ZEPHYR

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Executive summary

These guidelines summarize some of the key takeaways of the research carried out during the zEPHYR Project. The work of the different Early Stage Researchers (ESRs) touched on different themes - Consideration of Atmospheric Boundary Layer (ABL) inflow conditions in design, Multi-Disciplinary Approach to Blade and Rotor design, defining acoustic Emission Controls using noise maps, incorporation of Uncertainty Quantification in design phases, working on different benchmark cases in flat, complex and urban terrain, public access and open data access. The guidelines are divided into two parts - guidelines for wind turbines deployed in rural environments and urban environments, respectively. The guidelines range from choice of turbine, numerical simulation approaches for turbines, and improving noise acceptance and siting.

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Change log

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List of abbreviations

ABL	Atmospheric Boundary Layer
BPF	Blade Passing Frequency
CFD	Computational Fluid Dynamics
HAWT	Horizontal Axis Wind Turbine
IEC	International Electrotechnical Commission
LBM	Lattice Boltzmann Method
LES	Large Eddy Simulation
NTM	Normal Turbulence Model
SCADA	Supervisory Control and Data Acquisition
SWT	Small Wind Turbines
VAWT	Vertical Axis Wind Turbine
VLES	Very Large Eddy Simulation
WRF	Weather Research and Forecasting
WINEUR	Wind Energy Integration in the Urban Environment
WT	Wind Turbine
ESRs	Early Stage Researchers

1 Introduction

These guidelines summarize some of the key takeaways of the research carried out during the zEPHYR Project. The work of the different Early Stage Researchers (ESRs) touched on different themes - Consideration of Atmospheric Boundary Layer (ABL) inflow conditions in design, Multi-Disciplinary Approach to Blade and Rotor design, defining acoustic Emission Controls using noise maps, incorporation of Uncertainty Quantification in design phases, working on different benchmark cases in flat, complex and urban terrain, public access and open data access. The guidelines are divided into two parts - guidelines for wind turbines deployed in rural environments and urban environments, respectively.

2 Guidelines for WTs in rural environment

2.1 Development and exploitation of improved simulation methods for noise predictions

The effects of realistic airfoil geometry on leading-edge noise generation are still not thoroughly understood and modeled. Significant discrepancies are observed between the measurements obtained experimentally or numerically and the noise predictions yielded by low-fidelity methods (Paterson & Amiet, 1976; Moriarty, Guidati, & Migliore, 2004). These models are based on simple formulations developed for flat plates interacting with isotropic and homogeneous turbulence, whose acoustic response is modeled by means of a transfer function. This is the case, for example, of the widely employed Amiet's model (Amiet, 1975). Still, it has been assumed that the distortion of the incoming eddies due to the non-negligible thickness of realistic aerodynamic surface may significantly impact the noise generation, explaining hence the low accuracy obtained with the currently employed semi-analytical prediction methods (Buck, Oerlemans, & Palo, 2018; D. De Santana, Christophe, Schram, & Desmet, 2016). The characterization of this physical mechanism and the consequent integration in the low-fidelity models has been proved to be a valid and promising path to enhance the accuracy of the noise prediction in the case of thick airfoils (dos Santos, Botero-Bolívar, Venner, & De Santana, 2022; dos Santos, Botero Bolivar, Venner, & De Santana, 2023; Piccolo, Zamponi, Avallone, & Ragni, 2023).

The thorough description and modeling of the turbulence distortion and the resulting effect of the noise generation in the case of thick airfoils should hence be complemented with an enhancement in the modeling of the aeroacoustic transfer function, i.e., the function modeling the unsteady aerodynamic and acoustic response of the airfoil to the incoming perturbation. This function has indeed a relatively easy analytical formulation in the simple case of a flat plate, while more cumbersome numerical procedures are required in the case of bodies featuring a non-negligible thickness (L. D. De Santana, 2015; Miotto, Wolf, & De Santana, 2017). Yet, it has been demonstrated that the response of the airfoil is also affected by the geometry of the aerodynamic surface. Therefore, a step forward in the modeling of this transfer function would result in a significant improvement of the leading-edge noise-prediction methods.

The turbulence distortion caused the leading-edge noise produced by thicker airfoils to reduce. Therefore, the trailing-edge noise is dominant over a wider frequency range than it would not be expected with the current prediction methods (Botero-Bolívar, dos Santos, Venner, & de Santana, 2023). Furthermore, another physical phenomenon that is not currently considered during the design of wind turbines and the prediction of airfoil noise is the increase of the trailing-edge noise due to the inflow turbulence. When the free-stream turbulence is high and contains turbulent structures larger than the turbulent structures inside the boundary layer, which is the typical condition of wind turbines, the free-stream can penetrate the boundary layer, increasing the wall-pressure fluctuations close to the trailing edge and consequently, the trailing-edge noise (Botero-Bolívar, dos Santos, Venner, & de Santana, 2022, 2023). Improvements in the wall-pressure spectrum prediction methods need to be considered to take into account the effect of the inflow turbulence and account for the increase of the trailing-edge noise when inflow turbulence is present. Considering the turbulence distortion and the free-stream turbulence penetration would result in a more accurate prediction of airfoil flow-induced noise.

These low-fidelity aeroacoustic methods can also be used to design the airfoils of the wind turbine and optimize the noise produced without sacrificing aerodynamic properties (Kou et al., 2023). This is possible due to easy coupling with other low-fidelity aerodynamic models, enabling the possibility to run thousands of simulations in short periods of time. On the other hand, more advanced high-fidelity methods such as Large Eddy Simulations (LES) combined with aeroacoustic analogies, such as the Ffowcs-Williams and Hawkings (FWH) (Williams & Hawkings, 1969) can be used to verify the noise produced by the airfoil with better precision (Marino, Ferrer, Valero, & Ferret, 2022).

Expanding the noise source repertoire to include mechanical noise, stall noise, and tip-vortex noise would contribute to a more comprehensive understanding of the relevant noise sources to their rank ordering depending on the simulated scenario and suggest mitigation strategies. Particularly, tackling stall noise generated by gradual wind speed fluctuations stands as a valuable challenge.

2.2 Site-specific noise assessment studies

Prior to the deployment of a new wind farm, site-specific noise assessment studies, including terrain topology and the effects of atmospheric conditions on noise generation and propagation, should be performed. These studies would allow us to minimize the risk of curtailing the energy harvested to respect the noise limitations. Furthermore, it would allow to reduce the safety margins, optimizing the wind farm layout.

2.3 Development and exploitation of improved simulation methods for the assessment of the wind energy resources

Accurate evaluation of wind resources is critical in order to benefit from wind energy effectively. Improved simulation methods combine advanced computational algorithms and high-resolution data, allowing more precise modeling of complex wind flow patterns. These simulations provide a comprehensive understanding of the local wind resource potential, taking into account various parameters such as terrain, atmospheric conditions, and turbulence effects. In addition, these methods facilitate the determination of the most suitable locations for wind farms and assist in efficiently deploying wind turbines. In addition, the use of these advanced simulation methods, such as the so-called Weather Research and Forecasting-Large Eddy Simulation model (Skamarock et al., 2008) or high-fidelity turbulence-resolving Computational Fluid Dynamics (CFD) models, can increase the long-term viability of wind power projects by providing valuable information on power generation forecasts and operational strategies.

2.4 Real-time acoustic control of the wind farm to optimize the energy harvested

Industrial utilization of the outcomes of this project can be extended through the creation of a digital twin for wind farms. This system would employ real-time inputs of atmospheric conditions and Supervisory Control and Data Acquisition (SCADA) data to simulate noise spectra at critical locations. If necessary, it could trigger actions to mitigate noise, such as modifying blade pitch angles. This application opens the potential for impactful noise reduction strategies and operational optimizations.

2.5 Auralization and Psycho-Acoustics

The use of auralization to simulate wind turbine noise has become an important method for studying and gaining insight into the causes of noise annoyance. This technique allows for noise assessments in various conditions through listening tests, enabling researchers to link annoyance to different factors such as operating conditions or short-time spectra. By improving noise annoyance prediction models, auralization can also demonstrate the impact of wind turbines on the surrounding environment, ultimately promoting acceptance of this technology.

Furthermore, leveraging auralized signals to generate psycho-acoustic annoyance maps opens avenues for the design of a perceptually-driven wind farm layout.

3 Guidelines for WTs in urban environment

The global small wind market is expected to grow 20.2% by 2022 (Research & Consulting, 2017). Decentralization of the grid, certification regulations, noise, and safety are some of the key uncertainties involved in integrating wind turbines in urban environments, as shown in Fig. 1 (Alberto Álvarez Vilar & Nanaki, 2020). Horizontal axis wind turbines are more suited to rural and semi-urban wind conditions and are usually deployed in open areas or isolated buildings. They have higher power coefficients in unidirectional flow conditions. Such turbines also have a lower performance in high turbulence conditions (Francisco Toja Silva, 2013). The lower wind speeds typically encountered in urban boundary layers lead to a greater startup time. Vertical axis wind turbines (Savonius and Darrieus types) are more suited for urban environments, as they operate independent of wind direction and highly turbulent wind conditions.

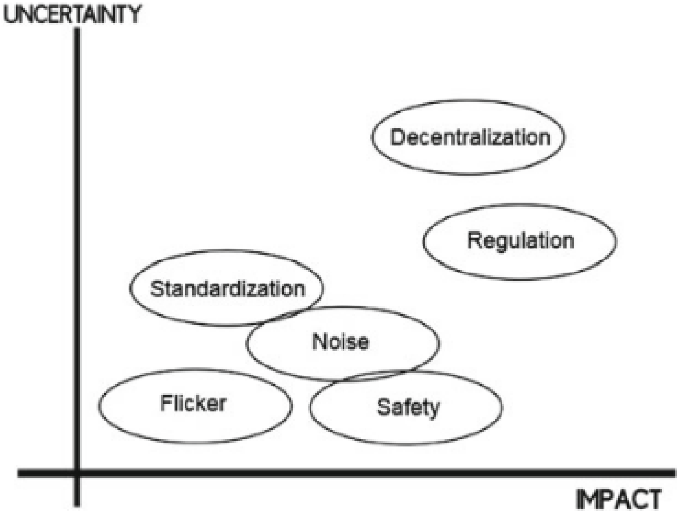

Figure 1: Uncertainties involved in the adoption of wind turbines in urban environments.

The Wind Energy Integration in the Urban Environment (WINEUR) project (Jadranka Cace, 2007) funded by the EU was focused on urban wind energy explorations. The Project highlighted five important points that must be taken into account while siting urban wind turbines:

1. The potential site should have an annual wind speed of at least 5.5 m/s.
2. The roof of the building/mounting mast of the wind turbine should be higher than 50% of the surrounding areas.
3. Incorporate a sloped roof to harness the acceleration of wind.
4. Ensure the structural strength of the roof to withstand static and dynamic loads induced by the wind turbine.
5. Consider the impact of flicker, noise propagation, and public acceptance of the wind turbines.

6. Safety issues and preventing catastrophic detachment of blades.

3.1 Importance of well-characterized urban wind field for aeroelastic simulation of urban wind turbine

The urgent need to address the global climate crisis necessitates the rapid replacement of fossil fuel-based energy sources with renewable alternatives. This transition requires extensive deployment of renewable energy infrastructure. In this context, the urban environment offers several advantages in terms of facilitating distributed renewable generation. However, the insufficient understanding of wind field characteristics within urban areas has led to inadequate safety measures for Small Wind Turbines (SWT), and poor performance (Smith, Forsyth, Sinclair, & Oteri, 2012; KC, Whale, & Urmee, 2019). The wind flow patterns in built environments differ significantly from those observed over flat and open terrains (Kaimal & Finnigan, 2019), primarily due to the non-homogeneous roughness of urban areas (Ricciardelli & Polimeno, 2006). Consequently, comprehending the flow characteristics in urban areas is of utmost importance to ensure structural safety and enhance the performance of SWTs (Stathopoulos et al., 2018). The International Electrotechnical Commission (IEC) 61400-2 standard (IEC 61400-2, 2019) is used for wind field simulation in urban environments for SWT by utilizing the Normal Turbulence Model (NTM). The NTM was developed semi-empirically using data from open and flat terrain. Thus, this leads to an invalid estimation of the dynamic loads on SWT in the built environment (Evans et al., 2017; Forsyth et al., 2018). To represent the statistical characteristics of urban wind fields well, using a high-fidelity approach such as LES is required. As LES showed its capability to capture the high turbulence intensity obtained in an urban environment and characterize well the spectrum in urban areas with complex flow (Vita, 2020; Vranešević, Vita, Bordas, & Šarkić Glumac, 2022).

3.2 Improving the choice of type of vertical axis wind turbine and operating conditions

The choice of the type of turbine depends on the local wind flow regime at a given site. For lower wind speeds, typically Savonius (drag-based) wind turbines are preferred, as they have a peak of power at lower wind speeds. Darrieus wind turbines. Darrieus VAWTs (lift-based), however, can peak higher peak power coefficients, which are more efficient compared to Savonius types. In terms of noise, Darrieus with helix angles of $45^{\circ}o$, $60^{\circ}o$ and $120^{\circ}o$ were examined at a fixed rotational speed of 3500 rpm (Venkatraman, Moreau, Christophe, & Schram, 2023a). Increasing the helix angle reduces tonal noise components, reducing the possible annoyance levels in terms of psycho-acoustics. Moreover, the helix angle also alters the orientation of the noise directivity (Venkatraman, Moreau, et al., 2023a), aligning it along the helix angle, suggesting radiation of noise away from the ground, which could be an added benefit of the helical turbines, apart from improving the fatigue life of the turbine by a more uniform production of torque over the revolution of the turbine. Some studies also highlight the importance of non-uniform inflow conditions, which are typically encountered in urban environments, showing a reduction in performance and noise levels. Hence, the investigation of Darrieus VAWTs under non-uniform inflow conditions and the introduction of a helical sweep could be valuable in improving the acceptability of these turbines in the urban environment.

3.3 Enhancing urban energy potential with Diffuser-Augmented Wind Turbine configuration

Beyond aesthetics, the DAWT configuration offers tangible advantages, in particular for urban areas. Their enhanced efficiency results in the generation increase of a significant amount of energy in areas with lower or inconsistent wind speeds, such as the roads on pedestrian levels or tall building rooftops.

A possible design improvement of DAWTs is the extended tail of the diffuser. This design modification delays the convergence point where the internal and external airflows of the diffuser meet. By pushing this convergence further down the tail, the regions of high and low-pressure merge later, resulting in the consequence of accelerated wind flow. This ensures a more consistent wind speed across the rotor, maximizing energy capture.

Urban environments, especially rooftops, often present turbulent and unstable wind flow patterns. The design of DAWTs can help align and stabilize this flow, and with particular designs incorporating a specialized flap allowing the turbine to automatically rotate and align with the prevailing wind direction. This not only ensures a more consistent energy yield over time but also reduces wear and tear on the turbine components, leading to longer operational life cycles and reduced maintenance costs.

One of the primary concerns with wind turbines in urban settings is their visual impact on the cityscape. DAWTs, with their sleek and modern design, can be integrated more harmoniously into urban architecture. The shroud or diffuser can be customized to match the aesthetics of the surrounding buildings, making them less obtrusive and offering a refreshing visual that compliments the cityscape and symbolizes progress and commitment to sustainability.

3.4 Improving noise acceptance and siting

- Noise curtailment strategies: The noise radiated from a Darrieus vertical axis wind turbine (VAWT) is propagated in different idealized urban scenes using a 2.5D ray-based engineering method (Venkatraman, Bresciani, et al., 2023). The noise maps for a wind turbine mounted on a rectangular high-rise building show low noise levels that could be within acceptable limits of 50 dBA, illustrating the advantages of installing a wind turbine at a higher location, not only for performance but also for noise impact (Venkatraman, Bresciani, et al., 2023). Additionally, the maps could also be useful to evaluate the extent to of the building facade is impacted by higher noise levels. A wind turbine operating at lower wind speeds could satisfy the noise regulations for urban environments that are more stringent at night (below 50 dBA for most European cities (Fabris, 2012)). A noise curtailment strategy could be proposed, limiting the operational speed of the turbine.
- Noise source directivity: A non-uniform noise directivity from numerical simulation data for a small H-Darrieus VAWT is used to highlight the asymmetry in noise propagation due to a different noise directivity, illustrating that some regions of the buildings could experience higher noise levels dependent on the directivity of the noise source (Venkatraman, Bresciani, et al., 2023). Hence, it could be useful to take into account the noise source directivity in noise propagation models.
- Noise certification: The 2.5D ray tracing model is also applied to a wind turbine in a realistic urban setting around a central square in Grenoble, France, capturing the complex scattering, reflection, and diffraction patterns. Such noise maps could be beneficial for the certification of wind turbines installed in urban environments.

3.5 Improved simulation approaches for the design of urban Darrieus wind turbines

Simulating VAWTs is quite challenging due to the unsteady flow physics experienced over the revolution. Simulation chains for aerodynamic and aero-acoustic predictions have been set up as a part of this project (Venkatraman, Moreau, Christophe, & Schram, 2021, 2022). Two-dimensional unsteady Reynolds-Averaged Navier-Stokes (URANS) models set using the flow solver ANSYS CFX were found to reasonably predict the tonal peaks at the blade-passing frequencies (BPFs), which are characteristics of the noise radiated by these machines. However, the applicability of this method would be limited to Darrieus VAWTs with horizontal blades (H-Darrieus). Three-dimensional Lattice Boltzmann method/Very Large Simulations (LBM/VLES) approach using the commercial solver PowerFLOW showed the span-wise stratification of the flow, even for H-Darrieus VAWT, and the induced span-wise flow for helical Darrieus VAWTs. The PowerFLOW LBM/VLES model was also able to accurately predict the noise spectrum when compared with available experimental data for Darrieus VAWTs (Venkatraman et al., 2022), along with some numerical performance benefits compared to traditional RANS-based approaches. Additionally, the immersed boundary-based methods such as LBM/VLES make it easier to incorporate the effect of end plates and the entire wind turbine system. The inclusion of these structures also plays a role in the power and noise prediction (Venkatraman, Moreau, Christophe, & Schram, 2023b).

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