Wind Energy Innovative Application on Shanghai Tower and Analytical Contrast with Other Buildings

Yiwei Hu1, *
1Shanghai World Language Academy, Shanghai 200233, China
*hu39@sas.upenn.edu

Abstract—In this paper, wind energy as well as its innovative technology (wind turbine) is introduced. Original source, application, categories, principles, products etc are presented as the background introduction. As the typical building that integrates wind turbines on its structure, Shanghai Tower is regarded as the reference group in this research. Bahrain World Center, Strata Tower and Pearl River Tower are three sustainable buildings that utilize wind turbine technology as well, which are comparative groups. The aim of this research is to investigate the effectiveness of wind energy technology and to differentiate between wind turbines on different buildings according to some dimensions such as efficiency, cost and availability. Moreover, the future prospects and probable improvements on the wind turbines will also be discussed in this paper.

1. Introduction

1.1. Background information
Energy is a necessary component of socioeconomic development and economic expansion. Specifically, wind energy emerges as a sustainable power source that is native to the area and play a vital role in moderating reliance on fossil fuels [1]. Onshore wind energy has a huge technological potential about 20,000,109 to 50,000,109 kWh per year. The economic potential of wind turbines is influenced by average wind speed, statistical wind speed distribution, turbulence intensities, and the cost of wind turbine systems [1]. Wind turbines, unlike other sources of electricity (such as coal, gas, and petroleum-based fuel), do not emit pollutants [2].

1.2. Shanghai Tower
The Shanghai Tower, about 632 meters tall, is located in Shanghai's Lujiazui financial district. This 127-story mixed-use mega-tall has shops, offices, a hotel, an observation deck, and a restaurant (SRIBS, 2014). In 2010, Shanghai Tower accomplished a Leadership in Energy and Environmental Design (LEED) Gold pre-certification certificate, and in 2012, it was awarded a Green Building Energy Labelling (GBEL) Three-star rating [3].

1.2.1 Renewable energy technology strategies

1.2.1.1 Ground Source Heat Pump System
To keep the interior area at a comfortable temperature, the ground source heat pump (GSHP) system transfers heat between the constant temperature of the soil and the building. The average yearly temperature of the Shanghai Tower's subsurface is 18.8°C and therefore 127 34-meter-long geothermal
pegs were buried. Each stake has a cooling capacity of 191 kW and a heating capacity of 302 kW. When compared to typical air source heat pumps, the GSHP system is 40% more efficient.

1.2.1.2 Ice Storage Air-conditioning
Ice storage refers to a tank where ice may be stored during off-peak hours, kept, and then thawed and used during peak hours. This system provides benefits such as lowering operating costs and greenhouse gas emissions, as well as lowering electrical power infrastructure investment owing to lower peak load energy usage.

1.2.1.3 Combined Cooling, Heat and Power
The CCHP system at Shanghai Tower operates for 335 days a year, 16 hours each day. The system's typical yearly production is around 11 million kWh, with an annual cooling capacity of around 9 million kW.

1.2.2 Sustainable building structure
Shanghai has an outstanding public transit system with a 13-line metro system, which helps to reduce the usage of private vehicles substantially. A set of wind tunnel studies are used to analyze the building's performance and define the ideal shape of the external skin of an asymmetrical tapering tower, which reduces wind loads and thus allows for the use of a lighter, more efficient construction that preserves natural resources.

1.3. Objective
The focus of this paper is on Shanghai Tower and the objective of is to investigate the wind energy application on Shanghai Tower and to compare different buildings that utilize wind turbines.

2. Technology (Wind turbines) application

2.1. Wind turbines
The wind turbines are becoming more and more significant as a prominent source of intermittent renewable energy. In countries around the world, the turbines in rural places are built in order to lower the energy costs and to reduce the dependence on conventional fossil fuels. Wind turbines are considered to generate the lowest greenhouse gas emissions, requiring the least consumption for water and having favorable social impacts [3].

2.1.1. Horizontal-axis wind turbines
These turbines should be directed toward the wind. Turbines used on wind farms for commercial electricity generation are usually three-bladed, which results in good reliability as they have low torque ripple.

2.1.2 Vertical-axis wind turbines
Moreover, the turbine can be incorporated into a building since it is intrinsically less maneuverable [4].

2.2. Wind Turbine integration on buildings
In most cases, the wind is utilized on farms to supply economic power with a renewable energy source. Nevertheless, the land is mainly constrained on urban and suburban regions, considered as a significant limitation on regions and large-scale wind turbine installations [5].

2.2.1 Wind turbine integration on Shanghai Tower
About 270 horizontally oriented wind turbines with a single capacity of 500 Watts and a sum of 135 kilowatts are installed on top of Shanghai Tower, as indicated in Fig.1. Additionally, there are 54 vertical-axis wind turbines, as shown in Fig.2, ranging in height from 565 to 569 meters. Wind turbines is estimated to produce 157,500kWh in renewable energy.
2.2.2 Wind turbine integration on Bahrain World Trade Center

The Bahrain World Trade Center's sailing-shaped office tower tapers up to 240 m in height, supporting three horizontal-axis wind turbines each 29 m in diameter which is shown in Fig.3. It also improves the turbine's power generation capability while reducing blade fatigue to acceptable levels when tilting the wind on the blades.

Vertically, the airfoil sections of the tower are decreasing in size as they taper upwards [7]. The wind turbines on the Bahrain World Trade Centre cover about 7% of total output energy.

2.2.3 Wind turbine integration on Strata Tower

At the top of the tower, three 19-kilowatt five-blade turbines are installed in the specifically designed venturi as shown in Fig.4.

As a major design component that significantly improves the potential operational output, wind turbines as a site-based renewable energy option can channel and guide wind. The architectural approach for Strata Tower is an iteration of the one used for the Bahrain World Trade Center, which employs the concept of a "Venturi" to control wind flow, but in a different way in between the two towers. Other notable differences include the project's magnitude, the fact that the three turbines are located externally on linking bridges, and the hot, humid environment, which necessitate full air conditioning to assist mitigate any unwanted auditory impacts[9]. The wind turbines on Strata Tower supply about approximately 50 000 kWh of renewable energy annually.
2.2.4 Wind turbine integration on Pearl River Tower

Pearl River Tower is a 71-storey, 309.6-m neo-futurist skyscraper at the intersection of Jinsui Road West. Inside the building, there are four 8 m tall vertical wind turbines, each with an interior opening on the left and right sides [10]. The orientation of the Pearl River Tower is parallel to the direction of Guangzhou's dominant wind, which seeks to maximize the power of the turbine, allowing for improved wind intensification and funneling through the openings. Pearl River Tower's design takes full advantage of the super-tall building's aerodynamic characteristics, which can result in a considerable increase in wind speed via the four apertures.

Wind turbines on the Pearl River Tower in Guangzhou have approximately 300,000 kWh capacity annually, which cover about 2% of the building’s consumption.

3. Comparison

3.1 Comparison of wind turbines on different buildings

It is necessary to compare different buildings with wind turbines as all of the four have their own unique characteristics. In order to make the comparison effective, the factors are divided into two categories, qualitative factors such as geographical location and climate which may lead to the differences in the availability of wind turbines and quantitative factors such as cost of turbines and efficiency which contributes to the effectiveness and feasibility of wind turbines. The comparison table is shown below as table 1.

| Buildings          | Location             | Cost of turbines | Efficiency                                      | Climate                  |
|--------------------|----------------------|------------------|-------------------------------------------------|--------------------------|
| Shanghai Tower     | Shanghai, China      | $118K            | 1,340,000 kWh of renewable energy supplied annually | Windy in summer and winter |
| Bahrain World Trade Center | Manama, Bahrain | $21K             | 7% of total energy consumed                      | Windy in summer           |
| Strata Tower       | London, England      | $93K             | 500,000 kWh of renewable energy supplied annually | Windy in both summer and winter |
| Pearl River Tower  | Guangzhou, China     | $40K             | 300,000 kWh of renewable energy supplied annually | Windy in summer           |

3.1.1 Location

Location of the buildings is a key dimension in comparing buildings with wind turbines as it determines the impact of the wind turbines on the surroundings either explicitly or implicitly. Noise pollution is a main and inevitable drawback of wind turbines though architects usually design innovative building structure to eliminate the noise as less as possible. Shanghai and London are renowned and prosperous metropolises where there are hundreds of towering constructions. As a result, the noise pollution created by wind turbines is accessible to adjacent buildings, posing a risk of noise pollution. Guangzhou and Manama are prosperous and fast-developing cities where acoustic impacts are not considered as a significant factor and where wind turbines are appropriate to be installed.
3.1.2 Cost of turbines
Cost of turbines is different in these four buildings, which indicates variable application range of wind turbines on these four different buildings. As there are about 300 wind turbines throughout Shanghai Tower with a single capacity of approximately 500 watts, the cost of turbines on Shanghai Tower is relatively higher. Besides, the wind turbines on Strata Tower are bigger, having larger capacity and efficiency, so the cost of turbines as well as the maintenance fee is also relatively high. For Bahrain World Trade Center and Pearl River Tower, there are smaller amount of wind turbines which therefore cost less.

3.1.3 Efficiency
Efficiency is a transparent determinant in measuring the effectiveness of the wind turbines. On Shanghai Tower, the wind turbines produce about 1 340 000 kWh of renewable energy annually. Besides, Strata Tower and Pearl River Tower are about to supply 500 000 kWh and 300 000 kWh of renewable energy, respectively. For the Bahrain World Trade Center, the output energy even overwhelms seven percent of the total energy consumed. Therefore, the wind turbines can be regarded as an effective way to utilize wind energy, which sustains and saves much energy.

3.1.4 Climate
Climate is an important factor for the availability of the wind turbines. For Shanghai and London, it is usually windy in both summer and winter, able to utilize wind energy almost all year round. For Manama and Guangzhou, the situation is a bit bitter, for the windy days are usually only in summer so the effective availability is in a shorter period in these two cities.

3.2 Comparison between utilization of different energies
As one of the renewable energies, wind energy takes up a prominent place in the goal of sustainability. As a lot of sustainable strategies are used in Shanghai Tower such as geothermal energy and solar energy, it is clear to compare them to conclude the effectiveness of wind turbines which is shown below as table 2.

| Technologies Factors | Energy utilized | General Capacity | Efficiency | Availability | Expiration date |
|----------------------|----------------|-----------------|------------|--------------|----------------|
| Wind Turbine Integration Technology | Wind energy | 1.67 Megawatts (per turbine) | Max: 59% General: 50% | High Buildings Windy Zones | 20 years – 25 years |
| Ground Source Heat Pump System | Geothermal energy | 50,000 Megawatts | Max: 21% General: 12% | Deep Soil Areas No Extreme Weather | 10 years – 25 years |
| Double-skin Facade | Solar energy | Reduce energy use by 40% | Varied | Areas with ample sunshine | Varied |

3.2.1 Energy utilized
Wind turbine technology, ground source heat pump system and double skin facade utilize different renewable energies which determines the usefulness. For the wind turbine integration technology, the turbines are installed on the top of the building where the wind energy is abundant and suitable. Besides, the wind energy are public goods which are both non-excludable and non-rivalrous [11], which means that it’s highly attachable in the reality. For the utilization of geothermal energy and solar energy, the geothermal energy is relatively scarce and hard for exploiting and solar energy is likely to have radiation which causes potential harmful consequences.
3.2.2 General capacity
Compared with GSHP system and double-skin facade which produces 50,000 megawatts and reduces the energy use by 40%, the wind turbine has a general capacity of 3 megawatts per turbines. As a result, though the wind turbine has a lower overall capacity than the other two, rather because turbines can be incorporated into structures on a large scale, the use of wind energy is practical and feasible.

3.2.3 Efficiency
Efficiency and energy cost are leading factors to determine the usefulness of a product [12]. Wind turbines is highly efficient, as much as 50% in general while the other two are either varied or below 20% in general. As the data shows, wind turbines are effective at consuming and renewing energy, making them appropriate for building integration.

3.2.4 Availability
Wind turbines are usually integrated with high buildings, which is a sensible and genuine idea as buildings are extremely common in major cities where the energy is produced in the places needed. Windy-days is another implementable determinant, for windy days are so common nowadays. Compared with ground source heat pump system and double-skin facade that require more limited and special places, wind turbine integration energy is excellent.

3.2.5 Expiration date
Average expiration date for wind turbines are about twenty to twenty-five years, which is relatively long-consuming and low-cost while the other two are more fragile [13]. Furthermore, because wind turbines have fewer and more recognizable components, their maintenance costs are low.

4. Evaluation

4.1 Evaluation about wind turbine technology

4.1.1 Pros

4.1.1.1 Renewable energy utilization
Wind integration technology utilizes the wind energy which is a clean energy, thus generates fewer emissions compared with the conventional sources such as coal and gasoline.

4.1.1.2 Wide availability
Wind energy is available and relatively abundant in most of the world, thus leading to high probability of utilization. Wind turbine integration technology has a wide availability as buildings are all around the world, providing sufficient conditions for the application.

4.1.1.3 High efficiency and low maintenance fee
Wind turbine has a high efficiency, low energy loss during the re-generation process. Wind turbines have minimal operating and maintenance expenses when compared to conventional power generation systems since no fuel is required and no pollutants are produced [14].

4.1.1.4 Large capacity
Wind turbine has a large capacity, higher than the general utilization technologies. Each wind turbine has an average capacity of 3 megawatts per year, which is more productive than many other technologies that utilize renewable energy.
4.1.1.5 Durability
Wind turbine is durable and is less plausible to damage. As there are typically less and easier components in the wind turbines, it is more accessible for the maintenance to work. In addition to that, the components inside the wind turbines are less likely to breakdown.

4.1.2 Cons

4.1.2.1 Scale and aesthetic impact on the environment
Wind turbines may not continue to expand in size at the current rate due to apparent harsh facts such as dimensions restrictions in road and rail transportation of pole sections, crane sizes that can lift them, and so on [15].

4.1.2.2 Noise
These unsteady structures may give rise to noise at certain wind speed, however they are not yet well understood, and the means to control and harness them has not yet been mastered [16].

4.1.2.3 Flickering shadows
One social acceptability issue of wind turbines is about the flickering shadows caused, which occur when the sun is low in the sky and shines past a wind turbine. This causes a psychological impact of shadow flicker leading to serious nuisance in the wider population, and also affecting some epilepsy sufferers[17].

4.1.2.4 Nuisances and impacts on human
The aesthetic effect and irritation of the new transmission poles and wires necessary to transfer the electricity from the wind turbine to the grid is another social acceptability criterion for wind turbines. Underground cabling is more expensive, but in many situations it may be utilized to alleviate these issues[16]. Despite metropolises’ support of wind power, negative reactions in local communities have been particularly strong, and one of the largest real costs to the local community.

4.1.2.5 Impacts on Fauna
The mortality of wildlife caused by wind turbines is another tough issue to overcome. Occasionally, flocks of birds have flown over the blades, causing some birds to be struck. Small migratory bats are harmed, with contact being the most common cause of death, although pressure differences caused by tip vortices, which are hypothesized to cause barotrauma, are also a factor.

4.2 Future prospects&extensions

4.2.1 Future plans
While many turbine designs exist, the bulk of turbines nowadays are designed with three blades on an upwind horizontal axis. The center tower of the turbine is rather big. One tendency that has emerged in tandem with the fast growth of capacity is the shift to bigger turbines. In fact, in the previous few decades, turbine sizes, particularly rotor diameters and hub heights, and hence nameplate capacities, have grown substantially. As indicated in Fig. 7 [18], the average new onshore turbine capacity is growing and is anticipated to continue to rise in the future.

Wind turbines should be optimized to enhance their aerodynamic performance below the rated speed while also enduring fatigue and severe loads above it [19]. Small aerodynamic and structural modifications in wind turbines can help reach this goal by increasing the AEP and lowering expenses. In compared to those involving larger hub heights and rotor diameters, the latter changes have a comparatively modest potential.
4.2.2 Improvements

In terms of high costs of wind turbine blades, many producers are considering using recyclable blades such as the plastic blades shown as Fig. 8. instead of the metal ones. The wind industry is thriving for the progress and commercialization of substitute technologies in order to give other alternatives for end-of-life goods to all composite-using industries. As a result, the wind sector is involved in several R&D initiatives.

The European Wind Energy Technology Platform published a blade recycling booklet with research and development suggestions for policymakers, which are mirrored in the tables below.

![Recyclable plastic blades](image)

**Fig. 6 Recyclable plastic blades[21]**

| No. | Detailed procedures |
|-----|---------------------|
| 1.  | Fund for research study that compares the economic aspect of new recycling innovative technologies, including market barriers. |
| 2.  | Promote proliferation of treatment ways and increase the popularity around Europe |
| 3.  | Set up large-scale demonstration demo to industrialize and figure out recycling solutions for turbine blades. |
| 4.  | Provide fund to investigate and support new processes that utilize recyclable materials from blades in other fields. |
| 5.  | Establish a European cross-sectorial platform in order to share practices in recycling. |
| 6.  | Promote reinforcement of value chain for recycling of waste from various sectors. |

![Installed wind capacity](image)

**Fig. 5. Installed wind capacity in the EU from 2000 to 2014 and EWEA targets for 2020 and 2030[20]**
Table 4 Design approach: Development of new materials for future blades [23]

| No. | Detailed procedures |
|-----|---------------------|
| 1.  | Provide funding for the development of newly-found high-quality materials. |
| 2.  | Demonstrate to test and integrate newly-developed sustainable materials onto wind turbine blades. |
| 3.  | Fund research of materials that enable more outstanding blade designs. |
| 4.  | Establish a full-scale demonstrator of the next generation wind turbine using materials that reduce maintenance fee and increase sustainability. |
| 5.  | Encourage designers to innovate and reuse during the process of structural design and materials selection. |

5. Conclusion

According to the results and discussions presented above, the conclusions are obtained as below:

Shanghai Tower, as a green-energy building, has various sustainable strategies especially wind turbines which utilize green energy with a large capacity, a wide availability and a long expiration date are efficient in energy using and re-generating.

Compared with other buildings that utilize wind energy, wind turbines all play a unique and significant role according to some dimensions such as location, cost of turbines, efficiency and climate in saving energy.

Wind turbines are repetitively innovating to reduce the cost of production such as using recyclable and cheap blades and to increase the efficiency.

References

[1] Windeurope.org. 2021. [online] Available at: <https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf>.
[2] Windeurope.org. 2021. [online] Available at: <https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf>.
[3] Evans, Annette; Strezov, Vladimir; Evans, Tim (June 2009). "Assessment of sustainability indicators for renewable energy technologies". Renewable and Sustainable Energy Reviews. 13 (5): 1082–1088.
[4] Paul Gipe (7 May 2014). "News & Articles on Household-Size (Small) Wind Turbines". Windworks.org.
[5] Stathopoulos T, Alrawashdeh H, Al-Quraan A, Blocken B, Dilimulati A, Parascivioiu M, et al. Urban wind energy: Some views on potential and challenges. Journal of Wind Engineering and Industrial Aerodynamics. 2018;179: 146-157.
[6] Fenix.tecnico.ulisboa.pt. 2021. [online] Available at: <https://fenix.tecnico.ulisboa.pt/downloadFile/281870113702791/Thesis.pdf>.
[7] Smith RF, Killa S. Bahrain world trade Center (BWTC): The first largescale integration of wind turbines in a 14 Renewable Energy - Resources, Challenges and Applications building.
[8] Ben Dymock.,Structural Design of Tall and Special Buildings. 2007;16(4): 429-439.
[9] Bogle I. Integrating Wind Turbines in Tall Buildings. CTBUH Journal [Internet]. 2011 [cited: 01 September 2019]; 2011(IV):30-34
[10] Li QS, Shu ZR, Chen FB. Performance assessment of tall building-integrated wind turbines for power generation. Applied Energy. 2016;165:777-788
[11] Oakland, W. H. (1987). Theory of public goods. In Handbook of public economics (Vol. 2, pp. 485-535). Elsevier.
[12] Longman Dictionary of Contemporary English. Archived from the original on 13 February 2018. Retrieved 9 May 2018.
[13] Gignac, J., 2021. Wind Turbine Blades Don’t Have To End Up In Landfills. [online] The Equation. Available at: <https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling/>.
[14] U. S. Department of Energy., 2013. Wind Power in America's Future. Dover Publications.
[15] Gignac, J., 2021. Wind Turbine Blades Don’t Have To End Up In Landfills. [online] The Equation. Available at: <https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling/>.
[16] Siemens 6.0 MW offshore wind turbine. http://www.energy.siemens.com/hq/pool/hq/powergeneration/renewables/windpower/6_MW_Brochure_Jan.2012. pdf
[17] Enercon (Website, tip design). http://www.enercon.de/p/downloads/EN_Eng_TandS_0710.pdf.
[18] EWEA (European Wind Energy Association). Wind in power – 2014 European statistics, Brussels: EWEA; 2015
[19] Capuzzi, M., Pirrera, A. and Weaver, P., 2021. A novel adaptive blade concept for large-scale wind turbines. Part I: Aeroelastic behaviour.
[20] Windeurope.org. 2021. [online] Available at: <https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf>.
[21] Fenix.tecnico.ulisboa.pt. 2021. [online] Available at: <https://fenix.tecnico.ulisboa.pt/downloadFile/281870113702791/Thesis.pdf>.
[22] ETIPWind (2019) How wind is going circular: blade recycling. Available online at https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf
[23] SUSCHEM (2019) Strategic Innovation and Research Agenda: Innovation Priorities for EU and Global Challenges. Available online at http://www.suschem.org/publications