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Urban wind energy: Some views on potential and challenges

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ABSTRACT

Urban wind energy consists of the utilization of wind energy technology in applications to the urban and suburban built environment. The paper provides some views on the progress made recently in the areas of wind resource assessment in the urban habitat; the utilization of suitable wind turbines for enhancing the exploitation of these resources; and the significant role of knowledge of building and urban aerodynamics for an optimal arrangement of interfacing augmented wind with its extraction mechanisms. The paper is not intended to be exhaustive, rather its purpose is to provide some views on the above-mentioned topics from the viewpoint of wind engineering and industrial aerodynamics in the context of buildings and cities.

1. Introduction

Wind has been used as an energy source since ages. The power of wind was used to sail ships, to mill grain and to pump water. Wind power is currently considered as one of the most viable alternatives to fossil fuels because it is renewable, widely distributed and clean with no greenhouse gas emissions produced during operation. In most cases, the energy of the wind is harnessed through large wind-power plants to supply economical clean power. However, in urban and suburban areas, the land is limited and this is considered a major restriction for the installation of large plants. An alternative option is to resort to building-integrated wind energy systems. Much less attention has been given to wind energy installations near buildings (Campbell and Stankovic, 2001; Beller, 2009; Sharpe and Proven, 2010). The concept of on-site micro wind energy generation is interesting because the energy is then produced close to the location where it is required. Campbell and Stankovic (2001) distinguish between three categories of possibilities for integration of wind energy generation systems into urban environments: (1) siting stand-alone wind turbines in urban locations; (2) retrofitting wind turbines onto existing buildings; and (3) full integration of wind turbines together with architectural form. Category 2 and 3 are often referred to as “building-integrated wind turbines”.

Most of the early actual installations of wind turbines in urban contexts have been established in category 1 (Sharpe and Proven, 2010). They were generally conventional Horizontal Axis Wind Turbines (HAWT), intended to be mounted on the top of masts in fairly open areas. The performance of these systems has been reported to be very site-specific (Peacock et al., 2008) and in many cases the proximity to buildings has decreased the performance (e.g. Mithraratne, 2009). Campbell and Stankovic (2001), Mertens (2006), Lu and Ip (2009) and Balduzzi et al. (2012a), among others, investigated the potential to take advantage of augmented airflow around buildings, addressing both category 2 and category 3 applications. Category 2 includes traditional or newly developed wind turbines that can be fitted onto either existing buildings or new buildings, without the need for specially modifying the building form. Examples are the roof-mounted ducted wind turbine by Grant et al. (2008), the modern adaptation to the Sistan wind energy mill by Müller et al. (2009), the Crossflex design by Sharpe and Proven (2010), which is a new development of a Darrieus turbine form, and the 3-in-1 wind–solar and rain water harvester with power-augmentation-guide-vane (PAGV) for a Vertical Axis Wind Turbine (VAWT) by Chong et al. (2011). Finally, category 3 consists of

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modified building forms for full integration of wind turbines. Well-known examples of buildings designed for integration of large-scale wind turbines are the Bahrain World Trade Center (2011), the Strata Tower in London (2011) and the Pearl River Tower in Guangzhou, China (2011). Fig. 1 shows the Bahrain World Trade Center Towers, where three wind turbines facing the prevailing wind direction are suspended on bridges between the two towers of the center.

As it is well known, the mean wind speed in urban environments is lower than the wind speed in rural areas. However, the wind speed in urban environments at particular locations close to tall buildings is dramatically high. Urban wind energy generation such as that produced by small-scale wind turbines installed on or around buildings can be defined as micro-generation. A key advantage of such installations is that the produced energy can be consumed directly at the site of installation and the owner of the building obtains free extra energy source. There is a growing interest in the use of wind power in buildings for distributed generation. Since the theoretically generated power is a function of the cube of the wind speed, a small increase in the wind speed can lead to a large difference in wind power generation. Therefore, it is of interest to properly assess the wind resource in an area and attempt to enhance it by various aerodynamics techniques. This is contrary to the traditional wind engineering approach where the focus is in reducing wind speeds and pressures to minimize wind-induced building loads and contribute to the economy of a safe building design (e.g. Isyumov and Davenport, 1975; Murakami, 1997; Stathopoulos, 1997; Baker, 2007; Solari, 2007; Franke et al., 2007; Tominaga et al., 2008; Blocken, 2014, 2015; and Meroney and Derickson, 2014).

The wind resource assessment in the urban habitat has been a topic of interest in the research world for many years. This paper seeks to provide some views on the progress made recently on different related fields. Initially, a brief introduction for the methods used for initial assessment of wind speeds in an urban location are provided with a focus on indirect methods such as atmospheric boundary layer wind tunnel testing and Computational Fluid Dynamics (CFD). Then, recent progress on some working mechanisms of wind turbines and the aerodynamics of the urban environment and their characteristics is discussed.

2. Estimation of wind speeds in an urban location

Several methods are used for the initial assessment of wind resources for a specific site based on data measured by meteorological stations. The most prominent and widely used are probabilistic mathematical functions such as Weibull and Rayleigh; wind atlas data; and indirect methods such as atmospheric boundary layer wind tunnel testing and numerical simulation with Computational Fluid Dynamics (CFD) (Ishugah et al., 2014). It was demonstrated that Weibull and Rayleigh probability functions are effective in case of open areas like offshore with high mean speeds (Jamil et al., 1995 and Adaramola et al., 2014). Also, there were attempts to fit models for wind speed distributions for energy applications. For instance, Mathew et al. (2002) offered an analytical approach to study the wind energy density, the energy available in the wind spectra, and the energy received by a turbine by using the Rayleigh wind speed distribution. Moreover, Mathew et al. (2002) addressed a method to identify the most frequent wind speed that carries the maximum amount of energy associated with it.

The prediction of the wind speed in the built environment is difficult, due to the varying roughness and the drag exerted by surface-mounted obstacles on the flow (and vice versa), which reduce the wind speed close to the ground. In addition, the presence of adjacent buildings influences the wind regime around a specific building in the urban environment. Therefore, it is conceivable that lacking accurate approaches for assessment of wind speed in urban areas is a major impediment to the successful development of micro-scale energy generation.

The most dependable method for the wind assessment in the urban environment is to directly measure the wind speed on-site (full-scale), ideally at the position and the height of the proposed wind turbine. However, measuring the wind speed at a site is both time consuming and expensive, let alone that it cannot work at the building design stage. Various approaches, including atmospheric boundary layer wind tunnels and Computational Fluid Dynamics (CFD), have been widely used to predict the wind speed in urban environment. Of these two approaches, wind tunnel experimentation is still considered to be the most practical and effective approach. However, there are problems as-

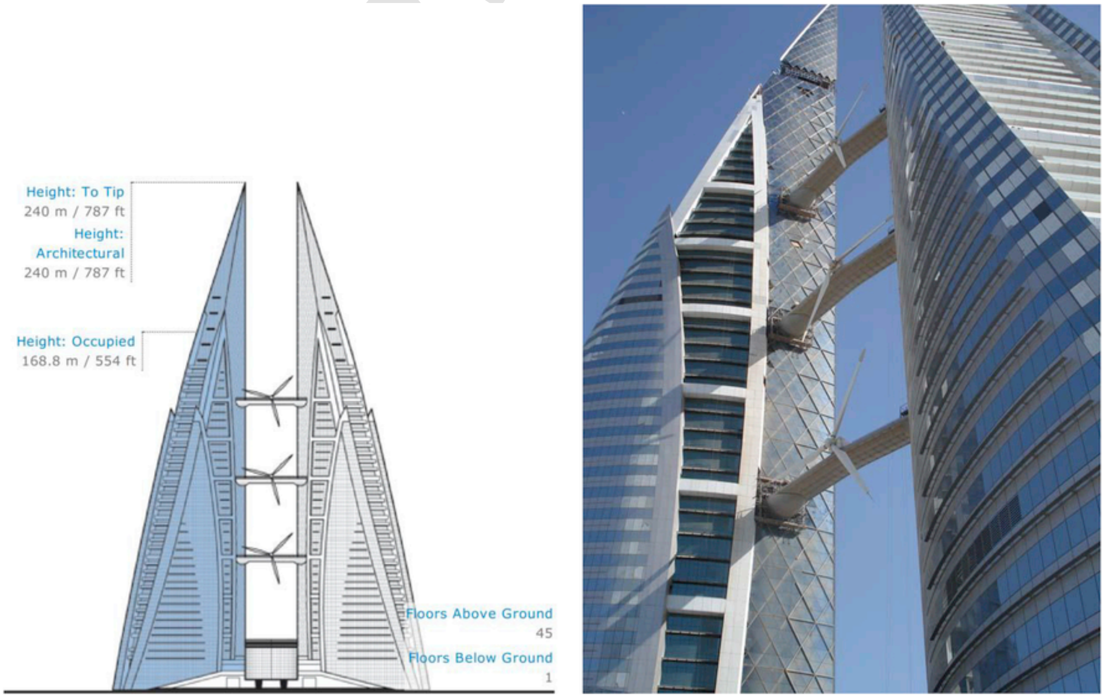

Fig. 1. Wind turbines integrated in between the Bahrain World Trade Center Towers. (http://www.skyscrapercenter.com/building/bahrain-world-trade-center-1/998).

sociated with the wind tunnel testing mainly related to dynamic similarity and high blockage ratios. In recent years, CFD has received a great deal of attention, and therefore, it has been widely adapted in several applications, mainly for the determination of mean flow conditions primarily for topics in environmental wind engineering such as pedestrian-level wind conditions, natural ventilation of buildings and wind-driven rain. However, the results of CFD simulations should undergo detailed solution verification and validation, as they are very sensitive to the wide range of computational parameters.

Most of the literature relevant to micro-energy applications consists of idealized parametric studies considering simple configurations, i.e. standalone cubes, prismatic buildings or groups of simple buildings. A few of such recent studies conducted for the purpose of specifying the optimal location of turbines include the following: Cheng et al. (2007) performed wind tunnel experiments on uniform urban-type surfaces of two different area densities to examine the influence of area density and array geometry on the aerodynamic characteristics of the considered surfaces. Heath et al. (2007) studied mean wind speeds at potential turbine mounting locations around a simple pitched-roof building and a matrix of similar pitched-roof houses for different wind directions using CFD. Lu and Ip (2009) investigated the wind flows over three configurations of two tall buildings by considering parameters such as building height, roof and distance using meteorological data. Wind flows over buildings were also modeled using CFD to locate turbines over and around buildings. Ledo et al. (2011) examined the wind flow characteristics over the roof in three suburban areas of buildings with three different roof profiles (pitched, pyramidal and flat) using CFD. Abohela et al. (2013) investigated the effect of the roof shape, wind direction, building height and surrounding urban configurations on the flow patterns above the roof to identify their effect on specifying the optimal location for turbines. Wang et al. (2015) carried out CFD tests to investigate the wind energy potential over roofs of two perpendicular buildings considering different building plan dimensions, heights and corner separation distances. Sari (2015) performed CFD simulations to study the influence of the roof pitch (20°, 30°, 40° and 50°) on the wind power density based on wind climate data analysis.

There are very few research studies on the wind power utilization over existing buildings in urban areas. Table 1 presents examples of recent actual building studies conducted by means of field measurements, wind tunnel experimentation and CFD. Details of the considered models, test descriptions, errors involved, as well as key findings are provided. Further discussion will be made on the study of Al-Quraan et al. (2016).

The study of Al-Quraan et al. (2016) has proposed a methodology for wind energy potential estimation by deriving wind speed data measured by meteorological stations, likely to be at airports, to a specific location above a building roof in urban environment with resorting to atmospheric boundary layer wind tunnels. Indeed, this study has shown that appropriate utilization of atmospheric boundary layer wind tunnel technology can provide an excellent methodology to obtain realistic estimates of urban wind energy potential within reasonable accuracy. Two actual building cases in Montreal with different upstream roughness homogeneity were considered. Fig. 2 (after Al-Quraan et al., 2016) shows these two cases along with a part of the corresponding wind tunnel model.

In the first case, field wind speed measurements are used to evaluate the wind energy potential for the EV building of Concordia University, a building with upstream rather homogeneous urban/suburban type of terrain – see Fig. 2 (a). In the second case, the Equiterre building upstream terrain is very rough and highly heterogeneous – see Fig. 2 (b).

In order to compare the calculated wind energy using the field measurements over the EV building roof and the estimated value using the proposed methodology, a three-cup anemometer was installed in one roof corner at a height of 2 m above the roof. The anemometer was

Table 1
Examples of recent studies for actual site locations.

Study	Data collection approach	Site Model (Concerned building)	Simulated Flow	Prediction/Errors	Key Findings
Lu and Sun (2014)	CFD	Lee Shau Kee building (97.4×38.7×69.9 m) (L, W, H). Kowloon, Hong Kong.	RNG k-ε.	No validation.	Minimum height 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 building roof.
Tabrizi et al. (2014)	CFD Field measurements from one location.	Bunnings warehouse H = 8.4 m. Port-Kennedy, Western Australia. Radius of the surrounding: 200 m	Steady RANS with k-ε. Computational domain (H): 0.2 km	Wind speed: Error < 20%.	A small HAWT is recommended to be installed in the middle of the roof.
Al-Quraan et al. (2016)	Wind tunnel experiments. Field measurements from two locations.	EV Building (76 m high) Equiterre building (23 m high) Montreal, Quebec, Canada.	Homogeneous terrain Nonhomogeneous terrain	Wind speed: Error < 5%. Wind Energy: 5% ≤ Error ≤ 20%	Accuracy of wind tunnel results depends on the upstream terrain.
Yang et al. (2016)	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.	Standard κ-ε. RNG κ-ε. Realizable κ-ε. Computational domain (L, W, H) 16×8×0.3 km	Turbulence intensity: Error < 56% (RNG k-ε model) Error < 20% (realizable k-ε model) Wind speed: Error < 20% (realizable k-ε model) Wind direction: Prediction of realizable k-ε is more reliable than RNG k-ε and standard k-ε.	Recommend increasing the hub height and install microturbines on the windward side of the building. Curved roof edges increase the power density.

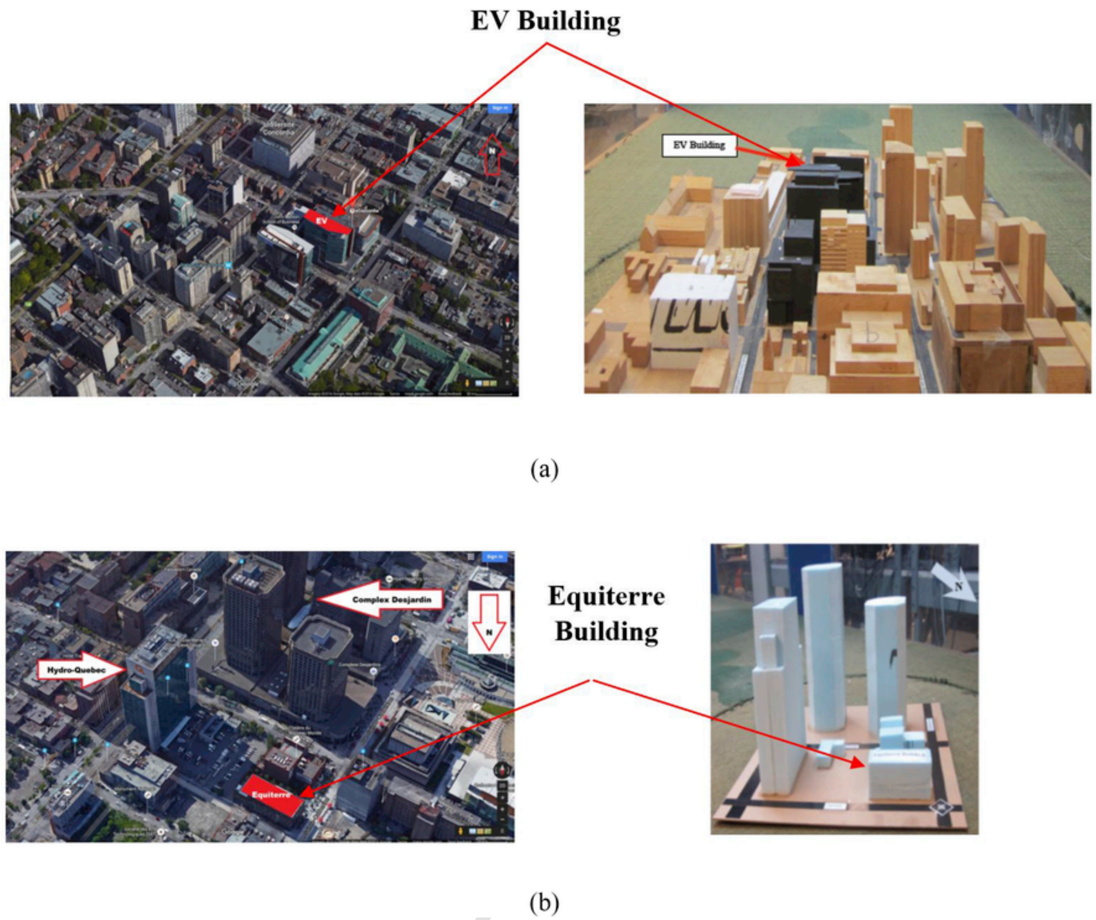

Fig. 2. Perspective View of the Considered Building Cases (https://www.google.ca/maps) and their Models in the Wind Tunnel: (a) EV Building case (homogenous). (b) Equiterre Building case (nonhomogeneous) (after Al-Quraan et al., 2016).

programmed to take one measurement every 5 s. The field measurement data were collected from the beginning of August 2013 to the end of October 2013. Also, another three-cup anemometer was installed in one corner above the roof of the Equiterre building, identical to the one on the roof of the EV building and with the same settings. The field measurement data - magnitude of the wind speed only - were collected for a 3-month period: November 1, 2012 to January 31, 2013. Certainly, the field data are very limited, but they were never intended to characterize the actual wind conditions in the measurement locations (including seasonal trends). Field data were only used to provide a limited window of opportunity to place them within the steadier wind tunnel predictions.

The obtained wind speed data were used to calculate the total available wind energy for the corresponding period. Fig. 3 (a) and (b) (Al-Quraan et al., 2016) shows comparisons between the field measurements of the available wind energy and their estimation for the two building cases considered. It can be shown that the error in the estimated wind energy, evaluated by [(field–estimated)/field] *100%, is less than 5% in the case of the homogeneous terrain – see Fig. 3 (a), whereas the obtained results show that the error between the wind energy estimated by the field measurement and that by the wind tunnel is less than 20% for the heterogeneous terrain – see Fig. 3 (b).

Comparison of the wind tunnel results with corresponding field measurement wind data in order to examine the validity of wind tunnel in providing realistic estimates of urban wind energy potential has shown that the suggested methodology is sufficiently accurate to be used, at least in the case of homogeneous terrain. Thus, high correlation between the estimation of the wind energy using the wind tunnel approach and the calculation based on field measurements above the roof of a building in homogeneous terrain has been noticed. On the other hand, in case of highly heterogeneously rough terrain, the discrepancy is higher but may still be acceptable for purposes of initial evaluation. In all cases the estimated values were lower than the measured values, so the assessment is on the conservative – see Al-Quraan et al. (2016).

The assessment of wind speeds in an urban location at initial stages of efficient planning and implementation of wind power development is a prerequisite procedure for estimating the wind energy potential. The assessment should not be only limited to wind speed, but it must also include turbulence and wind direction characteristics. However, the atmospheric boundary layer wind flows in urban areas are more complex and may differ from those simulated in atmospheric boundary layer wind tunnels and CFD, due to several reasons; such as heterogeneously rough terrain and the associated development of a multitude of internal boundary layers, thermal and humidity effects, and the deviation in wind directions with height (Weerasuriya et al., 2018). The boundary layer wind tunnels and Computational Fluid Dynamics (CFD) are considered as trusted approaches for such needed assessment.

3. Wind turbine designs

A large variety of wind turbine types and designs is available at present. Typically, efficient designs with high performance are influenced by several design criteria related mainly to the application to serve and the location where the turbine is to be installed. In fact, knowing the application and the location of the turbine to be installed is a key guid-

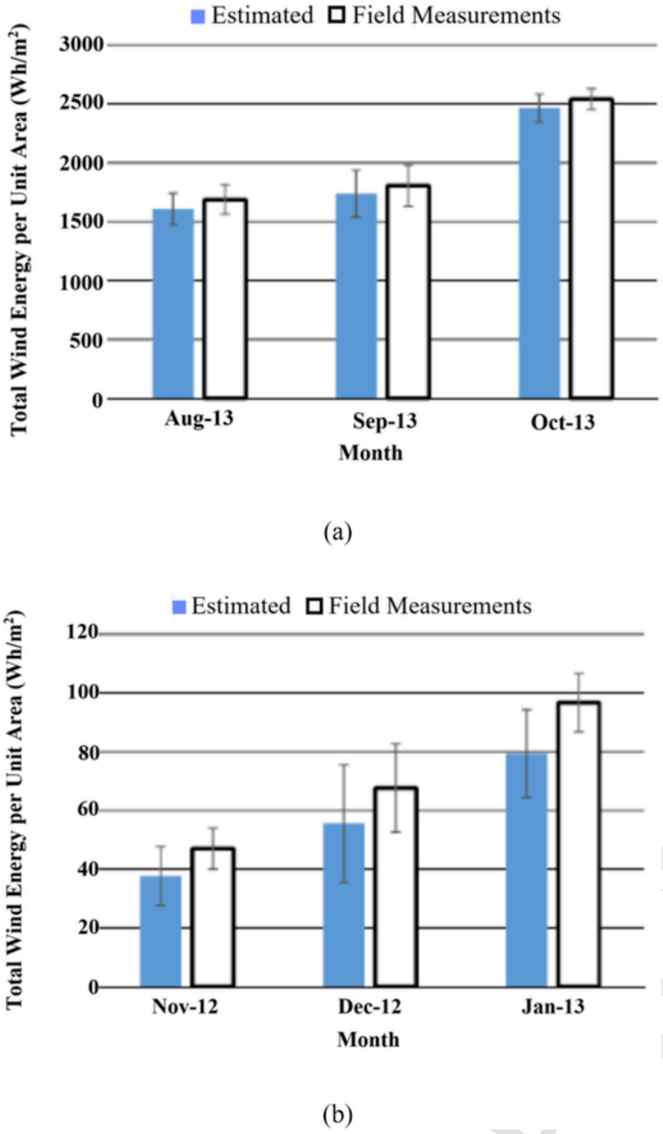

Fig. 3. Field Measurement Data and Estimated Total Wind Energy Potential per Unit Area with the Corresponding Error Bars above the Roof of (a) EV Building (homogeneous terrain) (b) Equiterre Building (nonhomogeneous terrain) (Al-Quraan et al., 2016).

ance for choosing the size of the turbine and its generator type, the method of control, and how it is to be constructed and operated. The power output of a wind turbine is dependent on the efficiency of the blades, the match of rotor characteristics with generator characteristics, location and available wind power, i. e, flow characteristics, density, mean wind speed and turbulence. As well, other constraints may play a significant role in the efficiency of the designs, e.g. size constraints, noise limitations, visual disturbances and low start-up wind speeds. Among these requirements and constraints, the performance of one particular wind turbine may be more optimized compared to the others.

In the wind turbine industry, there are two main design categories qualified for different environments to choose accordingly: horizontal and vertical axis wind turbines (Paraschivoiu, 2002). Horizontal axis wind turbines (HAWTs) are the most widespread type of wind turbines. Fig. 4 (a) presents examples of currently used HAWTs. Fig. 4 (b) shows examples of typical categories of vertical axis wind turbines (VAWTs), namely Savonius, Darrieus and H-Darrieus turbines.

The HAWTs are very sensitive to the direction of the wind and do not cope well with turbulent flow and buffeting. Therefore, HAWTs are suited to be installed in open areas with fairly smooth horizontal airflow and few upstream obstacles. Vertical axis wind turbines (VAWTs) are less influenced by changes in wind direction, evoke lower noise levels and tend to be more aesthetically pleasing. These characteristics make them more suitable for application in urban environments (Toja-Silva et al., 2013). However, the use of HAWTs is increasing in urban areas, in spite of the highly turbulent nature and directional variability of the wind; this is mainly because at present, the overall power efficiency of these turbines is deemed by many researchers and practitioners to be higher than that of VAWTs. It should be noted that VAWTs have a relatively high cut-in speed compared to HAWTs, which among other reasons restricts their use in urban environment.

Regarding the cost of energy (cost/kWh), the generated energy depends on the efficiency of the turbine, whereas, the cost envelopes the manufacturing, site preparation, installation and operation and maintenance costs. Eriksson et al. (2008) presented a comparative study between a HAWT and two types of VAWTs (Darrieus and H-rotor). A summary of this turbine comparison is provided in Table 2. Clearly, the cost of energy is strongly dependent upon the site and project specifications, but at present, HAWTs appear commercially more efficient than VAWTs.

The Savonius rotor is a vertical axis low speed wind turbine characterized as more inexpensive and simpler in construction. Savonius rotors are considered to be some of the oldest designs for wind turbines and they have proven to be well-suited to micro scaled urban operations due to their simple design and relatively low cut-in wind velocity (Saha et al., 2008). However, their power coefficients are generally low to very low, as opposed to those of Darrieus wind turbines. The Darrieus VAWT is one of the most suitable for rooftop integration, not only because of its higher power coefficients but also because it is visually less obtrusive and produces low-level acoustic emissions (Balduzzi et al., 2012b). In addition, recent designs of Darrieus wind turbines show good self-startup abilities (Batista et al., 2015). The differences in power coefficients between Savonius and Darrieus rotors are also reflected in the tip speed ratio, i.e. the ratio of tangential speed of the tip of a blade to the actual approach flow wind speed. For Darrieus turbines, this value can easily reach four, while for Savonius rotor turbines the typical value is one (Nagare et al., 2015).

Wind tunnel tests revealed that the vertical helical rotor wind turbines have power coefficients of about 0.4. Due to the strongly 3-dimensional nature of urban wind flow, VAWTs are fairly robust in view of variable wind direction and are better suited for exploiting turbulent flow (Ragheb, 2012). Furthermore, much work has been recently carried out on the effect of turbulence intensity on the aerodynamic behavior (power efficiency) of wind turbines, particularly VAWTs. Emejeamara et al. (2015) have analyzed the additional energy present in the gusty wind resource at two urban rooftop locations. It was found that significant additional energy is present in the gusty wind resource. Wekesa et al. (2016) have experimentally investigated this issue on the aerodynamic behavior of Savonius wind turbine in a closed wind tunnel. It was reported that turbulence intensity has dissimilar influences depending on the wind speed. Thus, the turbulence only enhances the performance at low wind speed and reduces the efficiency at high wind speed. Additional information regarding the advantages and disadvantages of the common types of urban wind turbines is available in e.g. the Wineur Project report (Cace et al., 2007).

Pagnini et al. (2015) presented an in situ experimental analysis for power performance of two small size wind turbines of identical rated power but realized with vertical and horizontal axis. The turbines were positioned in the same place exposed to two distinct regimes, low turbulence (wind blowing from the sea) and high turbulence (wind blowing from the land), as shown in Fig. 5. The values of power coefficients (C_p) presented in Fig. 5 were evaluated based on the monthly-mean values of the power output gathered by Pagnini et al. (2015) from Jan-

(a)

(b)

Fig. 4. Examples of common existing (a) Horizontal axis wind turbines (HAWTs) and (b) Vertical axis wind turbines (VAWTs). (Source: different websites; see references). [1]http://www.prweb.com/releases/2010/07/prweb4281554.htm. [2]https://www.energyonthehook.com/Eclectic-Energy-D400-Wind-Generator-p/ecld400.htm. [3]http://www.fortiswindenergy.com/montana/. 4 http://www.renugen.co.uk/wind-energy-solutions-wes5-tulipo-2-5-kw-wind-turbine/. 5 http://www.windworks.org/cms/index.php?id=64&tx_ttnews%5Btt_news%5D=95&cHash=702973dca5ecf0c94d5d52e4e6094888. [6]https://www.alibaba.com/product-detail/WindWall-3kW-Windturbine_109199832.html. [7]http://www.netzeroguide.com/savonius-wind-turbine/. [8]https://en.wind-turbine-models.com/turbines/93-dornier-darrieus-55. [9]http://lifefreeenergy.com/v/vertical-wind-turbine.html/page/2/.

Table 2
Differences of H-rotor, Darrieus and HAWT turbines (after Eriksson et al., 2008).

	H-rotor	Darrieus	HAWT
Blade profile	Simple	Complicated	Complicated
Yaw mechanism needed	No	No	Yes
Pitch mechanism possible	Yes	No	Yes
Tower	Yes	No	Yes
Guy wires	Optional	Yes	No
Noise	Low	Moderate	High
Blade area	Moderate	Large	Small
Generator position	On ground	On ground	On top of tower
Blade load	Moderate	Low	High
Self-starting	No	No	Yes
Tower interference	Small	Small	Large
Foundation	Moderate	Simple	Extensive
Overall structure	Simple	Simple	Complicated

uary to August 2012. By equation (1) and considering that the HAWT and the VAWT have a swept area of 78.5 m^2 and 46.5 m^2, respectively, the C_p is calculated based on the monthly-averaged velocity measured throughout the period considered for the power output. The density of air (ρ) is assumed to be 1.225 kg/m^3. It should be mentioned that there is some inconsistency in wind speeds obtained by the anemometer and what the wind turbine experienced (Pagnini et al., 2015). Fig. 5 compares the performance of the VAWT and HAWT systems. It was also observed that the HAWT is extremely sensitive to the direction of wind while the VAWT is able to capture energy carried by strong gusts of wind much more efficiently (Pagnini et al., 2015).

$$P_{generated} = C_p \left(0.5 \rho A V^3\right) \tag{1}$$

in which C_p is the power coefficient, A is the swept area, ρ is the air density and V is the average approaching wind speed.

In the past several years, urban wind power has attracted much attention. Therefore, research on the development of competent models of wind turbines for specific applications has quickly expanded and in-

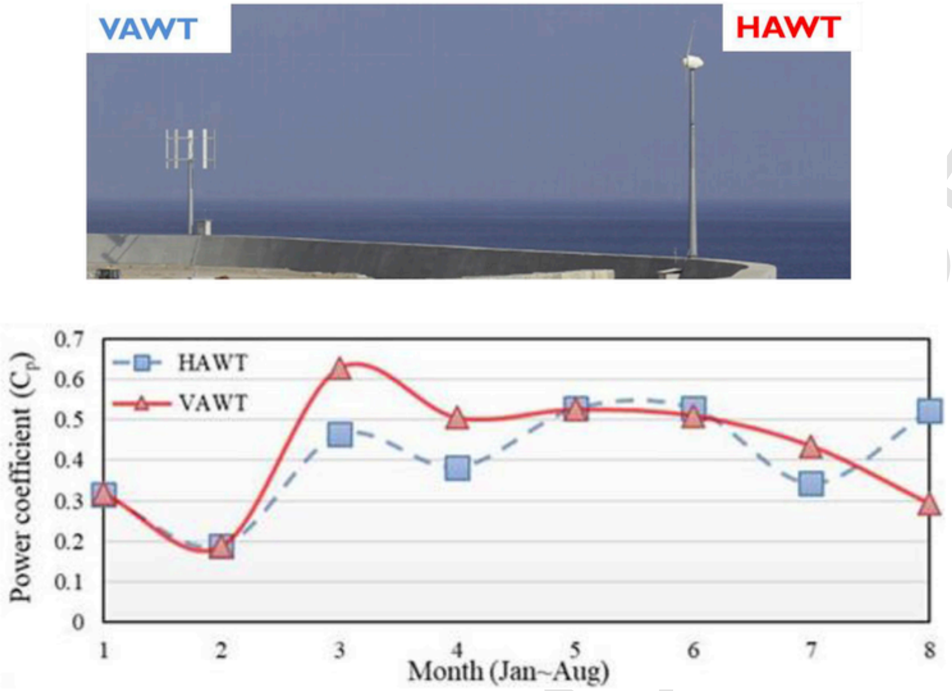

Fig. 5. Monthly-averaged power coefficients of two wind turbines based on the data from Pagnini et al. (2015).

troduced many new implementable wind turbine designs of maximized power harvesting performance. As such, building-integrated wind turbines and diffuser augmented turbines have attracted lots of interest, e.g., Mertens (2002), Müller et al. (2009), Walker (2011), Nishimura et al. (2014), Park et al. (2015), Li et al. (2016) and Chong et al. (2017).

Building-integrated wind turbines (BIWT) are an alternative for micro-scale energy generation, i.e., building-scale in urban areas. There is a growing number of installations of BIWT systems on high-rise buildings around the world. Generally, the installations exist in two forms, as illustrated in Fig. 6: Relatively large size wind turbines attached to the rooftop, placed between two adjacent buildings or inside openings within the buildings, small size wind turbine or a system of small wind turbines distributed on the roof or along the building height. The following are factors to be considered in the design of BIWTs, after inves-

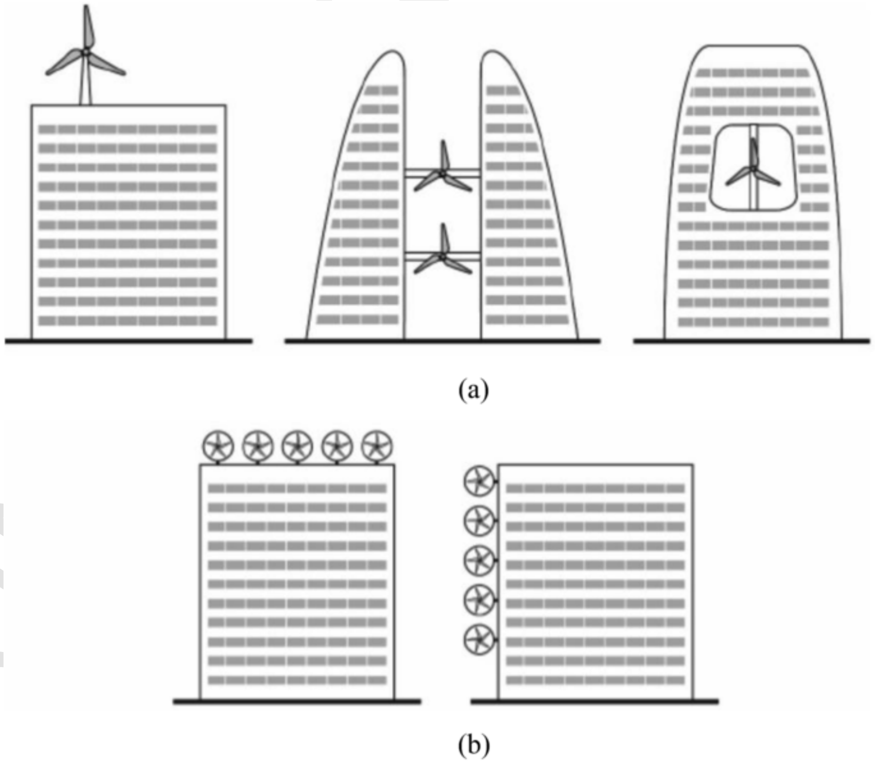

Fig. 6. Possible installation of BIWT: (a) Large size wind turbines and (b) System of small size wind turbines (Park et al., 2015).

tigating which turbine model is the best for the building, to achieve the performance expectations:

3.1. Effects of the urban surroundings on wind conditions around the turbines

Turbines are preferably installed on the highest building that is located as far as possible from the surrounding buildings to avoid unexpected wind regimes. Yang et al. (2016) affirm that geometric details of the windward structures clearly affect the power on the roof of the concerned building.

3.2. Effects of wind conditions on optimal turbine placement

Generally, building geometry plays a significant role in enhancing the power performance of wind turbines. For instance, buildings may be aerodynamically designed to scoop and funnel wind into turbines to take advantage of the wind velocity magnification. Chaudhry et al. (2014) have found, through a CFD investigation on the Bahrain World Trade center, that the circular aerodynamic shape is optimal for wind turbines around high-rise buildings compared to square and triangular shapes, especially for regions with a prevailing wind direction. The wind turbine works with high performance in strong laminar wind flow perpendicular to the HAWT rotor plane or the VAWT axis. On this basis, turbines placed on tall buildings with a flat roof are of high energy performance provided if they are placed outside the separation bubble. Chamfering the roof edge of the prevailing wind direction may also produce positive effects on their performance, since the speed of the flow may increase. Furthermore, placing the turbine within the middle zone of the roof at maximum attainable height may, again, enhance the turbine's performance. Abohela et al. (2013) found that wind turbines must be installed at height higher than 1.3 times the building height to avoid the region of high turbulence intensity inside the separation bubble. Also, an increase in the wind power density of 1.3–5.4 times at height 4 m above the roof was reported by Lu and Sun (2014). Toja-Silva et al. (2015) recommend, through their CFD investigation on a single building, minimum height from the roof surface of 19% and 31% of the building height if the HAWT is installed at upstream and downstream regions, respectively.

Multi-rotor turbine or multiple turbines can be placed at the same location or on the same building if possible to increase energy yield. Industries have traditionally resorted to upscale single rotor wind turbines, through increasing the size of blades, for the purpose of increasing the power efficiency. However, upscaling always results in an unfavorable weight and load increase on the turbines, as demonstrated by Sieros et al. (2012). Goltenbott et al. (2017) have experimentally examined the aerodynamics of two configurations of diffuser-augmented wind turbines (DAWTs) of two and three rotors in laminar uniform flow. The wind turbines were placed in close vicinity in the same vertical plane. It was found that power increases of up to 5% and 9% for the two- and three-rotor configurations were respectively achieved in comparison to a single rotor turbine.

3.3. Accurate prediction of wind power output for BIWT

Investigation of the wind regime where the turbine is to be placed should be carefully carried out by means of atmospheric boundary layer wind tunnels or CFD since slight differences in the wind regime may produce substantial effects on the power performance.

In addition to the previous requirements, the structural integrity of the building on which the turbine is attached should be ensured, thus the structural components and elements should be able to withstand the static and dynamic loads induced by the wind turbines. In this respect, aesthetic aspects are also of importance.

As already discussed, the theoretical maximum wind power is directly proportional to cube of the wind speed, and therefore, small increases on the wind speed lead to substantial increases in the wind power. A brimmed diffuser structure to envelope a rooftop VAWT can play a role in amplifying the wind speed approaching the turbine due to Venturi effects in the constricted flow path. Ohya and Karasudani (2010) tested a wind turbine system consisting of a diffuser shroud with a broad-ring flange at the exit periphery and a wind turbine inside it. It was found that the power output of the Diffuser Augmented Wind Turbine (DAWT) is increased by 4–5 times compared to conventional wind turbines due to concentration of the wind energy. Fig. 7 (b) compares the power curve of a Building Integrated Wind Turbine (BIWT) ($C_p = 0.381$) deduced from Park et al. (2015) with a conventional Savonius wind turbine ($C_p = 0.09$) based on data from Saha et al. (2008). As shown in Fig. 7 (a), the BIWT system directly utilizes the exterior wall façade of the building. The BIWT system was developed by combining a guide vane to effectively collect the incoming wind and increase its speed. The BIWT results, which are more than 4 times higher, fit well the field data measured. It should be mentioned that power curve of the conventional Savonius wind turbine was calculated based on equation (1), in which C_p is the power coefficient (0.09), A is the swept area, ρ is the air density and V is the average approaching wind speed. For comparison purposes, A and ρ are considered as those of the Building Integrated Wind Turbine ($0.238\,m^2$ and $1.225\,kg/m^3$, respectively).

Urban wind turbines are still at the initial stage of technological development. Lacking experimental data of wind turbines installed in urban settings stands as a strong drawback on the evaluation of turbine efficiencies and, consequentially, their viability. Although conventional wind turbines directly located in urban built-environment do not perform well, other wind turbines, especially VAWTs, still show good results but need further optimization for urban applications. Diffusers and shrouded brims around conventional wind turbines may lead to significant power output increases (Dilimulati et al., 2018).

4. Urban aerodynamics

An urban environment can be defined as an area with densely built-up settlements compared to other areas surrounding it. The aerodynamics of the urban environment is very complicated. Even though considerable progress has been reported toward understanding the aerodynamics of urban environment, urban wind flows are still being widely investigated experimentally and computationally. This is due to the fact that urban flows are influenced by various components of urban environment that are not possible to be examined independently, such as complexity of building geometries and configurations which play significant role in impacting the flow pattern. Many review studies in the wind engineering literature can serve as examples of reviews which provide the reached level of analysis and understanding with time, e.g., Ferziger (1990); Leschziner (1990); Murakami (1990) and (1997); Schatzmann et al. (1997); Stathopoulos (1997); Solari (2007); Blocken (2014), Meroney and Derickson (2014); and Meroney (2016).

It is well known that mean wind speeds in urban areas are lower than in suburbs or rural areas. Buildings, which form of the majority of urban buildings, provide form and frictional drag to the flow. This drag creates turbulence, which produces local rapid changes in the direction and the speed of the wind. Furthermore, pressure gradients across the buildings (between windward and leeward sides) and along their height induce strong wind eddies.

Besides building geometry, spacing of the buildings can also influence the aerodynamics of urban environment. Apparently, closely-spaced buildings can create higher form drag causing winds to move quickly over the top and form eddies between them. Also, such build-

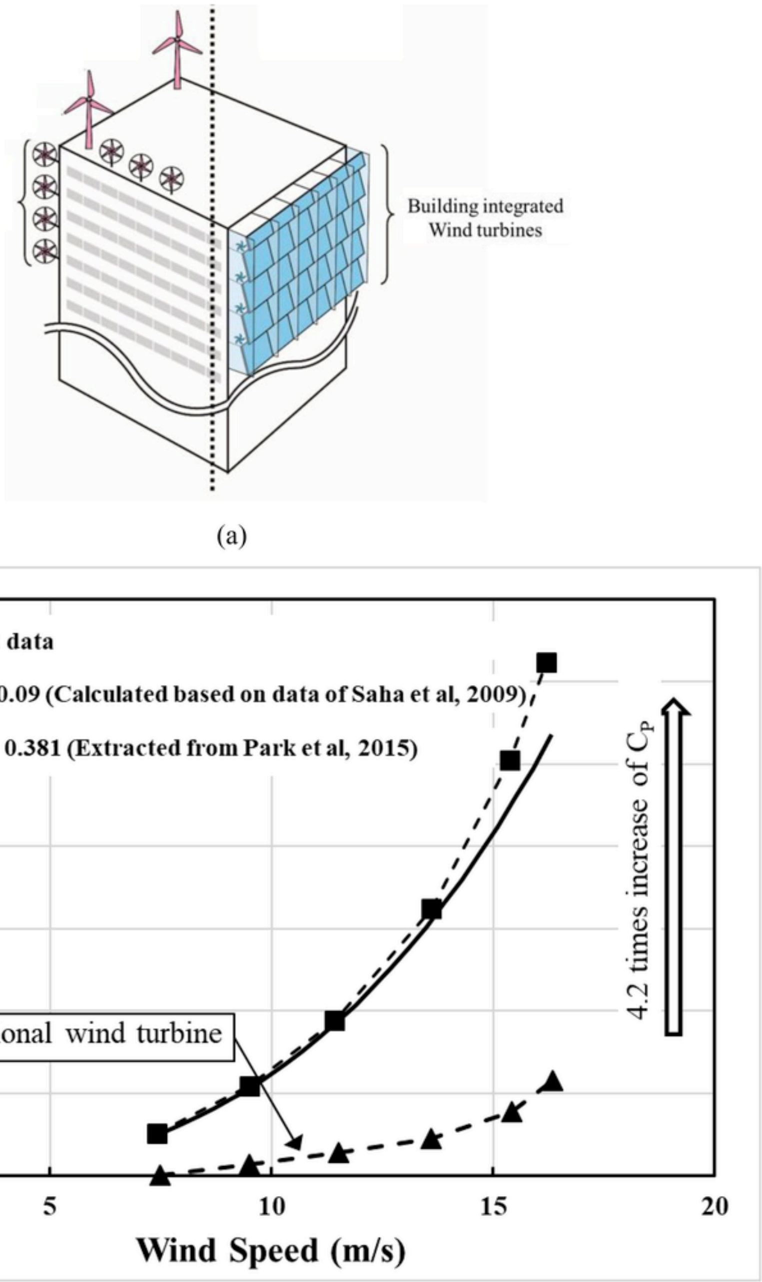

Fig. 7. (a) Building-Integrated Wind Turbine (After Park et al., 2015) and (b) Power curve comparison of BIWT based on data from Saha et al. (2008) and Park et al. (2015).

ing configurations may act as channels for the flow, in which the wind moves at faster speeds, particularly near ground level, as was indicated by Blocken et al. (2007 and 2008a). Roadside trees may play a significant role in impacting the wind flow of the urban street canyon, such that the trees planted in the sidewalk area perpendicular to the prevailing wind direction may reduce significantly the wind speed (Park et al., 2012).

Recently, there has been a growing interest in studying the aerodynamics of the urban environment. Most studies have focused on the dispersion of air pollution and on pedestrian level winds. Typical examples include: Dispersion of Air Pollution and its Penetration into the Local Environment (DAPPLE) project (Arnold et al., 2004; Barlow et al., 2009); Fernando et al. (2010); Blocken et al. (2013); Tominaga and Stathopoulos (2013); Blocken et al. (2016); Cui et al. (2016); and Xu et al. (2017). Also, the development of boundary layers over urban environment has been investigated and reviewed by several studies, i.e., Coceal and Belcher (2004); Burlando et al. (2007); Wang (2012, 2014); Razak et al. (2013); Barlow (2014); Blocken (2015); and Ricci et al. (2017).

In structural and evolutionary terms, the urban boundary layer, as depicted in Fig. 8 (Barlow, 2014), mainly consists of three parts: the urban canopy layer, the roughness sublayer and the inertial sublayer. The urban canopy layer is the lowest part, with a depth corresponding approximately to the mean roof height of the roughness elements (H). Through this layer, the flow is locally and strongly influenced by its interaction with the surface roughness and the flow channeling occurs parallel to the ground. In the roughness sublayer, which has a depth of 2–5H, the flow is still influenced by the surface roughness, albeit to a smaller degree. The inertial sublayer, where the flow is characterized by relatively homogeneous turbulence, is less affected by the surface roughness. Grimmond and Oke (1999) have proposed a set of 14 categories to assess the urban roughness parameters based on a comprehen-

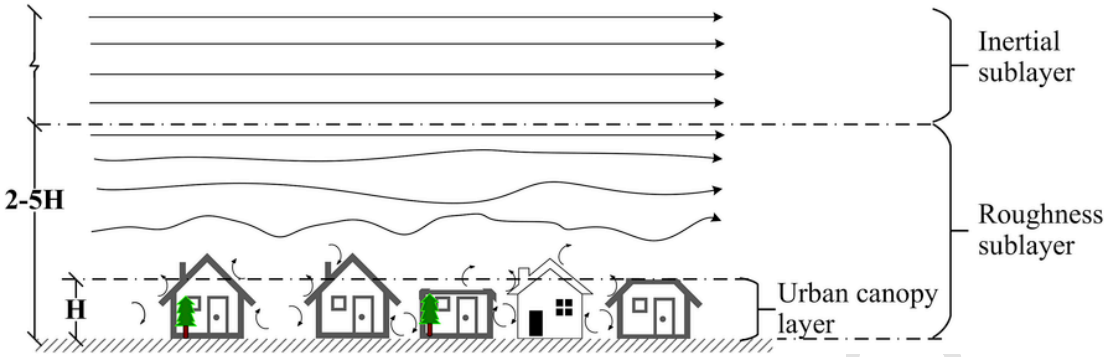

Fig. 8. Schematic illustration of boundary layers over urban environment (after Barlow, 2014). (H denotes the mean roof height).

sive review of wind flow observations covering areas of different urban roughness densities in terms of non-dimensional roughness coefficients ($f_d = z_d/z_H$ and $f_o = z_o/z_H$), where z_d is the zero-plane displacement length and z_H is the height of the roughness element. Values of $f_d = z_d/z_H$ range from 0.35 to 0.70 and values of $f_o = z_o/z_H$ range between 0.06 and 0.20. Drew et al. (2013) proposed a method for modifying the prediction of the Numerical Objective Analysis of Boundary Layer (NOABL) wind speed database for better estimation of the variability of the annual mean wind speed across an urban area by considering the impact of the surface on a neighborhood scale assuming uniform surface characteristics over 1 km^2. Kanda et al. (2013) carried out LES simulations for 107 urban surfaces and 23 idealized building configurations. It was found that the building height variations are more relevant with bulk flow properties than the complicities of the streets. Kanda et al. (2013) produced a database for profiles of horizontally-averaged wind speed, the standard deviations of the wind speed components normalized by the friction velocity u_*, turbulent kinetic energy normalized by u_* and total vertical momentum flux. Millward-Hopkins et al. (2013) compared the accuracy of three wind atlas methodologies for predicting above-roof mean wind speeds across several UK cities and derived two more complex methods which considered the wind directional effects and detailed building databases (building height heterogeneity). A recent study by Kent et al. (2017) used several databases to judge the methods of evaluation the aerodynamic roughness length (z_o) and plane displacement (z_d) of three nearby urban sites. Morphometric and anemometric analysis of aerodynamic parameters reveal that the estimated z_d ranges between 5 and 45 m and z_o between 0.1 and 5 m.

As already discussed, the wind flow in urban areas is characterized by high turbulence due to the high roughness of the ground surface. Flow turbulence generally negatively affects the power output performance of the turbine, induces wind loads and noise propagation. On the other hand, the mean velocity and the density of the airflow may increase in urban areas due to flow channeling and corner stream effects. This positively influences the power output performance of the turbine.

The Bahrain World Trade Centre (WTC), which is located at the edge of the Arabian Gulf, was completed in 2008 costing about $150 million. It is considered the world's first skyscraper with integrated wind turbines. The twin towers have a height of 240 m and support three 29 m-diameter large scale horizontal axis wind turbines. The two towers combined have an aerodynamic shape like a funnel creating a wind flow path to improve the power-generation efficiency. Measurements carried out by the meteorological stations documented that the average annual wind speed in Bahrain at 10 m height is 4.8 m/s with prevailing north-to-north-west direction. This level of wind speed was considered moderate and not economically viable for wind energy potential (Bachellerie, 2012).

Although the Bahrain WTC is an example of building-integrated wind energy where the system actually seems to function and to provide 8–10% of the electricity consumption of the building, the Bahrain WTC design would have yielded a substantially higher wind energy output if the buildings were positioned in diverging rather than the existing converging configuration – see Fig. 9, in line with earlier findings (Blocken et al., 2008b). From the wind energy point of view and based on wind-tunnel testing and CFD simulations carried out by Blocken (2016) on the modeled Bahrain WTC, it was found that the towers would produce 14 percent more energy output per year if they were turned 180° around. Moreover, integrating the wind turbines further downstream would have increased the efficiency up to 31% – see Fig. 10.

Clearly, the thorough study of building and urban aerodynamics is extremely relevant to the location and configuration of urban wind turbines for optimal performance. In addition, a study to optimize the operating performance of building integrated wind turbines would cost an insignificant percentage of the total cost of the building construction but could produce results that are very valuable and even essential to the success of the project. It is therefore strongly advised to perform such studies in the design phase in order to optimally utilize the knowledge and the potential benefits of urban aerodynamics to improve the performance of building-integrated turbines.

5. Summary and conclusions

Urban wind energy consists of the utilization of wind energy technology in applications to the urban and suburban built environment. The paper provides some views on the progress made recently in the areas of wind resource assessment in the urban habitat; the utilization of suitable wind turbines for enhancing the exploitation of these resources; and the significant role of knowledge of building and urban aerodynamics for an optimal arrangement of interfacing augmented wind with its extraction mechanisms. The paper is not intended to be exhaustive, rather its purpose is to provide some views on the above-mentioned topics from the viewpoint of wind engineering and industrial aerodynamics in the context of buildings and cities.

The paper has indicated that while substantial progress has been made in each of these fields, 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.

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European Commission, 2007, Yoshie et al., 2007.

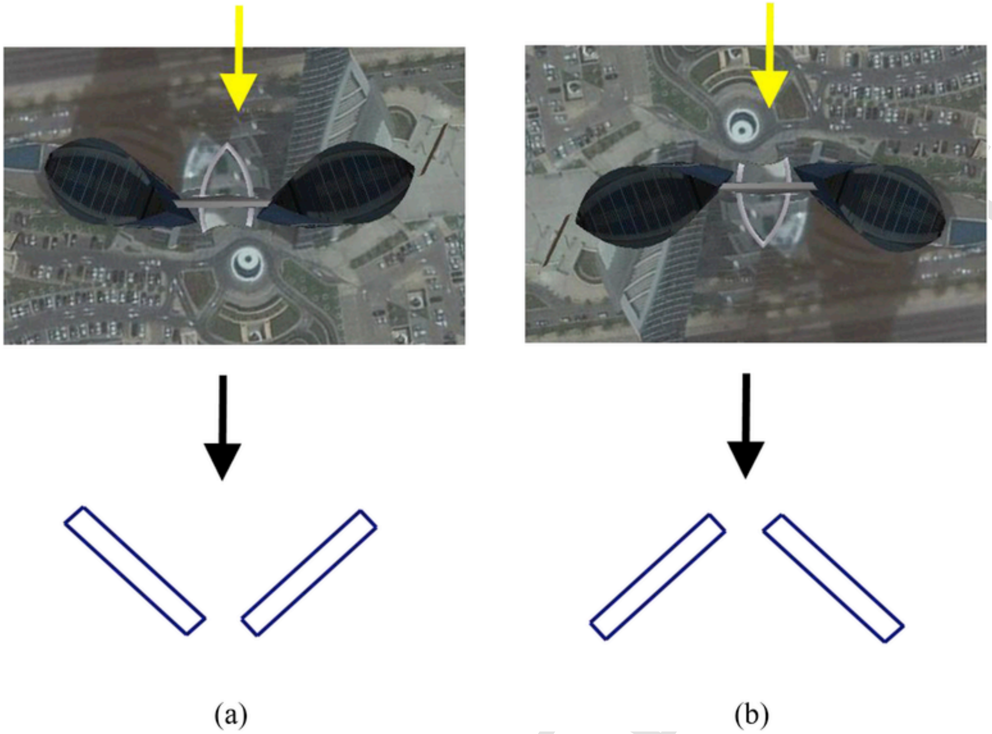

Fig. 9. Bahrain world trade center Configurations: (a) Converging (chosen). (b) Diverging (highest wind speed) (Blocken, 2016).

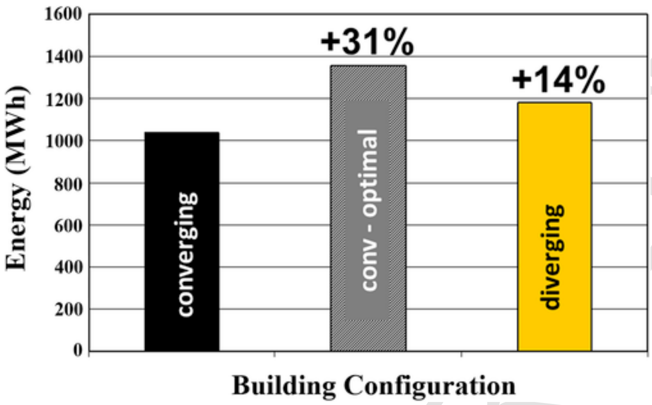

Fig. 10. Estimated Yearly Wind Energy Output using CFD (Blocken, 2016).

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