The Informed Application of Building-Integrated Wind Power

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ABSTRACT: This paper documents the design process of a building-integrated wind turbine array for a high rise building in Portland, Oregon. The primary motive of the investigation was to further the general field of knowledge on applications of building-integrated wind generation. Key issues addressed in the process include quantifying the wind regime, predicting wind flow over the structure, turbine selection, and the design of roof mounting to accommodate structural loads and mitigate vibration.
Keywords: wind power, energy, building-integration

INTRODUCTION

To judge from the pages of any recent architectural journal, incorporating small-scale wind turbines into buildings has become, at least on paper, very fashionable. Yet wind behavior in the urban environment is immensely complex and almost universally over-simplified in these proposals. As an indication of this complexity, the flow of wind over and around buildings often triggers multiple transitions of the air from laminar flow to turbulent, a process that is still not fully understood and has long been used as an example of Chaos Theory [1].

This paper documents the process of moving beyond a simplistic approach to a truly informed application of building-integrated wind power on a high-rise building in an urban setting. While the project is not located in an ideal regime for wind generation, the purpose of the exercise was to further the general field of knowledge and understanding of integrating small scale wind power into buildings. The research path can be mapped as four parallel investigations, the results of which were synthesized into a design solution. In retrospect the investigations can be posed as four simple questions:

1. At the geographical scale, is there enough wind to operate the turbines effectively?
2. At the building scale, where should those turbines be placed to maximize energy production?
3. At the equipment scale, what type of turbine would perform the best?
4. What pragmatic challenges need to be resolved in order to turn this investigation into a built reality?

GEOGRAPHICAL SCALE

The annual distribution of average hourly windspeeds for any given location falls into a probability density distribution known as the Weibull Distribution. The curve is characterized by two parameters: the 'scale' parameter describing the average of the wind speeds throughout the year, and the 'shape' parameter, describing the amount of attenuation – or "pointedness" – of the curve [2].

Predicting the actual Weibull Distribution for a specific site, particularly an urban one, is complicated by several sources of uncertainty. The potential for wind power generation varies as a cubed function of wind speed, making power output extremely sensitive to slight variations in wind velocity [3]. Wind behavior can vary significantly with small changes in location, limiting the reliability of wind resource data not measured close to the actual turbine site. The friction effect of the earth's surface creates a 'no-slip' condition, causing a wind velocity of zero at ground level. Over open terrain, the velocity profile of wind as a function of height above the ground is relatively predictable and defined as the log-law function. In an urban context, buildings produce drag and turbulence causing a much more complex situation. Each site in a city is unique and can vary greatly with a slight change in altitude or location [4].

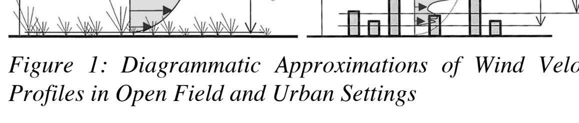


Figure 1: Diagrammatic Approximations of Wind Velocity Profiles in Open Field and Urban Settings

The most widely available wind data in the US comes from the National Weather Service which maintains anemometers at every major airport. While years of data are available, the collection sites on open airfields do not accurately reflect urban conditions. Locating long-term measured wind data for sites in downtown Portland proved difficult. Data sets were taken from the local airport and a local university building, neither of which were truly representative of the proposed turbine location. The two sets of data together clearly demonstrate the sensitivity of wind speed distribution on power generation. The data sets had identical annual average wind velocities of 3.6 m/s. A difference in the shape parameter of 1.7 to 2.8, however, changed the power output of a turbine by as much as 50%.

In order to predict the wind behavior at the top of a 270' tall building in a unique urban context, a wind data translation approach developed by a project collaborator was applied to the measured data. This approach accounts for the step change in surface roughness encountered by wind flow as it enters an urban area by approximating the revised internal boundary layer height and accounting for the effects of turbulent mixing downstream from this step change [5].

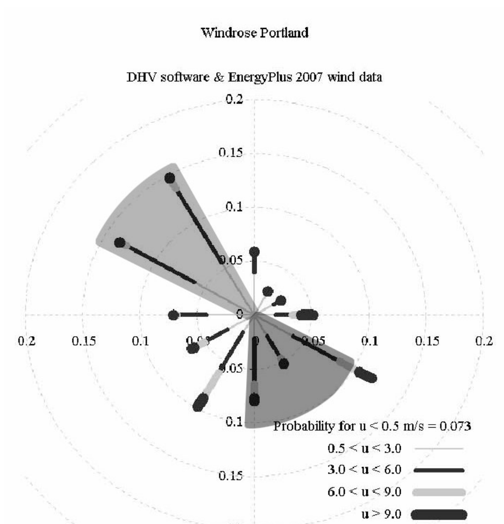
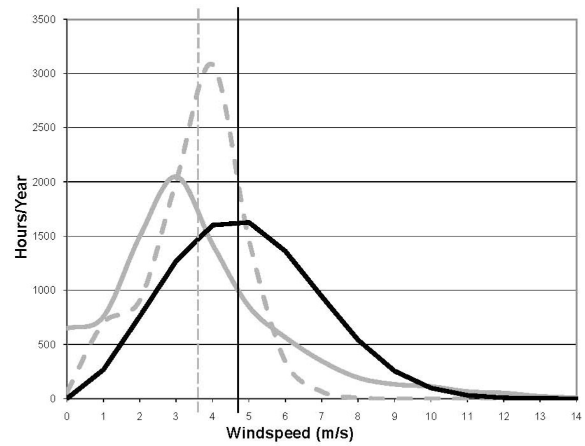


Figure 2: Wind Rose for Portland, Oregon, clearly showing the seasonally dominant wind directions

The local wind data, when plotted into a Wind Rose, revealed two fairly consistent, seasonally varying wind directions. During the summer months, the winds tend to approach the site from the northwest, while in the winter they originate through a slightly wider range of south-southwesterly directions.

The predicted wind speed and Weibull distribution at the top of the building yielded an estimated power production 40% higher than what was indicated by locally measured weather data.



	average speed (m/s)	shape parameter	annual generation (kWh)
Airport	3.6	1.7	1826
University	3.6	2.8	1180
Turbine Site	4.9	2.6	3067

Figure 3: Annual Wind Speed Weibull Distributions and Corresponding Predicted Turbine Power Generation for Two Sets of Measured Data ('Airport' and 'University') and a predicted Set at the Project Location

BUILDING SCALE

With the wind resource established at a large scale, the second point of investigation focused on where to position the turbines with respect to the building. An aeronautical engineering firm with a long history of innovation was contracted to help answer the new question facing the design team.

The aeronautical engineers immediately helped to clarify the question to be asked. The key to locating the turbines properly was in understanding the wind flow over the building. Rather than delve into computational work, these hands-on engineers preferred to work with a scale model in a wind tunnel. A 1:100 scale model of the top third of the building was built for the testing, with particular attention to structures on the roof that might affect wind flow.

The team conducted numerous "flow visualization" techniques in the wind tunnel including high-speed photographic recording of the flow of laser-illuminated smoke over the model. The most informative work was done with "instruments" consisting of replacement fishing rod tips fitted with various bits of thread, cassette tape, and propellers from toy airplanes.

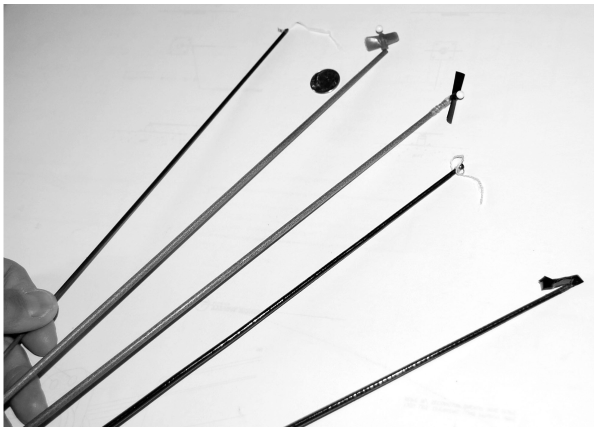


Figure 4: Instruments for Flow Visualization

The primary task of the wind tunnel exercises, apart from gaining a much better qualitative understanding of the wind flow patterns over the building, was to determine the location of the shear plane, or warped surface above which the building's effect on wind flow ends. The simple instruments proved remarkably sensitive to the complexities of wind flow over the model and allowed the team to locate the shear plane for each of the two dominant seasonal wind directions. Locating the turbines above the shear planes is critical to power generation by virtue of the higher energy embodied in the free-flowing wind, and to turbine endurance, which can be substantially shortened by the repeated hammering of turbulent wind flow [6].

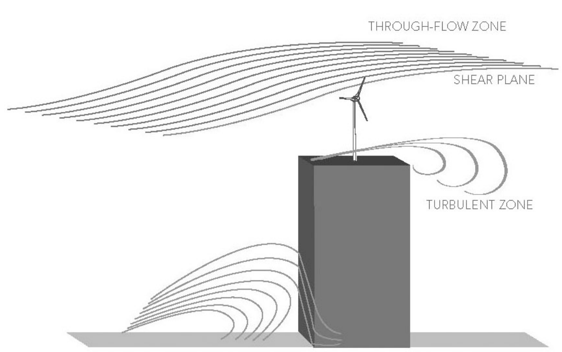


Figure 5: The 'Shear Plane' of Airflow Over a Building

Somewhat counter intuitively, for a building with a high aspect ratio and sharp corners the location of the shear planes remains fairly constant even with changing wind speeds [7]. This fact allowed the team to be reasonably confident that once turbines were correctly located in relation to these critical surfaces, they would be positioned to receive optimal wind flow over the entire meteorological year.

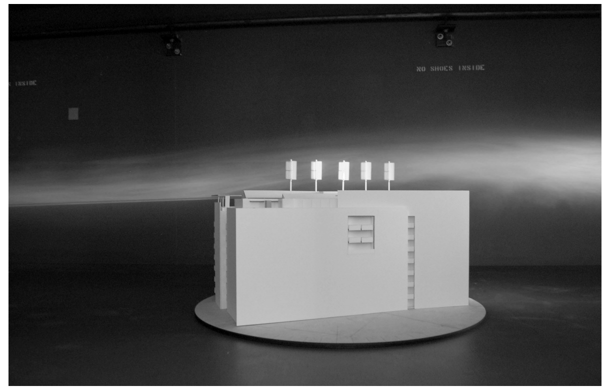


Figure 6: Flow Visualization Using Smoke

Overlaying the shear plane framework on the initially proposed turbine installation indicated that the team's initial instincts about turbine placement were sound but not perfect. The initial location was very near a pronounced 'valley' formed by the intersection of the two planes. Three of the five turbines were well placed to be above the two shear planes, while the two western-most turbines were below the shear plane for the southeasterly winter winds.

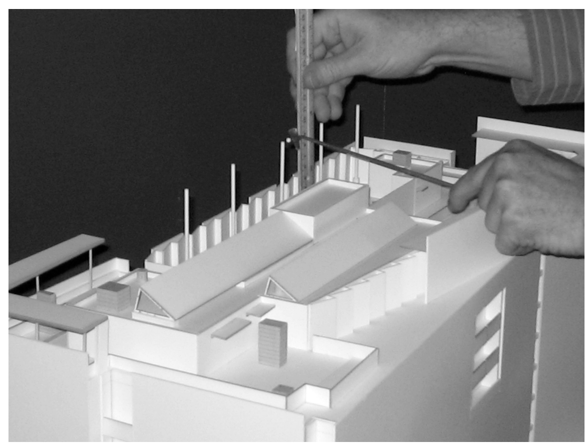


Figure 7- Flow Visualization Using Simple Tools

To ensure that the entire turbine array is always above the turbulent and eddying air, a planned fifth turbine was eliminated and the four remaining turbines were shifted to the east. As currently designed all four turbines are predicted to capture smooth, ambient wind flows from the two dominant wind directions.

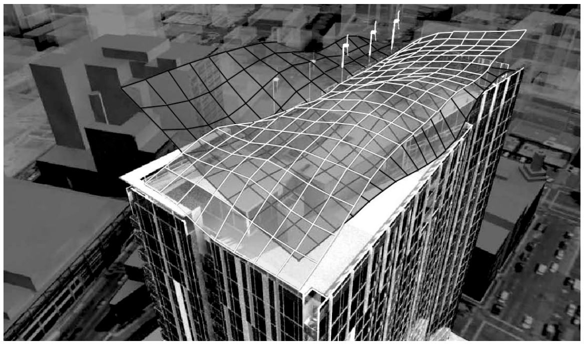


Figure 8: Graphic Depiction of the Experimentally Determined Shear Planes for Summer (white grid) and Winter (black grid) Wind Directions Overlain onto Initially Proposed Turbine Layout. Two of the turbines are well below the winter shear plane and would be subjected to low-energy wind and excessive turbulence.

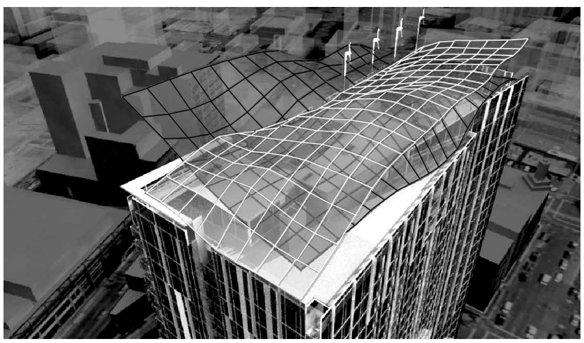


Figure 9: Modified Turbine Array Resulting From the Wind Tunnel Investigations

EQUIPMENT SCALE

Modern wind turbines are of three primary types. Savonius turbines are vertical axis machines with solid wind scoops which limit their efficacy in wind power production. Because the scoops do not act as airfoils they operate by drag only, literally being 'pushed' around by the wind. Consequently, the rotational velocity at their outermost point can never be faster than the wind, and the system is inefficient in producing electricity [8].

Darrieus turbines also have a vertical axis but employ air foils to harness lift effects, allowing the blades to turn faster than the wind. The increased speed improves the energy production of Darrieus turbines but they are hampered by the fact that at least one of the blades is always turning against the wind, limiting the overall turbine efficiency [9]. While vertical axis turbines in general benefit from being able to receive wind from any approaching direction without turning into or "searching" for the wind, Darrieus models are not inherently self-starting and require complex control systems to initiate rotation. [10]

Horizontal-axis turbines are the most efficient design as all their airfoil blades benefit from the oncoming wind. Mechanical complexity is added in that the turbine must turn to face changing winds (known as 'yawing'), but the increase in power production and long-term industry experience with the design more than make up for this complexity [11].

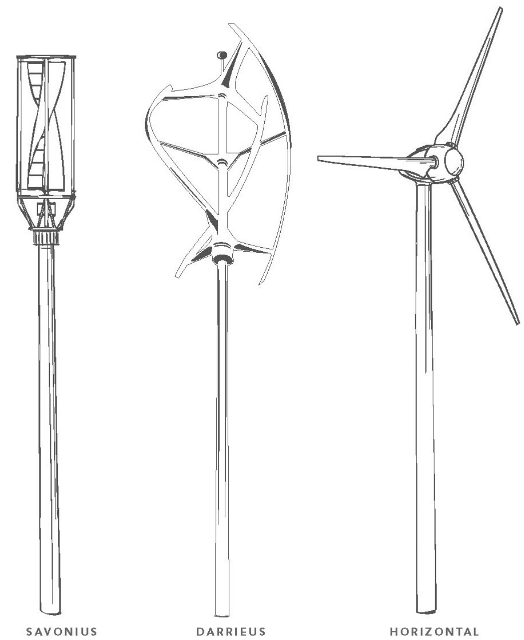


Figure 10: Wind Turbine Types

Performance curves for four building-scale turbines are compared in the graph in Figure 11. The output of the only Savonius model turbine in the figure, the Windside WS4, can be seen to drop dramatically at speeds above 10 m/s. This performance comparison, when overlain with the anticipated range of wind speeds at the proposed location, narrowed the search to horizontal axis turbines.

As an actual built work with both public- and private-sector investors, turbine selection for the project was conducted as much through careful consideration of pragmatic issues of reliability, certification, and required maintenance as through pure performance data. In addition to manufacturer's performance specifications, criteria for selection included production and in-service history of the company's product; product certifications by Underwriters Laboratories, Germanischer Lloyd, and others; availability of the product in North America; warranty conditions; and the existence of actual installations.

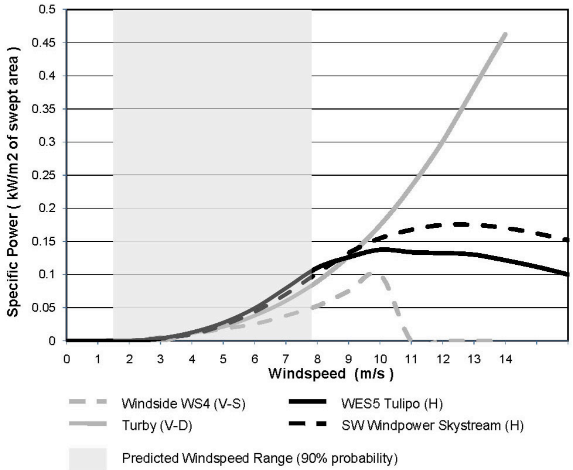


Figure 11: Published Power Curves for a Variety of Commercially Available Small-Scale Wind Turbines

An examination of many different small-scale turbine products from over 50 companies yielded only a few candidates meeting the established criteria. The small wind turbine industry appears to contain many emerging companies but few well-established manufacturers. Many turbine developers make claims of turbine performance that defy the Betz limit or other laws of physics. Many others publish theoretical Power Curves (indicators of performance at various wind speeds) that have not been tested. Still others seem to be unaware of the pragmatic requirement for UL and other certification programs for equipment connecting to a building's electrical system.

After an exhaustive search the team chose a new 12' diameter horizontal axis turbine designed and manufactured by Southwest Windpower, a company with a long history in small wind turbines. Known as the 'Skystream 3.7', the turbine features a passive yaw system to orient the turbine blades to the wind and a downwind blade design that eliminates the need for a tail or other orienting device. The unique blade shape is designed to maximize energy production at low wind speeds and to minimize turbine noise. The turbine has undergone extensive testing at the National Wind Technology Center [12] and has been approved by major certification programs.

PRAGMATIC CHALLENGES

Despite initial concern over the structural impact of mounting turbines atop 45' masts on the building roof, structural adaptations proved to be minimal. The maximum anticipated reactive forces at the base of the masts were evaluated by the project structural engineer based on structural codes and local wind speed history. Due to the seismic considerations already addressed because of the project location, the structure proved robust enough to transfer the turbine loads down to the foundation without any additional modification. Only a series of simple upstands needed to be cast into the concrete roof slab to receive the turbine mast mounting.

Long a concern of wind turbines at all scales, the potential for noise and vibration in the proposed project was particularly worrisome due to the turbine location directly over premium-level penthouse residences. Measured vibration data from the manufacturer as well as field inspections and measurements at actual installations helped the design team to define the potential problem and design a mitigating solution.

Vibration dampening at the base of the masts, in addition to that built into the turbine head, was required to prevent transfer of vibration into the building structure itself. A three point roof mount was developed which distributes loads onto three individual ring-and-bushing mounts in custom neoprene filled steel mount cases. The composition of the neoprene was tuned to dampen vibrations over the anticipated range of frequencies.

Airborne noise was addressed effectively by the turbine manufacturer in developing a turbine intended for installation in suburban and semi-rural environments. A scimitar-shaped blade form was specifically developed to minimize noise generation, particularly the discontinuity known as "tower thump," and the tip of the blade was the subject of considerable R&D on the manufacturer's part to arrive at a quiet solution. In third-party tests the turbines did not produce any more noise than would be produced by a rooftop air handler [13]. In addition, turbines are at their noisiest in strong winds which also produce ambient noise and mask the sound of the turbines.

The standard mast for the chosen turbine includes a hinged base to allow the mast to be lowered for turbine installation and maintenance access. A portable electric winch system was developed to raise and lower the masts on the rooftop to replace the standard methods developed for ground level installations.

As a result of the research and development on the part of the design team local and state agencies, initially disinterested in the project, have now committed funding. The state Department of Energy and a utility-funded alternative energy trust have provided tax credits and direct funding for 75% of the project cost.

An extensive instrumentation program is planned as a part of this project in order to monitor performance, validate the predictive work, and gain further insight for future installations. All research will be shared with the public in the interest of furthering the state of the art of building-integrated wind turbines. An anemometer on the building roof will track wind speed and direction which can serve as a baseline for evaluating turbine performance.

Additionally, various full-scale flow-visualization techniques have been discussed with researchers at the National Wind Technology Center, and a structured investigation will be conducted on the final installation. The primary interest is in comparing observed shear plane location and behavior with the wind tunnel predictions described earlier.

The turbines, mounted on 45' masts above the turbulent wind near the roof, will be a prominent feature of the building from the street and will be visible from rooftop common space for the rental apartments which make up the bulk of the building. In addition to furthering the knowledge base on the science of building-integrated wind generation, this project should do much to foster discussion of the prioritization of visible symbol versus effective generation (or efficiency) and the debate surrounding what, exactly, constitutes integrated design.

CONCLUSION

An exercise to integrate small-scale wind turbines into the design of an urban high-rise was undertaken with the expressed purpose of furthering the practical knowledge in this area. Investigations in four areas - geographical wind, building-level wind, equipment selection, and pragmatics - were conducted. As anticipated, this work suggests that the turbine array should produce in the range of only 1% of the electrical load of the building. Ongoing monitoring of the turbine performance and wind behavior will help to validate the predictions and investigative techniques employed in the design, furthering the general knowledge base on implementing turbines in an urban environment. The visual prominence of both the turbines and their performance data will serve to foster further discussion on the definitions and preconceptions of design integration and renewable energy generation.

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REFERENCES

1. Tatsumi, T. ed., (1984). Turbulence and Chaotic Phenomenon in Fluids: Proceedings of the International Symposium. Kyoto, Japan, 5-10 September 1983.
2. Statistical Distributions – Weibull Distribution – Overview and Examples, [Online], Available: http://www.xycoon.com/Weibull.htm [16 December 2008].
3. Mertens, S., (2007) *Wind Energy Study, Portland Building – Phase 1*, Report on commissioned research, DHV B.V., The Hague.
4. Mertens, S., (2006). *Wind Energy in the Built Environment: Concentrator Effects of Buildings*, Multi-Science, Brentwood, UK.
5. Mertens, S. *Wind Energy in the Built Environment: Concentrator Effects of Buildings*.
6. Van Bussel, G.J.W. and S. Mertens, (2005). Small Wind Turbines for the Built Environment, In *EACWE 4 –The Fourth European and African Conference on Wind Engineering*. Prague, July 11-15.
7. Mertens, S. *Wind Energy in the Built Environment: Concentrator Effects of Buildings*.
8. Eggleston, E. What are Vertical Axis Wind Turbines (VAWTs)? [Online], Available: http://www.awea.org/faq/vawt.html [12 December, 2008]
9. Planning a Small Wind Project, [Online], Available: http://www.windustry.org/your-wind-project/home-and-farm-scale-wind/planning-a-small-wind-project/planning-a-small-wind-proje [14 December 2008].
10. Blackwell, B.F., (1974). *The Vertical Axis Wind Turbine: How It Works*. Sandia Laboratories Energy Report. Albequerque.
11. Sagrillo, M., (2005). The Myth and Mysticism of Vertical Axis Wind Turbines. *Windletter: The Monthly Newsletter of the American Wind Energy Association 24 (1)*.
12. Migliore, P., J. Green, D. Calley and J. Lonjaret., (2005). Balancing Performance, Noise, Cost and Aesthetics in the Southwest Windpower "Storm" Wind Turbine. In *Windpower 2005*. Denver, May 15-18.
13. Migliore, P., J. Green, D. Calley and J. Lonjaret. Balancing Performance, Noise, Cost and Aesthetics in the Southwest Windpower "Storm" Wind Turbine.