Distributed Subtropical Coastline Emergency Energy Generation Using Building Integrated Wind Technology

Global population is projected to increase and aggregate in urban centers along the world's coastlines, many of which reside within the subtropical climate classification. Concentrated growth in densely built-up coastal urban environments is expected to contribute to unprecedented energy demand on a global scale..

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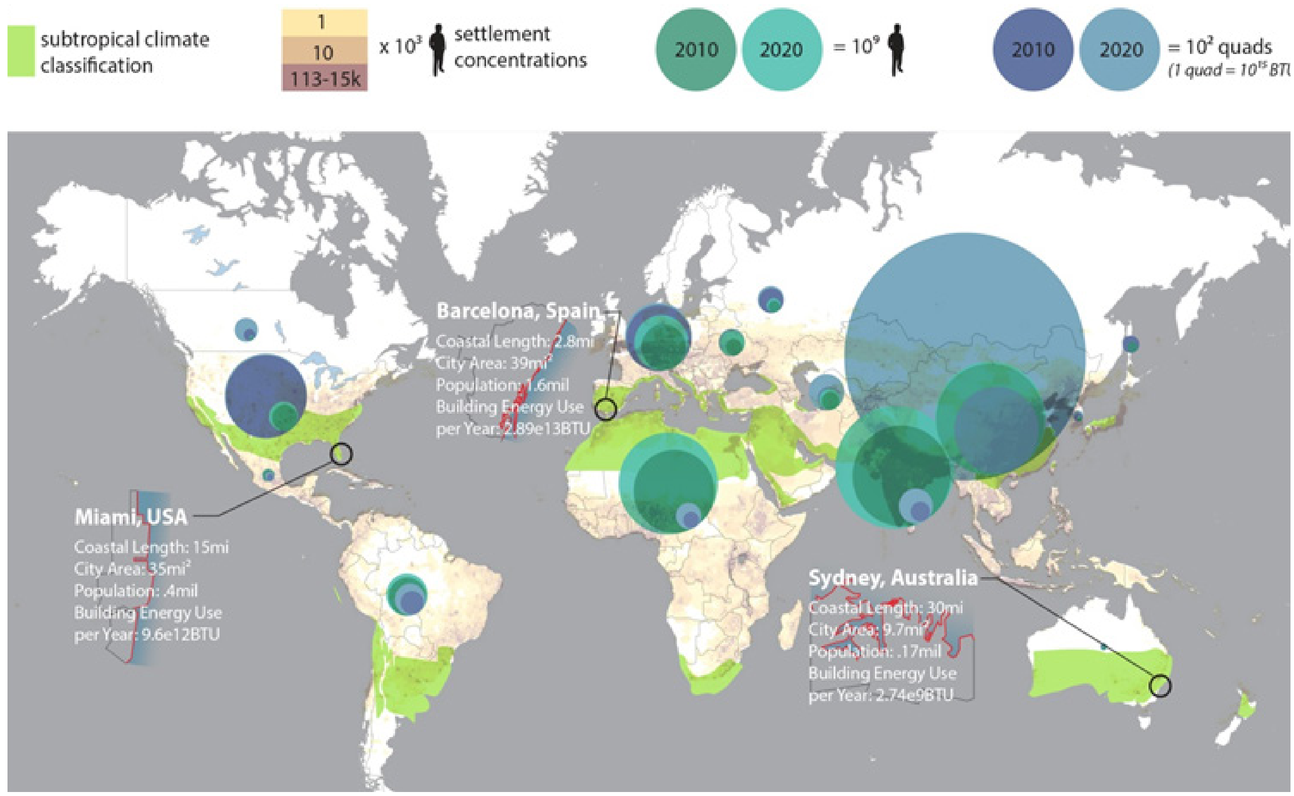
INTRODUCTION: GROWING DEMANDS AT VULNERABLE URBAN EDGES

Global population is projected to increase and aggregate in urban centers along the world's coastlines, many of which reside within the subtropical climate classification. Concentrated growth in densely built-up coastal urban environments is expected to contribute to unprecedented energy demand on a global scale,[1] particularly within nations currently experiencing the emergence of burgeoning middle class populations causing large-scale urbanization at a rapid pace [fig.1]. In addition, there is growing consensus that climate change comprises an increase in frequency and intensity of storm events, a pattern which renders densely populated coastal urban regions vulnerable.[2] Exacerbating this vulnerability is the widespread operational dependency on centralized power infrastructure, whose components can fail under the high-speed winds and driving rain that accompany severe weather. Tropical cyclonic effects regularly include destruction of overhead power lines and other infrastructure, as well as disruptions in fossil fuel availability. Such crippling and costly instances represent a lack of resilience affecting all urban energy infrastructure, but one that becomes particularly critical for vulnerable urban coastal communities. In light of projections for increased extreme weather in the coming decades, this precarious condition indicates a clear need for on-site supplemental energy that is locally available, renewable, and operable at exposed urban coastal sites during inclement weather. As part of an urban emergency management plan, the application of active flow control assisted wind energy production could reduce peak load building energy consumption and provide operational continuity of key services for towers such as elevators, water supply,



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circulation lighting and communications, through the safe, secure harvesting of onsite wind energy resources. This paper will evaluate the potential to alleviate the structural and energy harvesting challenges that have previously prevented the ubiquitous application of building-integrated wind energy by transferring novel air flow control technology from the field of aeronautics into building envelopes[9] in order to augment the aerodynamic performance of coastal urban structures through an adaptive response to changing wind patterns.

NEW OPPORTUNITY FOR BUILDING-INTEGRATED WIND ENERGY TECHNOLOGY

While direct exposure of coastal cities to offshore weather forces can result in the destruction of anthropogenic structures and built landscapes, the topology of urban centers adjacent to expanses of water also provides an opportunity for harvesting energy from consistently available wind flow, which can be utilized to increase infrastructural resilience to destructive weather effects by providing local emergency power to buildings during and following cyclonic events, in addition to reducing CO_2 emissions and contributing to global renewable energy objectives. Three geographically distinct cities within the subtropical climate classification are considered for the opportunity of providing a percentage of building energy needs through harvesting of the wind resource: Barcelona, Spain; Miami, USA; and Sydney, Australia. These locations are characterized by diverse climatic profiles and challenges unique to their geologic, economic, and ecological contexts. For coastal Australian cities like Sydney, for example, there is evidence to suggest that future tropical cyclonic activity will increase in frequency and intensity: according to the Sydney government plan for climate change, peak tropical cyclone intensity may increase by 5% to 10% and precipitation rates may increase by 20% to

Figure 1: Global Population Concentrations, Climate, and Energy Consumption: Projections

Data Sources: DOE, IEA, Koppen-Geiger Climate Classification, Sydney Catchment Authority, SEDAC-NASA

30%.[2] Additionally, all three cities have publicly stated their commitment to pursuing challenging sustainable energy integration goals. Miami buildings consume over 5 million Megawatt-hours of electricity per year, and produce over 50% of the city's greenhouse gases. According to the Miami government climate action plan

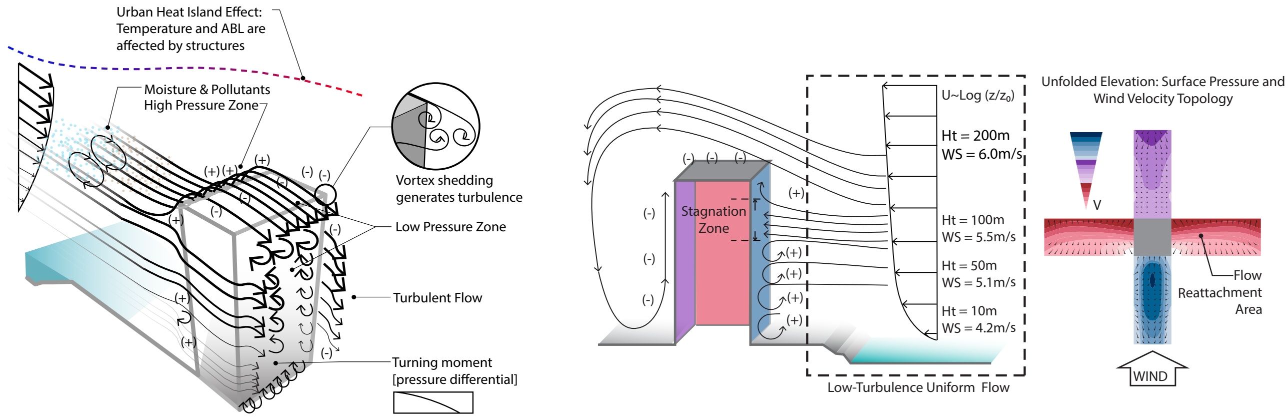
> The City will reduce 429,000 metric tons of greenhouse gas emissions primarily by increasing the use of renewable and cleaner energy sources and the use of more efficient, local sources of power.

Such resolutions are representative of a global trend towards commitment of industrialized nations to renewable energy strategies, 37 of which resolved adherence to the Kyoto Protocol during the first commitment period alone.[14]

Wind energy is among the most rapidly growing industries in the United States. The current growth in wind power use is expected to strongly continue in the coming decade. This has been reinforced by targets set by the DOE,[10] which aim for wind energy to supply 20% of all electricity generated by 2030. The building sector in the United States is the largest consumer of electricity, and currently uses 72% of all electricity produced. This number is expected to grow to 75% by 2025. A comprehensive study has concluded that building-integrated wind energy generation has the potential to contribute significantly to the energy requirements of buildings and contribute to peak load reduction.[8] Building- integrated wind turbines (BIWT) could be mounted onto buildings at a lower initial cost as compared with larger freestanding turbines, with the added benefits of power production at lower wind speeds, and reduced maintenance and equipment costs.[6] However, past efforts to integrate wind turbines at the building envelope in urban environments faced challenges in utilizing the wind resource effectively due to multiple social and technical challenges: limited turbine technology investment hindered development, which limited operational device efficiencies; complex wind characteristics in dense urban conditions produce a turbulent, low quality resource for the purpose of energy collection, rendering catchment strategies nonviable in such conditions; and nascent conceptual realizations of the technological application within architecturally- integrated proposals have generally thus far produced power outputs that are insufficient to substantially influence building energy consumption and savings profiles. The Warwick Wind Trials[13] found that manufacturers have tended to overestimate the output from existing turbine types, which have been plagued by low measured output due to turbulence around the building envelope. The viability of implementing turbine technology on buildings will be determined by turbine power output and the ability to adaptively control the direction of the wind resource as it passes through the turbine. Initial analysis of local flow regimes can ascertain the availability of the wind resource, but appropriate approaches for turbine integration in real-world projects must be practiced through cross-disciplinary collaboration at the schematic, or conceptual, design phase, in order to realize optimum savings.

DETERMINING VIABILITY OF TECHNOLOGY-BASED STRATEGY BY IDENTIFYING CRITERIA AND CRITICAL VARIABLE RANGES

One of the keys to determining the viability of utilizing wind flow at coastal urban conditions is assessing the site-specific qualities of the Atmospheric



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Boundary Layer, or ABL, defined as the volume of atmosphere around given structures that is affected by the morphologies and surface characteristics of the buildings in the surrounding urban environment, and whose height is influenced by the roughness characteristics of the landscape over which it moves [fig.2]. Within an ABL, average wind speed increases with height in a logarithmic distribution, while turbulence decreases. The presence of high-velocity, low-turbulence wind flow is critical in the assessment of building-integrated wind energy harnessing viability. The topology of many inland cities is characterized by a gradual dispersion of structure, and reduction in density, as represented by suburban development, industrial or utility plants, or rural clusters. This gradual mass dispersion enables turbulence to increase and wind speed to be reduced as flow approaches the urban center, which lessens the quality of the wind resource from an energy generation perspective. Coastal cities are, dissimilarly, typified by an abrupt sheer morphological juncture at the transition between the built-up aggregate volumes and open water surface. Challenges to harnessing wind flow are presented nonetheless by the complexities of the flow regime within any urban context: vortex shedding at the bluff building envelope exterior at the interaction domain between the physical building edge and the ABL, results in irregular eddying and turbulence in the flow field [fig.2]. However, at the coastal bluff building condition, the low surface roughness that characterizes open water contributes low frictional drag in the ABL, and assists in producing generally consistent flow that is directly available for use at an exposed site.

Figure 2: Boundary Layer Interaction at the Coastal Bluff Building Environment

Adapted from ASHRAE Fundamentals

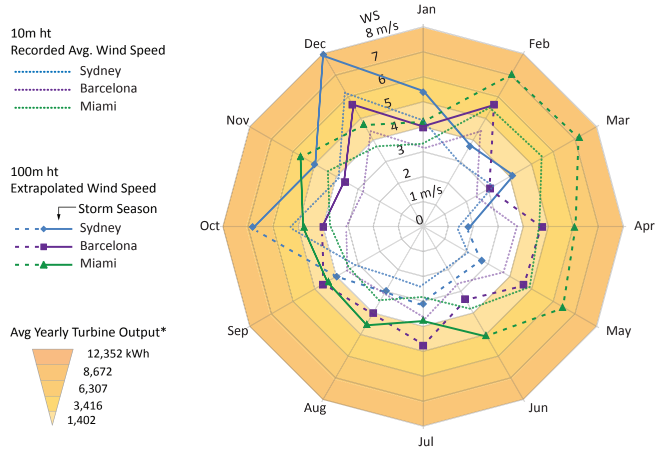
For a known height Z_r and a recorded speed at the given height, we can estimate wind speed at the target collection height using:

$$U_x = U_r (Z/Z_r)^{\alpha}$$

Where

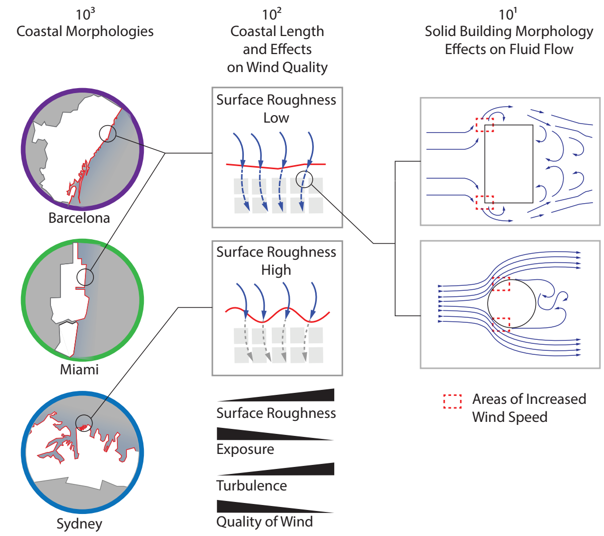
U_x = Unknown Wind Speed
U_r = Known Wind Speed at Reference Height
Z = Target Height
Z_r = Reference Height
α = Constant (based on surface characteristics)

In addition to verifying the uniformity or turbulence of wind flow at an energy collection site, the seasonal and diurnal variations in the prevailing conditions of wind flow, including frequency and speed must be well characterized in order to properly assess the viability of an urban site. Such comprehensive studies have until recently been relatively cost-prohibitive for most building sites, however emerging technology has greatly reduced the cost associated with site characterization.[8] During a tropical cyclonic event such as a hurricane, wind velocities typically exceed 50 m/s, beyond the point at which most turbines brake and cease collection to prevent damage to turbine parts and excessive structural vibration. The critical period following a destructive hurricane or other extreme weather, when floodwaters and widespread damage may prevent reactivation of the electric grid and access to fossil fuels for weeks, provides the opportunity for



Monthly Average Wind Speeds for 3 Case Studies at 100m Building Height and Corresponding BIWT Energy Values

Based upon power outputs for WPT 3000 7'dia model used in the Wind Energy Workbook developed by the National Renewable Energy Laboratory (NREL)



Influence of Solid Characteristics on Fluid Flow at the Coastal Subtropical Urban Environment

building-integrated wind energy generation to perform a critical role in power assistance. Therefore, an emergency design response that seeks to integrate wind energy technology must have the capability of operating within the critical range for the prevailing climate condition, with viability measured using average wind speeds, without reliance upon higher storm-rate velocities. The qualification of this requirement can be approached with analysis of the wind resource at the specific site location, using locally recorded climate data.

For climate data collection purposes, wind speeds are generally recorded at a height of 10m, but the logarithmic vertical distribution of flow within the ABL allows for extrapolation of wind speeds at higher elevations. The following formula is used to approximate wind speeds for building-integrated turbine viability estimations based upon height and surface characteristics, as shown using an example set of wind data values for Miami [fig.2].

The most critical component in turbine energy generation is wind speed, as power is proportional to the cube of wind speed[6]. For each of the three case study cities considered, average wind speeds recorded at a 10m typical height ranged from 1.4-6.2 m/s, a set which does not fall within the necessary turbine output spectrum for viability for the model used. However, due to global urbanization, the tall building typology is projected to predominate increasingly in the future, where the ABL comprises wind flow at increased speed. The surface characteristics of water permit calculation with the assumption that the wind resource is generally consistently available.

The parameterized extrapolation of average local wind speeds at a 100m height using the vertical logarithmic distribution(fig.3), posits greater viability of BIWT for the prevailing climatic condition for each of the three sites selected. Specifically, the city of Miami is characterized by the highest-velocity flow among the three, showing an extrapolated wind speed range falling entirely within the spectrum of viability; according to the preliminary

Figure 3: Monthly Average Wind Speeds + Storm Seasons for 3 Case Studies at 100m Building Height and corresponding BIWT Energy Values using Wind Energy Workbook data for WPT 3000 model developed by the National Renewable Energy Laboratory (NREL).

calculation, the city's coastal structures could be strong candidates for further analysis of BIWT implementation. Similarly, a large percentage of Barcelona's extrapolated wind speed range falls within the viability spectrum. Due to current global air flow patterns, European countries do not experience hurricanes, or cyclonic activity to the same degree as Miami and Sydney. As such, present implementation of wind energy generation in such locations could be considered for the attainment of renewable energy goals as well as strategizing for projected instability or increase in fossil fuel costs.

According to the DOE Buildings Energy Data Book section on Commercial Sector Energy Consumption for 2010, energy consumption per square foot for commercial buildings in the United States was approximately 107,700BTU, defined as delivered energy, which would be a more accurate figure to use than primary energy, given that site-located energy sources do not suffer the same transmission losses that centralized power plant-delivered energy does. If a 100m building comprising 135,000 SF in floor space consumed this average, its consumption would total 4.25X106 kWh annually. An emergency power supply of 15% of the building's total consumption, including pathway lighting and other basic building services, would total 637,500BTU. Using the preliminary wind speed and turbine output data from the U.S. city of Miami in Figure 3, an array of 50-60 small building-mounted turbines would provide the emergency power. This premise excludes the added benefit of higher-velocity winds in close proximity to a storm event, and would act as a minimum performance baseline set of calculations based upon prevailing local climatic conditions. The initial calculations in all three coastal urban case studies could prompt further discussion of viability, in greater detail, based upon promising preliminary estimates.

The determination of building-integrated wind is not reliant solely upon building height; morphology substantially affects the interaction region between the fluid boundary layer and solid building mass, and therefore the quality of the wind resource. Vortex shedding is a fluid turbulence phenomenon that occurs immediately past the point at which airflow is intercepted by a solid object, and whose behavior alters depending upon building geometry. BIWT can be implemented in existing rectilinear building projects with less-than-optimal efficiencies, but in cases of new construction, morphological considerations can be integrated early in the design process. Such a strategy can improve turbine performance by planning for manipulation of flow separation and reattachment within the fluid-solid interaction region. Vortex shedding with rectilinear extruded tall building geometries occurs at the corners, as illustrated in Fig.5. A circular extruded building mass, lacking abrupt corner transitions in plan, is a comparatively more aerodynamic geometry. The behavior of the flow field around the geometry changes: reattachment occurs at the sides of the building mass.[7] This phenomenon presents the opportunity to capture the wind resource more effectively at the building edge of the aerodynamic structure.

In addition, flow behavior around a cylindrical body, given rotational symmetry, is similar from multiple flow directions. Vertical axis wind turbines (VAWT) are designed on a similar principle, to capture flow from multiple directions, useful for environments with inconsistent directional flow origin, including coastal urban landscapes. A strategy implementing a circular extruded building mass and VAWT technology could improve turbine effectiveness in such environments. In addition, smoother, less-faceted building geometries are capable of withstanding higher wind velocities with less damage due to hurricane or other storm weather effects. If wind energy collection is present as an objective at the schematic point of the design process, the architectural problem can expand to include trade-off optimization of variables including quantity of leasable floor space, provision of emergency power, reduction of the building's carbon footprint, and lowered operational costs for building occupants. In a real-world project scenario, decisions as to the extent of modification to each variable could be made based on its assigned value within the scheme.

Integral to a real-world viability analysis of wind energy is the examination of local geographical context, as it is an oversimplification to assert that a coastal edge condition comprises a linear boundary and total exposure between the built environment and open water surface. In the ABL wind speed calculations, the exponential constant α represents the surface roughness of the landscape over which the ABL flows, and by which the flow regime is influenced. A linear condition is atypical among the three case studies selected (fig.3). For Sydney, the uniformity of flow that engages coastal structures can be presumed to experience an increase in turbulence due to the high surface area of the coastline edge in plan. The accuracy of wind speed calculations can be increased by adjusting α to reflect the greater surface roughness. In the case of Miami, exposure of coastal structures to water is less obstructed, indicating that the use of the α value for a water surface results in higher-accuracy estimates. In addition to initial estimates, real-world building design methodologies for projects including BIWT should encompass thorough viability analyses using anemometer measurements taken at the intended collection site.

Flow control technology synergistically addresses the four principal impediments facing BIWT: 1. Managing Turbulent Air Flow; 2. Minimizing Noise and Vibration; 3. Ensuring Structural Safety; 4. Ensuring Reliable, High Efficiency Power Output.

These speeds can potentially generate power from a virtually untapped resource at costs that compare favorably with retail rates paid by building owners. However, turbines perform optimally in 'uniform' wind, in which the air flows in a single direction, whereas even on top of tall buildings the flow is often highly turbulent. As wind comes over the top of the building, it separates into streams, creating turbulence, thereby affecting the power output and structural requirements for the turbine to 'brace' against the wind. As a result, the common recommendation is to elevate a turbine at least 30 feet above a bluff body, including the building itself, creating an expensive and unsightly structure above the building, which is still subject to turbulence and safety issues. Siting and accurate wind prediction are critical, and the need to augment and provide control over the wind resource at the building surface is clear. Active Flow Control, a new approach adapted from the aeronautical industry, could enable the augmentation of the power output of Building Integrated Wind turbines while lowering the overall optimal height off the rooftop, thus significantly widening the potential for retrofit applications to many existing building types that would currently be unable to viably integrate turbine technology. Currently, improving a building's aerodynamic performance relies on a Solid-based Aerodynamic Modification (SAM),

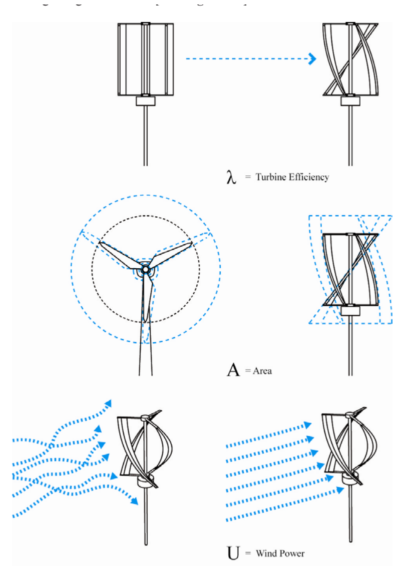


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Figure 4: Turbine Variable Relationships

The equation for wind power potential of a turbine is generally expressed as:

$Pt = ½ρU^3λA$

Where:

Pt = Power produced by the turbine, W
ρ = Air density, kg/m^3
U = Wind speed approaching turbine, m/s
λ = Wind turbine efficiency
A = Projected area of turbine 90º to the wind resource, m^2

mainly by shaping the building and/or the turbine geometry or structure. The proposed Fluid-based Aerodynamic Modification (FAM) approach is fundamentally different: fluid flow is used to improve the aerodynamic `shape' of the structure.

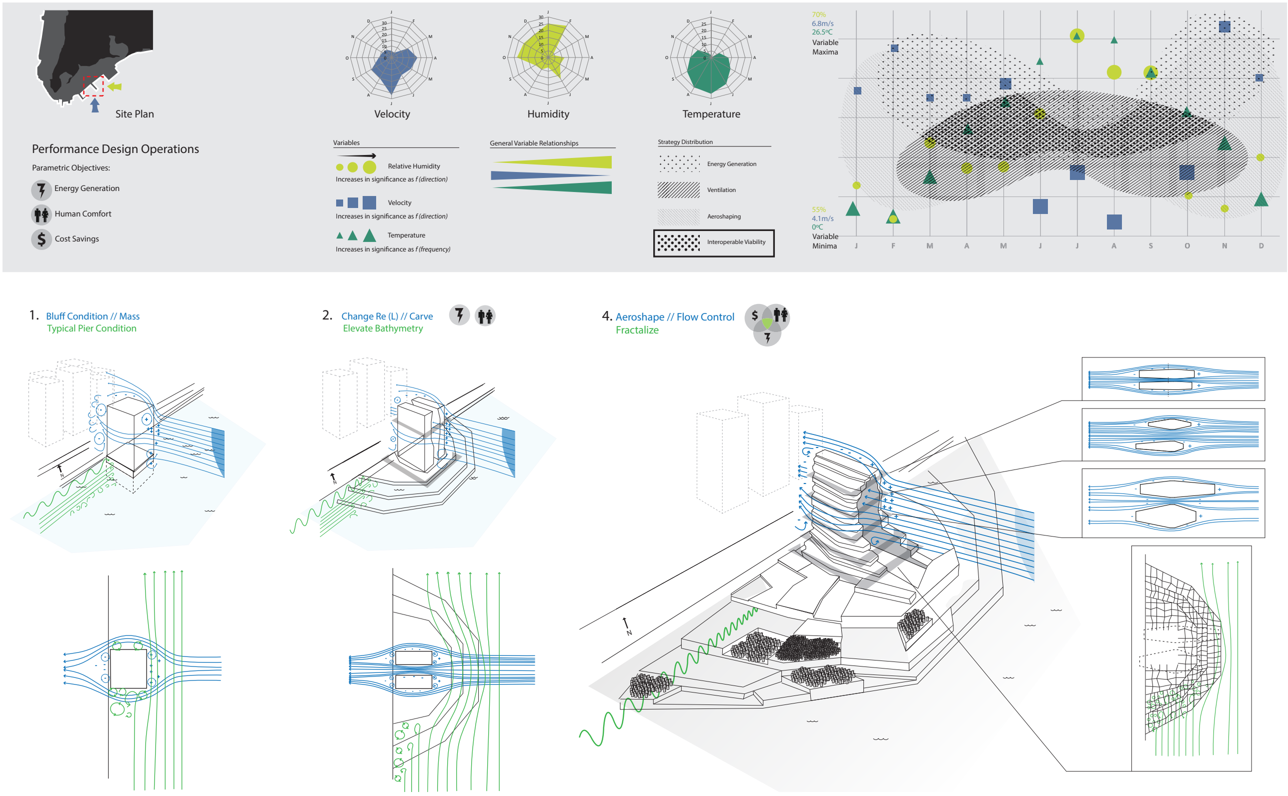
If the turbines cannot adapt rapidly to these changes, it further reduces their yields and imposes additional stresses on them.[8] The feasibility of building-integrated wind turbines depends largely on turbine power output. Urban wind flows are characterized by turbulence, and frequent variations in the direction of flow. Power output is significantly constrained by limitations on turbine swept area due to safety and structural concerns, and by the cost of installation, which is negatively impacted if tall mounting structures are required to lift the turbine rotors above the zone of turbulence typically found in urban conditions. If the turbines cannot adapt rapidly to these changes, it further reduces their yields and imposes additional stresses on them.[8]

Many of the improvements for increasing the power output for BIWT have focused on turbine design by improving wind turbine and blade efficiency and increasing the projected area of the wind turbine perpendicular to the approaching resource.[8] The aim of this work is to improve the quality of the resource, i.e. to increase the velocity and the quality of the air flow which affects the turbine's motion, while also relieving the structural load on the building by channeling the flow directly into the turbines closer to the building structure. Flow control objectives can, in addition, be achieved through multiple technological means. While turbines are a current realization of harnessing goals, the approach of flow control is not restricted to turbines, but is open to myriad forms of resource extraction and redistribution. As research in the area of flow control continues, it is anticipated that the performance technology will continue to evolve and assume new mechanistic forms.

VISION FOR INTEGRATION

Though not technically classified as subtropical, many coastal cities experiencing rapid urbanization are vulnerable to tropical cyclonic activity and other impacts of climate change, such as sea level rise. For example, New York City, while classified as temperate, experiences a hot-humid climate characterization during the summer months; like Miami, this time frame falls partly within the hurricane season at the eastern coast of the United States, rendering this heavily urbanized coastal region a strong candidate site for feasibility studies on the integration of active flow and BIWT technology. Large-scale replication of such strategies that harness and redistribute the wind resource, could have a substantial mitigating impact on disaster aftermath at the New York City urban edge. An academic conceptual design problem allowed for theoretical projection of a wind strategy integrated with local climatic site data, within the framework of an architectural process that included programmatic and real estate constraints.

This schematic projection considers preliminary viability of a wind strategy as part of a performative whole-building matrix approach to design, that prioritizes the resolution of parametric energy future-focused objectives with an architectural workflow. Critical to the process of innovation is the exercise of iterating schematic variations that test the synthetic potential of hypotheses considered. This snapshot of a single instantiation out of many possible outcomes that the process could produce, demonstrates a way in which a



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strategy inclusive of solid and fluidic modification within coastal architecture can meet design criteria while contributing to greater resilience in energy security and, in aggregate proliferation, urban power infrastructure.

FURTHER RESEARCH CONSIDERATIONS AND INQUIRY

It is critical for planners of future urban environments to consider how structural damage, economic losses, and loss of life can be mitigated during future disaster scenarios brought on by severe storms as part of larger fluctuating patterns in global climate. Preventative disaster design strategies are paramount, but in addition, if a locally available emergency power source can be provided through BIWT-produced energy to urban coastal populations during, and in the critical period following, a severe storm event, then a design response developed with integrated wind energy harvesting should be capable of operating at the critical range for the prevailing wind condition. Not only does wind energy availability represent a local and consistent support resource during infrastructural breakdown, it reduces CO2 emissions and other building-emitted pollutants during normal use, thus reducing the building carbon footprint and in aggregate effect, of coastal cities. In addition, globally outlined renewable energy goal attainment can be expedited through the energy savings realized with the use of building-integrated wind, increasingly so as technology investment enables greater efficiencies and sophistication of turbine equipment, and designers, engineers, and researchers work towards early-process cross-disciplinary response strategies with a holistic, adaptive approach. A coastal architecture characterized by careful consideration towards the spectrum of effects of wind flows, including damage from high-velocity storm winds, high structural costs particularly in tall building typologies where turning moment forces are most severe, and the potential for energy harnessing, constitute an appropriate and prescient design approach when implemented in concert with a broad range of climatic response strategies (e.g., solar optimization, rainwater harvesting, geothermal energy transfer) that are appropriate for the urban ecological context within which a given building is situated. Local climate and urban ecological information can provide a framework through which technology viability and architectural optimization can be designed synergistically, and can be developed. This process enables innovation at the schematic design level, which fundamental analysis and response is critical if we are to address the breadth of issues brought on by urbanization and global energy consumption. It is important to proceed with the notion that the promotion of a "one-size-fits-all" technology prescription is not acceptable as a robust, responsive solution across a diverse range of climatic and resource profiles, as well as ecological and cultural contexts, that the spectrum of subtropical coastal urban centers represents.

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