis wind turbine (VAWT) shafts, they do not need to orient into the wind to generate power. Thus VAWTs may have an advantage in this regard over HAWTs in the built environment because the wind direction may change more frequently than in a conventional SWT site.

VAWTs have two general topologies. They generate power through drag, such as the Savonius design, or they generate power through aerodynamic lift, such as the Darrieus design. It should be noted that the Savonius design is not purely a drag-driven machine because it is based on both drag and suction forces. The Savonius design has higher efficiency than a pure drag-driven machine but a relatively low efficiency compared with lift-driven machines.

The Darrieus design has a higher maximum efficiency than the Savonius, yet efficiencies of Darrieus designs are generally lower than conventional HAWTs (Mertens 2006, Beller 2011). However, a Darrieus design is only self-starting when the blade chord lengths are large (high solidity), which generally reduces overall aerodynamic efficiency. Most Darrieus designs require a push-start, which is usually accomplished by the generator consuming power and acting as a motor. It can be difficult to use aerodynamic methods to regulate turbines from over-speeding, and this is particularly true of Darrieus designs.

BWT Industry Barriers

One of the near-term actions proposed in this roadmap is to conduct a BWT market assessment. It is understood that BWTs will support a specific market niche; however, the market potential in the United States has not yet been quantified. Although the capacity additions from BWTs toward meeting overall U.S. installed capacity objectives may be small, the contribution toward acquainting the public to wind technology may be invaluable.

Industry stakeholders attending the Rooftop and Built-Environment Wind Turbine Workshop identified barriers to BWT deployment in the following five key areas:

- Safety
- Wind resource
- Turbine technology
- Building interactions
- Non-technical obstacles.

The challenge for BWTs can be summarized as a need to understand the wind resource in the built environment, combined with a lack of measurements and model results to assist in the development of international design and test standards. Specific design guidelines are lacking in IEC61400-2.

The following section summarizes input from workshop attendees regarding these five key barrier areas.

Table 1. Summary of BWT Barriers

Safety	Wind Resource	Turbine Technology	Building Interactions	Non-Technical Obstacles
The effect of a high-fatigue environment on BWT life is poorly understood. BWTs lack the following safety features: -Braking redundancy -Fail-safe features -Ice- and part-shedding containment.	The following aspects of the wind resource in the built environment are poorly understood: -Turbulence and directional variability -Wakes, eddies, and separation zones -Three-dimensional wind speed profile and distribution. Existing wind resource maps do not translate to the built environment.	The following aspects of turbine technology in the built environment are poorly understood: -Control strategies to reduce vibration and noise -Loads measurements and yaw rates. Design and test standards for BWTs (especially for high-fatigue environments) are non-existent.	Resonance frequencies (linked building-turbine vibrations) are poorly understood. Code compliance is difficult (most codes do not address BWTs; existing codes add great uncertainty; additional zoning and permitting may apply). Mechanical and electrical integration are costly and difficult.	Hazards exist for personnel installing and servicing BWTs. Outreach and education are required as credible BWT information is limited. Economics (project costs and return on investment) are unpredictable.

Safety

Safety is the most critical BWT barrier area. BWTs are installed on or in close proximity to buildings, people, and other property, so a catastrophic failure could damage property, injure people, and tarnish the wind industry's image.

This report outlines several important safety aspects. The barriers are characterized by a need for better understanding of the wind resource and turbines designed for that resource. Turbines must be developed with:

- Fatigue resistance
- Braking redundancy
- Fail-safe features
- Strategies for ice- and part-shedding containment.

Fatigue Resistance

There is a lack of understanding regarding how the built-environment inflow conditions impact the fatigue life of BWTs. Lower average wind speeds in the built environment may reduce one aspect of fatigue loads on BWTs. However, increased turbulence intensity and directional variability will increase another aspect of fatigue loads on a turbine, reducing its design life. A better understanding of the fatigue issues in the built environment is required to remedy safety concerns. Once data exist, they must be refined to develop conservative safety factors found in IEC standards, as noted above.

Braking Redundancy

BWTs require a redundant braking method to stop the rotor even if the turbine has partially failed, leaving the primary brake inoperable. A BWT must not be allowed to operate without control or load (a condition in which the rotor spins uncontrollably fast and may lead to catastrophic failure). If an SWT in a rural environment enters rotor overspeed, the owner typically protects himself and others by staying away until the winds calm and the rotor can be stopped by other means. In a built environment, waiting for calm winds is not an option.

Fail-Safe Features

If a BWT were to fail, it must not be allowed to do so in a catastrophic manner. The BWT must remain intact if the turbine suffers damage from an external event or from failure. BWTs should incorporate fail-safe mechanisms and design philosophies.

Ice- and Part-Shedding Containment

Ice-shedding and part-shedding incidents have been infrequent, but risks are present, and increased numbers of built-environment installations also increase the magnitude of these concerns. It is worth noting that parts and ice can be tossed long distances, and it is difficult to predict where they may land. Part-shedding cannot be predicted, but there must be a way to contain this safety hazard. Ice-shedding can be expected after an icing event, but no SWTs on the market automatically detect or respond to ice build-up.

Figure 4. Example of roof-mounted BWTs at the Museum of Science, Boston, Massachusetts. ***Photo from Boston Museum of Science, NREL/PIX 18005***

Wind Resource

The wind resource is site specific, and in the built environment, large differences exist among sites with small vertical or horizontal separation. Information on and understanding of the wind resource in the built environment is critical for designing BWTs, micrositing, and estimating the energy production. However, the built-environment wind resource is not well understood. Unlike rural environments with few obstructions and adequate estimates for average wind speed and turbulence, limited knowledge exists that can be applied to wind resources in the built environments.

As with other BWT barriers, the wind resource barrier is primarily a lack of information and understanding. Important areas to address include:

- Turbulence and directional variability in the built environment
- Wakes, eddies, and separation zones
- Three-dimensional wind speed profile and distribution.

In addition to increasing existing knowledge in each of these areas, an effort to use an integrated and validated approach is required.

Turbulence and Directional Variability in the Built Environment

Besides average wind speed, turbulence and directional variability are also important. Because of the surrounding structures, the built environment has higher turbulence and directional variability than rural environments. Unfortunately, only rough estimates exist for turbulence intensity, and even fewer exist for directional variability. Additionally, a better metric for turbulence may be turbulent kinetic energy (TKE),[3] which requires high-frequency wind measurements in three dimensions. Few sites are currently instrumented for this measurement type. However, the use of a single number cannot communicate the range of turbulent phenomena that could occur. For example, gustiness is a form of turbulence in which a large vortex travels with the wind and passes a measurement location or wind turbine (Mertens 2006). In the built environment, in addition to ambient turbulence (large vortices traveling with the wind), turbulence is also generated locally by shear and wake-inducing building features (Mertens 2006). An investigation into the most appropriate turbulence parameters and standard for data collection is required.

Wakes, Eddies, and Separation Zones

Most SWT designs and experience pertain to relatively low-inflow turbulence, which is common to open areas in rural settings (Beller 2011). Wakes, eddies, and separation zones mean increased turbulence in the built environment. These are complex turbulent phenomena, and the lack of information on them impedes BWT design criteria, micrositing, and production estimates.

Wakes behind cylinders and other bluff body shapes studied in the laboratory are generally well understood, but it is not trivial to apply those results to the built environment because of large wind resource variations (in speed and direction) and urban topography (Yersel and Gobel 1986, Hurley 1997). Computer models of wakes, eddies, and separation zones are generally inadequate for the small scale of interest for BWTs.

[3] TKE is the mean kinetic energy per unit mass associated with eddies in the wind. TKE = 0.5 $(u'^2 + v'^2 + w'^2)$ where u'^2, v'^2, and w'^2 are the mean square velocity fluctuations in x, y, and z direction, respectively.

High-resolution models can provide useful information regarding the larger-scale structure of flows in urban environments, such as flow channeling and separation, and gross characteristics of wakes. However, details of these flow structures are difficult to simulate due to limited representations of important small-scale structures within the built environment. Limitations on computational resources and a lack of data to validate models further limit simulations. Consequently, BWT designers do not have many tools or adequate guidance to help them design to and account for wakes, eddies, and separation zones (Kalmikov et al. 2010).

High-resolution, three-dimensional wind measurements at multiple locations within built environments are required to provide data to improve computational models. Such model simulations are extremely time-consuming to set up, execute, and analyze. Therefore, simplifying computational parameters, applying appropriate boundaries, and developing data analysis tools for built environments are required to develop usable BWT toolkits.

Three-Dimensional Wind Speed Profile and Distribution

Estimates exist for wind speed distributions and profiles in rural environments, but their application to the built environment is not appropriate. Standard models of vertical wind profiles (e.g., the log or power laws) do not apply at BWT locations, and alternative approaches are needed for predicting the wind fields above buildings at BWT heights (Beller 2011). Additionally, in the rural environment, the wind distribution is approximately two-dimensional: The wind increases with height, but the vertical component to the wind is limited (the IEC standard requires up to 8 deg vertical inflow) (IEC 2006). On the contrary, the built environment has large vertical components as wind moves over and around buildings. Winds in built environments will have different probability distributions (mostly non-Weibull distribution) than rural environments, and these distributions will be further modified due to building blockages and diversions. Understanding the horizontal and vertical wind speed profiles and distributions is critical to BWT design and predicting production.

Figure 5. Skystream turbine in San Francisco, California. ***Photo from Danielle Murray, Department of the Environment, San Francisco, NREL/PIX 18445***

Wind Resource Maps

Wind resource maps provide an estimate of the wind resource at different heights. Resource maps work reasonably well at heights well above the ground and far from obstacles. For SWT sites with good exposure to the prevailing wind directions and without major obstacles (such as groves of trees) within at least several kilometers, an onsite measurement campaign may not be necessary. However, this is not true for built environments. Existing wind resource maps may provide an initial estimate of the high-level and unobstructed wind resource, but they must be translated to lower heights and obstructed areas of the built environment (a map is only representative for heights above approximately 20 times the roughness length z_0) (Mertens 2006).

Modeling of simple obstacles has been performed, and knowledge exists that can be used to roughly translate existing wind maps to the built environment. However, buildings and obstacles block and alter the wind around them, so built environments are much more complicated than solitary or simplified obstacles. Data exist regarding flow around buildings, and it has been used to validate models. Although the approach for understanding the wind resource at a given site remains the same, much of this modeling work was performed in the context of Atmospheric Transport and Dispersion of contaminants in cities and not in the context of wind energy (Beller 2011). Without an initial assessment of the wind resource, BWT owners must invest in and complete an onsite measurement campaign or install a BWT with no knowledge of the wind resource. Both options are financially risky. A wind resource map for built environments or an equivalent tool for estimating the wind resource should be developed.

Turbine Technology

Most SWTs were designed for the open areas common to rural environments. However, as discussed above, the built environment has significantly higher turbulence and wind direction variability. This means the turbine extreme, deterministic, and stochastic loads will be different and probably higher in the built environment. Historical and derived design guidelines, testing methods, and control strategies developed for SWTs must be revised for BWTs.

Figure 6. Swift wind turbines at Meijer Inc.'s headquarters in Walker, Michigan. ***Photo from Cascade Engineering, NREL/PIX 17895***

Turbine technology barriers to BWTs consist of a lack of knowledge as to how the built-environment wind resource affects the turbine. After enough measurements are conducted and the resulting information is analyzed and disseminated, appropriate BWT designs, controls, and tests can be developed. The following areas are characterized by a lack of knowledge and are therefore BWT technology barriers:

- Control strategies to reduce vibration and noise
- Loads measurements to validate dynamic models and yaw rates
- A standard for BWT design and testing.

Control Strategies to Reduce Vibration and Noise

Vibration and noise issues will impede BWT acceptance and deployment. Due to the close proximity of people, acoustic emissions will be even more important in the built environment than for SWTs in rural environments. Strategies and controls to mitigate noise must be developed for BWTs to encourage acceptance and to conform to community noise ordinances.

Similarly, vibrations and noise issues will also be more important for BWTs than for conventionally mounted SWTs because BWTs are often mounted on buildings. Most vibration control and mitigation strategies for BWTs are custom solutions and therefore expensive and uneconomical. In most cases, the vibration is damped by installing rubber pads on the tower. When BWTs are installed without knowing the potential effects, they may have to be removed if the vibrations prove to be a nuisance. This issue poses an economic risk for the owner.

Loads Measurements and Yaw Rates

The aforementioned increased turbulence and directional variability could result in higher (peak) loads on BWTs. Gusts will cause large forces on the blades and increases in rotor speed. Stronger and sharper gusts from the built environment will increase this effect. For HAWTs, direction variability will cause the turbine to yaw, and if the directional wind change occurs quickly, large gyroscopic forces will be exerted on a moving rotor, tail (if applicable), and yaw system. It should be noted that for the few SWTs that fail, yaw forces are sometimes the cause. With the increased directional variability of the built-environment wind resource, extreme yaw changes will be more important to BWTs.

BWT Design and Testing Standard

As with SWTs, there is a growing demand for BWT certifications. Consumers want to know that they are investing in a safe product with proven performance, as demonstrated through standardized testing and review. Testing standards exist for large turbines and SWTs, but standards specific to BWTs do not exist.

BWTs need to be tested and reviewed for the increased loads (due to increased turbulence) and not to current standards, which are inadequate. Additional modifications to existing standards may be necessary to ensure that certified BWTs have the same reliability and quality as properly installed and certified SWTs.

Testing to standards is important for product safety, but it must also be affordable. If testing is too expensive, the added cost could undermine the economics of BWTs.

Building Interactions

Many BWTs are mounted to buildings, so interactions with buildings are a major design and siting concern. Furthermore, whether they are attached to or detached from the building structure, BWT systems have electrical integration considerations. The barriers regarding building interactions are further complicated by the multitude of building types and locations. Concerns include not only mounting the BWT on buildings but also:

- Resonance frequencies

- Code compliance
- Mechanical and electrical integration.

Resonance Frequencies

BWT vibrations will in general be much higher than natural frequencies of buildings. Concerns remain regarding excitation of resonance frequencies for buildings of different construction types and heights. Conversely, there is interest in the effect of building vibrations on a BWT and its tower. Besides whole-building resonance frequencies, individual building components may be excited by BWT vibrations. An increased understanding of linked building-turbine vibrations is needed to remove this barrier.

Code Compliance

Most, if not all, building codes do not specifically address BWTs. Searching for and complying with the existing applicable building codes could be daunting and expensive, and the outcome may not be favorable. The uncertainty of this process adds an additional barrier to the process of BWT code compliance.

Figure 7. Windspires at Adobe Systems Inc., in San Jose, California. ***Photo from Windspire Energy, NREL/PIX 18000***

Proximity to people and property may create additional zoning and permitting issues. If these policies are crafted well, they will reduce hazards to personnel installing and servicing BWTs and will facilitate BWT installations. However, poorly informed zoning and permitting policies will create a barrier for BWTs.

Mechanical and Electrical Integration

Integrating BWTs with a building's mechanical and electrical systems can present a barrier. Besides a mounting system that mitigates vibration transfer to or from the BWT, aesthetics, function (particularly service and maintenance access), and cost are other barriers. In some cases, the design and materials for the BWT mount can cost as much as the turbine and the rest of the installation.

Electrical integration of BWTs also presents a barrier. Besides connecting to the building's electrical system and ensuring proper grounding, radio frequency interference presents concerns. Additionally, lights may be required by the Federal Aviation Administration if the BWT is significantly above the roof level. BWTs may be connected to the electric grid or used to charge the battery on site. While policy barriers are common to grid-connected BWTs, both of these options have financial and technical limitations (Chiras 2009).

Non-Technical Obstacles

The fifth and final area of BWT barriers is non-technical obstacles:

- Hazards to personnel installing and servicing BWTs
- Outreach and education
- Economics.

Hazards to Personnel Installing and Servicing BWTs

Many of the safety issues pertaining to BWTs were addressed in the safety section, but additional concerns exist regarding hazards during BWT operation, installation, maintenance, and inspections. Servicing BWTs requires additional procedures due to the limited space in built environments, particularly rooftops. These can be addressed with knowledge of best practices and enforced through procedures.

Figure 8. A SWIFT wind turbine at a municipality's Board of Public Works building. ***Photo from Cascade Engineering, NREL/PIX 17889***

Outreach and Education

Interest in renewable energy has increased dramatically in the past few years, and many people want to generate their own electric power. Potential benefits need to be weighed against the costs and hazards of BWTs. Little knowledge currently exists about BWTs, and finding and understanding credible information often requires help from an expert. The lack of readily accessible, public information is a barrier to BWTs.

Economics

While initial cost is not the driver for some investing in BWTs, it still presents a significant barrier to others. Another part of the economic barrier is the return on investment. In many cases, the BWT's production will offset some electricity purchases, but if production is not predictable, then savings will not be predictable either. Other economic incentives will depend on the utility provider and local, state, or federal policy. Many questions regarding BWT economics must be addressed at the outset of the BWT project. The lack of knowledge about financial cost and benefits of BWTs presents a major barrier, although many BWT projects have little to do with turbine economics and more to do with using renewables to market green values.

BWT Stakeholder Actions

This section outlines actions to address the five areas of barriers presented in the previous section. The action categories are organized by timelines:

- Near-term: should be implemented during the next 3 years
- Medium-term: should be implemented in 4 to 7 years
- Both near-term and medium-term: require immediate to medium-term effort.

Regardless of when each action takes place, all of them should help increase the BWT knowledge base to aid BWT owners, industry, and government. Local and state governments in particular should benefit from increased knowledge as they establish BWT policy.

Near-Term Actions (0-3 Years)

Near-term actions require immediate attention to overcome BWT barriers. In some cases, these actions are needed without delay. In other cases, the actions will be a precursor to medium-term actions. In all cases, actions should increase the knowledge of BWTs and improve the industry.

Produce a Consumer Guide and Fact Sheets

A consumer guide and fact sheets based on the best available information about BWTs are needed. These publications should:

- Help educate potential BWT owners and stakeholders
- Answer basic installation questions, including best methods for estimating wind resource, energy production, and cost
- Provide information on existing BWT installations and where to find additional information.

Produce Risk- and Hazard-Focused Fact Sheets

Creating risk- and hazard-focused fact sheets would address concerns of installers and permitting and planning agencies. They should provide information on the following topics:

- Applicability of existing building codes
- Building-integration barriers related to mechanical, electrical, and control systems
- Mounting methods
- Grid interconnection
- Radio frequencies interference
- Ways to reduce vibrations associated with BWTs

- Safety barriers, such as installation risks, fail-safe strategies, and actions to reduce ice shedding if appropriate.

Create Standardized Resource Data Assessment Protocols

Creating wind resource data assessment tools and methods should help standardize data collection and provide a more efficient means of conducting research and comparing wind resources and BWTs. In terms of wind resource, consistent, high-quality, three-dimensional data must be gathered. This wind speed and turbulence data should be collected from multiple locations to address wind resource questions. An example for the application to turbine technology is gathering load and yaw rates across multiple turbines in multiple test locations.

Survey and Analyze Existing Data

BWT costs and a range of installation and maintenance costs should be compiled. Some BWT owners may not want their costs published, so the costs data could be presented anonymously as averages and ranges. Cost data should help potential owners decide whether BWTs are right for them.

Figure 9. BWTs at the Boston Museum of Science. ***Photo by Joe Smith, NREL/PIX 18461***

Analysis of existing data can provide a picture of the BWT market as a whole. This could be useful for policymakers, manufacturers, and investors to understand where and why BWTs are being installed.

Although limited in quantity and quality, existing turbine performance data should be analyzed. Of particular interest is the power performance of BWTs. Power performance measurements require high correlation between anemometer-measured wind speed and the wind experienced by the turbine, so care must be taken to verify the validity of existing BWT power performance data. The BWT power performance data should be compared to the same model's IEC power performance tests. Understanding the differences between power curves should also help establish better estimates of BWT power production.

If vibration measurements exist, they would be very useful in defining best-practice installation and design protocols.

Other measurements of interest are the wind resource of built environments. Average speed measurements are important for verifying wind resource models of built environments. If the data are three-dimensional and have a high enough sampling rate, it would be useful for calculating turbulence parameters.

Investigate and Compare Wind Resource Modeling Methods

There are several methods for modeling and predicting built-environment wind resources. CFD and wind tunnel testing are often cited. Of particular interest are field experiments to study flow in an urban environment in the context of Atmospheric Transport and Dispersion of contaminants.

Figure 10. A Windspire vertical-axis wind turbine in the built environment.
Photo from Windspire Energy, NREL/PIX 18464

Measurements as well as models exist for cities such as Oklahoma City, Salt Lake City, New York City (Manhattan), and various European cities. Those data could be used to model and compare the wind energy resource.

Besides CFD and wind tunnels, models using measure-correlate-predict (MCP) procedures and analytical methods exist.

Each modeling technique has some success in the built environment, as well as limitations. Investigations should be conducted to identify the strengths and weakness of each and how their predictions compare to measured wind data. Comparisons include:

- Accurate prediction of annual average wind

- Ability to provide a wind probability distribution, including extremes and non-standard wind conditions (wind speeds and turbulence)
- Accounting for turbulence parameters
- Accuracy of energy production estimates
- Cost to implement.

These comparisons should help to establish rules for providing initial estimates of wind resource and turbulence parameters. Knowledge of these should help to estimate the cost of energy.

Summary of Near-Term Actions

Table 2 summarizes the actions needed immediately and through approximately 3 years and the BWT barriers addressed.

Note: Safety is a primary concern, and many actions that address safety barriers are addressed in the Both Near-Term and Medium-Term Actions section. Note that there are no near-term actions that quantifiably address safety due to the need to collect measurements and model results first and then build safety into the standards and their resulting designs.

Medium-Term Actions (4-7 Years)

This section outlines the actions that need to be taken in approximately 4 to 7 years to develop testing and design standards for the BWT industry. In most cases, the prerequisite data and experience do not exist, so these actions cannot be implemented now.

Create Best-Practice Recommendations

Best-practice recommendations should be created based on existing knowledge and research findings. Turbine manufacturers, installers, stakeholders, policymakers, and the general public should utilize these actions. Through these recommendations, all BWT barriers should be addressed.

- *Safety:* Recommendations should address issues of ice- and parts-shedding and braking redundancy. Towers should be accessible from the roof without endangering workers and provide access to BWTs. Setbacks from buildings and rooftop limitations should also be addressed.
- *Wind resource:* Recommendations should include how to avoid wakes, eddies, and separation zones, as well as where to place BWTs for the highest average wind speed. It should also address the issues of turbulence and directional variability and their impacts on BWTs.
- *Turbine technology:* Draft IEC standard language should be created to define the design envelope using information on turbulence and directional variability. Understanding of yaw rates, loads, and fatigue in comparison to other SWTs will be gained. Fail-safe BWT designs and testing methods will be developed.

Table 2. Near-Term Actions and Barriers Addressed

Actions	Safety	Wind Resource	Turbine Technology	Building Interactions	Non-Technical Obstacles
Produce a consumer guide and fact sheets					Lack of credible BWT information
Produce risk- and hazard-focused fact sheets				Mechanical and electrical integration issues	Lack of credible BWT information (installation, planning, permitting)
Create standardized resource data assessment protocols		Poor understanding of: -Turbulence and directional variability in the built environment -Three-dimensional wind speed profile and distribution	Poor understanding of: -Load measurements -Yaw rates		
Survey and analyze existing data				-Costly and difficult mechanical and electrical integration -Poor understanding of resonance frequencies	Unpredictable economics (project costs and return on investment)
Investigate and compare wind resource modeling methods		Poor understanding of: -Wakes, eddies, and separation zones -Turbulence and directional variability			

- *Building interactions:* Approaches should include mounting, integration, and vibration mitigation. Building codes for different building types should be reviewed, and recommendations should be made regarding areas of applicability to BWTs.
- *Non-technical obstacles:* Barriers of cost and hazards to personnel installing and servicing BWTs should be addressed. Cost estimates should be provided in terms that can be useful to most potential BWT installations.

Adapt Data Assessment Tools

Data assessment tools already exist for some aspects of wind energy, and some of these could be adapted for BWTs. As discussed previously, wind resources are assessed for horizontal winds, but in built environments the winds have a vertical component. This presents the opportunity to adapt existing wind resource assessment tools for three dimensions. Wind maps are widely used, but their application and effectiveness need to be evaluated and adapted for the built environment.

Cost of energy calculators exist and are widely used; however, they perform poorly in terms of predicting the cost of energy of turbines in complex terrain. Hence, their predictive capability in built environments is highly dubious. The existing cost of energy calculators must be modified and adapted for BWTs.

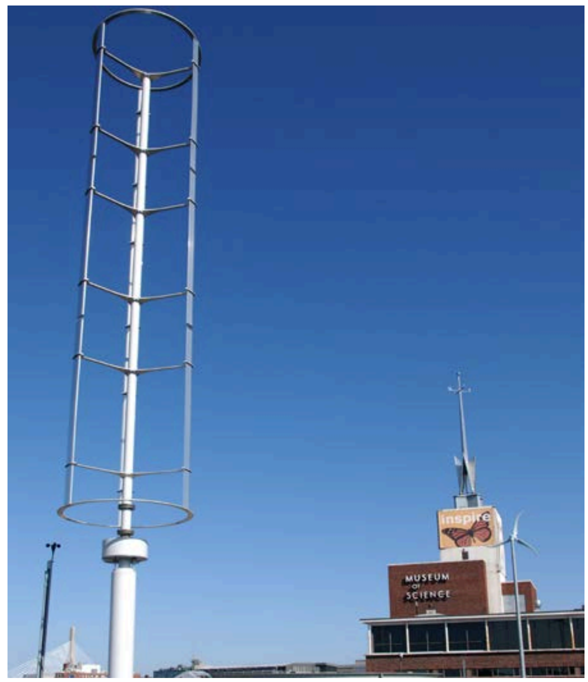

Figure 11. Windspire vertical-axis wind turbine at the Boston Museum of Science. ***Photo from the Boston Museum of Science, NREL/PIX 18007***

Instrument Existing BWTs

By instrumenting existing BWTs with measurement devices, all the identified BWT barrier areas should be addressed.

- *Safety:* A good understanding of the events immediately prior to any failures should be known.
- *Wind resource:* Emphasis should be placed on three-dimensional wind speed profiles, turbulence, directional variability, and wind probability distributions.
- *Turbine technology:* Load, yaw rates (for HAWTs), and vibration frequencies should be measured. Load cells, strain gauges, and yaw encoders will correlate BWT response to wind speed and direction data. Incorporating knowledge of turbulence

parameters and directional variability should also increase a model's ability to predict BWT performance. Additional actions should include applying instruments and condition monitoring for any common failure modes identified using the reliability database (near-term action).

- *Building interactions:* Building resonance due to turbine vibrations should be better understood.
- *Non-technical obstacles:* Barriers to be addressed include actual energy and power production. Down-time and repairs should be documented, and this should relate to the cost of operating and maintaining a BWT.

Conduct Model Validation at Demonstration Sites

Wind resource models should be compared to each other as a near-term action. As a medium-term action, researchers would follow up by comparing model results (CFD, wind tunnel, MCP, and analytical methods) to field measurements for various demonstration sites. These sites should be highly instrumented and representative of potential BWT installation sites. Ideally the location of a demonstration site would be within one of the Atmospheric Transport and Dispersion field test cities or another city with extensive anemometry data for model validation. Models should be checked for their ability to predict wind speed distribution and the location of wakes, eddies, and separation zones. Other items of interest that may be compared are turbulence parameters and directional variability.

The critical component for this action is the use of sonic anemometers or other types of three-dimensional wind measurement devices placed in areas appropriate for BWTs. This will also require some locations with multiple instruments to characterize and compare the special variation of the wind in close proximity to buildings – an array of anemometers across height and length to capture eddies, wakes, and separation zones.

This validation should further improve rules for built-environment wind resources and cost of energy estimates.

Provide Recommendations to Governing Bodies and Standards

Wind turbines are certified to a standard, such as the IEC's set of wind turbine standards, designated as IEC-61400. These standards require turbines to be tested in ways that should reflect their actual use and demonstrate actual performance. At present, BWTs are not included in any standard.

Recommendations must be made regarding appropriate BWT testing. Additionally, the IEC-61400 standard, which is the basis for most other wind turbine standards, does not provide design criteria appropriate to the wind loads a BWT could experience. This action should modify or add tests for BWTs to ensure their safe and reliable operation.

Besides providing recommendations to the IEC, information and recommendations could be provided for building codes and municipal governments contemplating BWT regulations.

Figure 12. University of California - Davis Bergey wind turbine. The university is conducting BWT research. ***Photo from the University of California – Davis, NREL/PIX 17899***

Conduct Turbine Research and Development

Research and development should accelerate the deployment of safe, durable, and effective BWTs. This action can answer specific concerns and develop better methods for future integration. New control methods can be tested to reduce noise and vibrations (reduced noise and vibrations will be important for BWT acceptance). While some research has been conducted on SWT noise reduction, these issues are not as important for rural installations as for built environments, and consequently, much more research is required. Accelerated fatigue testing due to gusts and yawing can be researched. Additionally, other mechanical and electrical building integration barriers may be overcome.

Examples of areas in which research and development can be applied include:

- Comparison of yaw mechanisms
- Containment of failures (e.g., by using tethers on blades, nacelle, base)
- No single point of failure and redundant, independent braking mechanisms
- Rotor-speed control through inverter loading for vibration mitigation; tuning BWTs to avoid exciting building frequencies
- Tip-speed control to reduce noise (e.g., at night)
- Resonance.

Summary of Medium-Term Actions

The following table summarizes medium-term actions that will require effort in approximately 4 to 7 years and the BWT barriers addressed.

Table 3. Medium-Term Actions and Barriers Addressed

Actions	Safety	Wind Resource	Turbine Technology	Building Interactions	Non-Technical Obstacles
Create best-practice recommendations	BWTs lack braking redundancy, parts-shedding and ice-throw containment	Poor understanding of wakes, eddies, and separation zones		Mechanical integration issues (develop and refine mounting strategies)	Hazards to personnel installing and servicing BWTs
Adapt data assessment tools		Poor understanding of 3-D wind resource -Existing wind resource maps do not translate to the built environment			Unpredictable economics (create economic assessment tool)
Instrument existing BWTs		Poor understanding of: -3-D wind resource -Turbulence and directional variability	Poor understanding of loads and yaw rates (measure and correlate to 3-D wind)	Poor understanding of resonance (measure and correlate to 3-D wind)	
Conduct model validation at demonstration sites		Poor understanding of: -Wakes, eddies, and separation zones -Turbulence and directional variability (measure)	Poor understanding of loads and yaw rates (measure)		

Actions	Safety	Wind Resource	Turbine Technology	Building Interactions	Non-Technical Obstacles
Provide recommendations to governing bodies and standards		Poor understanding of 3-D wind resource	Non-existent BWT design class	Model effects of building codes	
Conduct turbine research and development	BWTs lack braking redundancy, fail-safe turbine features		Vibrations and noise (address control strategies to reduce)		

Both Near-Term and Medium-Term Actions

The actions in this section require immediate to medium-term effort to reduce BWT barriers and improve the industry.

Create a Reliability Database

A BWT reliability database should provide a central location for logging all BWT failures. By tracking failures, this database could be used to identify issue patterns, minimize repeated similar mistakes, and improve designs and design requirements. This database could be made public, limited access could be granted, or a combination of both could be implemented. It is expected that it will be used by owners, policymakers, installers, and manufacturers. Although each group will have its own database need, the goal is to improve BWTs' safety and quality.

Figure 13. An example of a roof-mounted vertical-axis wind turbine in San Francisco. ***Photo from Danielle Murray, Department of the Environment, San Francisco***

Measure Loads and Yaw Rates

Turbulence and directional variability experienced by BWTs will be higher than for most SWTs designed for a rural environment, and this will probably result in higher loads on BWTs. Gusts will create large forces on the blades and increases in rotor speed. Stronger and sharper gusts will increase this effect. For HAWTs, direction variability will cause the turbine to yaw, and if the directional wind change occurs quickly, large forces will be exerted on a moving rotor, tail (if applicable), and yaw axis. It is critical to measure and therefore better understand the extreme loads and yaw rates that BWTs experience.

Produce Case Studies

Case studies of existing and future BWT installations, including lessons learned, should be produced to help develop best practices. They should show trends of installation cost and energy generation, thus helping to show BWT cost of energy and payback. Additionally, case studies should be useful in reviewing the applicability of existing building codes and ordinances to BWTs, therefore helping to develop future codes and ordinances.

Conduct Site Wind Resource Assessment through Measurement and Validate Analytical Models of the Wind Resource

The most likely instrument for wind resource assessment in an urban environment is the sonic anemometer because it measures wind in three dimensions and is durable enough for field measurements, although SODAR[4] and LIDAR[5] also remain possible. An array of anemometers at a single location combined with high sampling rates can provide detailed measurements of the wind's structure (turbulence, directional variability, and shear) at that location. Measuring three-dimensional winds should reduce the barriers of unknown wind speed, turbulence parameters, and directional variability in the built environment. Detailed knowledge of the wind resource is necessary for understanding the wind loads on a BWT and to avoid wakes, eddies, and separation zones. Measurements should also improve predictions of energy output and therefore answer questions about cost.

These measurements can be used to validate numerical models such as CFD models and stochastic models (e.g., TurbSim). With advancements in computer performance, many CFD packages are available today, and more important, these packages are widely used as a tool for wind flow analysis. There are few commercially available CFD packages, such as UrbaWind and PlayBox, that are especially made for wind flow analysis in the urban environment (Beller 2010, Fahssis et al. 2010). In the past, the CFD wind flow analyses have mostly been used for dispersion studies, but now they are increasingly being used to assess the wind resource for wind turbine technology. However, the use of CFD in the area of wind resource assessment for the urban environment is emerging and needs validation through site measurement. Similarly, TurbSim is an NREL-developed computer code that outputs a turbulence inflow field to be used in aero-elastic models for wind turbine loads response calculation, such as ADAMS and FAST (also developed by NREL). TurbSim uses several spectral models, including two IEC models, the Riso smooth-terrain models, and several NREL site-specific models (Jonkman 2009). Among these models, the IEC models might be used for the built environment, but their applicability must be ascertained through site measurement and validation. A new

[4] Sonic Detection and Ranging; used for remote sensing of wind speed and direction.
[5] Light Detection and Ranging; used for remote sensing of wind speed and direction.

stochastic model specifically for the built environment can also be integrated into TurbSim to expand its relevancy in the built environment.

High-resolution wind measurements can be the basis for rules for the built-environment wind resource, which should improve energy production and cost of energy estimates, resulting in increased deployment of BWTs.

Build Demonstration Sites

BWT demonstration sites should have strong and dynamic winds. They should display proper installations and offer information about installation costs and energy production. Demonstration sites should also be used to increase public understanding and acceptance.

Besides displaying a BWT's operation, some additional uses of a demonstration site include displaying and explaining:

- Compliance with building codes and local ordinances
- Mechanical and electrical integration of BWTs and their towers to the building
- Ice build-up potential and actions to mitigate ice throw
- Resonance and vibration mitigation
- When and how to perform maintenance.

Conduct Turbine Testing

Rigorous field testing should find flaws quicker than display and demonstration sites. Additionally, procedures can be established to protect the workers from a turbine failure at a test site; public safety would not be an issue.

Some tests may be conducted on the complete wind turbine system, allowing for comparison of different BWTs. Conversely, tests may be designed to answer specific questions about turbine components or operational details. Tests length may vary, but it is important to control as many variables as possible. A dedicated test site can provide that control, whereas demonstration sites cannot.

Tests at dedicated test sites may be developed to answer questions about:

- Loads
- Yaw rates
- Wear
- Fatigue
- Condition monitoring and frequency for scheduled maintenance
- Resonance frequencies.

Test sites should provide input on how standardized tests are conducted safely and efficiently.

Summary of Both Near-Term and Medium-Term Actions

The following table summarizes actions that require immediate and sustained effort and the BWT barriers addressed.

Table 4. Near-Term and Medium-Term Actions and the Barriers Addressed

Actions	Safety	Wind Resource	Turbine Technology	Building Interactions	Non-Technical Obstacles
Create a reliability database	-BWTs lack containment features for parts-shedding and ice-throw -BWTs experience shortened lifetime in high-fatigue environment			Mechanical and electrical integration issues	Hazards to personnel installing and servicing BWTs
Conduct BWT test measurement campaign for loads and yaw rates			Poor understanding of loads measurements and yaw rates		
Produce case studies				-Mechanical and electrical integration issues -Poor understanding of resonance	-Hazards to personnel installing and servicing BWTs -Unpredictable economics
Conduct site wind resource assessment through measurement and validate analytical model(s)		Poor understanding of: -3-D wind resource -Wakes, eddies, and separation zones -Turbulence and directional variability	Poor understanding of loads and yaw rates		-Unpredictable economics

Actions	Safety	Wind Resource	Turbine Technology	Building Interactions	Non-Technical Obstacles
Build demonstration sites	-BWTs lack containment features for parts-shedding and ice-throw -BWTs experience shortened lifetime in high-fatigue environment	Poor understanding of: -3-D wind resource -Wakes, eddies, and separation zones -Turbulence and directional variability	Poor understanding of loads and yaw rates	-Mechanical and electrical integration issues -Poor understanding of resonance	-Hazards to personnel installing and servicing BWTs -Unpredictable economics
Conduct turbine testing	BWTs experience shortened lifetime in high-fatigue environment		Poor understanding of: -Loads and yaw rates -BWT class design -Fatigue	-Mechanical and electrical integration issues -Poor understanding of resonance	Lack of outreach and education (noise and permitting issues)

Strategy

This section outlines the strategy to implement the actions outlined in the previous section and identifies necessary expertise and resources. The strategy focuses on two main areas:

- Understand the built-environment wind resource
- Develop testing and design standards.

Understand the Built-Environment Wind Resource

Investigating the built-environment wind resource should be a closely coordinated effort between modeling and measurements. This process will probably be iterative as data from different anemometer locations are compared to model-based simulations and experiments of the flow around buildings in areas of high turbulence. The model-based methodologies should then be updated to better predict for diverse sites.

Validate and Develop Models

Actions to understand the built-environment's wind resource should start with sites that have already been modeled, preferably in the wind tunnel and through CFD. Results would be compared to each other and with three-dimensional field measurements. The anemometers should be sited in multiple locations where BWTs would likely be installed. Wind modeling and validation efforts are already underway at the University of California-Davis (UC-Davis) and Massachusetts Institute of Technology (MIT). Researchers at UC-Davis have studied wind turbine siting by verifying wind tunnel data with site measurements (Strataridakis et al. 1998). A similar effort was carried out at MIT by comparing the site measurement data with a CFD model (WEPA 2010).

Besides city-wide modeling, smaller areas have been modeled. For the Twelve West building in Portland, Oregon, Zimmer Gunsul Frasca Architects LLP used Cermak Peterka Petersen, Inc. for wind tunnel modeling of the firm's roof-mounted Skystream turbines.

Some university campuses, such as the Massachusetts Institute of Technology, George Mason University, and Penn State, have computer models of the wind resource on campus.

Penn State has a wind tunnel model of part of its campus and a meteorological department, which may prove useful as well. The Massachusetts Institute of Technology has several anemometer locations and sets of LIDAR measurement data. Working with these and other universities to validate and further develop models could greatly enhance the understanding of the built-environment wind resource.

Modeling software is increasingly available to end users; some products include UrbaWind (software developed by Meteodyne) and Wind Analytics (software developed by Wind Products, Inc.). Some modeling companies sell their software to other companies or individuals who can then model their built environment and predict the wind resource. Validation of commercial CFD software could be performed at any location with sonic anemometers. Ideally, these would be compared to areas with anemometers that have already been modeled, such as San Francisco, New York City, and various university campuses.

Besides commercial software, models are being developed at Lawrence Livermore National Laboratory. The laboratory has not used its CFD software for BWTs, but it has been used in built environments. It could be modified to be directly applicable to BWTs.

The IEA is working on Task 27, which has developed the Recommended Practices for Consumer Small Wind Labeling and is beginning to develop a recommended practice for the built environment. Research conducted under IEA Task 27 on the built environment will help to develop an IEC load case specifically for the built environment turbine and will be discussed in the fourth revision of the IEC standard. Some of the universities involved with the IEA work are analyzing three-dimensional built-environment data for turbulence intensity, wind speed, and wind direction characteristics. Comparing BWT models with the IEA team should be beneficial to all parties. The IEA also has access to a large set of wind speed measurements.

The IEC is modeling turbine loads. Because the load models are directly related to the wind resource model, collaboration with the IEC could benefit both. Plans have been discussed to develop a built-environment wind class and loads methodology requirements. This effort will follow the IEA work, as well as work in countries to better understand inflow and turbine response.

Figure 14. Bergey turbine outfitted with two three-dimensional sonic anemometers that measure wind speeds upwind and in the tail wake. *Photo by Dave Corbus, NREL/PIX 13175*

NREL developed the software TurbSim, which simulates the turbulent inflow to a turbine. This is then used to simulate turbine response to wind loads and forces in other NREL-developed software. For reasons mentioned earlier, modifying TurbSim for the built environment would be useful for BWT designers.

Conduct Measurements

Wind speed and direction measurements should be in three dimensions, so sonic anemometers will probably be utilized. Any group with sonic anemometers and three-dimensional wind data in the built environment would be valuable. Coordination with built-environment modelers could identify optimum locations to deploy anemometers.

Ideally arrays of anemometers would be deployed to investigate the special variability of the wind resource.

Measurements must be taken for validating TurbSim. Validation of TurbSim is necessary before it is used to design BWTs. NREL should provide guidance for evaluating TurbSim's capabilities and application for modeling the wind resource in the built environment.

Develop Testing and Design Standards

BWT testing falls into two categories:

- Initial and high-risk testing (should only be performed where risk to the public and property is eliminated)
- Tests on BWT installations (conducted after the high-risk testing to continue to gather and improve knowledge).

Test BWTs at an Established Test Site

BWTs should be tested at an established test site with staff members who have expertise in safely testing wind turbines that can be applied to testing BWTs.

Buildings at the test site could be inventoried for potential BWT installations and testing and then modified for various types of BWT testing. Along with this effort, flow models could be employed to understand wind flow around the building with and without a BWT installed. BWTs can be moved so that optimum turbine locations can be determined. This should be of great value in providing guidance and best-practice advice.

In addition to testing BWTs, three-dimensional measurements of the wind resource can be made and used to validate models. Additionally, multiple anemometer measurements, upstream and downstream of buildings, would improve knowledge of wake, eddies, separation zones, turbulence parameters, and directional variability. These high-resolution measurements would complement wind resource measurements listed in the previous section.

NREL and some universities have expertise in building science. This can be applied to investigate interactions between the turbines and buildings, especially vibrations. Highly instrumented BWTs and buildings, in addition to fully characterized winds, would provide much valuable data to the BWT industry.

A site dedicated to testing has several advantages over an urban location. A test site could have buildings that move (e.g., adjustable pitch roofs, modular building layouts, etc.) to measure flow blockage and turbulence, thus providing additional control for simulating turbulence in the built environment. The general difficulty of testing in an urban area, where anemometer placement is restricted and ambient noise level is high, makes it less attractive than a test site. Also, comparing results from different cities may be problematic, and results from a test site may be no more different from one urban site than urban sites are from each other.

One such wind turbine test site is NREL's NWTC. Independent testing of BWTs at the NWTC would provide information to consumers and guidance to other organizations as they develop their own BWT test sites.

The NWTC is also an ideal place for research and development. This is important in researching BWT safety concerns such as fail-safe design, braking redundancy, ice throw and parts-shedding, and shortened turbine life due to high fatigue.

Figure 15. An example of a vertical-axis wind turbine in San Francisco. ***Photo from Danielle Murray, Department of the Environment, San Francisco, NREL/PIX 18447***

In addition to testing, NREL personnel are involved in standards development. Knowledge gained during testing at the NWTC could be incorporated into future standards. This may include developing a BWT classification or a modification of existing standards to accommodate BWT designs and to adequately test them.

Test BWTs in the Built Environment

Testing in the built environment requires a partnership with the owners and neighbors. These tests could have more restrictions than tests at a turbine test site, but testing BWTs that are installed in the built environment will be more realistic. Regardless of the location of BWT testing, safety is the main concern, especially when people and property are in close proximity. The following are examples of BWT partnerships that could be pursued.

- Several individuals and institutions have expertise that can be used for testing BWTs in the built environment. Sander Mertens of Ingreenious is an example of a leading expert on BWTs, and the knowledge, advice, and contacts of such individuals would be beneficial.

- The Warwick Wind Trials in the United Kingdom demonstrated SWTs in the built environment. This work increased the level of BWT knowledge, and it should be used for case studies and best-practice guidance.

- Several other groups and individuals have installed and tested BWTs; for example, the University of California at Davis; TUV-NEL's[6] Meyers Hill test site near Glasgow, Scotland; and Spain's CIEMAT[7] facility. All have valuable BWT experience that can provide input for best-practice guidelines. In addition, their

[6] TUV-NEL is a for-profit multinational test and certification agency.
[7] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

experience can be the foundation for a reliability database to track BWT weaknesses and potential liabilities, as well as best practices.

- The Boston Museum of Science has established its Wind Turbine Lab with five types of turbines installed on the museum's roof. This is an ideal institution for publishing findings of tests conducted on the roof (Museum of Science 2011). Additionally, museum staff members have experience and are able to offer advice on best practices.

- Several federal facilities are interested in BWTs as part of the Federal Energy Management Program. BWTs installed on federal buildings as part of the program could be instrumented to provide power performance and other test data. Ideally, flow models and wind tunnel validation would be accomplished before BWT placement. The test anemometer and BWT location should be calibrated to provide a high correlation between measured wind speed and what is experienced by the BWT. These rigorous and methodical power performance tests are greatly needed.

- Southbank University has experience with roof-mounted turbines in central London (Day and Dance 2011).

- The University of Salford in the U.K. has experience in acoustic testing SWTs in the built environment (Moorhouse 2011) and should be engaged for many types of BWT acoustic tests.

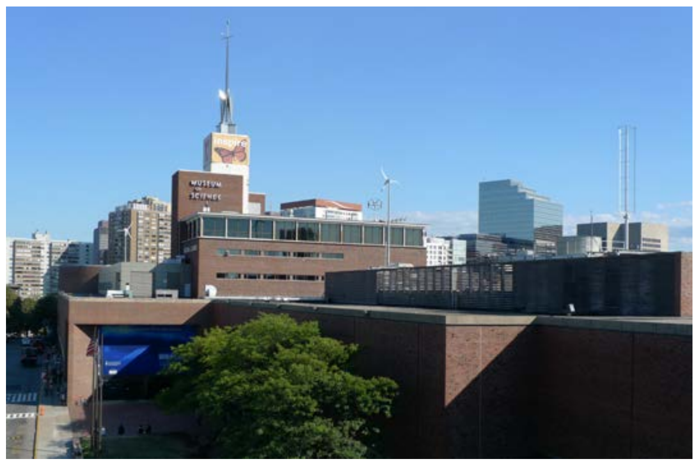

Figure 16. The Boston Museum of Science currently has five turbines in its Wind Turbine Lab. *Photo from the Boston Museum of Science, NREL/PIX 18001*

In addition, BWT manufacturers can provide great value. For example, Cascade Swift and Quiet Revolution have knowledge of the wind resource in the built environment and how it affects their products. These and other manufacturers can provide input into best practices and provide partnerships for advanced turbine testing.

Strategy Summary

There are four strategic areas for accomplishing the actions designed to address barriers to BWT deployment. Each area is summarized below, including the most pressing actions that they address.

Note: Actions for "Understanding the Built-Environment Wind Resource" are highly iterative; models require data for validation, and measurements are generalized in models. Both provide a basis for BWT design and testing.

Table 5. Strategy Summary

Understand the Built-Environment Wind Resource		Develop Testing and Design Standards	
Validate and Develop Models	**Conduct Measurements**	**Test BWTs at Established Turbine Test Site (i.e., the NWTC)**	**Test BWTs in the Built Environment**
Model comparison: CFD & tunnel (near term)	Create or adapt data assessment protocols (medium term)	Make best-practice recommendations (medium term)	Produce a consumer guide and fact sheets (near term)
Validate model at installations (medium term)	Conduct measurements at demonstration sites: CFD & tunnel to installations (medium term)	Conduct model validation at demonstration sites: CFD and wind tunnel to installations (medium term)	Produce a risk- and hazard-focused fact sheet (near term)
Make best-practice recommendations based on existing knowledge (medium term)	Make recommendations to governing bodies and standards (medium term)	Make recommendations to governing bodies and standards (medium term)	Analyze existing data for actual turbine performance (near term)
Validate turbine inflow models with 3-D measurements (both)	Conduct sonic anemometer measurements (both)	Conduct turbine research and development (medium term)	Create a reliability database (both)
Build and instrument demonstration sites and validate flow models (both)		Conduct turbine testing (both)	Make best-practice recommendations (medium term)
		Conduct sonic anemometer measurements and validate TurbSim (both)	Create or adapt data assessment tools (medium term)
			Instrument existing BWTs (medium term)
			Build demonstration sites (both)
			Conduct turbine testing (both)
			Produce case studies (both)

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Appendix I: Types of Built-Environment Wind Turbines

There are four types of BWT installations:

- Building-mounted on the side of a building (Figure 17)
- Building-mounted on the roof (Figure 18)
- Building-integrated wind turbine (Figure 19)
- Ground-mounted in a built environment (Figure 20).

Figure 17. Building-mounted (side) wind turbine at the Boston Museum of Science. ***Photo by Joe Smith, NREL/PIX 18463***

Figure 18. Building-mounted (roof) wind turbine at the Boston Museum of Science. ***Photo by Joe Smith, NREL/PIX18460***

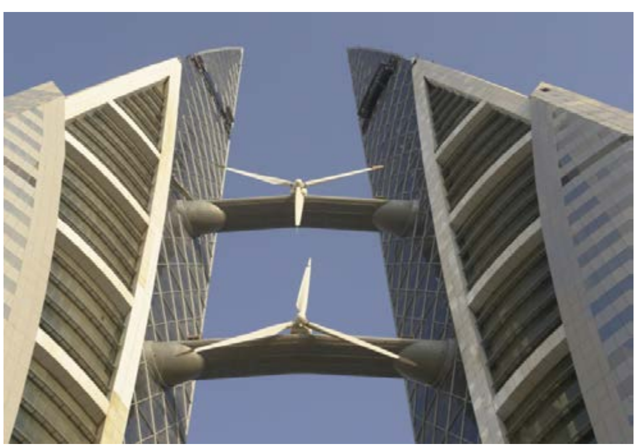

Figure 19. Building-integrated wind turbine at the Bahrain World Trade Center. ***Photo from iStock/6924031***

The majority of BWTs are roof-mounted SWTs (Figure 18) with a rated power of 10 kW or less (Wineur, 2005). For a conventional HAWT, this means a rotor diameter of less than approximately 7 meters (23 feet). Besides HAWTs, several VAWTs have gained public interest, and some manufacturers market their VAWTs for urban and suburban installations.

The building-integrated wind turbine (Figure 19) employs an unconventional design to allow for wind turbine placement within the structure. Building-integrated wind turbines are architecturally noteworthy and require extensive engineering expertise and added cost. With most building-integrated wind turbines, issues of aerodynamics, vibration, and building interaction have been studied, and potential effects have been mitigated. Building-integrated wind turbines are custom designed, and their installations typically do not represent Universal Building Code practices that influence structural resonance frequencies. Therefore, this roadmap does not address them.

Ground-mounted turbines (Figure 20) require consideration for installing and raising the turbine as well as decreased production due to the poor wind resource found in the urban environment.

Figure 20. This Aeroturbine at the Randall Museum in San Francisco, California, is an example of a vertical-axis wind turbine in the built environment. ***Photo from Danielle Murray, Department of the Environment, San Francisco, NREL/PIX 18443***

Appendix II: Rooftop and Built-Environment Wind Turbine Workshop Attendees

The following people attended the Rooftop and Built-Environment Wind Turbine Workshop on August 11-12, 2010, at the National Wind Technology Center in Boulder, Colorado:

John Breshears, ZGF Architects LLP

Craig M. Briscoe, ZGF Architects LLP

Brad Cochran, CPP Inc.

John Dunlop, American Wind Energy Association

Guillaume Dupont, Meteodyn America Inc.

Graham Eastwick, Encraft

Fort Felker, National Renewable Energy Laboratory

Trudy Forsyth, National Renewable Energy Laboratory

Sue Ellen Haupt, Penn State

Feitau Kung, National Renewable Energy Laboratory

Michael Lenartowicz, Intertek

Dave Lubitz, University of Guelph

Becki Meadows, National Renewable Energy Laboratory

Sander Mertens, Ingreenious BV

Jeff Mirocha, Lawrence Livermore National Laboratory

Pat Moriarty, National Renewable Energy Laboratory

Guy R. Nelson, Western Area Power Administration contractor

Rich Peek, Cascade-Swift

Karin Sinclair, National Renewable Energy Laboratory

Joe Smith, National Renewable Energy Laboratory

Susan Stewart, Penn State

Russell Tencer, Wind Products Inc

Marian Tomusiak, Museum of Science, Boston

Case van Dam, University of California - Davis

Dawn White, Accio Energy

Appendix III: Workshop Agenda

Wednesday, August 11, 2010

9 – 9:30
Trudy Forsyth
Welcome and introductions

9:30 – 11:30
Sander Mertens, Ingreenious BV
"Urban Wind Turbines: Identifying a New Branch"

Data and observations presentations moderator: Case van Dam

12:30 – 1:30
Graham Eastwick, Encraft
"Lesson Learned during the Warwick Wind Trials: A Study of 23 Roof- and Building-Mounted Turbines"

1:30 – 2:15
Craig Briscoe and John Breshears, ZGF Architects
"A Portland Case Study: Predicted and Measured Results from a Small Wind Installation on an Urban Highrise"

2:15 – 2:45
Marian Tomusiak, Museum of Science, Boston
"Lessons from the Boston Museum of Science Wind Turbine Lab"

3 – 3:35
Case van Dam, University of California – Davis
"Research on Wind Power in the Built Environment"

3:35 – 4:10
David Lubitz, University of Guelph
"Measurement and Assessment of the Wind Environment near Low-Rise Buildings"

4:10 – 4:55
Patrick Moriarty, National Renewable Energy Laboratory
"Aeroacoustics and Vibration of Wind Turbine Systems"

4:55 – 5:40
Rich Peek, Cascade – Swift
"Manufacturer's Perspective"

5:40 – 5:50
Remarks

Thursday, August 12, 2010

8:30 – 8:45
Welcome back, recap

Modeling presentations moderator: Jeff Mirocha

8:45 – 10
Brad Cochran, CPP Wind
"Modeling Airflow over Buildings Using Wind Tunnel Data and CFD Models"

10 – 10:45
Guillaume Dupont, Meteodyne
"Use of a CFD Model for Wind Assessment in the Built Environment: Introduction to the UrbaWind Model"

11 – 11:30
Russell Tencer, Wind Products
"Wind Analytics: Modeling Software for Small Wind Turbine Siting"

11:30 – 12
Susan Stewart, Penn State
"Mapping Wind Power Resources around Buildings"

12 – 12:30
Jeff Mirocha, Lawrence Livermore National Laboratory
"Development of Multi-Scale Mesoscale/CFD Modeling Approaches"

Parallel Focus Group Discussions

1:30 – 2:30
Moderator: Jeff Mirocha
"Strategies for Model Improvement"

2:30 – 3:30
Moderator: Case van Dam
"Strategies for Data Improvement"

Whole Group Discussions

3:45 – 4:45
Moderator: Trudy Forsyth
"Strategic Outline of Research Priorities"

4:45 – 5
Closing remarks

Appendix IV: Roadmap Reviewers

Bret Barker, U.S. Department of Energy

Michael Derby, U.S. Department of Energy

Guillaume Dupont, Meteodyn America Inc.

Katherine Dykes, Massachusetts Institute of Technology

Graham Eastwick, Encraft

Fort Felker, National Renewable Energy Laboratory

Michael Jason Fields, National Renewable Energy Laboratory

Sue Ellen Haupt, Penn State

Feitau Kung, National Renewable Energy Laboratory

Michael Lenartowicz, Intertek

Dave Lubitz, University of Guelph

Sander Mertens, Ingreenious BV

Jeff Mirocha, Lawrence Livermore National Laboratory

Danielle Murray, City of San Francisco

Jason Roadman, National Renewable Energy Laboratory

Susan Stewart, Penn State

Russell Tencer, Wind Products Inc.

Marian Tomusiak, Museum of Science, Boston

Case van Dam, University of California - Davis

Jeroen van Dam, National Renewable Energy Laboratory

Appendix V: Contacts Summary

Table 6. Summary of Contacts, Affiliation, Expertise, and Interests

Point of Contact	Affiliation	Email	Expertise	Interests
Case van Dam	University of California - Davis	cpvandam@ ucdavis.edu	Rooftop BWT; atmospheric boundary layer wind tunnel used for urban wind resource measurements	Continuing BWT work in wind tunnel
Danielle Murray	City & County of San Francisco	danielle.murray@sf gov.org	San Francisco urban wind and energy planning, community outreach	Refining model of San Francisco urban wind resource; developing a small wind turbine test, certification, and demonstration facility; looking for partners
Dave Lubitz	University of Guelph	wlubitz@ uoguelph.ca	Sonic anemometry to assess the flow field above a peaked-roof building; anemometer arrays to assess obstacle wakes; atmospheric boundary layer wind tunnel used to assess BWT placement	Installing rooftop-mounted BWT in 2011; developing wind resource assessment tools and characterizations; developing design guidelines and testing procedures
Graham Eastwick	Encraft	Graham.Eastwick@ encraft.co.uk	Warwick Wind trials; noise and vibration studies; site selection, permitting, and project management	Advising clients on the best renewable energy system options for their projects; participating in studies to increase practical knowledge
Guillaume Dupont	Meteodyn America Inc.	guillaume.dupont@ meteodyn.com	CFD development (UrbaWind software)	Generating 1-m resolution wind maps of major U.S. cities for which wind data are available (San Francisco, New York City), also including TKE comparisons

Point of Contact	Affiliation	Email	Expertise	Interests
Katherine Dykes, Alex Kalkimov, Cy Chan	Massachusetts Institute of Technology	dykesk@mit.edu kalex@mit.edu cychan@ csail.mit.edu	Assess MIT campus wind resource for suitability for small-scale wind turbines within a built environment	Improving CFD results with LiDAR data and GIS models of MIT campus
Jeff Mirocha	Lawrence Livermore National Laboratory	jmirocha@llnl.gov	Urban CFD modeling for atmospheric dispersion purposes; simulation of boundary layer flow over complex terrain	CFD modeling of urban landscapes for turbine siting; modeling of turbulent stress loading; incorporating mesoscale inflow boundary conditions for CFD simulations
Marian Tomusiak	Boston Museum of Science	mtomusiak@ mos.org	Rooftop Wind Turbine Lab data analysis	Communicating data and experiences with rooftop wind turbines
Michael Lenartowicz	Intertek	michael.lenartowicz @intertek.com		Measuring and simulating load
Russell Tencer	Wind Products Inc.	rtencer@ wind-products.com	BWT manufacture; developer of wind energy modeling software designed for the built environment	Establishing guidelines to protect industry from bad turbine and poor installations; working with partners to educate potential consumers
Sander Mertens	Ingreenious BV	sandermertens@ ingreenious.com	Fluid dynamics; wind resource assessments; measurement analysis; Measurement Correlate Predict procedures; CFD simulations of the built environment; wind tunnel measurements of BWTs; open-air BWT tests	All theoretical and empirical BWT issues; certifying BWTs
Sue Ellen Haupt	Penn State	seh19@psu.edu	Wind power density mapping in built environments; wake impact	Defining the flow interaction with the BWT; leveraging air pollution knowledge to form CFD models of various scales

Point of Contact	Affiliation	Email	Expertise	Interests
Susan Stewart	Penn State	sstewart@psu.edu	Detached Eddy Simulation CFD analysis of cube-shaped building and a pitched-roof building; building VAWTs and testing in wind tunnel and dynamometer; on-campus HAWT with 2-Hz data; BWT design concept review	TKE and yaw variability in the built environment and their impact on design and standards; advancing knowledge to the point at which IEC recommendations can be made; refining and improving Detached Eddy Simulation model