DESIGN INVESTIGATIONS ON BUILDING-INTEGRATED WIND ENERGY: LESSONS FROM AN ARCHITECTURE STUDIO

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ABSTRACT
The project described in this paper explores ideas for building-integrated wind energy (BIWE) in middle-rise buildings in northwest Pennsylvania. The project combines technical, environmental and aesthetic research and design studies by an interdisciplinary team of architects, architectural engineers, aerospace engineers, landscape architects, and meteorologists. The project forms a testing ground for new architectural strategies for a place-based approach of wind turbine implementation in buildings and the urban environment. While current research focuses primarily on technical performance and the economics of wind turbines, this project combines research on wind behavior around buildings and in the urban environment with design investigations of wind-optimized building forms and the aesthetic potential of turbine integration in architecture. Moreover, the project intends to link this research to the education for sustainable architecture and technology, and aims at sharing insights with the wider professional community and the public.

The paper describes the first step of this project, a design studio in which twenty-seven architecture students developed strategies to integrate wind turbines in their design projects of a maritime museum in Erie, PA, advised by architects Dr. Ute Poerschke and Malcolm Woollen. The main objective was to observe how emerging architects approach this design task of turbine integration while creating architectural entities for a meaningful environment. The paper summarizes the first step of the research, outcomes of an academic design studio and a symposium on BIWE with architects, engineers, turbine industry representatives and artists.

1. INTRODUCTION
In Spring 2010, a team of Penn State researchers and instructors from the Departments of Architecture, Architectural Engineering, Landscape Architecture, Meteorology, and the Applied Research Laboratory collaborated to launch an interdisciplinary project of building-integrated wind energy (BIWE). In contrast to research that focuses primarily on technical performance and the economics of wind turbines, the project’s primary objective is to combine research on wind behavior around buildings and in the urban environment with design investigations of wind-optimized building forms and the aesthetic potential of turbine integration in architecture. Moreover, the project intends to link this research to the education for sustainable architecture and technology, and aims at sharing insights with the wider professional community and the public.

The paper describes the first step of this project, a design studio in which twenty-seven architecture students developed strategies to integrate wind turbines in their design projects of a maritime museum in Erie, PA, advised by architects Dr. Ute Poerschke and Malcolm Woollen. The main objective was to observe how emerging architects approach this design task of turbine integration while creating architectural entities for a meaningful environment. The paper summarizes the design process, categorizes different design approaches, and evaluates the design outcomes concerning their level of building integration and efficiency. Providing the findings to engineers and landscape architects, the architects intend to receive feedback for potential changes of the integration strategies in the design process, and thus to initiate an iterative process of refinement and improvement of the integration of turbines in buildings and the urban environment from technical, social, environmental and aesthetic perspectives.

2. STUDIO SETUP
For this design studio, we focused on BIWE in middle-rise buildings in Pennsylvania with the objective to study the potential of this new approach for our immediate
surroundings. Middle-rise buildings, defined as buildings with four to seven stories, form a common building type in urban and semi-urban locations and their size allows the integration of small wind turbines that can exploit minimum wind speeds of 8.5mph. Skyscrapers were not part of this investigation, although they are potentially able to harvest far more wind energy.

A hypothetical site at the waterfront in the city of Erie, PA, was chosen because Erie has one of the highest wind energy potentials in Pennsylvania. The project task was to design a 52,300sf addition to the existing Erie Maritime Museum, designed by Weber Murphy Fox Architects and opened in 1998 as part of the revitalization efforts for the Erie waterfront. Its main collection piece is the reconstructed Flagship Niagara, the famous sailing ship that won the Battle of Lake Erie in the War of 1812. The addition consists of a large workshop space for the restoration of ships, exhibition spaces and an education center with auditorium.

The students initiated their exploration through lectures covering wind behavior and wind turbine technology held by architectural engineer Dr. Jelena Srebric and energy engineer Dr. Susan Stewart. Both experts also participated in several design reviews during the semester. Later in the semester, a symposium was organized. Invited guests were architects, wind turbine manufacturers, and an artist. These guests gave presentations on their work related to wind energy and reviewed the students’ projects. More information about the symposium will be given later in this paper. At the end of the semester, the final studio reviews became a nexus for new discussions with wind energy experts from other disciplines as aerospace engineering and landscape architecture.

3. EVALUATION OF WIND ON SITE

When wind turbine integration at a particular site is considered, the understanding of wind direction, velocity, and frequency is the most important part of a site assessment. For the purpose of a design studio, this was easier said than done. The wind data from the airport, as the only data set for the city of Erie downloadable from the U.S. Department of Energy website, indicates that the winds at the airport are mostly from the south (Fig. 1-2). Comparing this with data collected for a location closer to the site by the Pennsylvania State Climatologist, it was observed that the winds at the closer site originate more from the southwest, but still inland (Fig. 1-3). However, this wind rose was still not trustworthy because between this location and the actual design site is a 40’ lake bluff. The design site is located at the lower side of the grade change and therefore maybe in a wind shadow to these inland winds. Additionally, the air movement from Lake Erie landwards could not be evaluated. In other words, if this had been a real project, data collection from the site for at least one year would have been the only way to find out the actual wind conditions. Knowing that “the major factor affecting accuracy of energy output predictions is the accuracy of wind speed prediction,” (Encraft 2009, p. 33) an optimal layout of turbines and accurate prediction of energy output can be achieved only with this information. Improvement of wind condition prediction is an avenue of research we are currently exploring.

Fig. 1: Map showing project site at Lake Erie (top right), and wind data sites (airport and location closer to site).

Fig. 2: Airport site: wind frequency rose (left) and wind energy rose (right).

Fig. 3: Closer site: wind frequency rose (left) and wind energy rose (right).
To continue our design studio, we needed to ‘assume’ the main wind direction and intensity. Although this was not fully satisfactory, we learnt from this site assessment process that missing local wind data could stop the consideration of integrating turbines on site already at an early design stage because a design team might not be able to wait for the results or the client may not want to invest in the data-logging phase. This experience is completely different from exploiting solar information, which is fully accessible through geometric investigations and weather files consisting, for example, of sky coverage data. Rules of thumb exist for the integration of solar technology, for example tilt angels for photovoltaics and solar heating, but only limited for wind. Convenient computational simulation tools are available for solar paths and daylighting but evaluating or simulating airflow in an urban environment is a difficult and time-consuming task. Therefore, in many respects, wind energy integration in the architectural design process is more demanding than that of solar energy.

4. APPROACHING THE INTEGRATION OF WIND TURBINES IN ARCHITECTURAL DESIGN

What can be considered ‘good’ integration? Mounting a high mast on a roof and adding a turbine does not seem to be the correct response for many middle-rise buildings. Integration should involve designing a technical, aesthetic and meaningful unity of building, wind turbine, all other spatial and physical building systems, and the environment. Balancing such divers elements in a project does not mean to find a compromise between them, but instead to grow them beyond their singularities to an ideal synthesis. The building design process aims at such an idea of integration.

In general, publications on BIWE have not yet initiated a discussion about aesthetic quality. Most publications address technical and economic efficiency and are written by engineers. Investigations concerning the visual and spatial impacts of BIWE on our built environment and reflections concerning buildings as meaningful expressions of our society are rarely undertaken.

Looking closer into the technical and economic publications on BIWE, the conclusions drawn are relatively discouraging. Most publications not only critically discuss the question of wind turbine integration in architecture but even doubt its usefulness. Alex Wilson in his article *The Folly of Building-Integrated Wind*, for example, states that “building-integrated wind doesn’t make much sense as a renewable-energy strategy” and that this technology is “usually a bad idea” (Wilson 2009, p.1). Wilson mainly compares big versus small turbines, the latter being even more ineffective when building-mounted: “Perhaps the greatest impediment to building-integrated wind energy is the economics. While large free-standing wind turbines provide the least expensive renewable electricity today, small wind turbines are far less cost effective, and when small turbines are put on buildings, the costs go up while the production drops” (p.12). Wilson, well known for his engagement in sustainable building and executive editor for *Environmental Building News*, lists his article under his “paradigm-shifting articles in EBN.” However, since he does not clarify where research is needed in the field of turbine integration, his article is counterproductive for researchers and designers searching for this paradigm shift. Research shows that there are, in fact, zones of very high velocity in urban areas due to local wind channeling (Johnson and Hunter 1999). As the cost of electricity rises, the incentive to harvest local renewable energy without transmission loss will increase. To prepare for this time, the problems of wind turbine installation on buildings and in the urban environment need to be creatively addressed in research and design inquiry to improve technical output as well as aesthetic integration for a meaningful environment. Such problems are:

**Airflow turbulences**: Urban and suburban areas deal with much higher airflow turbulences than open fields. Turbines can capture most efficiently laminar, non-turbulent winds. Currently, turbines cannot effectively harvest highly turbulent airflow and the region of high turbulence in the flow around buildings has generally much lower wind speeds and thus wind power densities. An additional complication is that this region shifts locations on the building with changes in wind direction. When integrating turbines in a design, it is useful to study turbulences around buildings and on roofs, for example with Computational Fluid Dynamics (CFD) software, and to avoid the placement of turbines at building parts with high turbulences. Locating wind turbines around 30 feet above potential obstacles like trees or buildings is a common rule of thumb for harvesting laminar winds.

**Noise**: Turbines can produce aerodynamic and structure-borne sound in a building. Aerodynamic sound is emitted from the spinning of the blades as the wind passes through. Structure-borne sound emerges from the vibration of a turbine propagating in the building structure. Careful design of the structural integration of the turbine with the building can eliminate or dampen the latter, while aerodynamic noise is a design factor for the turbine and can be lowered by reducing the tip speed ratio of the turbine (below its optimum value). Furthermore, a deployment of a shroud to encase a wind turbine could also reduce the aerodynamic noise (Bahadori 1984).

**Turbine impact on building structure**: Turbine weight must be considered in the dimensioning of a building structure. The turbine rotation causes vibrations in the mast or...
substructure that need to be addressed as an additional load for the structure.

Safety: Because very few small wind turbine products on the market have undergone certification processes, safety is currently a great concern for small wind turbine installations on buildings. The Small Wind Certification Council has recently formed an independent certification body to certify that small wind turbines meet or exceed the requirements of the newly formed AWEA Small Wind Turbine Performance and Safety Standard. Currently 25 turbines are in the application stage of going through this process. Once certified turbines are identified, this will help alleviate many safety concerns.

While all of these aspects need to be carefully addressed, there are some advantages of small turbines integrated in buildings and the urban environment as compared to larger turbines installed in open fields that are worth considering. First, no or less land or water area is needed for BIWE projects. This also implies that there are no additional access roads needed, reducing secondary impacts of farmland reduction and forest fragmentation. Although the costs for additional building structure to carry turbine weight and vibration load are currently larger than for free-standing turbine towers, smaller substructures can be used and foundations or masts might not be necessary at all, thus material use can be reduced. The transportation and installation of small turbines is easier as compared to big turbines. BIWE uses short-distance cabling and allows for a short-distance grid connection. And finally, the scale of small turbines allows for a more subtle aesthetic impact on the environment in comparison to large turbines.

In the design studio, parallel to discussing turbine siting as a technical problem, the questions of aesthetic integration of turbines and their cultural meaning within a building quickly arose. Questions of the interconnectedness and relatedness of technical systems and design idea and the understanding of forming an artful entity of all building elements and requirements were vividly discussed. The program of a maritime museum and the location at the lakeshore turned out to be well chosen because it allowed the students an inherently conceptual, contextual and even poetic approach to the topic of wind. While investigating various aspects of wind, they were enabled to connect topics of sailing ships, history of seafaring, and historic windmills with the technical topics of natural ventilation and modern energy generation from wind. The latter became a means to express the former. For future design studios we realized that it is exactly the combination of a technical task and poetic program that can help students understand how technical systems can become integral parts of a building design and an artful and meaningful contribution to our world.

5. SYMPOSIUM

At a two-day symposium held at the beginning of the last quarter of the semester, architects, turbine industry representatives and an artist presented their views on BIWE and turbine products and provided input for the students’ projects. It was held on November 12th and 13th, 2010, and the following experts were invited:

- John Breshears and Craig Briscoe, ZGF Architects
- Michael Jantzen, Artist
- Bill Schmitz and Mark Matthews, WindTamer Inc.
- Tom Zambrano, AeroVironment Inc.

First, each invitee gave a presentation on their particular expertise as related to wind energy in architecture and the urban environment. John Breshears and Craig Briscoe described the design and construction process of the ZGF project Twelve West in Portland, Oregon, the first urban high-rise in the U.S. with four wind turbines on the roof. Michael Jantzen, an internationally known artist interested in the sculptural potential of wind turbines, illustrated how his work merges art, architecture and sustainable technology, in particular photovoltaics and wind turbines, Bill Schmitz and Mark Matthews introduced shrouded wind turbine technology and presented their product. Tom Zambrano, senior scientist for energy and environmental technologies and expert on fluid dynamics, presented the development and implementation of technology initiatives particularly related to wind energy.

During the symposium (Fig. 4-6), a general consensus on several points became apparent. Though all acknowledged that more research would be required to reduce the payback time on BIWE, most agreed that wind turbines attracted public attention as a symbol of environmental responsibility and as an object of kinetic beauty. John Breshears and Craig Briscoe said Twelve West and its wind turbines became a landmark in Portland and seeing turbines in the urban environment could help people with behavioral modification of their energy consumption. Having cooperated with BMW Designworks to create wind turbine designs, Tom Zambrano felt that design was critical to gain wide acceptance for BIWE and that architects need to embrace the task of integrating wind energy technology in architecture and the built environment. Michael Jantzen confirmed that his pavilions with monumental wind turbines were intended to highlight the kinetic quality of this technology as well as its environmental promise. His standpoint that the aesthetic value of our built environment must precede questions of efficiency stood in contrast to the one of Mark Matthews, for whom economic questions concerning renewable energies need to be answered first. Through these discussions, the role of the architect as the advocate of both standpoints was well elucidated.
6. CATEGORIZATION OF DESIGN APPROACHES

Of the 27 designs that integrate wind turbines, nine (33%) used horizontal axis wind turbines (HAWT), fourteen (52%) vertical axis wind turbines (VAWT), and two (7.5%) both HAWT and VAWT. Two designs (7.5%) didn’t use wind turbines at all but proposed instead to transform the vibration created by wind pressure on a façade or mast into electrical power.

As far as the integration of HAWTs is concerned, two designs installed them on a roof, five on separately standing masts (e.g. Fig. 12), three integrated in a façade surface (e.g. Fig. 11), and one in a building tunnel. As far as the integration of VAWTs is concerned, four used them on the roof (e.g. Fig. 9), one on separately standing masts, two in a funnelling building shape (e.g. Fig. 10), and nine used them horizontally laid (e.g. Fig. 7 and 8). The following main strategies of integrating wind turbines were developed:

6.1. Wind Turbines mounted on Roof Top

Nine projects have HAWTs and VAWTs mounted on roofs. The sample project by Justin Konicek (Fig. 7) uses four VAWTs laid horizontally approximately 15 feet above the flat roof. The sitting might have the disadvantage that the turbines are too close to the flat roof where wind power density is low and high turbulence may occur. Considering the rule of thumb mentioned previously, the height of the turbines should be around 30 feet above the roof to get into the laminar flow field. This is on the same order of the building height itself in this case. Since the design strategy of forming a horizontal line parallel to the roof fits well to the horizontality of the entire building one might test if this line of turbines can be raised even higher above the roof.

6.2. Wind Turbines mounted on Roof Parapet

Six studio projects have wind turbines mounted on the roof parapet where wind speed is higher than at the façade or on the roof itself. The strategy was inspired by AeroVironment projects realized throughout North America. Three of the student projects used VAWTs horizontally laid to form a line parallel to the roofline. Through this arrangement, the rotation of the turbine blades parallels the roofline and is
thus perceived visually higher integrated than a row of propeller-shaped HAWTs, in which the circular rotation of the blades is perpendicular to the roofline thus standing in contrast to the horizontal line. The placement of eight VAWTs in the sample project by William Bunk (Fig. 8) is clearly defined between clerestories at the highest and windiest location of the building. Lower building parts in front of the parapet might cause turbulences and need further investigation and maybe removal.

6.3. Double Roof

Two projects explored the idea of exploiting the Venturi effect by funneling wind through a double roof system and integrating turbines within the two roof layers. The sample project by Kelly Ryan (Fig. 9) uses six magnetically levitated VAWTs which are presented as a technology that reduces noise, vibration and energy loss and that can be used for low wind environments.

6.4. Funneling Building Shape

Similar to the strategy mentioned before, this approach of turbine integration exploits the Venturi effect by creating a wind-funneling situation within the building, however not in a double roof system. Three projects explored this strategy, two of which used VAWTs. The sample project by Marjorie Dona (Fig. 10) creates the funnel within a three-story glass cube that is placed on a flat roof. Angling the sides of the funnel increases the captured wind area.

6.5. Façade Integration

The idea behind the façade integration approach is to not only capture wind flow from the main wind directions but also from the ascending airflow at the façade. Two projects from the studio might fit in this category with HAWT and VAWT both used. The expressive sample project by Kyle Schillaci (Fig. 11) uses one comparatively large HAWT at the top of the building design. A large sidewall channels more wind towards the turbine and it needs to be further
studied if this causes unwanted turbulences. Being the tallest structure of all projects with a turbine placed at the highest point one might expect that the wind energy output would be the greatest. However, this needs further study.

Fig. 11: HAWT integrated in façade. Project by Kyle Schillaci (section, model).

6.6. Landscape Integration

Five projects follow the approach to place wind turbines adjacent to the designed building in the landscape (including the water) while creating a contextual relationship to the building and the surroundings. The sample project by Ryan Orr (Fig. 12) uses six HAWTs to create a horizontal ‘sky level’ that reflects the ‘water level’ while both define a space in between in which the design takes place. In the design, the verticality of the masts of turbines and ships is contrasted with the horizontality of water, land and surrounding buildings thus poetically emphasizing the program of a maritime museum.

Fig. 12: Wind turbines integrated in landscape. Project by Ryan Orr (site plan, model).

7. CONCLUSIONS AND NEXT STEPS

The role wind energy will play in the sustainable fulfillment of our energy demands is well known. The question about the particular contribution that architecture and the urban environment will make in this challenge is not answered yet. The integration of small wind turbines in buildings is just at its infancy, and investigations about optimized energy performance and aesthetic integration have just started to become research and design foci for engineers and architects.

Similar to the development of building-integrated photovoltaics (BIPV) more than twenty years ago, the current approaches to BIWE are accompanied by both enthusiasm and criticism. BIPV has successfully integrated topics of energy effectiveness with visual and spatial appearance of our environment and can serve as a model for further investigations in BIWE. Wind generation on buildings has the potential for further engineering inventions, advertising renewable energy, symbolizing a future entirely fueled by clean energy, visualizing the environmental context (‘a windy place’), and inspiration for kinetic objects. While all the components of an
environmentally responsible building are not entirely visible or understandable to the public, wind turbines, on the other hand, are supremely understandable. They catch the eye and offer a compelling statement about an owner’s responsibility for the environment. After curious visitors have made an effort to ascend to a roof to see turbines, they also can serve as an invitation to learn more about the unseen sustainable components of the building. They can also represent the productive power of larger turbines in open spaces and promote a new sensitivity to local environmental conditions. While discussing what cost-effectiveness for our society really means, people might invest in BIWE for these reasons. Meanwhile, we anticipate that BIWE will continue to be the subject of increasingly high profile experimentation and public fascination.

Fig. 13: CFD simulation of a box-shaped project (such as in Fig. 7 and 8) at the Erie site. The simulation shows the increased wind velocity at the building parapets.

Future development and closing the gap between evolving technical research and known design solutions will depend on interdisciplinary collaboration. At its best, this collaboration process can be described as an iterative loop between engineers and architects that starts with the exploration of feasibility, continues with alternative design developments and ends with refined efficiency and formal integration. In the next steps of the project, we are currently investigating how to better simulate and map wind flow by taking the site at Erie and representative designs from the Erie design studio. Simulating single designs is one effort (Fig. 13). Another approach currently under way is to integrate geo-design principles and geospatial tools to analyze the overall three dimensional space of urban wind to inform site selection, building orientation and the building envelope and then to adapt the categories of student designs and study them within this system. Moreover, we are taking sonic anemometer data on a six-story campus building to help build the base of knowledge on the turbulence levels experienced in the built environment with the intent of providing insight into proper turbine design and selection for this application.

There are many more aspects open for research that we have not addressed in our project such as economic or policy questions for which we like to invite researchers to form an even wider collaborative team with us.

8. ACKNOWLEDGEMENTS

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9. ENDNOTES

2 http://www2.buildinggreen.com/about/people/alexwilson [accessed 2/2/2011]
4 The presentations were recorded and are available from the authors upon request.

10. REFERENCES

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