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Review

A Review of Urban Wind Energy Research: Aerodynamics and Other Challenges

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Abstract: Urban wind energy research is crucial for the success or failure of wind turbines installed in the built environment. Research in this field is fragmented into various research groups working on different topics in isolation with seemingly few efforts of integrating the various fields. This review aims at highlighting the synergies between the various advances, particularly in aerodynamics, but also in other areas. Past and current work has been focused on establishing reliable wind statistics at the site of interest. Advances in building aerodynamics have provided new insight on the local flow occurring at the rotor location. An outlook toward future research and the need to treat the different flow scales in a holistic manner is emphasized given also the recent advances in rotor aerodynamics related to the effect of flow skewness and turbulence. This will shed light on the critical issues that need to be addressed by scientists in order to make urban wind energy viable for decentralized generation. Various other present challenges are discussed briefly including structural aspects, noise emissions, economics and visual impact. Research in this field should be the guidepost for more targeted certification standards, in an effort to regularize the small wind energy market.

Keywords: urban wind energy; wind resource; small-scale wind turbine; Vertical Axis Wind Turbine (VAWT); Horizontal Axis Wind Turbine (HAWT); building integrated wind energy

1. Introduction

1.1. Overview

Perhaps the major challenge of urban wind energy exploitation is associated with the complex aerodynamics that govern urban wind energy systems. The aerodynamic performance of small Vertical Axis Wind Turbines (VAWTs) or even Horizontal Axis Wind Turbines (HAWTs) is heavily influenced by the condition of the inflow given that these are situated in the proximity of buildings or other urban elements. The variability of this inflow condition and the complexity of the system to counteract this variability are the main driving points behind urban wind energy research.

Unfortunately, despite plenty of documented efforts by industries, urban wind energy has many a time been motivated by a need to highlight the energy consciousness of buildings and urban architectural designs. This has also led to turbine designs that are driven by aesthetics rather than functionality with sometimes exorbitant claims on the latter with no certification. Failed projects have inevitably resulted in the consequence of a relatively small uptake when compared to large-scale machines.

Despite these difficulties, the concept of localized power generation remains attractive. The scientific community, as will be shown throughout this paper, has been very active in providing

knowledge accessible to industry. COST Action TU1304 (WINERCOST—Wind energy technology reconsideration to enhance the concept of smart future cities) has been specifically set up to address issues related to urban wind energy. The action provides an interesting platform for the regrettably sparse research groups working in this field to share their research and build a more concerted effort to make urban wind energy ultimately more robust TU1304 WINERCOST Action: Wind Energy Cities [1].

1.2. Scope

The primary scope of this review is mainly the aerodynamic aspects of urban wind energy. Other aspects such as structural, acoustic nuisance, visual impact or economic factors are also discussed since these are all crucial aspects in this area.

In the past, as will be shown throughout this article, there have been reviews that discussed various aspects of urban wind energy. These however mainly deal with either the design of small-scale wind energy systems or more commonly with the wind resource in the built environment. The current review provides a broader picture by considering the latest findings in aerodynamic aspects at various scales and then linking these findings to other less prominent fields of research in urban wind energy, which include noise emissions, economic aspects and visual impact.

The review is therefore meant to provide researchers in urban wind energy an overall perspective on the overarching principles behind urban wind energy generation with emphasis on the need for an integrated holistic approach for future endeavors.

1.3. Organization of the Review

The review is organized into six sections. First, the latest approaches and methodologies used to study the wind resource in urban environments is discussed. As will be discussed, this is an essential pre-requisite in any serious siting of small-scale wind turbines. The local flow physics around the building geometry is discussed with reference to a number of studies that focus on certain generic building geometries. In Section 2.3, the particular issues relevant to small-scale VAWTs and HAWTs are discussed elucidating the various challenges including structural integrity. Less conventional rotor designs are also discussed in a different section with some reference to shrouded turbines. Reference is also made to building integrated wind energy where building form is either designed a priori with wind energy exploitation in mind or building design is exploited for flow augmentation. Finally, research in other aspects is discussed including noise emissions, visual impact and economic factors.

2. Review of the State of the Art

2.1. Urban Wind Resource

One of the major topics of scrutiny in urban wind energy is the quality of the urban wind resource. The aerodynamics of small- to medium-scale wind energy systems in the built environment remains ultimately dependent on the urban micro-climate. For this reason, a section of this review is dedicated entirely to this aspect. There are various literature reviews tackling this important topic including that of Arnfield [2], Mills [3], Walker [4] and Ishugah et al. [5]. The work of Arnfield [2] provides a comprehensive overview of the state of the art in this field with important references to the different scales of flows and turbulence found in the urban environment. Emphasis is also made on the urban heat island effect, but this is of little to no relevance to the ensuing discussion. Nonetheless the author makes an important distinction, on the basis of works by other authors, between the Urban Canopy Layer (UCL) and the Urban Boundary Layer (UBL). The former can be considered to be the distance from the ground to approximately roof level. The latter is the region, from roof level and above, that is affected by the presence of the urban zone. This makes both regions important from the point of view of wind energy harvesting. The paper by Mills [3] is also worth mentioning here and also gives some historical perspectives to the subject. The relevant flow scales depicted in various articles can be encapsulated by the sketch in Figure 1.

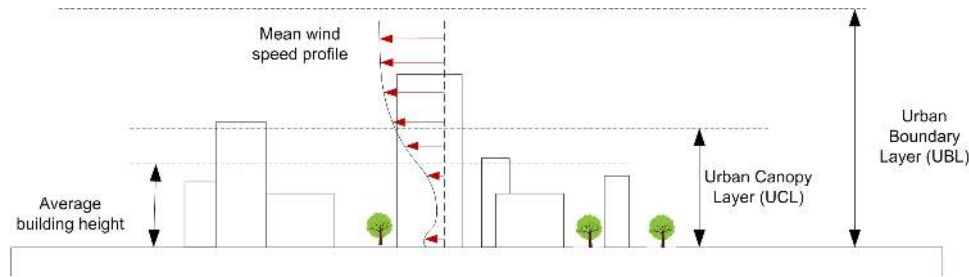


Figure 1. The urban wind profile, mainly composed of the Urban Boundary Layer (UBL) and the Urban Canopy Layer (UCL). Figure adapted from Ng et al. [6].

2.1.1. Analytical and Engineering Based Approaches

A simple equation for the mean wind speed profile for the atmospheric boundary layer under neutrally-stable conditions is given by the well-known log-law as follows Oke [7]:

$$U(z) = \frac{u_*}{\kappa} \ln \left(\frac{z-d}{z_0} \right) \quad (1)$$

where u_* is the friction velocity at the ground surface, κ is the von Karman constant (~ 0.40), z is the height above the ground, z_0 is the aerodynamic roughness height, which is dependent on the terrain type (see Table 1), and d is called the zero-plane displacement at which the wind velocity is 0 m/s. Below this displacement height, the flow is affected by obstacles such as buildings.

Table 1. Surface roughness lengths for various terrain types. Source:Burton et al. [8].

Terrain	Roughness Length (m)
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees	0.1
Open farmland, few trees and buildings	0.03
Flat grassy planes	0.01
Flat desert, rough seas	0.001

Drew et al. [9] performed corrections to wind speed data available across Greater London at the typical turbine heights. The model showed relatively low average wind speeds, and the authors proposed that small-scale wind turbines should be located on the outskirts of the city. For the purpose of roof-mounted wind turbines, the local wind speed at building roofs would be of interest. The ideal method to find these wind speeds is to perform direct measurements of wind speed (and other quantities such as turbulence) on building roofs over a statistically significant period of time. In general, such measurements for urban wind energy exploitation might not be convenient given the intrinsic energy yield limitations of small wind turbines. Due to this, various researchers have considered other approaches of how to estimate the wind speed on building roofs. Usually, these approaches require some data from meteorological stations close to the building site, but this is in many cases unavailable. The models would then enable one to find the annual expected energy yield of the wind turbine.

Millward-Hopkins et al. [10,11] proposed an analytical methodology to scale the logarithmic velocity profile of Equation (1) on the basis of the geometric data of buildings and vegetation found in the urban zone. This can be used to find an informed estimate of the wind speed at hub height of the turbine. Millward-Hopkins et al. [10] report “reasonably accurate” comparisons between the adopted methodology and the anemometer measurements at various locations in four different cities in the United Kingdom. The authors however clearly state that the methodology is limited when it comes to more detailed flow conditions at the roof. In contrast with this method, Al-Quraan et al. [12] proposed an alternative approach to find the wind velocity at the roof of a building. The methodology

requires meteorological and wind tunnel measurements. Briefly, the authors used the wind profile power law as a basis to find the velocity at a particular location just upstream of the building of interest using the meteorological measurements further upstream from the zone. With the aid of wind tunnel measurements, the ratio of velocity at the building roof of interest to an upstream velocity can then be found. This ratio is then used to find the actual wind velocity at the building roof. Schematically, the concept is illustrated in Figure 2. Full details of the method can be found in the full paper. The method was validated using two case studies: (i) with homogeneous upstream terrain and (ii) using non-homogeneous upstream terrain. For the former case, the error between the roof measurements and the proposed method was less than 5%, while in the latter case, the reported error was 20%.

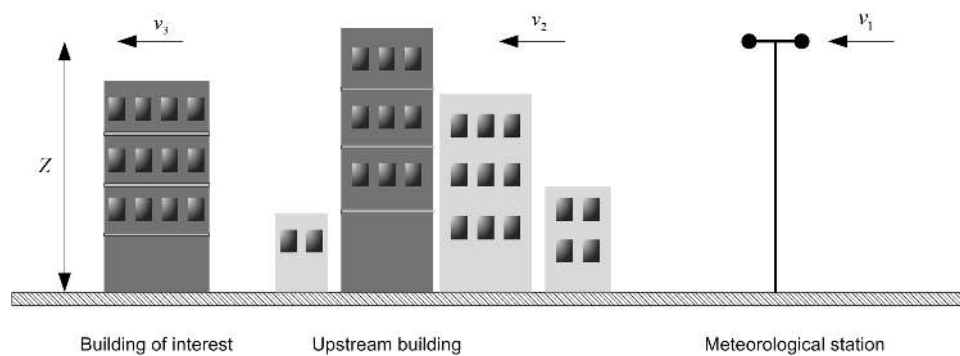


Figure 2. Determination of the velocity v_3 at the building of interest (shaded) using meteorological information. Wind tunnel tests on the same urban zone would be carried out in order to find the ratio $\frac{v_3}{v_2}$. Figure adapted and simplified from Al-Quraan et al. [12].

2.1.2. Probabilistic Methods

A different methodology compared to the previously mentioned methods can be found in earlier literature by Mertens [13], who made use of a Weibull and Rayleigh probability distributions $f(u_s)$ for the wind speed u_s at a height Δh above the roof. This was used to estimate the energy yield from the turbine. The approach was fully described in the paper and was useful given that the method took into account the height of the turbine above roof level. The energy yield can then be found by the probability of the wind speed multiplied by the power output of the turbine at that wind speed:

$$E = T \int_{u_i}^{u_o} f(u_s) P(u_s) du_s \quad (2)$$

where E is the energy, T is the time of operation, u_i is the cut-in wind speed, u_o is the cut-out wind speed and $P(u_s)$ is the power output of the turbine at wind speed u_s . The probability distribution $f(u_s)$ was also used in other studies such as by Safari and Gasore [14], but contrasting with the work of Mertens [13], these simply give distributions of the undisturbed flow. On the negative side, the probability distribution by Mertens [13] required the use of CFD data for the estimation of the changes in wind speed at various locations on the building roof. No details were given regarding the CFD simulation in Mertens [13], but the method certainly accounted for more localized effects found on roofs compared to the methodologies proposed by the authors mentioned earlier. The approach by Al-Quraan et al. [12] was overall more straightforward than this method by Mertens [13], but its limitation in the presence of non-homogeneous upstream terrain limited its applicability in various scenarios and is something that needs further work.

Lately, Simões and Estanqueiro [15] reported yet another approach where an urban digital terrain model was used as a complex terrain input to a commercial software WindSim[®]. Another commercial software Meteodyn[®] was then used for the modeling of a sub-region within the urban zone in order to directly model the details of the building geometry over a small area. Correction factors were then

applied to the wind resource maps found from the WindSim simulations. The methodology was also validated, and an error of around 10% on the mean wind speed was noted. The model needed wind probability distributions as an input. The scope of the approach was to be applied for large areas and hence to provide informed decisions for urban planning purposes. Details of the urban fabric can also be modeled accurately if these are available. More local studies on the flows over building roofs have been performed by Balduzzi et al. [16] using CFD analysis of the flow field in the built environment in a typical European urban zone. The purpose of this study was to assess the feasibility of installing roof-mounted wind turbines. This work highlights, if anything, the need to quantify accurately the flow field around individual buildings as opposed to the low resolution characterization found in some of the studies mentioned in this section. This paves the way for the discussion in Section 2.2 regarding the current state of the art in building aerodynamics and eventually turbine aerodynamics. Before doing so, a more detailed critical analysis of the CFD approaches used to quantify the wind resource is necessary.

2.1.3. Urban Wind Resource Using CFD Approaches

In CFD models of flows in the urban environment, the boundary condition for the inlet wind speed to the domain follow the relationships proposed by Richards [17], Harris, R.I, Deaves [18] and Richards and Hoxey [19] for the mean wind speed profile, turbulent kinetic energy and the turbulent dissipation rate, respectively:

$$U(z) = \frac{u_*}{\kappa} \ln \left(\frac{z + z_0}{z_0} \right) \quad (3)$$

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \quad (4)$$

$$\epsilon(z) = \frac{u_*^3}{\kappa(z + z_0)} \quad (5)$$

where u_* is the wall friction velocity and C_μ is a turbulence model constant. Wall functions are used with turbulence models the do not integrate the flow up to the wall (such as the $k - \epsilon$ models). These wall functions require the specification of the sand grain roughness height k_s and the roughness constant C_s (usually taken as 0.5 Blocken et al. [20] due to the absence of particular guidelines). Blocken et al. [20] provided an interesting relationship for the sand grain roughness to preserve the horizontal homogeneity of the boundary layer:

$$k_s = \frac{9.793z_0}{C_s} \quad (6)$$

Yang et al. [21] claimed that a much better homogeneity can be attained by means of the use of the modified equations for k and ϵ :

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \sqrt{C_1 \ln \left(\frac{z + z_0}{z_0} \right) + C_2} \quad (7)$$

$$\epsilon(z) = \frac{u_*^3}{\kappa(z + z_0)} \sqrt{C_1 \ln \left(\frac{z + z_0}{z_0} \right) + C_2} \quad (8)$$

where C_1 and C_2 are model constants obtained by means of data fitting with wind tunnel measurements (−0.17 and 1.62 respectively). These expressions have been used by Abohela et al. [22] in their study on the effect of roof shape on the flow and hence the energy yield from roof-mounted wind turbines.

Gagliano et al. [23] proposed an interesting methodology wherein CFD simulations were applied directly to inform decision making. The results from the CFD simulation of the urban wind

environment were used in a Geographic Information System (GIS) to be able to provide more informed decisions with regards to the placement of urban wind turbines on the basis of the expected power production. Such a tool provides a very practical approach for easy implementation of urban wind turbines. The limitations are basically associated with the CFD model itself depending on the predictive accuracy required.

2.2. Building Influence and Wind Energy Exploitation

As illustrated in Figure 3, the flow around a simple cubic building is relatively complex. Over the sides of the building including the roof, a separation zone will result. A horseshoe vortex (also apparent in Figure 3) will be present. On the leeward side of the building, a highly turbulent wake can be found with interesting vortical structures found close to the building leeward façade. This is of little practical importance in the context of wind energy exploitation, but is of course important in problems such as pedestrian wind comfort.

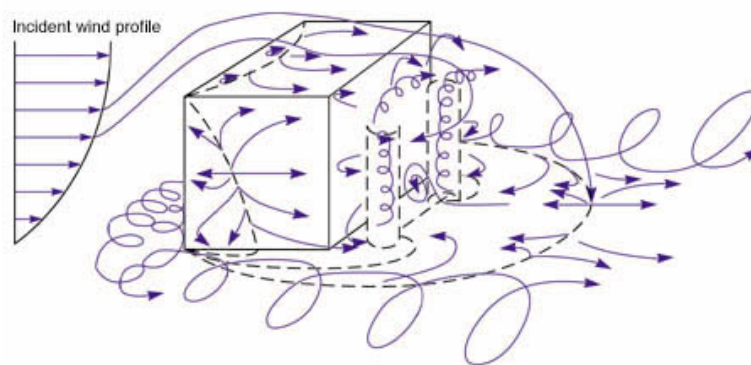


Figure 3. Conceptual representation of the flow around a building. Image courtesy of Laboratory LLN. [24].

The main regions of interest in urban wind energy are those where flow amplification can occur. Such flow accelerations are well known to occur above the roof, as well as the side façades (parallel to the wind flow) (see Figure 4a,b). In practice, in highly urbanized zones, adjacent buildings would prevent such a possibility. Another option, which has been employed in twin tower complexes such as the Bahrain World Trade Centre, is turbines located in between buildings (see Figure 4c). There have been various studies in this regard including both numerical and experimental work. The aim of these studies was in most cases not directed towards wind energy harvesting, but rather to other issues such as for example determination of surface pressures or pedestrian wind comfort. Experimental measurements of isolated building flows have been carried out in wind tunnels using hot wire measurements (Kawamura et al. [25], Murakami et al. [26], Kamei and Maruta [27]), scour techniques (Livesey et al. [28]) and infrared thermography (H. Wu [29]). These studies were carried out with the intention of studying flows at the pedestrian level. More interesting to this review article is the experimental work carried out using Stereo Particle Image Velocimetry (SPIV) (refer to Arroyo and Greated [30] for more information on this technique). With this technique, 3D velocity field information over a plane can be obtained, thus allowing one to establish regions where flow acceleration can be present.

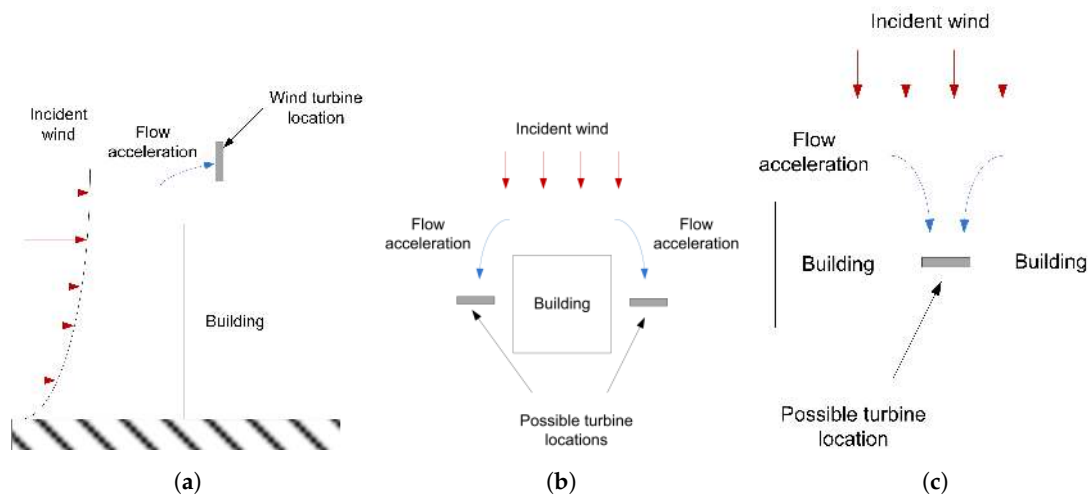


Figure 4. Possible turbine placement to exploit flow acceleration. (a) Roof turbine; (b) side façade turbine; (c) between buildings turbine.

Some computational work using Computational Fluid Dynamics (CFD) has also been performed such as Yu et al. [31], Shao et al. [32], Murakami and Mochida [33], Wright and Wood [34] and, more recently, Lu and Ip [35], Lu and Sun [36] and Toja-Silva et al. [37]. Many of these studies are aimed at studying the flow amplification around buildings. An important conclusion can be extracted from the mentioned studies. The separation regions such as the sides and roof of the building are difficult to predict using RANS techniques such as the standard $k - \epsilon$ model, which in particular shows an over-estimation of the turbulent kinetic energy near the edge of the building. Non-linear $k - \epsilon$ models have been shown by Wright and Wood [34] and Shao et al. [32] to provide better prediction. The latter authors compare the various re-attachment length predictions on the roof and behind the buildings obtained using the various models (including Large Eddy Simulation (LES)). Unfortunately, the authors did not discuss the separation bubble height above the roof. This is very important when considering the turbine vertical positioning above the roof. In any case, the LES approach provides the best overall prediction capability compared with experimental data as expected. We next discuss some crucial details of the latest developments in CFD modeling of building aerodynamics, which are thought to be crucial in the determination of the local flows, which are of interest in urban wind energy.

Mertens [13] provided details of the roof flow in terms of the separation bubble size. The separation streamlines as obtained by the authors are shown in the adapted Figure 5a. The Reynolds Stress Model (RSM) was used as a turbulence model. The authors reported a strong sensitivity to the surface roughness z_0 . The model used a relatively small domain, and it was not clear whether any tests for horizontal homogeneity of the wind profile were made. Despite all this, the discrepancies in the roof separation layer are still expected to be a function of the roughness particularly due to the roof roughness itself.

The work of Mertens [13] is also important as it gave information on the skew angle that would be expected relative to the flat horizontal roof. For the case presented (details of the building dimensions can be found in the full paper), the skew angle was greatest at the building windward edge and reduced downwind along the roof to around -5° – -10° at the roof center depending on the roughness used. This is shown in Figure 5b, adapted from Mertens [13]. The skew angle will affect the turbine performance both in the case of a HAWT (which would correspond to yawed flow with yaw angle equal to the skew angle), as well as a VAWT. The definition of this skew angle is given in Figure 6. For the former type of turbine, the performance degrades from the axial flow condition by the well-known relation (see R.P. Coleman, A.M. Feingold [38]).

$$\frac{C_P}{C_{P,0}} = \cos^3 \gamma \quad (9)$$

where C_P is the power coefficient of the yawed turbine, $C_{P,0}$ is the power coefficient for the axial flow turbine and γ is the yaw (or in this context, the skew angle). For the range of skew angles found in the study of Mertens [13], the C_P might vary from 0.96–0.99 of the C_P corresponding to the axial flow condition, which is not particularly detrimental. No such simple relation exists for the case of a VAWT, but as will be discussed, Simão Ferreira et al. [39] showed that the maximum power coefficient was attained at a non-zero skew angle. More studies are needed on the variation of the skew angle on different sideways positions on the roof.

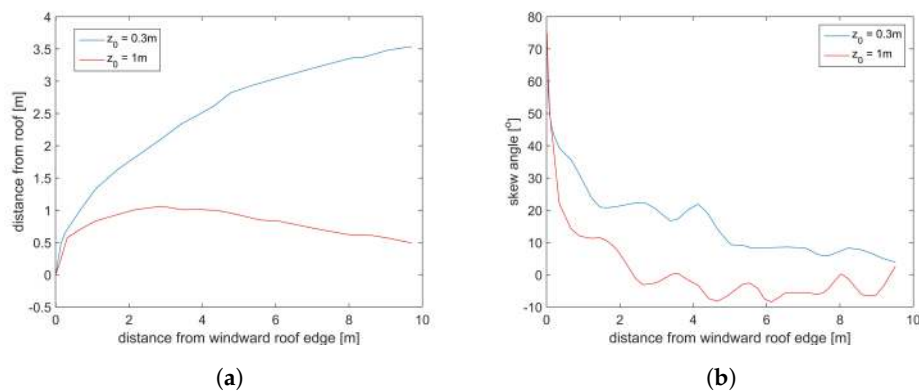


Figure 5. Separation streamlines and skew angle above the roof for different roughnesses. Figures are adapted from Mertens [13]. (a) Separation streamlines above the roof. (b) Skew angle above the roof.

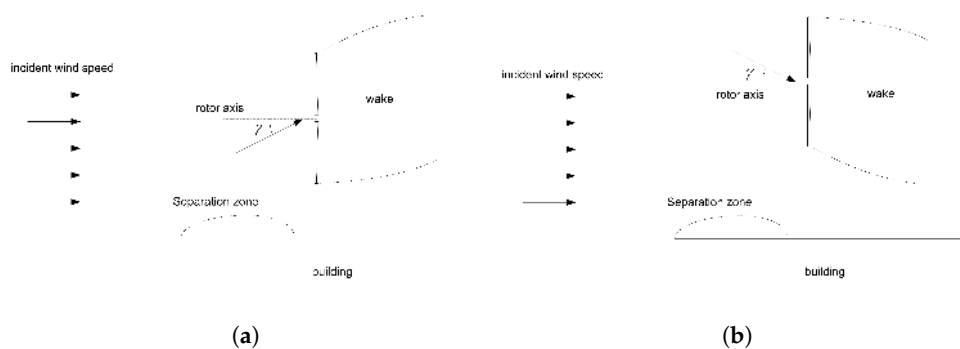


Figure 6. Skew angle γ definition. (a) Positive skew angle (wake directed away from the roof). (b) Negative skew angle (wake directed towards the roof).

Much of the reviewed literature in relation to studies on how buildings can provide flow amplification, which is interesting for wind energy capture, considered cubic-shaped buildings in isolation, or an array of cubic buildings. Abohela et al. [22], using a CFD approach, studied the effect of different roof shapes (including flat, domed, gabled, pyramidal, vaulted and wedged) on the flow acceleration. It transpired that the vaulted roof could provide an increase in energy yield of 56.1% at the center of the roof. The work of Toja-Silva et al. [40] provided another extension to that of Abohela et al. [22] and investigated different building wall shapes. The cylindrical wall provided an even better performance than the flat (cubical wall case) with low turbulence intensities. The authors reported that the influence of turbulence intensities can have a very negative impact on performance. This contrasts with wind tunnel tests using different turbulence intensities carried out on VAWTs, which will be discussed in the next section.

2.3. VAWT/HAWT Aerodynamics for Urban Wind Energy

2.3.1. Horizontal Axis Wind Turbines

The aerodynamic literature on HAWTs is abundant particularly for large-scale and wind farm applications. Small-scale HAWT research for urban wind energy use is much less documented compared to small-scale VAWT research given the better suitability of the latter (see Toja-Silva et al. [41] for more discussions related to this). One of the main reasons is due to the fact that the VAWT operation is independent of the wind direction, and as was discussed earlier, the wind resource in the built environment can have overly complicated features. Usually, small-scale HAWTs for urban deployment have a wind vane in order to direct the turbine rotor perpendicular to the main flow direction. This can lead the HAWT to operate in short periods of yaw, a phenomenon that is important and has been studied for large-scale turbines (refer to Micallef and Sant [42]).

HAWTs need to be installed outside of flow separation zones around buildings including the roof separation zone. At the same time, the height of the turbine above say the roof level needs to be acceptable in terms of standards or policies that might apply. The effect of the roof surface does not seem to play an important role in the wake aerodynamics, as shown in the paper by Troldborg et al. [43], who studied the ground effect. The authors used an actuator disc approach and showed that there was a marginal effect on the power coefficient of the turbine due to ground proximity. For HAWTs, the influence of skew was for all intents and purposes equivalent to yaw unless the skew angle was negative (directed towards the roof in the case of roof-mounted turbines). In such a case, the influence of the roof might be more important, but to the author's knowledge, no literature exists in this regard.

The performance of a HAWT rotor located on a roof-top was recently assessed by Micallef et al. [44] using a hybrid approach modeling both the building and the turbine modeled as an actuator disc. The turbine C_p was found to increase even in the close vicinity of the roof, but above the separation zone. The work provided some indication on the lower limit that the turbine can be placed over the roof without significant deterioration in performance. The study was however limited to the optimal tip speed ratio condition only. A contour of the resulting velocity magnitudes is shown in Figure 7. Using a similar, but more simplistic approach, Guerri et al. [45] considered also the influence of parapet walls on the performance. These were found to have an important effect. These types of modeling approaches where the effect of the rotor is included as part of the flow solution are important given that a wind turbine is effectively another force on the flow. The previous discussion on the research in building aerodynamics does not consider such influence, and hence, the conclusions on the optimal turbine locations may be modified on the basis that the flow field is changed due to the influence of the rotor itself. The extent of this effect is dependent on various factors, including the frontal surface area of the rotor, as well as the operating thrust. These issues have not been discussed rigorously in the literature and certainly need more investigation.

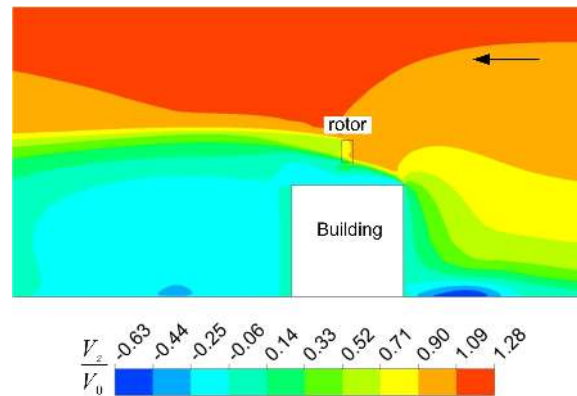


Figure 7. Normalized velocity (perpendicular to rotor axis) with the free stream from a hybrid rotor and building model. The case shown is for a turbine height, which is 1.3-times the building height. The interaction of the rotor and building wakes are clearly visible. Adapted from Micallef et al. [44].

Since the wind resource is rather limited in urban environments, one of the main desirable features of a small-scale turbine is the minimum start-up torque required, which is determined by what is commonly known as the cut-in wind speed. Ebert and Wood [46] showed that for a HAWT operating at low wind speeds of 4 m/s, gusts were found to be beneficial to start off the turbine. Wright and Wood [34] have performed field studies on small-scale HAWTs and showed that most of the starting torque is contributed by the root, while as expected, most of the power generated is then contributed by the outboard regions of the blade. No studies can be found to the author's knowledge dealing specifically with root blade design for small-scale wind turbines, which can provide new insight on the design to attain lower cut-in wind speeds.

For large-scale wind energy studies, certain wind tunnel studies are performed (due to the tunnel size limitations) on small-scale rotors with the Reynolds number equivalence, which cannot be attained. Such studies are in fact carried out using blade Re in the order of a few hundred thousands. On the other hand, full-scale turbine blades operate at Re in the order of a few million. Most of these experiments in fact assume Re independent behavior of the blades. The experimental data from experiments such as those mentioned earlier are nonetheless suitable for the study of small-scale rotors, and no assumptions can be required regarding Re effects.

2.3.2. Vertical Axis Wind Turbines

VAWTs can fall under two main categories: Darrieus and Savonius rotors. The former is usually considered a lift type rotor since most of the torque is generated by means of lift forces. On the other hand, the Savonius rotor is a drag type rotor, which mostly operates through the action of drag forces. The literature on Savonius rotors has been reviewed by Chen et al. [47]. Furthermore, a very comprehensive review of the timeline of Darrieus VAWT development can be found in the recent work by Tjiu et al. [48,49]. VAWTs are also being considered for large-scale implementation including offshore wind energy applications. The technology was also reviewed by Jin et al. [50]. All these reviews highlight the extensive body of knowledge generated on VAWT technologies.

The research in VAWT aerodynamics for urban wind energy is abundant. Most of this is nonetheless focused on the rotor operating under idealized operating conditions, far from the complex urban conditions found in the built environment. The reason for this is mostly due to the already complex aerodynamics that characterize the VAWT.

The bound circulation on a VAWT blade varies along the blade as a result of the non-uniform induction field and also varies in time due to the rotation of the blade causing a windward and leeward motion, which changes the angle of attack periodically. The variation of bound circulation along the blade gives rise to trailing vorticity, whereas the time variation of bound circulation gives rise to

shed vorticity. In the wake, self-interaction of this vorticity field results in complex wake kinematics. Howell et al. [51] performed both wind tunnel experiments and CFD work focusing on the power coefficient of a VAWT under different tip speed ratio conditions, solidity and blade surface finish. The 2D simulations took into account only the shed component of vorticity and therefore tended to over-predict the power coefficient. The major limitations with the wind tunnel tests were the relatively small rotor size that was used, which limits the maximum blade Re attained. Recently, the work by Tescione et al. [52] and Tescione [53] provided an excellent characterization of the straight-bladed Darrieus VAWT wake using experimental Stereo Particle Image Velocimetry (SPIV), as well as 3D free-wake vortex panel methods. Figure 8 shows contours of the out of plane vorticity as obtained from the SPIV measurements presented in Tescione [53]. Other related work detailing the VAWT rotor aerodynamics for low solidity rotors can be found in Lam and Peng [54] and Peng et al. [55].

Simão Ferreira et al. [56] provided direct visualization of the leading edge vortex due to the dynamic stall phenomenon (see Figure 9). The tests were carried out for a single-bladed rotor at a low tip speed ratio of two. The study was therefore focused on the fundamental generation and convection of the circulation for the purpose of numerical model validation. The authors however acknowledged that the experimental uncertainty can be considerable. Armstrong et al. [57], using a full-scale, high solidity rotor, also experimentally highlighted the dynamic stall phenomenon on VAWT blades and the resulting interactions. In this case, the observations for dynamic stall were carried out by means of light-weight tufts attached to the blade. Dynamic stall was also numerically modeled with CFD by various authors such as Wang et al. [58], who claimed good correspondence with experimental data except at very high angles of attack. There has also been an attempt to model the VAWT rotor and the dynamic stall phenomenon using CFD. McLaren et al. [59] performed such an analysis and highlighted the complicated blade-vortex interactions. These are particularly relevant since the authors made use of a high solidity rotor. The authors claimed that these have considerable impact on power extraction. Later numerical analysis of dynamic stall was carried out by means of 2D CFD by Almohammadi et al. [60], who emphasized the strong sensitivity on the transition model used in the simulation, which would improve the prediction of laminar separation bubbles. Despite the past efforts in CFD modeling of VAWTs such as Lanzafame et al. [61], McNaughton et al. [62], Raciti Castelli et al. [63] and Trivellato and Raciti Castelli [64], it is felt that there is still the need for more studies on the resulting blade wake interactions and the suitability of turbulence models in this regard. Furthermore, it would be interesting to consider the effects of such phenomena under the more complicated wind flow behavior found in the built environment.

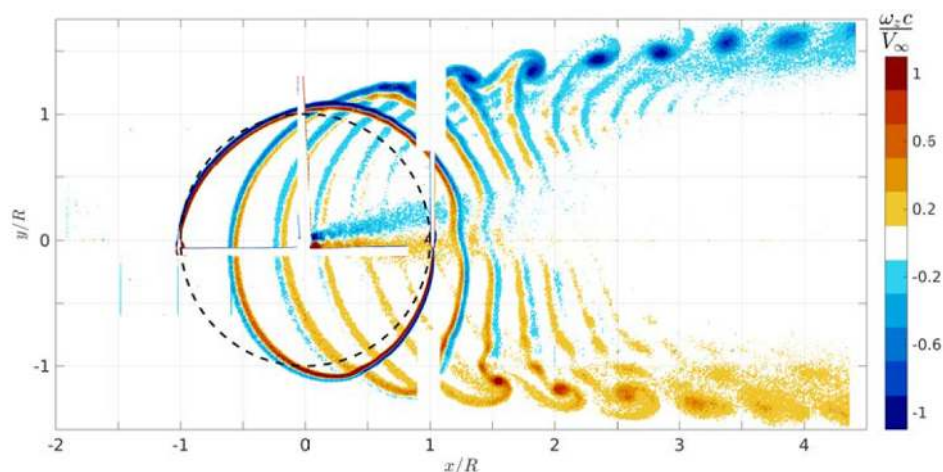


Figure 8. Contour plot of vorticity (out of plane) at the equatorial plane of a three straight-bladed VAWT. Results are obtained from Stereo Particle Image Velocimetry (SPIV) measurements. This provides a clear picture of how shed vorticity distributes itself particularly towards the wake edges. Image courtesy of Tescione [53].

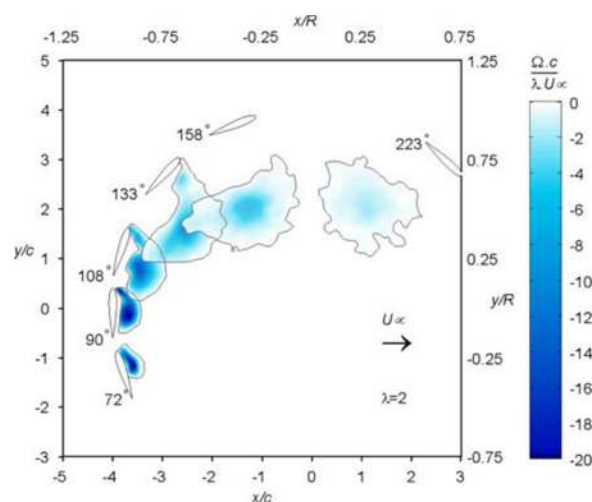


Figure 9. Evolution of the leading edge vortex circulation for different blade azimuthal positions. Image courtesy of Simão Ferreira et al. [56].

The work by Howell et al. [51] mentioned earlier explored also the influence of blade roughness effects and Reynolds numbers. The authors claimed that below a critical Re number of 30,000, the performance of the VAWT reduced for a smooth blade surface. The authors hypothesized that this was due to an earlier laminar to turbulent transition for a rough surface causing the boundary layer to remain attached with the consequence of a lower drag. Beyond this critical Re , the performance improved with a rough surface finish of the blades. This issue of blade roughness has very important implications given the exposure of urban wind turbines to possible causes of roughness including ice, insects and salt deposition (in coastal areas), amongst other factors.

The presence of skewed flow on roof-mounted wind turbines as highlighted earlier in this review and by Mertens [65] points to the need for dedicated aerodynamic analysis of this phenomenon. This skew is well known to be detrimental in the case of HAWTs, but favorable for VAWTs, as shown in the same paper and by other authors such as Simão Ferreira et al. [39]. The main limitation of the work by Mertens [13] and Mertens et al. [66] is the fact that the skew angle calculated did not include the influence of the turbine itself on the roof, which would certainly alter this angle due to its own

blockage to the flow. The results of Mertens [13] and Simão Ferreira et al. [39] were consistent in that an increase in the power coefficient of around 0.2 from the non-skewed case may be observed at a skew angle between 25° and 30°. From Figure 6b, it is clear that such an angle can be attained towards the leading edge of the roof. CFD work by Chowdhury et al. [67] also provided some interesting physical insight of the skewed flow phenomena for VAWTs, but was not aimed at turbines operating in built environments.

As discussed earlier, turbulence in the built environment is the norm rather than the exception. The influence of turbulence on the rotor operation becomes therefore very relevant in urban wind energy. Unfortunately, there have been few studies tackling this issue directly applied to VAWTs. Miao et al. [68] showed how turbulence can reduce the sensitivity of the turbine performance to the Re number using wind tunnel testing. Ahmadi-Baloutaki et al. [69] also performed tests on a model VAWT under controlled wind tunnel conditions using different levels of turbulence intensities (up to 10%) by means of turbulence grids. The authors showed that there was some improvement in performance with high turbulence levels compared to the very low turbulence intensity of 0.5%. The study was unfortunately very limited in that a very small, non-optimal regime of tip speed ratios was used for the tests. The authors also claimed that the start-up of the turbine was improved with increasing turbulence intensity. Wekesa et al. [70] performed both wind tunnel measurements, as well as CFD calculations on a Savonius rotor. The authors carried out tests for ‘no turbulence’ conditions (tunnel background turbulence $I < 0.46\%$) and a ‘turbulent’ case with turbulence intensity $9\% < I < 14\%$. The range of tip speed ratios considered was adequate such that the peak power coefficient could be clearly distinguished. The results obtained were consistent in some way with the work of Ahmadi-Baloutaki et al. [69]. Nonetheless, some interesting conclusions were made regarding the fact that the power coefficient was increased when using relatively low velocities. The authors made a reference to Maldonado et al. [71] to support this finding and stated that this may be caused by the prolonged attached flow as a result of turbulence to higher angles of attack. At higher velocities (greater than 8 m/s), the power coefficient was found to be smaller than for the ‘no turbulence’ case. This was attributed by the authors to gusts, which caused furling.

Recently, Onol and Yesilyurt [72] performed coupled 2D CFD and rotor dynamics modeling in order to determine the power performance of a small-scale VAWT under gusty wind conditions specified in the IEC61400—Wind turbines: Part 1 Design Requirements standard [73]. In terms of the free stream wind velocity U_0 , the gust start time t_0 , the gust amplitude speed u_e and the gust period T_g :

$$U = \begin{cases} U = U_0 - 0.37u_e \sin\left(\frac{3\pi(t-t_0)}{T_g}\right) \left[1 - \cos\left(\frac{2\pi(t-t_0)}{T_g}\right)\right], & \text{if } 0 \leq t - t_0 \leq T_g \\ U_0, & \text{otherwise} \end{cases} \quad (10)$$

The authors reported a higher average power coefficient C_p than the steady wind speed case, but the oscillations were of course much larger. Nonetheless, the influence on the generator power production was noted to be much lower. This means that a more pertinent problem would be the issue of fatigue loading rather than electrical power production. Unsteady inflow 2D simulations were also carried out by Wekesa et al. [70] for case studies in Kenya. 3D calculations and experimental validation would be very interesting for future work and are also highlighted in the conclusions by Bhargav et al. [74]. The authors found a higher C_p under fluctuating winds, which was claimed later by Onol and Yesilyurt [72]. Testing in the built environment of small-scale wind turbines is relatively limited from the literature. One interesting example (which however considers an open field site) is Kjellin et al. [75], who carried out measurements on a 12-kW H-rotor. The authors presented the variability of the measured C_p . The variability in C_p for this particular testing campaign was of the order of 30%. The variability in the wind resource was expected to be more for the case of an urban site.

2.3.3. Structural Considerations

Apart from the need to ensure that small wind turbine blades can structurally sustain extreme events such as gusts, the unsteady environment characterizing urban areas is the cause of concern for fatigue performance of blades and support structures. Indeed this issue is another phenomenon that requires a different design approach compared to the large turbine counterparts. Mouzakis et al. [76] reported that fatigue loading in a complex terrain environment may increase by more than 30%. Studies specifically targeted for urban wind turbines are limited. Bashirzadeh Tabrizi et al. [77] studied the flapwise bending moments on the NREL 10-kW small wind research turbine. The main conclusion was that the Normal Turbulence Model (NTM) (see Equation (11) where σ_1 is the standard deviation of the longitudinal wind speed, I_{15} is the characteristic turbulence intensity at 15 m/s and V_{hub} is the hub wind speed) specified in the IEC6400-2 [78] standard, which is specified for open terrain locations, is not suitable for application in the aero-elastic and fatigue analysis of small wind turbines. The authors suggested improving this model by adjusting the integral length scale in the Kaimal spectra used in TurbSim/FAST codes.

$$\sigma_1 = I_{15}(0.67V_{hub} + 5) \quad (11)$$

Hamdan et al. [79] reviewed the possibilities of using Structural Health Monitoring (SHM) of VAWT wind turbine blades used in urban areas for local climatic conditions in Malaysia. Such measures can increase costs, but provide useful insight on the turbine structural performance in situ. Pourrajabian et al. [80] performed an aero-elastic optimization for small wind turbine blades. A hollow blade was found to be the optimal design by decreasing rotor inertia (and hence, smaller cut-in wind speed) while at the same time sustaining the relevant operational stresses. The cost-effectiveness of using such blades for urban wind turbine applications is not clear, but the optimization exercise is useful nonetheless. Shah et al. [81] referred to alternative materials for composite wind turbine blades. The same authors (Shah D, Schubel PJ, Clifford MJ [82]) have shown that a Pultruded Fiber-Reinforced Plastic (PFRP) small wind turbine blade does not exceed the design fatigue loads over a 20-year lifetime.

2.4. Rotor Design

Islam et al. [83] provided a detailed review of design methods used for Savonius-type rotors. Another recent paper concerning Savonius-type rotors is that by Kumbernuss et al. [84], where the authors discussed the sensitivity of certain design parameters such as the overlap ratio and phase shift angle on the performance of the rotor. Larin et al. [85] performed an optimization analysis on position, blade number and circumferential length for a horizontal Savonius rotor. Interestingly enough, the paper proposed a synergistic approach where the building was included within the simulation. This is, to the author's knowledge, the first example of a model combining both the building and the full rotor in one simulation (the study by Micallef et al. [44] modeled the rotor as an actuator disc only). Bianchini et al. [86] on the other hand reviewed the design methods for Darrieus H-VAWTs. Aslam Bhutta et al. [87] provided a more general review of the design and development of all types of VAWTs.

The design of VAWT wind turbines has been lately addressed by considering the airfoil design. Selig and McGranahan [88] performed wind tunnel tests on six airfoil types for application as small wind turbines. Lately, with the increased interest in multi-MW VAWTs, Ferreira et al. [89] studied an optimal airfoil shape for these types of machines. The conclusions, still applicable for small-scale turbines, stated that the design for surface roughness is in conflict with the control of the dynamic stall phenomenon. Studies on blade design can be found in Bedon et al. [90] and Kear et al. [91]. The latter focused on the optimal chord distribution for a troposkein VAWT geometry. Various design optimizations of the overall rotor can be found, including those by Wang et al. [92] and Al-Bahadly [93].

More novel proposed designs can be found in Chong et al. [94], Kumbernuss et al. [95], Prince et al. [96] and Yao et al. [97]. Perhaps the most interesting and well-researched solution to improve the performance of urban wind turbines is the shrouded rotor concept (for an introductory aerodynamic overview, the reader may wish to refer to Hansen [98]). By employing a diffuser all around an HAWT rotor (see Figure 10), a flow acceleration and therefore increased mass flow rate through the rotor may be attained. This mass flow increase depends on the diffuser itself. By employing an airfoil section, a lift is generated all around the diffuser, which causes a circulation and hence an increased flow through the rotor. It can be theoretically shown that the increase in the power coefficient (C_p) of the rotor is proportional to the ratio of the mass flow rate through the diffuser and the mass flow rate through the rotor when the diffuser is not present (Hansen [98]). In effect, this means that the Betz limit can be exceeded. This was confirmed by Gilbert and Foreman [99] with wind tunnel experiments and later by Hansen et al. [100] numerically. Reports of shrouded rotor research date back to Lilley and Rainbird [101]. Lately, more renewed interest in the subject has arisen with the works by Aranke [102] with a study focused on optimizing synergistically the shroud and blade geometries. Applications of shrouded rotors in the built environment were investigated by Krishnan and Paraschivoiu [103] using a numerical approach. The authors reported an improvement in C_p from 0.135–0.34 by using a diffuser. Dighe et al. [104] also performed CFD computations, but highlighted the need for more experimental testing using advanced techniques such as particle image velocimetry.

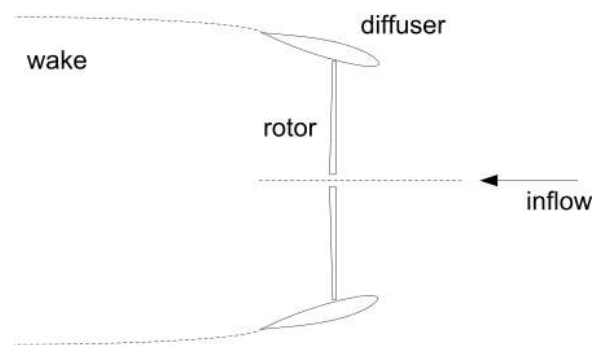


Figure 10. Shrouded rotor concept. The diffuser enables a flow acceleration, increasing the performance of the rotor.

For VAWTs, the analogue of a shrouded rotor would be a wind booster where the rotor is contained between an upper and a lower surface. Studies specifically on this type of configuration are rare. Müller et al. [105] mentioned efficiencies exceeding the Betz limit. The authors admitted that the effect of certain parameters of interest on the performance such as the blade number was unclear. Korprasertsak and Leephakpreeda [106] performed an optimization analysis on the rotor design itself in terms of the number of blades, their shape and their pitch angle. This provides a solution for low wind speed areas. Despite the general lack of literature on wind boosters, building integrated wind energy generally provides similar solutions where the building is intrinsically designed to provide the effect of a wind booster. This will be discussed next.

2.5. Building Integrated Wind Energy

As was seen, the building presents a useful means of modifying the flow in order to increase the inflow velocity to the wind turbine. When the building is designed specifically for this purpose, the turbine is called a Building Integrated Wind Turbine (BIWT). Some recent examples of this are given in ELMokadem et al. [107] and Ishugah et al. [5]. Various novel designs for BIWTs were also discussed in van Bussel and Mertens [108]. Chong et al. [109] and Chong et al. [110] even proposed to integrate the wind turbine with other technologies located on the building including cooling towers and a solar

and water harvester, respectively. These novel demonstrations provide new possibilities of how to intelligently harness wind energy in the urban environment.

Some case studies of actual projects implementing wind turbines in buildings were presented by Sharpe and Proven [111], Li et al. [112] and Heo et al. [113]. The CFD work of Heo et al. [113] showed that the action of the building was similar to that of a shroud or a duct, and hence, a C_p higher than the Betz limit was claimed. It was also found that, contrary to the isolated turbine, the turbine was not sensitive to a yawed inflow. Not only this, axial flow was not necessarily the condition that yielded maximum power. The authors claimed that the yaw angle for maximum power corresponded to -10° (the negative indicates a north-westerly direction). This angle will of course depend on the building shape. Li et al. [114] performed wind tunnel measurements, and similar conclusions to the later work of Heo et al. [113] were presented. Another important point is the influence of surrounding buildings. In addition, it was found that the resulting wind loads on the building were reduced.

Flow between building passages in relation to pedestrian wind comfort have been discussed in Blocken et al. [115]. The authors concluded that the highest flow amplification occurred in diverging rather than converging configurations. This is contrary to the principle governing the 'Venturi effect', which is the same principal the author rejected in the case of building flows due to the unconfined flow above the building Blocken et al. [116]. This was confirmed recently by Allegrini and Lopez [117] using PIV wind tunnel experiments.

Another form of building integrated wind energy makes use of ducted micro-turbines such as found in Grant and Kelly [118], Grant et al. [119] and Park et al. [120]. Operating power coefficients of 0.3 have been observed, but it remains unclear how such ducted micro-turbines can benefit dramatically the energy budget of the building especially when one considers operational and installation costs. From an aerodynamics point of view, the research is understandably lacking.

2.6. Other Factors

2.6.1. Noise and Vibrations

Usually, small wind turbines operate in the vicinity of habitable/occupied spaces, which implies that noise levels should be within acceptable (legislative) levels. An obvious approach in the design of urban wind turbines is to reduce aerodynamic noise emission and lower the design rotational speed. Liu [121] recently reviewed the noise generation and de-noising techniques used for large-scale turbines. Noise emissions can be of an aerodynamic or a mechanical nature. Studies on noise emission from large-scale wind farms are common (see for example Pedersen and Waye [122]). The authors concluded that annoyance due to visual impact was correlated to annoyance caused by noise. Bakker et al. [123] reported that there was no direct effect of wind turbine noise in terms of sleep disturbance or psychological stress. Noise emissions from wind farms are however of greater concern than those due to micro- or small-scale wind turbines. Studies specifically targeted at this scale of turbines are therefore rather limited. Taylor et al. [124] on the other hand reported a correlation between the general attitude towards wind turbines and the perception of noise emanating from these machines in the built environment. Typical sound levels reported are 45 dB(A) corresponding to a 7-m/s wind. Such levels are of the order of vapor compression air-conditioning units commonly found in built environments. De Santoli et al. [125] evaluated (only qualitatively) the noise impact, amongst other factors, of a 3.7-kW micro-wind turbine. The approximated noise emissions were quantified as 45 dB(A)–50 dB(A). A survey carried out within the EU IEE project WinEur [126] in 2006 revealed that 63% of the urban wind turbines on the market had a source noise level of less than 40 dB(A), at a wind speed of 5 m/s, which indicates that urban wind turbine noise issues can be dealt with in the design. All these recent studies may lead to the conclusion that in general, noise emissions do not present particular issues. Researchers in the field of rotor aero-acoustics are nonetheless still active in the optimization of small-scale wind turbine noise performance. Ma et al. [127] reported the successful application of coarse mesh CFD aeroacoustic models for the prediction of a small wind turbine. Using

a CFD unsteady RANS-based approach, Mohammed Mohamed [128] claimed that a Darrieus rotor with decreased solidity can reduce noise emissions by up to 7.6 dB. Göçmen et al. [129] performed airfoil design optimization with reduced noise emissions by up to 5 dB for a small-scale turbine. Lee and Lee [130] performed experimental measurements of the influence of trailing edge bluntness on the aerodynamic noise.

Vibrations occurring in structures should be minimized since they cause fatigue damage and may lead to further noise emissions. Proper design of the components of a small wind turbine and proper choice of tower and foundation should result in low vibrations. Crucial in this respect is the tuning of the natural frequencies of the tower. Consequences for the operating wind turbines on buildings are evidently that operating at the natural frequencies of parts of the building, such as floors and walls, should be avoided. The fundamental frequency f_0 of the building (with height H_B) can be approximated by:

$$f_0 = \frac{46}{H_B} \quad (12)$$

This is, according to Mertens [131], usually well below the operating frequencies of the wind turbine.

2.6.2. Social Acceptance

Various social acceptance studies have been performed for large-scale wind projects such as in Khorsand et al. [132], Molnarova et al. [133] and Johansson and Laike [134]. The literature is very much lacking on a proper social study on the visual impact of urban wind energy. There are various references showing concern related to this aspect such as Müller et al. [105], Abohela et al. [22] and Ayhan and Saglam [135]. The rotor and building aerodynamics are crucial factors in determining the visual impact of small-scale wind energy systems installed on roof tops. This is because as was mentioned earlier, both the height above the roof, as well as the location on the roof are important variables. These factors are still missing especially in the social sciences literature. This highlights the disjoint existing between the various disciplines. In an interesting study by Evans et al. [136], the authors state:

The community responses to the (urban wind) proposals were complex and varied and could not adequately be encapsulated by ‘nimby’ (not in my back yard) assignments.

and go on to show how no clear conclusions have been drawn yet, possibly because of the virtually wide range of settings that are possible.

2.6.3. Economics

Sunderland et al. [137] noted that for micro-wind turbines to be economically feasible in the urban environment as compared to a rural environment, the optimization of efficiency of the turbine must be targeted. The authors presented results for the Levelized Cost Of Energy (LCOE), which is defined as the cost of energy to break even over the entire lifetime of the turbine. The study did not include any feed-in tariff considerations. Results are reported from Sunderland et al. [137] in Table 2 for convenience. In the U.K., the cost of energy reported by the authors stands at 0.98 eur, which is still prohibitively large. These factors highlight the need for further research on turbine performance.

Table 2. Levelized Cost Of Energy (LCOE) for various countries for rural and urban contexts. Adapted from Sunderland et al. [137].

Cost of Energy Context	Rural (eur)	Urban (eur)
Sri Lanka	0.17	0.69
Ireland	0.36	1.20
U.K.	0.34	0.98

This in itself means that the cost of energy increases. The authors therefore emphasize the need for sound policy making with government subsidization. This broad picture from design optimization to market analysis was provided by Scappatici et al. [138]. The authors used numerical models such as BEM for the aerodynamics and Finite Element Analysis (FEA) for the structural part to design a blade with minimal costs. It is felt that the test conditions of loading are a major limiting factor for the outcomes of the paper, which did not include a consideration of the complex loading conditions experienced in built environment operation. Nonetheless, the holistic design approach is certainly worth noting. Various other examples in the literature deal with economic and policy aspects within a local context such as Hosseinalizadeh et al. [139], Fera et al. [140], Wang and Teah [141] and van Bussel [142]. Others (see Teschner and Alterman [143]) tend to focus more on policy at local/regional level.

3. Challenges and Future Perspectives

Wind energy research has been lately very focused on large-scale machines with upscaling becoming a mainstream trend. All this is reflected in the low number of publications dealing specifically with urban wind energy when it comes to major conferences such as The Science of Making Torque from Wind conference. Van Kuik et al. [144] provided a very detailed overview of the European Academy of Wind Energy (EAWE) viewpoint of the long-term research challenges, which need to be addressed by the various research groups working in wind energy across Europe. No specific mention of small-scale wind energy applications is made in this document despite the fact that the challenges found on large-scale systems might still be relevant to small-scale systems. It is nonetheless worthwhile to note that, as seen in this broad review, the challenges governing urban wind energy need to be tackled with a different mind set. The synergistic influence of the urban, building and rotor scales can no longer be ignored or even considered in isolation. Much of the presented research has treated these problems distinctly by focusing on resource assessment, isolated or multiple building simulations or rotor aerodynamic studies. Some recent research on the other hand has been pushing towards building-turbine simulations with minor simplifications of the problem. This has been mainly driven through simulation work permitted of course by cutting-edge computing technology. Resolving the full range of scales from urban flows to blade scale flows seems for now beyond the capability of current computing technology. The experimental landscape is also plagued by its own challenges. SPIV is becoming ever so popular in labs and allows the measurement of 3D flows over a substantial area. Unfortunately, the size of even the largest atmospheric boundary layer wind tunnels does not allow sufficient upscaling of models to be able to have blade Reynolds numbers that are large enough to be practically feasible for investigation (due to the very small size that would be required). On-site measurements seem to be more feasible, but certainly require a different measurement technique than SPIV. Some interesting developments are being made in large-scale PIV systems (see Scarano et al. [145]), which can provide interesting opportunities for future on-site measurements. Table 3 classifies various research articles on the basis of the following categories:

1. scale: urban, building, turbine or multi-scale
2. methodology: wind tunnel testing, on-site testing or simulation
3. outcome: turbine design guidelines, new methods or simulation guidelines

Two important factors can be highlighted here; first, local turbine aerodynamic studies have been studied extensively, and secondly, simulation guidelines need to be researched more extensively. For the latter, studies on how to simplify multi-scale problems would be desirable to have. This may include guidelines on topics such as primitive aerodynamic models of porous zones to model building blocks and actuator discs for rotor modeling.

Furthermore, in view of the other issues discussed in this review such as noise emissions, visual impact and economics, it is hoped that standards and certifications of small-scale wind turbines progress at the same pace as scientific developments and, likewise, small turbine manufacturers make a paradigm shift to take these advances on board.

Table 3. Topics addressed by various literature sources in the field of urban wind energy aerodynamics.

Publication	Urban Scale	Building Scale	Turbine Scale	Multi-Scale	Site Testing	Wind Tunnel Testing	Simulation	Turbine Design Guidelines	New Methods	Simulation Guidelines
Drew et al. [9], Millward-Hopkins et al. [10,11]	✓				✓				✓	
Al-Quraan et al. [12]	✓				✓	✓	✓		✓	
Safari and Gasore [14]					✓					
Mertens [13]				✓			✓		✓	
Simões and Estanqueiro [15]	✓						✓		✓	
Balduzzi et al. [16]				✓			✓	✓		
Yu et al. [31], Shao et al. [32], Murakami and Mochida [33], Wright and Wood [34], Lu and Ip [35], Lu and Sun [36], Toja-Silva et al. [37], Wright and Wood [34], Shao et al. [32], Abohela et al. [22], Toja-Silva et al. [40]		✓					✓			✓
Micallef et al. [44]				✓			✓	✓		
Guerra et al. [45]				✓						
Ebert and Wood [46]			✓		✓		✓	✓		
Wright and Wood [34]			✓		✓			✓		
Howell et al. [51], Tescione et al. [52], Chong et al. [94]			✓			✓	✓	✓		
Lam and Peng [54]			✓				✓	✓		
Peng et al. [55], Armstrong et al. [57]			✓			✓		✓		
Lanzafame et al. [61], McNaughton et al. [62], Trivellato and Raciti Castelli [64]			✓				✓			✓
Raciti Castelli et al. [63]			✓				✓	✓		
Mertens [65]		✓					✓	✓		
Simão Ferreira et al. [39]			✓			✓		✓		
Chowdhury et al. [67]			✓				✓	✓		
Miau et al. [68], Ahmadi-Baloutaki et al. [69]			✓			✓		✓		
Wekesa et al. [70], Kear et al. [91]			✓			✓	✓	✓		
Onol and Yesilyurt [72], Bedon et al. [90], Kear et al. [91], Wang et al. [92]			✓				✓	✓		
Wekesa et al. [70]			✓		✓			✓		
Kjellin et al. [75]				✓	✓			✓		
Selig and McGranahan [88], Ferreira et al. [89]			✓			✓		✓		

4. Conclusions

The science of small-scale wind energy systems has some distinguishing features from their large-scale counterparts. The aerodynamics of these systems has been studied extensively in both controlled and uncontrolled conditions. Research is however very sparse, with research groups focusing on the separate issues.

The latest work in urban wind energy resources has focused on establishing engineering methods for the determination of the wind statistics at particular points of interest, usually roof tops. One particular method reports errors varying between 5% and 20%, which leaves room for improvement. CFD-based methods of urban wind resources quantification have been reported throughout the review with errors of around 10% on the wind speed. Most publications from the past few years have therefore focused on simplifying this procedure, as well as improving the accuracy of these predictions.

Building aerodynamics has seen a number of efforts in the past few years in relation to pedestrian wind comfort. Flow phenomena on roof tops has been studied in some detail by researchers in the past decade with some interesting results as regards flow amplification and flow skewness. Skew angles at the center of rooftops range from -5° – 10° , which has a direct impact on rotor performance. Particular building shapes and their influence on the local aerodynamics have been investigated mainly by means of CFD models with energy yield improvements of up to 56.1% for vaulted roofs.

Rotor aerodynamics have found much attention in the literature for small-scale machines, but mostly for VAWT-type turbines given the advantages that they provide for such applications. The influence of turbulence and gusts needs more efforts from the scientific community since these issues are predominant throughout almost the entire operational lifetime of the turbine. In addition, they have important roles to play in the determination of cut-in wind speeds. Studies on standstill blades are needed in this regard.

Various novel designs for urban wind turbines have been proposed in the scientific literature with very much the same trend as in the industrial scenario. Unfortunately, designs that promise improved performance would lead to exorbitant manufacturing costs and most probably more rigorous testing for certification purposes. The Darrieus VAWT remains the most commonly-researched rotor type for such applications, and further research in their operation under urban flow conditions is certainly the most promising way forward.

Building integrated wind energy is an interesting concept, but it is seldom the case that buildings are designed in such a way so as to have maximum exploitation of wind energy generation unless this is done to promote a building's image. In any case, it provides an interesting field of research.

Studies on noise emissions of small-scale wind turbines in the urban environment were noted to be scarce. Some studies have reported noise levels of around 45 dB(A), which are comparable to those from vapor compression refrigeration units found commonly in urbanized locations. Of similar scarcity are the studies on visual impact. The latest economic studies of small-scale wind energy result in levelized costs of energy of 0.98 eur per kWh in the U.K. This instigates further motivation for optimizing energy extraction.

Urban wind energy research needs to move from a state of isolation to a more synergistic research field with issues ranging from the urban up to the rotor scale. In aerodynamic research for instance, only five publications were noted that considered a multi-scale approach. This brings new challenges in both computational and experimental research, but is something that can give an extra drive to this industry, which has time and time again struggled. This in conjunction with proper certification regulations is the key to any foreseeable progress.

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