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Wind Turbine Integration to Tall Buildings

Ilker Karadag and Izzet Yuksek

Abstract

Having a far distance from the ground levels exposed to turbulent wind conditions, tall buildings have the potential of generating wind energy. However, there are many challenges to incorporating wind generation into urban areas. These include planning issues besides visual impacts. So, as to integration, there is a need for a combined approach that considers wind energy harvesting besides these issues. At this point, a multidisciplinary approach can fill the gap between the architectural design and the wind engineering processes. Based on this approach, this chapter presents design strategies from the literature to integrate wind energy to tall buildings using computational fluid dynamics (CFD) simulation. It is intended to guide further researches on wind energy and consequently to contribute to the environmental quality of urban areas and sustainable development of the cities.

Keywords: building-integrated wind turbines, building aerodynamics, wind energy, computational fluid dynamics (CFD), wind efficient design

1. Introduction

Tall buildings are common forms of urban settlements, and they involve too many functions with plenty of spaces on a low base area with the advantages of having too many floors. Besides, they have important impacts on local wind characteristics around the near-field urban area. Strong winds are usually acceler-ated at the roof level within the urban environment around tall buildings, due to particular aerodynamic configurations generally associated with this type of build-ings. When it comes to a simple rectangular tall building, it is the flow separated from the windward side edge of the roof which led to shear layers with increasing wind velocities [1]. This flow may result in high wind velocities and turbulent wind conditions. For wind energy harvesting, higher wind speeds are mostly desired to a limit velocity, but higher turbulence levels are mostly not intended since the fluc-tuations in wind speed reduce the energy extracted from the wind turbine. Besides the turbulence, intensity increases the fatigue loads on the wind turbine. So, the assessment of wind flow around the building is very important for a thorough understanding of the flow characteristics.

Assessment of the wind flow around the buildings is conducted with both experimental and numerical methods. The experimental method ensures reliable information as to airflow in and around buildings; however, the available data is mostly limited due to the expensive experimental processes which require too many

sensor locations for high-resolution data. Besides, the approach is not practical for an architect or engineer trying to determine the optimal location of the wind turbine. The parametric tools embodied in CFD codes make it very easy to try different geometrical forms or a principal form with different angle of attacks. However, the experimental method may extend the time consumed on optimization since it requires re-configuration of the experimental setup. In addition, wind tunnel testing has some limitations which CFD overcomes. As stated in [2], CFD does not have scaling problems and similarity constraints since simulations can be conducted at full scale.

The literature as to wind energy harvesting mostly constitutes of the planning and design issues of the wind farms; unfortunately, rare studies have been conducted on wind turbine integration to tall buildings located in dense urban areas. In this chapter, beyond describing wind energy systems of a number of tall buildings, a design methodology from architectural and engineering perspectives is proposed. Within this study, CFD assessment of the wind conditions around a number of tall buildings is given with the estimated amount of the energy generated with the wind turbine. First, the wind turbine integration strategy of these cases is described from the architectural design perspective. Then, brief information about these buildings and their surroundings are explained. Following that, the results of the numerical simulations are given and conclusions are derived.

2. Methodology for the assessment of wind energy potential in an urban area

Wind energy potential assessment mostly starts with climate data analysis. So, a thorough understanding of the local climate which is based on a detailed analysis of long-term (at least 30 years) meteorological data is required [3]. After this data has been achieved, a correlation between terrain roughness of the meteorological station site and the examined urban area is set. For this aim, aerodynamic information of the site and the building are investigated.

Mostly, meteorological stations are located on open areas which have aerodynamic roughness length of $y0 = 0.003$ m, where wind speed is measured at 10 m height and the mean wind speed values are taken on an hourly basis. To transfer this data to the site examined, a logarithmic wind speed profile can be used since it provides mean wind speed distribution with height taking aerodynamic roughness lengths into consideration. These data are used as the inlet boundary condition for CFD simulation to achieve wind speed velocities at different heights from the ground.

The result of the combination of weather data and the aerodynamic information is used in the CFD simulation as an input to assess wind velocities and turbulence conditions around the building accurately. At this point, it is required to use a convenient mathematical model. The turbulent flow within urban or industrial environments is in general modeled by the Navier-Stokes Equations [4]. In detail, as being an economical solution, steady-state 3D Reynolds-averaged Navier-Stokes (RANS) equations are used mostly. On the other hand, large eddy simulation (LES) undeniably has the potential to provide more accurate and more reliable results than simulations based on the Reynolds-averaged Navier-Stokes (RANS) approach. However, LES entails a higher simulation complexity and a much higher computational cost. The equations in these turbulence models are solved with commercial or open-source CFD codes. The most important point for the architect or engineer who will run the simulation is to comply with the CFD guidelines. The best practices largely advised in the literature are the Architectural Institute of Japan (AIJ) CFD

guidelines [5] and the COST 732 Best Practice Guideline for CFD [4] simulation of flows in the urban environment. In both of these guidelines, the grid dependence of the solution is advised to be checked. It should be confirmed that the prediction result does not change significantly with different grid systems. In the best practice guidelines, it is indicated that at least three systematically and substantially refined grids should be used so that the ratio of cells for two consecutive grids should be at least 3.4 [4]. The value of 3.4 means finer grids with 1.5 times the grid number in three dimensions. As a practice, to improve the computational mesh in the necessary regions where solid geometry and fluid field contacts and separation of flow occur is advised.

Criteria for convergence are another important parameter of numerical simulations. For this purpose, as indicated in the Architectural Institute of Japan (AIJ) CFD guidelines, it is important to confirm that the solution does not change by monitoring the variables on specified points or by overlapping the contours among calculation results at different calculation steps [5].

A large computational model needs to be created, and different zones with respect to aerodynamic roughness lengths should be arranged. For instance, in the wind comfort study [6], the nearby area around the analyzed tall building is modeled explicitly (zone 2), and the far field containing an urban area with tall buildings is implicitly modeled (zone 3) using aerodynamic roughness length of y0 = 2 m (**Figure 1a**). While the whole domain area is 1400 m by 2600 m, the area with explicitly modeled buildings was 400 m by 400 m. An upstream domain extension of 5H and a downstream domain extension of 15H were left in the domain as advised in the guidelines [4]. The site of interest in the center of the computational domain is modeled in detail (zone 1). This zone includes smaller computational cells than the zone at the extension of the explicitly modeled region as illustrated in **Figure 1b**. A high-quality and high-resolution grid that consists of only cut cells is developed to gain fast convergence.

Once the meshing process was complete, boundary conditions were determined (inlet, outlet, etc.), the appropriate turbulence model and wind velocity profile were selected, and CFD simulations are run. Then the analysis results were examined in detail in a post-processing software, and the necessary conclusions are derived. At the last stage, an appropriate wind turbine model was chosen, and design proposals were developed to integrate the chosen wind turbine system to the case building. Then, the amount of energy that can be produced with the proposed system is calculated. In predicting power output from a wind turbine, a common approach in the literature is to take the power curve provided by the manufacturer
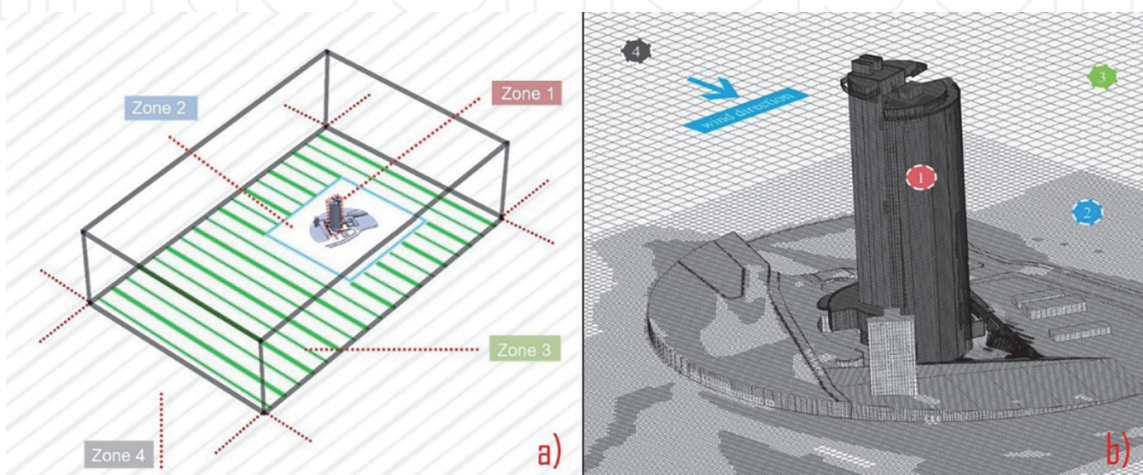

Figure 1.
Computational domain with zone management (a) and mesh refinement levels of different zones (b) [6].

and combine it with a wind speed frequency distribution function, such as a Weibull distribution or Rayleigh distribution, and integrating across the range of wind speeds in which generation takes place.

3. Building-integrated wind turbines

In most cases, the energy of the wind is gained through wind farms to supply economical clean power with a renewable energy source. However, the land is restricted in urban and suburban regions, and this is regarded to be a significant limitation on large-scale wind turbine installation. An alternative choice is to use building-integrated wind energy systems [7]. Wind energy installations near buildings have received far less attention [8–10]. The idea of the on-site generation of micro-wind energy is significant because the energy is being generated near where it is needed. In [8], the authors distinguish between three categories of possibilities for integration of wind energy generation systems into urban environments: (1) locating stand-alone wind turbines in urban locations, (2) retrofitting wind turbines onto existing buildings, and (3) full integration of wind turbines together with

Study	Data collection approach	Site model (concerned building)	Simulated flow	Key findings
Lu and Sun [11]	CFD	Lee Shau Kee building (97.4 × 38.7 × 69.9 m) (L, W, H). Kowloon, Hong Kong	RNG k-ε	Minimum height of 1.4 m above the roof is recommended for turbine installations. Building proximity effects can increase the wind power significantly (1.5–5.5 times) at 4 m above the building roof
Tabrizi et al. [12]	CFD field measurements from one location	Bunnings warehouse H ¼ 8.4 m. Port-Kennedy, Western Australia. The radius of the surrounding: 200 m	Steady RANS with k-ε. Computational domain (H): 0.2 km	A small HAWT is recommended to be installed **in the middle of the roof**
Al-Quraan et al. [13]	Wind tunnel experiments	EV Building (76 m high) Equiterre building (23 m high) Montreal, Quebec, Canada	Homogeneous terrain	Accuracy of wind tunnel results depends on the upstream terrain
Yang et al. [14]	Field measurements from two locations. CFD field measurements from 10 locations	The building has dimensions of 68.9 × 62.5 × 33.5 m (L, W, H). Central metropolitan Taipei, Taiwan	Nonhomogeneous terrain standard κ-ε. RNG κ-ε. Realizable κ-ε. Computational domain (L, W, H) 16 × 8 × 0.3 km	Recommend increasing the hub height and install microturbines on the windward side of the building. Curved roof edges increase the power density

Table 1.
Examples of recent studies for actual site locations [7].

architectural form. Categories 2 and 3 are often referred to as building-integrated wind turbines (BIWT). Within the scope of this chapter, category 1 is excluded since to position a stand-alone wind turbine in an urban area is not a form of the building-integrated wind energy system.

As to category 2, there are very few research studies on wind power utilization over existing buildings in urban areas. **Table 1** shows examples of recent actual building studies conducted by means of field measurements, wind tunnel experimentation, and CFD. Details of the considered models and test descriptions, as well as key findings, are provided in the table [7].

Category 3 includes aerodynamically designed building forms for full integration of wind turbines. As is well known, in urban environments the mean wind speed is lower than the one in rural areas. The wind speed in urban areas, however, is significantly high at specific locations near to tall buildings. It can be described as micro-generation to produce urban wind energy such as that generated by small-scale wind turbines installed on or around tall buildings. As previously stated, a main benefit of such systems is that the energy generated can be consumed straight at the assembly site, and the building's user obtains renewable additional energy. The use of wind power for distributed generation in tall buildings is becoming increasingly appealing. Since the theoretically produced energy is a function of the wind speed cube, a tiny rise in wind speed can lead to a significant difference in the generation of wind power. It is therefore of concern to correctly evaluate the wind resource in an urban area and try to improve it through different aerodynamic methods. This is opposite to the traditional strategy of wind engineering where the priority is on decreasing wind speeds and pressures in order to minimize wind-induced lateral loads to secure structural system.

When it comes to building-integrated wind turbines, the Bahrain World Trade Center, the Strata Tower in London, and the Pearl River Tower in Guangzhou, China, are very important examples and pioneers in this field. Therefore, their wind turbine integration strategies are given in the following subsections correspondingly to depict the interdisciplinary approach between architecture and wind engineering.

3.1 Bahrain world trade Center

The Bahrain World Trade Center is the focus of a master scheme to refurbish an existing hotel and shopping mall on a distinguished location overlooking the Arabian Gulf in Manama, Bahrain's central business district. The two 50-story sail-shaped office towers taper to 240 m high, supporting three horizontal-axis wind turbines with a diameter of 29 m (**Figure 2**). The elliptical plan forms and sail-like profiles function as airfoils, funneling the onshore breeze between them and producing a negative pressure behind them, thus accelerating the wind speed between the two towers. Vertically, tower form is also a consequence of the airflow dynamics. Their airfoil sections are decreasing in size as they taper upwards [15]. Combined with the increasing onshore breeze velocity at increasing heights, this impact produces a near-equal wind velocity regime on each of the three turbines. Understanding and using this phenomenon is one of the main variables that enabled the practical implementation of wind turbine systems into a design of a tall building. Wind tunnel experimentation verified how the towers' forms and spatial relationship reshape the airflow, forming a "S"-like flow whereby the center of the wind stream stays almost perpendicular to the turbine within a 45° wind azimuth, either side of the central axis. This improves the power generation capacity of the turbines while at the same time decreasing fatigue on the blades to acceptable levels during wind skewing across the blades [15].
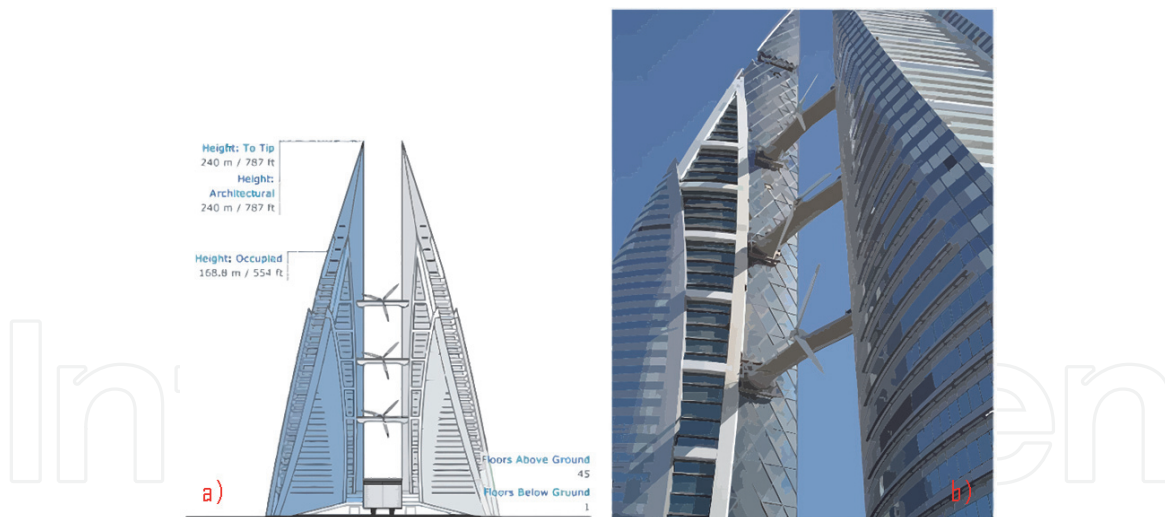
Figure 2.
Wind turbines integrated in between the Bahrain world trade Center towers; elevation view (a) and a general view from the pedestrian level (b) [7].

The horizontal-axis wind turbines placed between the towers are normally pole-mounted and rotate to match the wind direction to maximize the energy output. Therefore, it is very hard to place such turbines to tall buildings located in a climate with variable direction wind conditions. Most architectural projects deploying building-integrated, horizontal-axis turbines, as in the case of the Bahrain World Trade Center, implement the concept of a fixed turbine. It seems more useful to deploy vertical-axis wind turbines since they advantage from the benefit of being fully omnidirectional. However, large-scale verified vertical-axis turbines were not accessible for building applications at the moment of design development for this building. The fixed horizontal turbine suffers the disadvantage of being able to function only with wind from a restricted azimuth range, if issues with blade deflections and stress are to be prevented due to excessive skew flow. The form of the towers was designed from the beginning of this project to catch the upcoming wind and channel it between the towers. Comprehensive wind tunnel testing latterly validated by CFD, illustrations of which are displayed in **Figure 3**, showed that the upcoming wind is in fact deflected by the towers in the form of a S-shaped streamline that runs through the space between the towers at an angle within the wind skew tolerance of the wind turbine. Engineering projections indicate that the turbine will be capable of operating between 270° and 360° of wind directions, but, to be on the safe side, turbine calculations and initial operating regimes are set on a more limited range between 285° and 345°. The turbine will automatically follow a "standstill" mode in all wind directions outside this range. It is no coincidence that the buildings are oriented towards the prevailing wind which is extremely dominant. The funneling of the towers amplifies the wind speed up to 30% at the turbine position. Together with the form of the towers (bigger impact at ground) and the velocity profile of the wind (lowest at ground), this amplification has the impact of balancing the energy output to the extent that the upper and lower turbines generate 109 and 93% compared to 100% for the turbine at the middle [15].

3.2 Strata tower, London

Strata Tower is a tall residential building in central London (**Figure 4**) which was the tallest one when it was constructed in 2005. The architects in the design team of the tower examined the effectiveness of several alternatives to achieve the most suitable lean, clean, and green option. As a residential tower, general energy
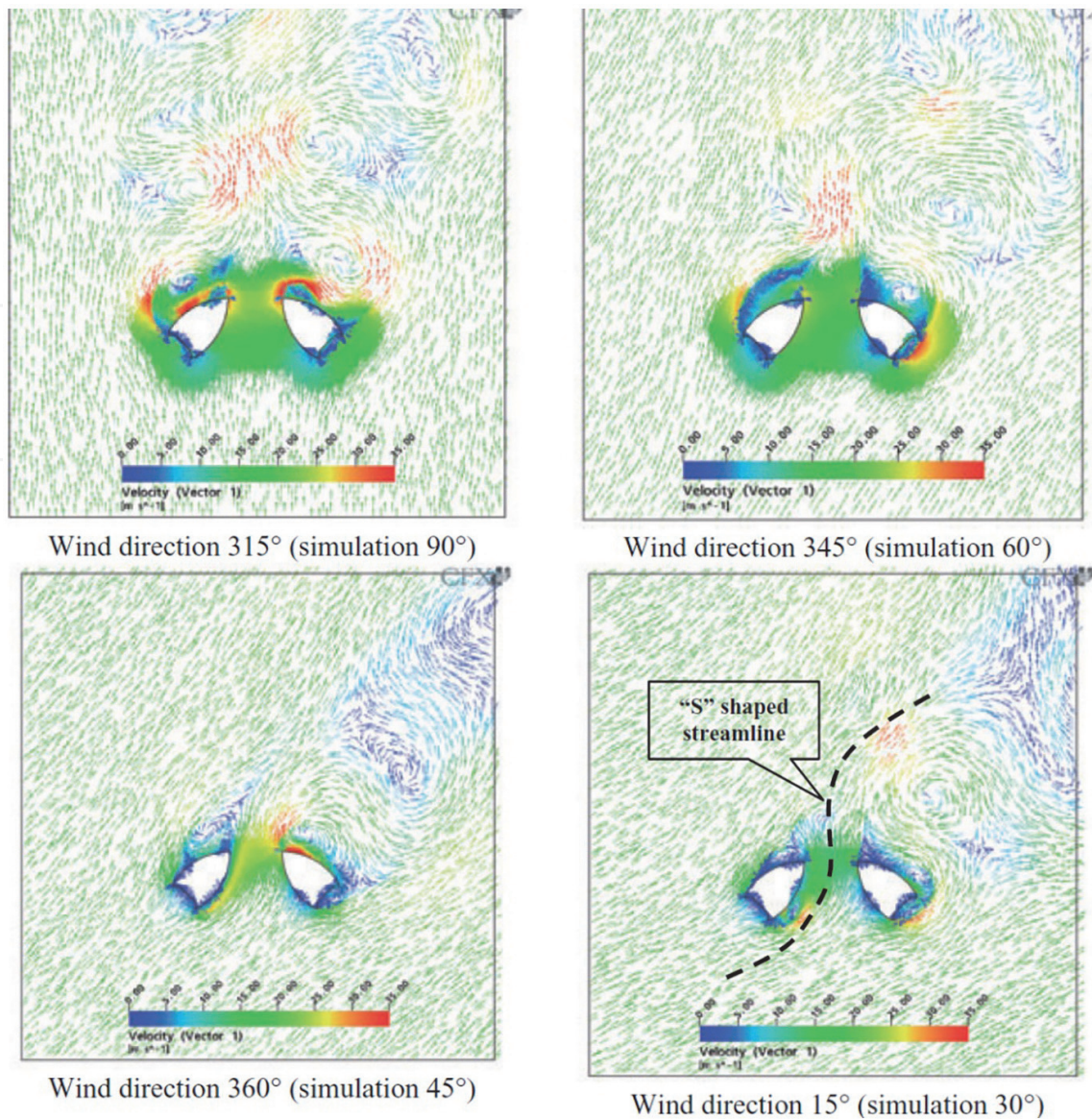
Figure 3.
CFD images by Ramboll, showing airflow patterns near towers, simulated at the level of the top turbine for different free, undisturbed wind incidence angles with respect to an "x" axis (i.e., horizontal line connecting towers).

consumption loads are significantly lower than similar retail or commercial office development, and thus the chance of achieving the required percentage of renewable energy on-site is comparably more possible [16].

The architects initially did not plan to design a building with wind turbines; however, they came through an extensive sequence of design alternatives, assessing each renewable option on their own merits and in the context of the site. For instance, ground source water solutions were thought, but the site's harsh limitations meant that the water pools would not be far enough from each other to remain feasible. Moreover, energy savings would be reduced by pumping through the entire building's height. Photovoltaic option was also thought, but the corresponding technology available at that time (2005) would have led to 80% of the southern facade being enclosed with photovoltaic (PV) cells, this too far compromising the amount of glazing needed to provide sufficient daylight into the spaces and views from the apartments. Commercial problems prevailing in 2005 would also have rendered this choice too costly, added to which photovoltaics have a life-span of about 15 years and must be kept carefully clean. This alternative would have had a major impact on service fees. Photovoltaic integration would also negatively affect the facade's cost per square meter. Similarly, biomass boiler option

Figure 4.
Strata SE1, London © will Pryce.

Figure 5.
Orientation study based on prevailing wind direction; site plan sketch with wind rose (a) and an illustration of airflow distribution around the tower (b) © BFLS.

was also considered, but the ongoing energy costs related with transporting and delivering the fuel, and the availability issues of such fuel, along with the need for a 150-m (492-foot) flue operating the entire building height, meant that this option was marked down. As such, a number of options inevitably lead to a wind energy-based solution [16].

The wind rose for London has a mainly south-westerly axis in summertime; therefore the curved facade was appropriately oriented to catch wind from this prevailing direction (**Figure 5**).

Once considering the introduction of wind turbines as a site-based renewable energy option, funneling and guiding the wind is a main design element that can considerably improve the wind turbines' prospective operational production. In fact, the design solution for Strata Tower is another iteration of that taken for the Bahrain World Trade Center also using the concepts of a "Venturi" to direct wind flow, but differently in between the two towers (**Figure 6**). There are also other significant distinctions—particularly the scale of the project, the reality that the three turbines are installed externally on linking bridges and the hot-humid site which required full air conditioning to help tackle any negative acoustic effects [16].
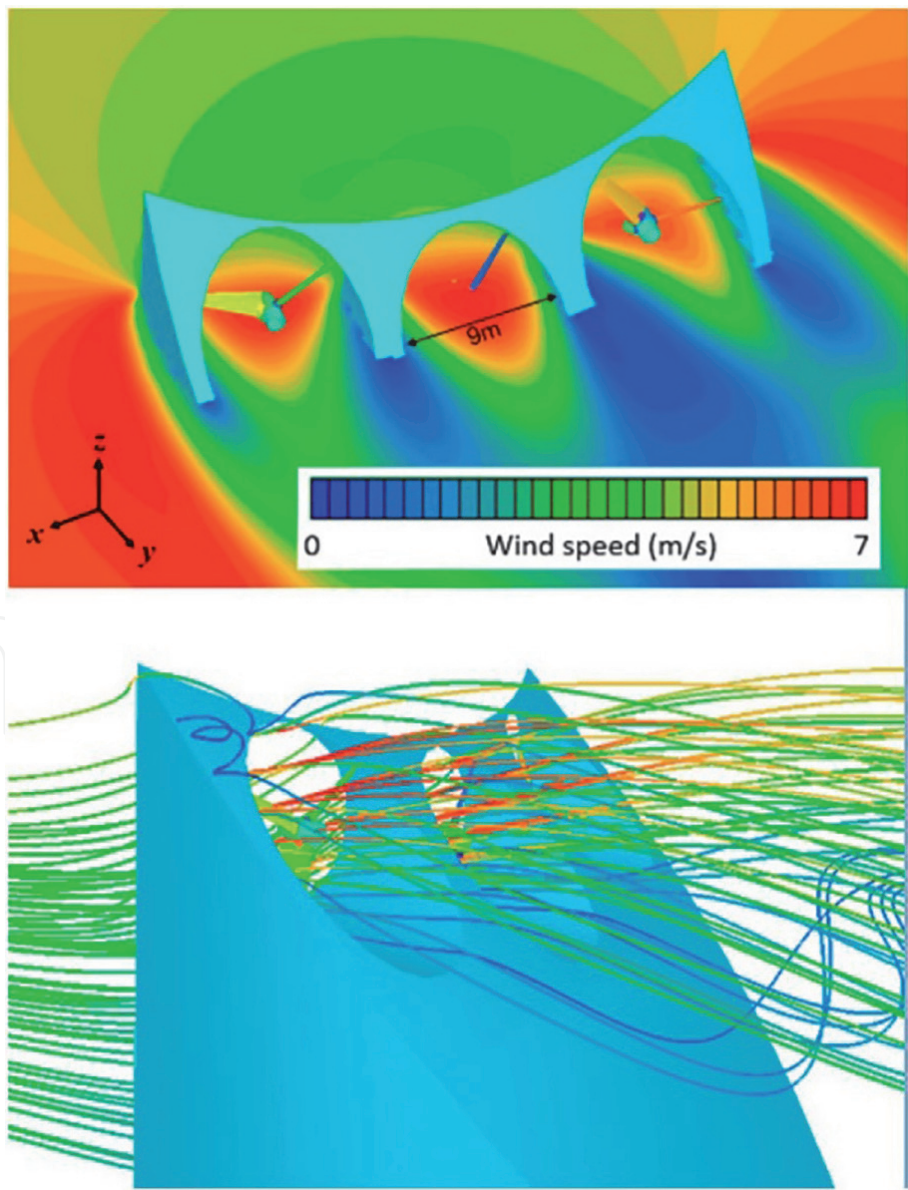

Figure 6.
Strata tower: Airflow patterns around the wind turbines [13].
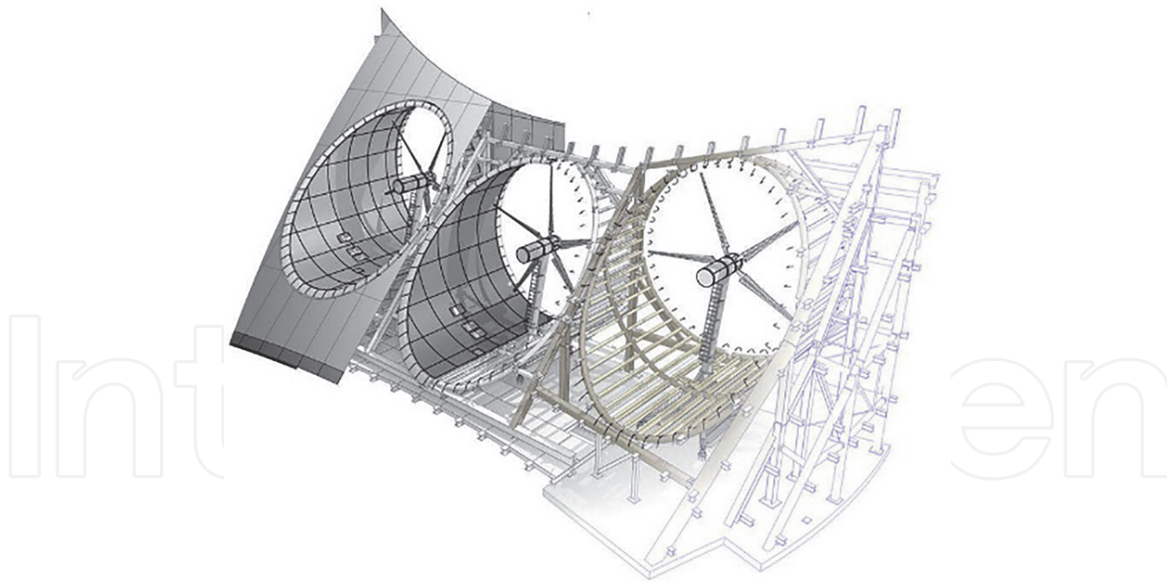
Figure 7.
Strata SE1's turbine deck © BFLS.

The turbines do produce noise, like any other typically roof-mounted piece of plant. The Venturi-like enclosures, however, effectively concentrate the noise away from the flats instantly below into two sound cones. All measures to regulate and minimize noise generation have been discussed, and these measures have actively improved efficiency in some cases. Within the Venturi-like enclosures, careful placement of the turbines on the plan has a significant impact both in general performance and in regulating noise output. Furthermore, in contrast to the more standard three-bladed turbine used on larger versions, opting for a five-bladed turbine provided further noise decreases (**Figure 7**) [16].

To sum up, the energy output needed for building-integrated wind turbine solution is completely case dependent. The overall production requirement for Strata Tower is 50 megawatt hours of electricity per year in the case of the design load requirement. This is about 8% of the complete energy consumption of the building.

3.3 Pearl River tower, Guangzhou, China

A typical instance of BIWTs and building-integrated photovoltaic (BIPV) in Asia is the Pearl River Tower in Guangzhou, China. It is a 309-m-high 71-story building completed in 2011 and designed to increase velocity through the nozzle effect by making flow openings in the building (**Figure 8**) [17]. Inside the building are mounted a total of four 8-m-high vertical-axis wind turbines, each at the inner opening on the left and right sides [18]. There are four openings in the Pearl River Tower adjacent to the two-level mechanical floors (Floor 24, from 104 to 111.3 m, and Floor 50, from 205 to 212.7 m), with a bell-mouthed form at both ends of each opening. Opening-1 and opening-2 are at the lower elevation, with opening-1 being placed on the west and opening-2 on the east. Likewise, opening-3 and opening-4 are located in pairs next to the upper mechanical floor (**Figure 9**). The Pearl River Tower's orientation is parallel to Guangzhou's prevailing wind direction, which seeks to maximize turbine power output. Furthermore, the Pearl River Tower is aerodynamically formed with a concave wall on the southern surface and a convex wall on the northern surface that enables better intensification and funneling of the wind through the openings (**Figure 9**).
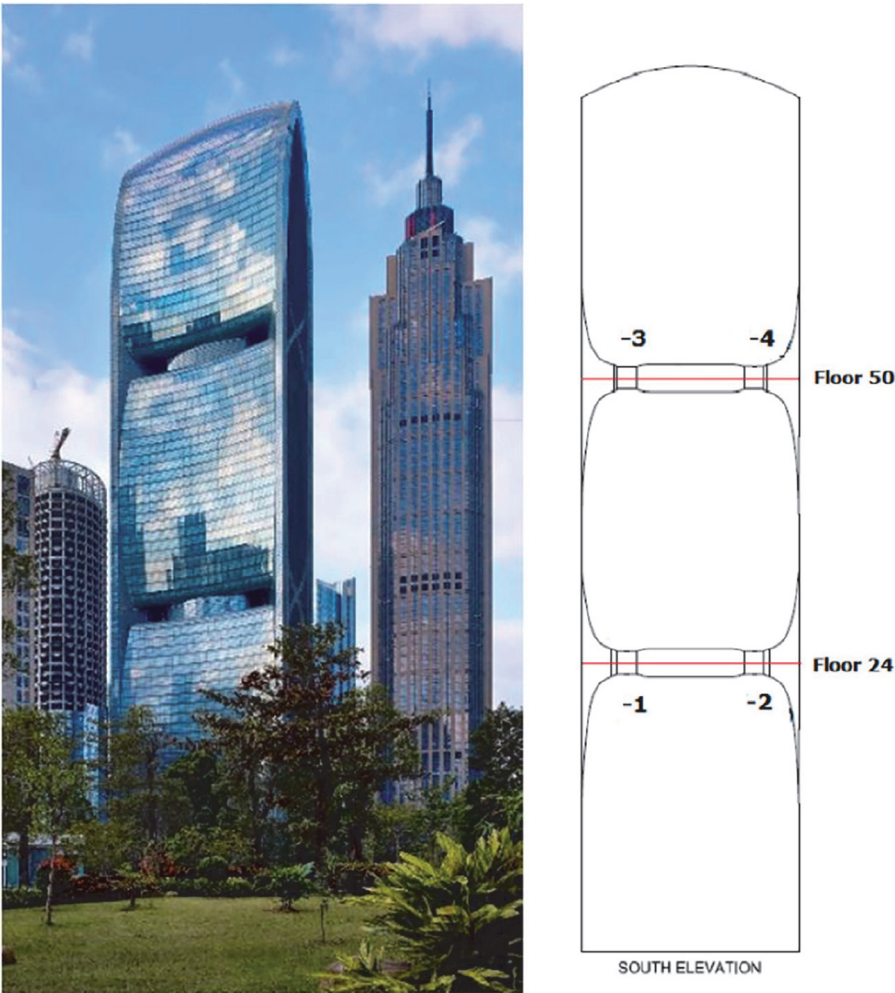
Figure 8.
Pearl River tower: Positions of the openings [18].

A helix-shaped vertical-axis wind turbine is installed on the floors inside each of the four openings (**Figure 10**). These turbines have an 8-kW rated power with 25 m/s rated speed. Such a turbine is designed to generate electricity when there is a
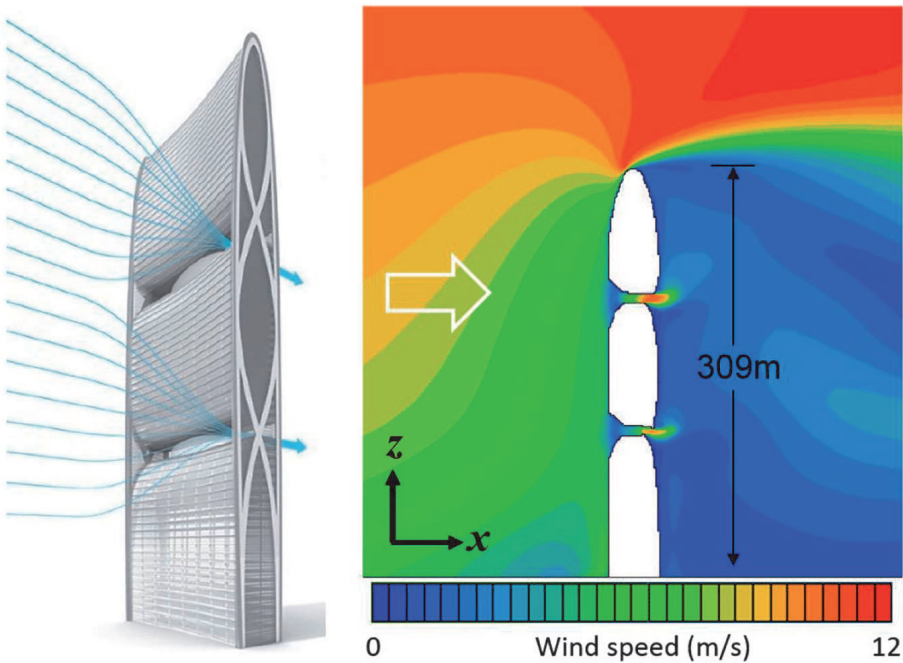

Figure 9.
Pearl River tower: Airflow patterns around the wind turbines [17].

a)   b)
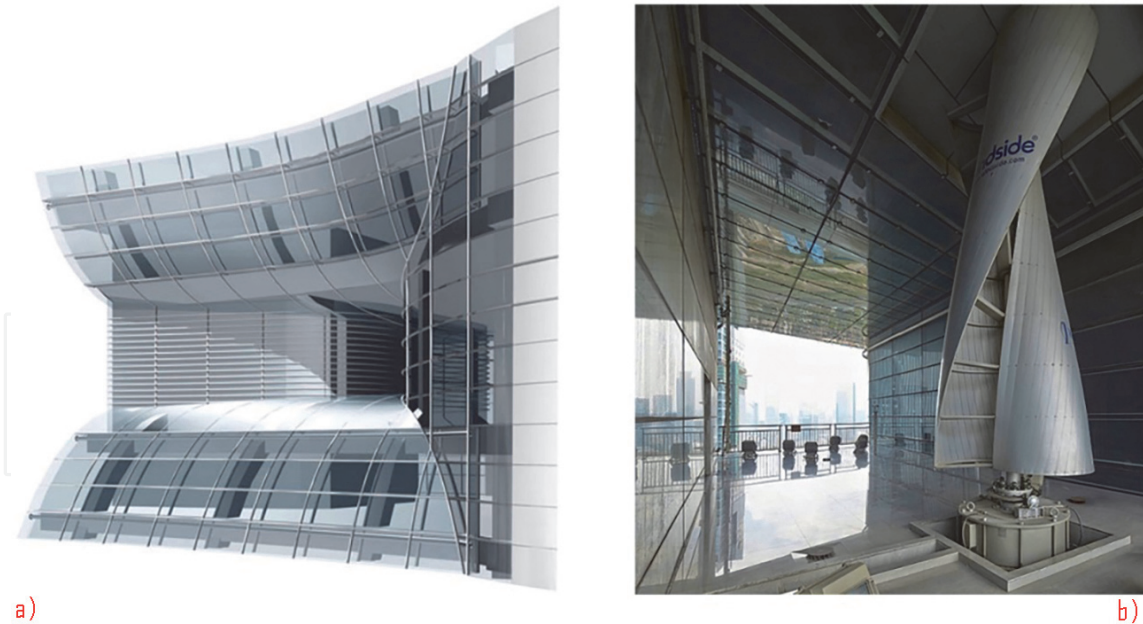
Figure 10.
Pearl River tower; aerodynamic configuration on the facade (a) and the detailed view of the helix-shaped vertical-axis wind turbine (b) © SOM.

wind velocity range of 2.7–40 m/s. This turbine's swept area is about 10 square meters. It is worth noting that while vertical-axis wind turbines (VAWTs) may usually have lower energy efficiency than widely used horizontal-axis wind turbines (HAWTs), they appear to be particularly favored in urban wind energy development. Due to the lower tip velocity, the noise effect of VAWTs is relatively low, and VAWTs in urban settings can resist high turbulence. Most remarkably, VAWTs are omnidirectional, so wind and turbulence can be extracted more efficiently from all directions with reduced loss of effectiveness. This is particularly appealing for the installation of wind turbines in urban settings where wind direction is extremely variable owing to adjacent buildings and structures' interference effects [18].

It has been shown through the results of the study [18] that the design of Pearl River Tower makes a good use of the aerodynamic features of the super-tall building, which can result in a significant enhancement of wind speed in the four openings. However, due to the mostly weak wind condition in Guangzhou, the estimated power outputs from the four building-integrated wind turbines are relatively low. Nevertheless, it is expected that the integration of wind turbines into tall buildings will have a remarkable potential to contribute a significant part of the energy requirement of tall buildings in urban areas having high wind velocities.

4. Conclusions and further research

Urban wind energy is the use of wind energy technology in urban and suburban built environment applications. This chapter offers only some opinions on the progress made in the evaluation of wind resources in urban regions, the use of appropriate wind turbines to enhance the utilization of these resources, and the important role of architectural and urban aerodynamics in designing buildings accordingly to increase wind energy output. It is not meant to be comprehensive, but rather it is preferred from the point of view of architects in the context of buildings and cities to provide some perspectives on the abovementioned subjects. It is indicated that while important progress has been made in the field, there is a

strong need for additional comprehensive research, especially in the area of urban aerodynamics and wind resource assessment, in order to optimize the generation and utilization of urban wind energy.

It is also concluded that wind conditions can change considerably depending on the building form. Therefore, CFD simulation is required to analyze the effect of the form of the building, accurately. Aerodynamically designing the building leads to improvement in power density and may potentially result in large changes in spatial variability. On the other hand, preliminary comprehensive studies as to the wind resource assessment are very important for the efficiency of a wind turbine system; otherwise, it would not be possible to benefit from this type of system, sufficiently. It is also derived that to accurately position the wind turbine, detailed analyses should be conducted on determining highly turbulent flow areas which can reduce the amount of energy yielded from the wind turbine.

Moreover, it should be noted that research on wind turbine integration to buildings has been mostly conducted by wind engineers. Wind engineering solutions are very crucial in developing building-integrated wind energy systems. The advanced analysis methods that combined with CFD simulations give important aerodynamic information about the building and the nearby field. However, when it comes to proposing aerodynamic form optimization based on the data produced, the solutions should not be free of architectural context, since a very basic change even affects the form of the building. At this point, cooperation with architects is significant when integrating wind energy systems to buildings, since an interdisciplinary approach may fill the gap between the wind engineering solutions and architectural design processes. In collective research, the effect of several factors may be assessed; consequently, this may widen the perspective of the contribution of wind engineering to the improvement of urban wind energy strategies.

The environmental benefits of using a sustainable energy system can be examined, further. For instance, it is very probable to see that using wind turbines leads to a significant decrease in carbon emissions. For this purpose, the elimination of carbon emissions which would be released for the equivalent energy yielded from fossil fuels can be calculated in further studies.

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