Performance of a Building Integrated Wind Farm

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ABSTRACT: Energy use in buildings accounts for nearly half of the carbon dioxide emissions in the world. The growing demand of renewable energy as well as the increased confidence and interest in low-energy building design has led to innovative solutions. Buildings can be used to accelerate local wind speed, such that they create a favourable environment for optimised energy extraction of wind power locally. Not only would the wind turbines integrated building offer the opportunity to harness and maximise the wind energy available in an urban environment, once erected, their presence would undoubtedly promote the importance of renewable energy, whilst generating interest and augmenting general awareness. There are various ways of integrating buildings with wind turbines, such as locating turbines on roofs, between shaped buildings, and in a duct through buildings. The current investigation is the first of its kind to integrate a vertical wind farm in an office tower in an urban environment. A geometrical twist is incorporated from the base of the office tower to the height of the wind farm, as an active response to the climatic analysis, such that the wind power extraction region faces the prevailing North-west winds.

Conference Topic: 1 Sustainability and high-rise buildings
Keywords: wind energy, building integrated wind farm

INTRODUCTION

Renewable energy is being integrated into buildings in order to reduce emissions, improve the efficiency of buildings and help to meet the increasing stringent targets on energy consumption.

The World Trade Centre (WTC) Freedom Tower is designed to be of a high internal quality whilst also being a highly energy efficient building by adopting many passive and low energy strategies as follows:

- Bio-climactically correct response to massing;
- Natural daylighting;
- Natural ventilation;
- Advanced facade design;
- Energy efficient HVAC and lighting systems that maximise passive energy sources;
- Energy efficient appliances.

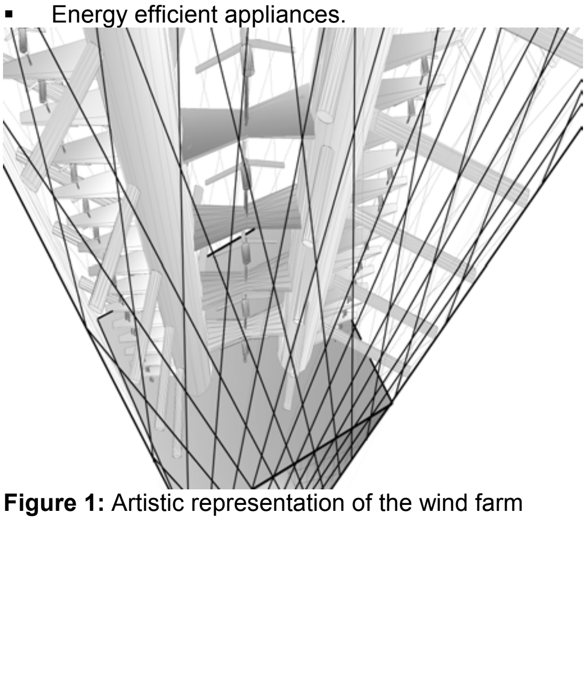


Figure 1: Artistic representation of the wind farm

Renewable energy concepts that supplement the energy efficiency have been explored and they offer the following advantages:

- On-site electricity generation, reducing grid dependency;
- Possibility of revenue stream, from displaced utility costs of imported energy, once installation has been paid back;
- Possibility of revenue stream for the trading of Renewable Energy Certificates (RECs), currently estimated at 1cent/kWh of displaced energy;
- Visual statement, reinforcing the buildings green credentials;
- Demonstration of state-of-the-art building and integrated renewable building options including the first ever urban vertical wind farm.

The key renewable proposals for the tower are:

- A vertical wind farm
- A photovoltaic panel installation

This paper focuses on the urban wind farm integrated in the World Trade Centre Freedom Tower.

1. MOTIVATION

Wind is widely available, free, and perhaps the most predictable of natural energy resources on an annual basis. Wind turbines convert the energy of the wind into electricity – cheaply, efficiently and without damaging the physical environment.

The combined wind rose at La Guardia, JFK and Newark Airports (see Fig. 1) shows that the prevailing winds are from the northwest, northeast and south directions, with the strongest wind coming from northwest. [1]

The wind energy rose differs from the corresponding energy rose at a given site because the wind energy is proportional to the cube of wind speed, and for this reason the wind energy is mainly driven by the prevailing wind directions.

It is known that wind speed increases with height, and since the amount of wind power is proportional to the cube of wind speed, this means that the potential extractable wind power is substantial. The energy available at mid-level of the vertical urban wind farm is 8,185 kWh/m² which is approximately 4.8 times as much as that at 10m. Coupled with a low energy building, wind energy can provide a significant proportion of the energy needs.

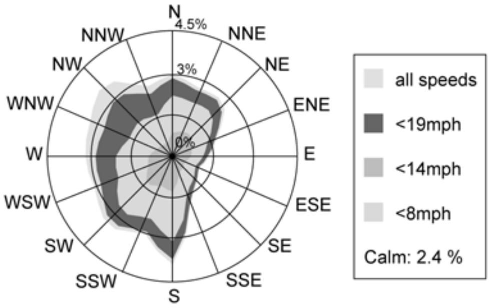


Figure 2: Annual wind rose at site (10m)

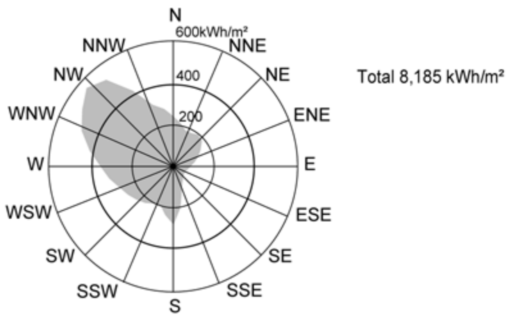


Figure 3: Energy rose at mid-level of the wind farm (411m)

Wind farms, mostly located at rural areas, have been receiving increased attention on a global scale. The energy generated by these wind farms requires transportation. The possibility of producing wind energy at urban locations where it is consumed is attractive, as it would significantly reduce both transmission and infrastructure costs. The wind characteristics in a built environment are different to that in the open country, namely due to the lower mean wind speeds and higher turbulence levels because of the presence of roughness imposed by buildings. The interaction between bluff bodies, such as buildings and wind power extraction machines is complex, but if understood, can be manipulated to make a positive impact to the environment.

There are many various ways of integrating buildings with wind turbines are installations on roofs, between shaped buildings, and in a duct through buildings. Recent research mostly involves integrating a small number of wind turbines in a building [2, 3]; the current investigation is an innovative design that incorporates a vertical wind farm in an office tower in an urban environment.

2. TOWER DESIGN PRINCIPLES

Detailed analysis indicates that prevailing wind energy comes from the northwest. The strategic responses of the wind farm integrated tower are:

- Maximise wind power harvest by twisting the tower such that its upper storeys face the prevailing wind;
- Locate the wind farm at high level to maximise wind energy harvest, and minimise turbulence levels;
- Mitigate the northwest wind at pedestrian level at low levels of the tower;
- “Urban” roughness reduces the rate of increase of velocity with altitude and increases gustiness and turbulence. Positioning the wind farm at high altitude will eliminate these issues.

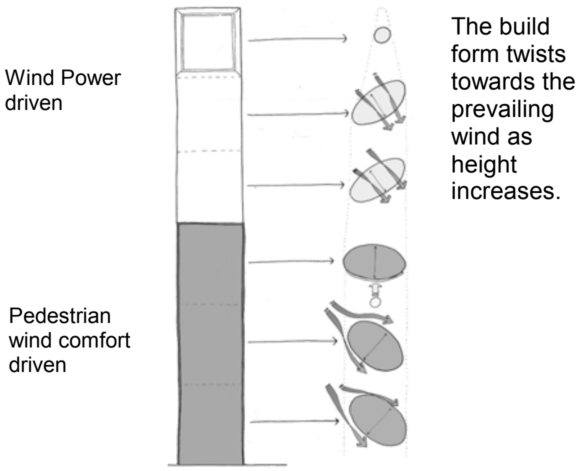


Figure 4: Form Finding

3. ANALYSIS

The objectives of the current investigation are to:

- Identify opportunities for wind power generation;
- Review building integrated turbine technology
- Maximise opportunities through strategic responses;
- Demonstrate design concepts in response to analytical and computational findings.

3.1 Method

The potential of harvesting wind power has been identified using the long-term historical wind data measured at La Guardia, JFK and Newark Airports. The actual wind distribution at the WTC site differs from those at local airports, for the reasons given below, and requires to be recomputed with the aid of statistical tools and knowledge of the variation in the terrain types around the site.

The nature of the wind depends on roughness effects caused by building masses and heights, hence the type of terrain. This means that the vertical distribution of wind with height from the ground level varies for terrains such as urban, countryside and open-field. It is therefore necessary to apply the roughness correction, which takes local topography and building masses into account, to the collected wind data.

3.2 Strategic Response to wind power analysis

The variation of wind power with height and direction has been assessed in detail, and the strategic response is illustrated in Fig. 5. Aerodynamics and architecture are integrated by:

- Manipulating the build form to modify wind speeds and directions to improve pedestrian wind environment;
- Designing the build form to capture wind from prevailing directions.

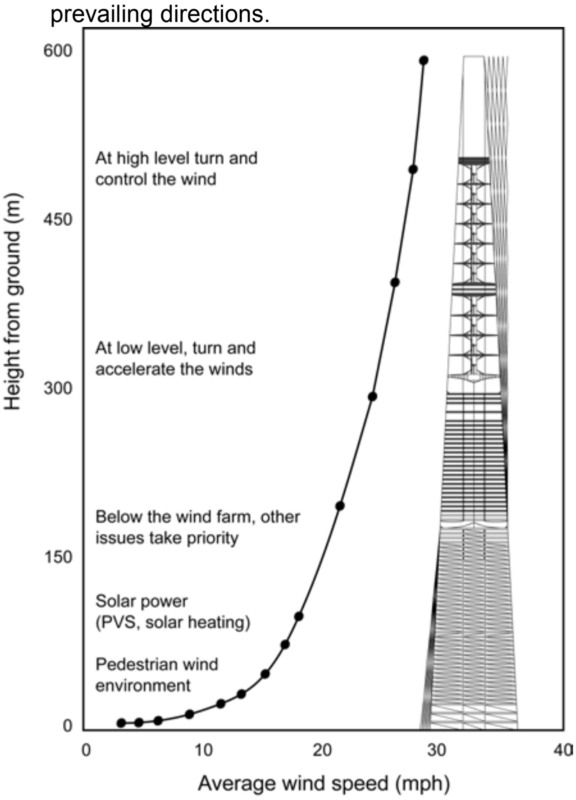


Figure 5: Building response
Variation of wind speed with height

3.3 Wind turbines

Wind turbine blades exploit the principle of lift or drag to cause the blades to move, effectively capturing the energy from the wind. The rotational energy captured by the blades is then turned into electrical energy by the electric generator connected to the rotor.

The power curve in Fig. 6 indicates that doubling the wind speed will lead to an eightfold increase in power. Therefore when siting the turbines in the urban environment particular attention should be given to using building "speed-up" to increase wind speeds.

The upper limit of kinetic energy available for extraction from the wind stream is denoted the "Betz" limit and is circa 59% of the available wind energy. Theory indicates that it is simply not possible to extract all the kinetic energy. Modern turbines approach this limit, but the delivered electrical power is less due to subsequent losses at the shaft and generator. Typically, the overall efficiency, measured in terms of the electrical power output will be around 30-40%.

Due to a number of constraints imposed by the economics, technical limits of the energy conversion systems and availability of wind, turbines are designed to work within a range of speeds, typically between 5.6 mph (2.5m/s) and 56 mph (25m/s). Within these operational limits, the power output varies as illustrated in Fig. 6.

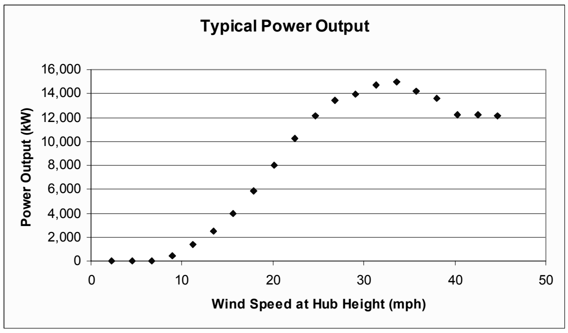


Figure 6: Typical Power Output

The following shows some of the criteria in specifying a turbine for WTC. The list is not exhaustive.

- Geometric dimensions, e.g. rotor diameter;
- Efficiency and performance characteristics;
- Low cut-in speed and high cut-out speed to maximise wind capture and thus power output
- Fatigue;
- Turbine survivability
- Safety
- Environmental Impact
- Electromagnetic interference
- Static and dynamic loading
- Noise and vibration
- Life span
- Buildability and procurement
- Economic payback

3.4 Types of Wind Turbines

Wind turbines are classified into two general types: horizontal axis and vertical axis. A horizontal-axis machine has its blades rotating on an axis parallel to the ground (see Fig. 7), whereas a vertical axis machine has its blades rotating on an axis perpendicular to the ground, as shown in Fig. 7.

Horizontal-axis wind turbines are the most common wind turbine design. The axis of blade rotation is parallel to the wind flow. Some machines are designed to operate in an upwind mode, with the blades upwind of the tower. In this case, a tail vane is usually used to keep the blades facing into the wind. Other designs operate in a downwind mode so that the wind passes the tower before striking the blades.

The machine rotor in a downwind mode naturally tracks the wind without a tail vane.

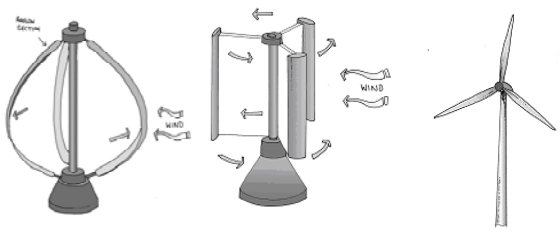


Figure 7: Vertical-Axis Wind Turbines and Horizontal-Axis Wind Turbine

Vertical-axis machines do not depend on wind direction, unlike horizontal-axis wind turbines. Although vertical axis wind turbines have existed for much longer, they are not as common as their horizontal counterparts. The basic vertical axis designs are the Darrieus, which has curved blades, the H-Type, which has straight blades, and the Savonius, which uses scoops to capture the wind. The types of turbines are reviewed in Table 1.

3.5 Design Approach and Concepts

The tower is approximately 536 m tall, with offices up in the lower portion, and an antenna at the top. The unoccupied centre portion is ideal for wind energy extraction (see Fig. 5). The two centre cores that run vertically through the antennae portion can be manipulated to optimise wind flow for wind turbine integration.

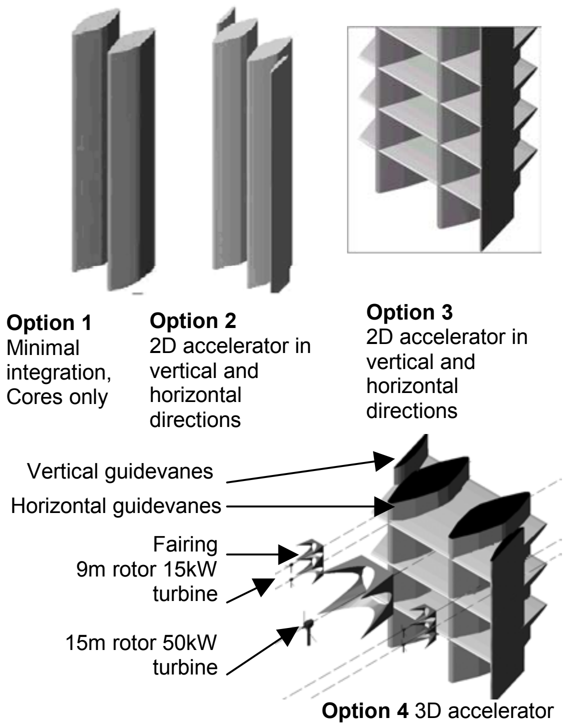


Figure 8: Four design concepts

The current approach reviews the incremental aerodynamic and architectural integrations with increasing complexity.

Four design concepts have evolved following from the analysis and are shown in Fig. 8. The base case, Option 1 involves integrating turbines between and outside the two cores. The aerodynamic profile of these cores can be optimised to produce a more uniform flow for the internal turbine [1 & 2]. Option 2 aims to improve the wind profile for the turbines located external to the cores, the outriggers. Options 3 and 4 present further aerodynamic integration with the addition of horizontal profiles and in-fills to improve the three-dimensional aerodynamics. The characteristics of each option are discussed in Table 2.

Table 1: Review of turbine types

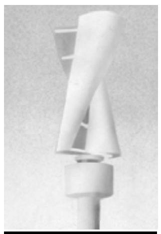
Horizontal-Axis Wind Turbines 	• Lift-type machine • Typically produces more power than vertical axis wind turbines • Has to be positioned in the wind direction. • Can operate in two opposite directions by pitching the blades by 180°
Vertical-Axis Wind Turbines (Savonius Configuration) 	• Drag-type machine • Special construction for stormy wind • Wind direction independency
Vertical-Axis Wind Turbines (Darrieus Configuration) 	• Lift-type machine • Lower aerodynamic efficiency than horizontal-axis turbine • Wind direction independency
Vertical-Axis Wind Turbines (H-Type) 	• Lift-type machine • Whole aerofoil contributes to energy production • Centrifugal forces can be problematic • Wind direction independency

Table 2: Design Concepts

Design Option	Aerodynamic integration	Structural integration	Architectural integration
1	Rough aerodynamics Increased fatigue loading on turbines Reduced turbine performance	Minimum integration effort No additional structure or aerodynamic surfaces	Turbine relatively visible
2	Better wind steering	Some integration effort Additional structural or aerodynamic surfaces required for flutter and structural concerns	Turbine relatively visible
3	2D aerodynamics in two directions Good wind steering Good wind concentration	Some integration effort Additional structural or aerodynamic surfaces required	Turbines not readily visible
4	3D aerodynamics Good wind steering Excellent wind concentration	Considerable integration effort Additional structural or aerodynamic surfaces required	Turbines not readily visible

3.6 Computational Fluid Dynamics

The shape of the cores was varied to assess the quality of the flow at the turbine location, in terms of speed-up and uniformity. The former is desired to maximise wind energy yield whilst the uniformity of flow is essential for reducing blade loading, fatigue and possible failure risks. (see Fig. 9).

These requirements should be satisfied for the widest range of prevailing wind directions. The optimum form, shown from a series of systematic computational fluid dynamics (CFD) modelling, is highlighted.

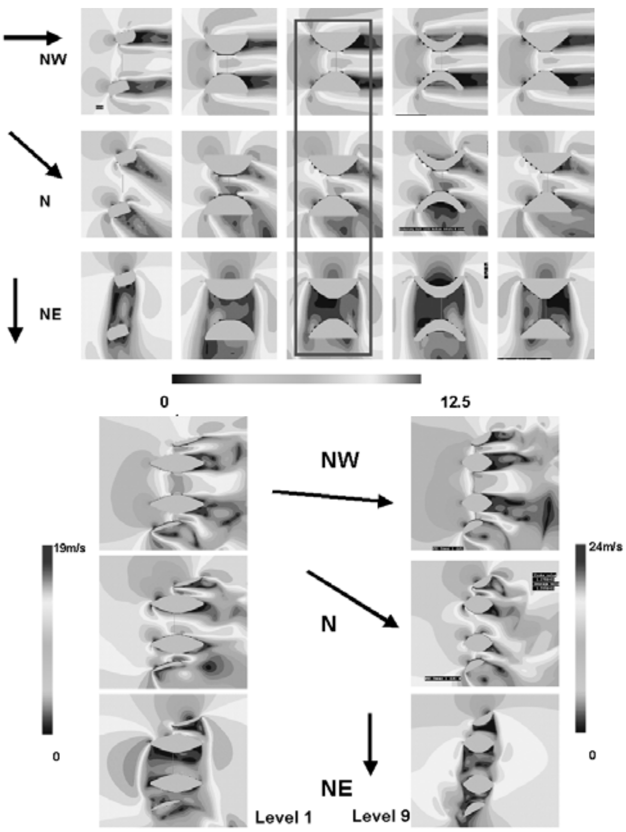
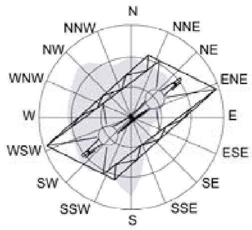
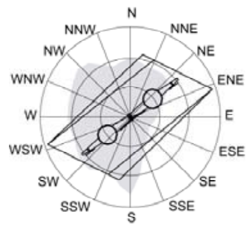


Figure 9: Computational Fluid Dynamics Results

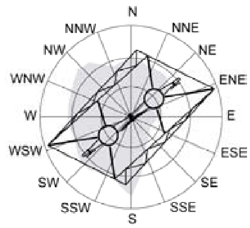
3.7 Wind Tunnel Testing



Level 9 wind farm



Level 4 wind farm



Level 1 wind farm

Figure 10: Base case in Wind Tunnel Testing showing cylindrical centre cores

Wind tunnel testing was performed on the base case with the two centre cores as shown in Fig. 10. The two cylindrical cores require the simplest architectural and structural integrations, and are spaced far apart to minimise adverse aerodynamic interference on the turbine output, whilst still providing the desired local speed-up. Figure 10 also shows the tapering floor plate and the geometrical twist in response to the prevailing wind direction. Figure 11 shows the wind farm section of the tower.

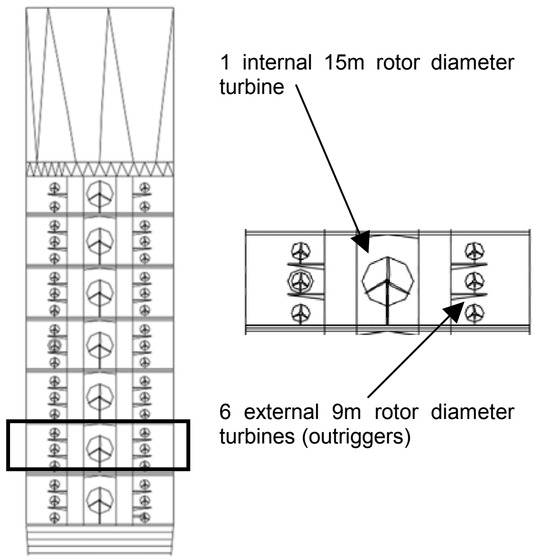


Figure 11: Tower integrated wind farm in tower

The current investigation examines the aerodynamic performance of the turbines for two cases: fixed and free to yaw by conducting wind tunnel tests. Discs of known resistance were to simulate the wind turbines. Smoke visualisation was employed to gain a better understanding of the flow.

Flow velocity measurements were conducted in the wake as well as at locations near the simulated wind turbines. The collected data is used in conjunction with long-term wind frequency data to estimate the annual energy production.

4. RESULTS

The detailed measurements show that the presence of the centre cores do indeed help to direct the wind through the wind turbines for both cases of fixed and free-to-yaw turbines, and thereby magnifying the wind power capture.

An uniform wind distribution was observed at the wind turbine for wide range of approaching wind angles of 70°, that is ± 35° away from the plane perpendicular to the face of the wind turbines. Wind power capture was still noted for winds coming from outside this range, though somewhat reduced. The outriggers are more sensitive to the wind direction, compared to the centre turbines [4].

The power coefficients for both fixed and free-to-yaw turbines are significantly higher than that for the unducted case, that is stand-alone turbine in the absence of buildings, as shown in Fig. 12. The augmentation in annual energy production is approximately 5 % and 50% for the fixed and free-to-yaw turbines respectively compared to the unducted case. The increase in annual energy production for the free-to-yaw case is up to six times as much as that from the fixed turbines.

The estimated yearly energy yield for the fixed turbine configuration and yawed turbine configuration are 17.7GWh and 25.5 GWh respectively. Figure 13 shows the energy use and production of the current building tower compared to other buildings in New York [4].

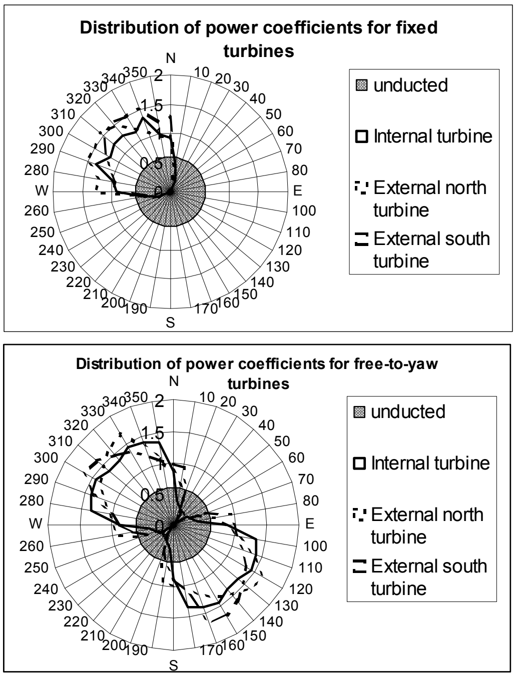


Figure 12: Power Coefficients for fixed and free-to-yaw turbines [4]

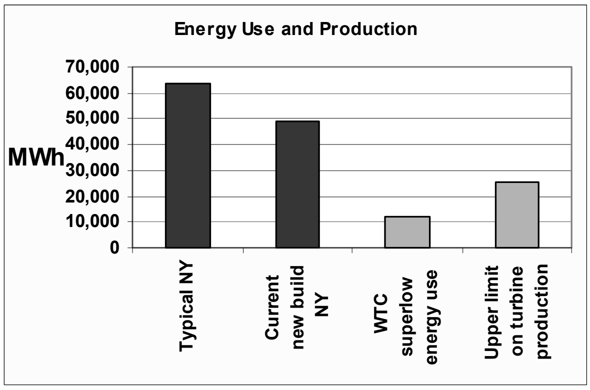


Figure 13: Energy use and production

5. CONCLUSIONS

The new Freedom Tower demonstrates how a tall building can harness natural resources by responding to the external climate, it represents the future of architecture where buildings become self sufficient.

Renewable energy can be generated in every city, and every building. The current development proves that architecture that are designed along sustainable principles are not only better buildings, but actually improve the environment they are within by producing energy.

The novel integration of a vertical wind farm in an office tower in a built environment has been shown to give promising energy yield. The current study has demonstrated the underlying concept, and paved the way forward with sustainable building design.

ACKNOWLEDGEMENT

The authors would like to acknowledge the partnership with Skidmore Owings & Merrill and Studio Daniel Libeskind.

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