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IMPROVING SUSTAINABILITY AND RESILIENCE OF FUTURE CITIES POSITIONING OF WIND TURBINES WITHIN THE URBAN ENVIRONMENT

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Abstract. *Wind Energy technology represents the most technically advanced and diffused renewable resource. The willingness to foster its economical profitability has brought to new uses of the technology, especially in unconventional locations. In particular, the Urban environment is promising in reducing the costs associated e.g. to the large infrastructure wind farms require. However, several technical and non-technical issues remain unsolved, spacing from the understanding of the actual wind resource available to the actual response of wind turbines. This contributes to foment the lack of confidence in wind energy and its societal acceptance. The lack of knowledge is an issue that adds sharply to NIMBYism rhetoric mechanisms. In this work, various possibilities and limits of Urban Wind Energy are introduced, with a focus on the urban wind resource. A suitable high-rise building configuration is taken as a reference and simulated using CFD, to discuss the possible strategies in optimising the positioning of wind turbines, which strongly depend on their relationship with the built environment. The challenges related to such a methodology are also introduced, with special reference to the necessity of accurately modelling the signature turbulence for the reliable aerodynamic design of the new generation of small and medium size wind turbines.*

1 INTRODUCTION

By 2050, 66 per cent of world's inhabitants is estimated to be residing in urban areas [1]. The population is also estimated to increase steadily to 7.4 billion people. As an effect, the expected scenario is the continuous growth of urban areas. The concept of sustainable development gleams as the main world institutions face the risks this growth means to humanity [2]. However, the concept of sustainability immediately links to the concept of energy. Endless research has been dedicated to the understanding of the best Energy Mix to tackle the demanding request of energy and the problems renewable source inevitably experience, especially regarding their stochastic variability [3], however an unambiguous solution is still awaited and renewable have some difficulty in affirming their role in the Energy Mix, especially regarding their social acceptance. This is particularly true for wind energy. If on one hand wind energy is recognised to be a robust and one of the most promising way of providing sufficient energy to meet society's needs with minimum waste, yet more research is needed to increase their efficiency, reliability, affordability, and safety to the standards of traditional technologies [4].

This is actually already underway, as demanding governmental directives, such as those of the European Union [5], have fostered a renewed interest in setting the technological knowledge a step further. As regarding wind energy, this means that two major areas of research efforts are noticeable. The first one refers to the next generation of large Wind Energy Converters (WEC). Besides the construction of new multi-megawatt wind farms, either on- or off-shore, the repowering of the existing old wind turbines is the practical consequence of taller wind turbine (WT) hub heights and higher capacity of generators. The enhancement of the structural response represents the key point of research, by improving the structural design and detailing. Going up has, however, some drawbacks [Ref.], which have set the other major research aim, which is improving the harvesting possibility in low wind sites, such as the urban environment. In fact, the increasing lack of new suitable high wind sites, the reluctance of the large public towards the modification of the rural landscape, together with the costs associated with the infrastructure needed to transport the electricity to the users, suggest that it might be worth trying a reverse approach, harvesting energy directly at the consumption site, attempting to cut off many cost entries [4]. Reversing the conception of wind energy production near the site of consumption would suit countries like the Hashemite Kingdom of Jordan, which reveals abundancy of wind energy in its eastern regions (Fig.1a), while the large majority of the population resides in the north-western part (Fig.1b), with limited wind resources [6].

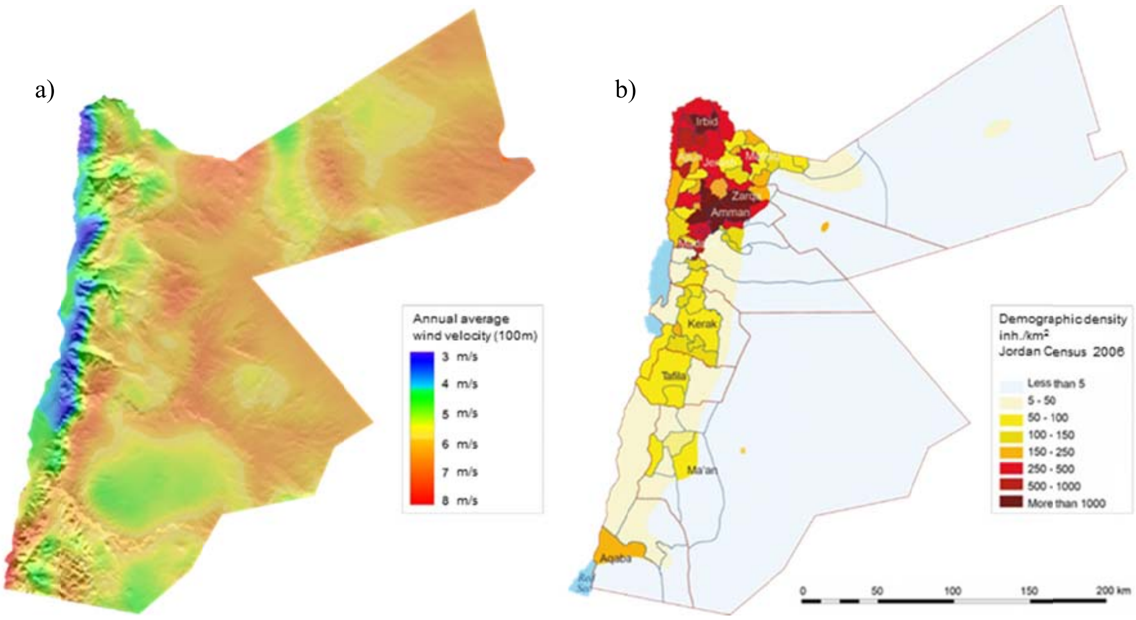

Figure 1. a) Annual mean wind speed in Jordan at 100m [6]; b) Demographic density of Jordan [7]

This simple line of reasoning shows the intrinsic connection of urban renewable energy with human activities, rather than mere engineering arguments [8]. This is actually the core of the issue with the social acceptance of wind energy, which is only partially related to technical issues [9].

This second reverse approach is the topic of the present work. In Section 1 the raison d'être of Urban Wind Energy (UWE) will be reviewed and discussed. In Section 2, the research fields associated with UWE will be addressed and the implications with the topics of building aerodynamics will be discussed. In Section 3 a simple numerical model will be introduced to show the necessity in further research to cover the gaps in the understanding of the positioning strategies of wind turbines within the built environment, stating the necessity of setting research priorities.

2 BRIEF REVIEW OF URBAN WIND ENERGY DEFICIENCIES

2.1 Is Urban Wind Energy worth investigating?

Urban Wind Energy is a recently developed niche of wind energy, dealing with the harvesting of wind energy within urban premises. The necessity of creating such a research niche has emerged for a variety of reasons.

i) The small wind energy market involves a large number of businesses and numerous workplaces [10]; ii) The fiasco of a large percentage of urban applications has been noticed [11]; iii) The necessity of improving the energy performance of single buildings shows that microgeneration could represent a factual advance; iv) The intrinsic difference of the wind resource in the urban environment, if compared with the usual flat terrain conditions, poses different premises to the design and assessment process [12]; (v) Harvestable wind energy is indeed present in the urban environment and enhanced by the presence of buildings, which can represent a not-irrelevant share out of the global wind energy capacity [11].

To understand this last point, if a typical Jordanian household is taken as reference, then it would require *5'089 kWh/y* of electricity [13]. As the average sized small wind turbine has been estimated being *0.85 kW* [10], then supposedly installing such wind turbines in the optimal position would still yield roughly 30% of the rated power on a yearly base, considering factors such as the variability of the wind. A yearly electricity production of $0.85\ kW \times 0.3 \times 365 \times 24\ h = 2'233.8\ kWh/y$ would be then achieved. This simple and very rough emphasises that theoretically a Jordanian household could save almost half of the electricity expenses by installing a small wind turbine, in supposedly optimal conditions. However, reality is much more complicated, as the attention to the correct positioning of wind turbines around a building has only recently gained attention following resounding failures of applications. As many detractors criticise the efficiency of urban wind and strong difficulties are experienced by municipalities and pundits to convince the general public of the possible benefits of implementing wind energy. The reason for that is strongly related to our lack of understanding of the actual power produced by WECs, which means in turn, the lack of a convincing optimisation strategy for the positioning of the devices for gaining a reliable production of energy.

2.2 How to arrange Wind Turbines within the Built Environment?

Besides non-technical issues and social acceptance [Ref.], the positioning of WECs within the urban environment is undoubtedly the core issue with Urban Wind Energy. This immediately translates to a new type of WT, meaning the Building Augmented Wind Turbine (BAWT, also Integrated or Environment: BIWT, BWET, or BWT). The building must be interpreted not only as a support for WTs, but also as a way of enhancing wind energy harvesting, by locally diverting and concentrating the wind flow. This can be put into practice in many ways (Fig.2). The mutual positioning of BAWTs within the built environment encompasses a number of typical situations:

i) WTs mounted on top of buildings (Fig. 2b-i), which represent the large majority of the applications;

ii) WTs mounted on the façade of buildings (Fig. 2b-ii);

iii) WTs which are integrated within the building itself using its shape as a local catalyser for the inflow wind (Fig. 2b-iii) [14], [15];

iv) WTs mounted in the vicinity of buildings (Fig. 2b-iv), which might include bigger WTs [16] and can be transposed to the case of complex terrain onshore wind energy [17].

Being wind energy a resource harvested on large areas of land, the concept of Distributed generation rises [18]. UWE and BAWT can be accounted as a first attempt of Distributed Wind Turbines (DWT). Energy generation with DWTs could represent the final scope of current urban wind energy applications: to multiply the number of devices, with an efficient positioning, in order to provide a reliable share of energy at the consumption site [19].

Figure 2. a,b) WT and buildings: i) on rooftop, ii) on façade, iii) integrated, iv) in vicinity; c) flow enhancer [20].

A brief incomplete review of the works focusing on the understanding of building aerodynamics for wind energy purposes is now given, to introduce the scope of the present work. Two main scopes of investigation exist: street canyons and high-rise buildings. These actually represent the most suitable locations for wind energy to be harvested more efficiently. The large majority of investigations focuses on the assessment of the flow pattern, trying to locate spots with optimal augmentation of the mean flow, giving an assessment of the levels of turbulence to be avoided.

The importance of the role of the building shape is recognised as crucial. Stankovic et al. [15], Mertens et al. [21] have focused their attention on the total optimisation of the shape of high rise buildings towards the implementation of BAWT with their architecture. This has shown to be viable in a handful of applications, such as the Bahrain World Trade Centre, however the success of the application is highly dependent on the estimation of the actual inflow, which might prove to be tricky, and leading to possible fiasco. Some works further propose a way to enhance the harvesting by slightly enhancing the shape of high-rise buildings [20].

Further works [22]–[24] are focused instead in the assessment of the re-circulation zone above the roof of high-rise or juxtaposed buildings: all results confirm velocity augmentation and enhancement of turbulence intensity are the features of the flow pattern. Abohela [24] and Toja-Silva [25] focused their work in the identification of the roof-top shape which most suits urban wind energy harvesting. A univocal determination of the optimal configuration is however difficult to achieve, because of the role of non-technical issues, such as aesthetical and architectural problems. Balduzzi et al. [26] focused on the choice of the best suited wind turbine for an urban configuration. Vertical Axis Wind Turbines (VAWT) are recognised as the most viable choice, due to their response to urban highly turbulent flows. However, as confirmed by Pagnini et al. [27], Horizontal Axis Wind Turbines (HAWT), show to yield more energy.

Research is in agreement in stating that enhanced turbulence levels are the most important issue related to UWE. Whether VAWT or HAWT are used their efficiency is biased by a generalised lack of understanding of the turbulence effects on the aerodynamics of WECs [28]. Therefore, the attitude is to avoid locations with turbulence intensities higher than 0.15 [29]. Though an effect of turbulence is highlighted often with special regards to the fatigue limit state [30] and the power output [31], yet a comprehensive methodology lacks a better understanding of the effects of turbulence on the aerodynamics [32]. However, the actual turbulence statistics and their location around buildings set up a challenging research panorama: the knowledge about the flow pattern around building does not yet allow a reliable positioning strategy, while the actual aerodynamic response of wind turbines under highly turbulent flows is almost unexplored.

For these reasons, research on building aerodynamics is developing a niche focusing on the surrounding flow pattern to locate wind energy harvesting opportunities. As anticipated, the urban environment represents both an opportunity, for the local increase in wind velocity, but also a likely threat, due to the enhanced presence of turbulence.

It has been shown that the shape of the roof itself has a major impact on these parameters. Toja-Silva et al. [25] in particular developed further the studies of Abohela [24] towards the assessment of the best shape for wind energy purposes. They have found that having a curved roof enhanced the possibilities for wind energy harvesting. However, the criteria chosen for defining the optimal location are not universally agreed, therefore more research on the performance of wind turbines in a turbulent environment is needed.

Khauyllirina et al. [33] studied the effect of two adjacent high-rise buildings with the aim of exploiting the street canyon effect. These works confirm the importance of the understanding of the wind pattern, the possibility of enhancing the wind energy resource and the choice of the proper wind turbine for use.

The large majority of UWE applications involve existing buildings. These are characterised by the presence of a flat roof. This is particularly true for high-rise buildings. Computational Fluid Dynamics is a popular tool in the assessment of the flow pattern around buildings [34]. Many works have investigated the flow pattern on rooftop of high-rise buildings. It appears that the research is actually converging towards the necessity of proposing accurate flow data for the specific configuration of interest, stated the extreme variability of conditions a single building shape can have.

2.3 Research gap and aim of this work

It is difficult to state the precise limits of the needed knowledge. The built environment offers an opportunity to the global renewable energy market and could give a contribution to the energy mix towards the abatement of costs. However, this brief review has immediately prompted the issues to be addressed to make any statement on the topic:

i) the aerodynamic response of WECs under turbulent inflows;
ii) the flow pattern around buildings and the detection of relevant parameters;
iii) the possible ways of enhancing wind energy harvesting using buildings;
iv) the social acceptance and the mediation with non-technical issues.

This work is an attempt of enhancing the discussion about the importance of the correct assessment of the turbulence pattern around buildings, more than the estimation of the mean velocities, for the rightful success of UWE applications. To fulfil this aim, following objectives are envisaged:

i) To investigate the flow around a model high-rise building using a steady-state CFD RANS simulation;
ii) To validate the model using available experimental data [35];
iii) To give a preliminary comparison with higher quality CFD LES data, focusing on turbulence quantities.

3 EXPERIMENTAL SETUP AND METHODOLOGY

3.1 The experimental setup

In this work, the geometry of the computational domain is taken from the experiment by Hemida et al. [36], carried out in a series of wind tunnel experiments at the Atmospheric Boundary Layer (ABL) Wind Tunnel Lab of the Ruhr-University of Bochum (RUB), within the scope of the COST-Action TU1304 WINERCOST. The RUB wind tunnel has a cross section of *1.6m* × *1.8m* and a length of *9.4m*, in an open tunnel configuration with fan behind the test section (Fig.3a). The ABL is simulated equipping the wind tunnel inlet with a castellated barrier, turbulence generator fins, and roughness cubes (from *3.6cm* to *1.6cm*) working as roughness elements (Fig.3b). The high-rise building model has a 1:300 scale, with a height-to-width ratio of $H/D=3$, where $H=400mm$ and $D=133.3mm$ (Fig.3b). Fig.3d shows the model mounted on the rotating test table of the wind tunnel.

Results include the velocity pattern above the rooftop, measured using a hot wire anemometer at different locations of the roof (1, 2, 3, 4 in Fig.3c) and surface pressure on the rooftop. However, this technique does not account for reversed flow, so results have been interpreted accordingly to detect separation. A specific focus has been given to turbulence intensity; it has been measured re. the velocity components in the *y* and *z* directions, *u* and *w*, for $z/D>0.1$. Time histories of each signal have been obtained using a length window of *131s*, and all results are referred to the width of the model $D=133.3mm$ and the reference velocity $u_{ref}=u(z=H)=15.85m/s$ (Fig.4a).

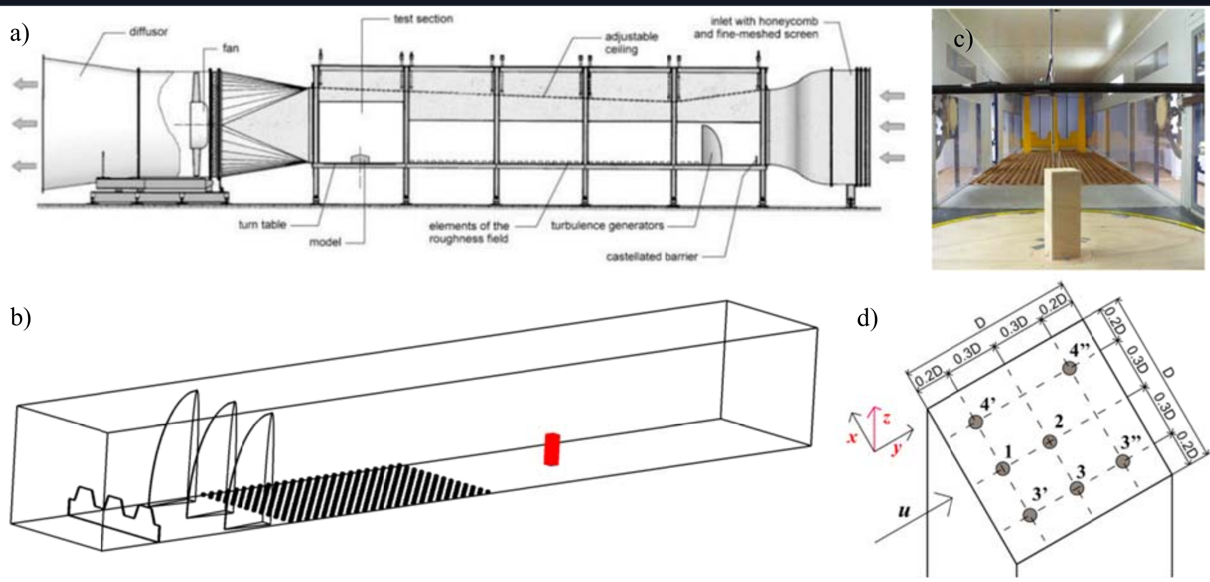

Figure 3. a) Wind Tunnel of the Ruhr-University Bochum; b) Schematic of the ABL devices with the model; c) photo of the wind tunnel with the model mounted on a turning table [17]; d) Schematic of measurement positions.

The measurements of the velocity around the models have showed (as expected) that near the surface the flow is reversed, because of a separation bubble. Above *z/D~0.3*, turbulence intensity declines to about *0.1* for both *u* and *w*, matching the one present in the upstream flow. This suggests that the building affects turbulence intensity up to a height of about one third of its width. Fig. 4c shows that wind velocity has the maximum increase of about *25%* at about *z/D~0.3*, at the centre of the roof (Pos.2). This is just above the shear layer between the separation region and the upstream flow, which is in agreement with previous experiments [20]. At the upstream edge (Pos. 4'), the maximum velocity occurs at a lower height, meaning that the it is maximised downstream to Pos.1. Beneath the maximum velocity area, the flow is highly turbulent. The turbulence intensity has its minimum value at the middle of the building, also for different directions of the wind. It has also been found that different direction yield separation cone vortices, which have a smaller size and height than the normal direction.

The inlet profile of mean velocity and turbulence intensity are shown in Fig.4a. Fig.4b shows the measurement for Pos. 1 and 2, while Fig.4c and Fig.4d show those for Pos.3 and 4, respectively. These values are used as validation of the numerical model developed in this work.

4 NUMERICAL MODEL AND METHODOLOGY

The geometry as in Fig.3b is simplified and tested in the numerical model. A steady state RANS (Reynolds Averaged Navier-Stokes) simulation has been developed using the *k-ω* SST turbulence model, to get a brief idea of the flow pattern and check if the mesh requirements are met. The objective is to have a rough estimation of the turbulent quantities at stake. A preliminary comparison with the LES (Large Eddy Simulation) approach is then proposed, in order to discuss the importance of modelling the fluctuating statistics. In fact, even though the RANS approach has shown good viability for the estimation of the averaged fields, it is hindered by the modelling of fluctuating statistics [37].

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A block structured mesh has been constructed, having $y^+\sim 1$ and choosing the blocking strategy in order to limit the along-flow size of the elements to respect the CFL condition which imposes $Co<1$. This has brought to the choice of a time step of $\Delta t=5e^{-5}$ for the LES model presented. The Smagorinsky-Lilly model has been chosen as Sub-Grid Scale model (SGS), with the use of the van Driest damping function[1]. This allows a correct behaviour at the wall to be modelled, as a fixed constant would impose unphysical turbulence near the wall, where the viscous effects are more important, as known.

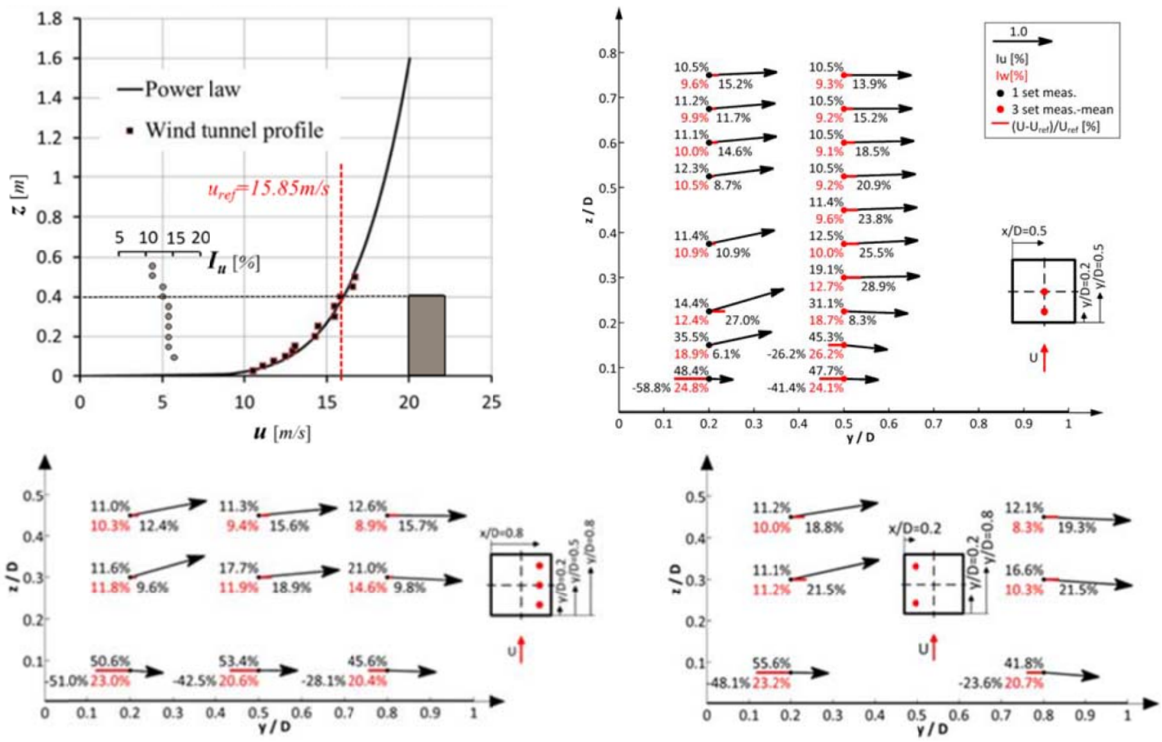

Figure 4 a) Wind-tunnel velocity profile ahead of the model; b) Velocity vectors, I_u and I_w as measured at pos. 1 and 2, c) Poss. 3', 3 and 3'', d) Poss. 4' and 4'' [36].

[1] A damping function, such as the one formulated by Van Driest $l_{sgs}=C_{sgs}\Delta\left(1-e^{-y^+/A^+}\right)$, where $A^+=26$, lowers the value of the model constant C_{sgs} or C_s in those regions of the flow where viscosity effects become preponderant. In fact, the Smagorinsky model uses a fixed constant to take into account the SGS effects, potentially yielding an unphysical behaviour. The eddy viscosity reads $\nu_{sgs}=\left(C_{sgs}\Delta\right)^2|\tilde{S}|=\left(C_{sgs}\Delta\right)^2\sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}}$ where the Smagorinsky model constant has been set to $C_s=0.17$.

4 PRELIMINARY RESULTS AND DISCUSSION

The preliminary results (shown in Fig. 5, 6 and 7) show that the flow pattern is as expected as previous models.

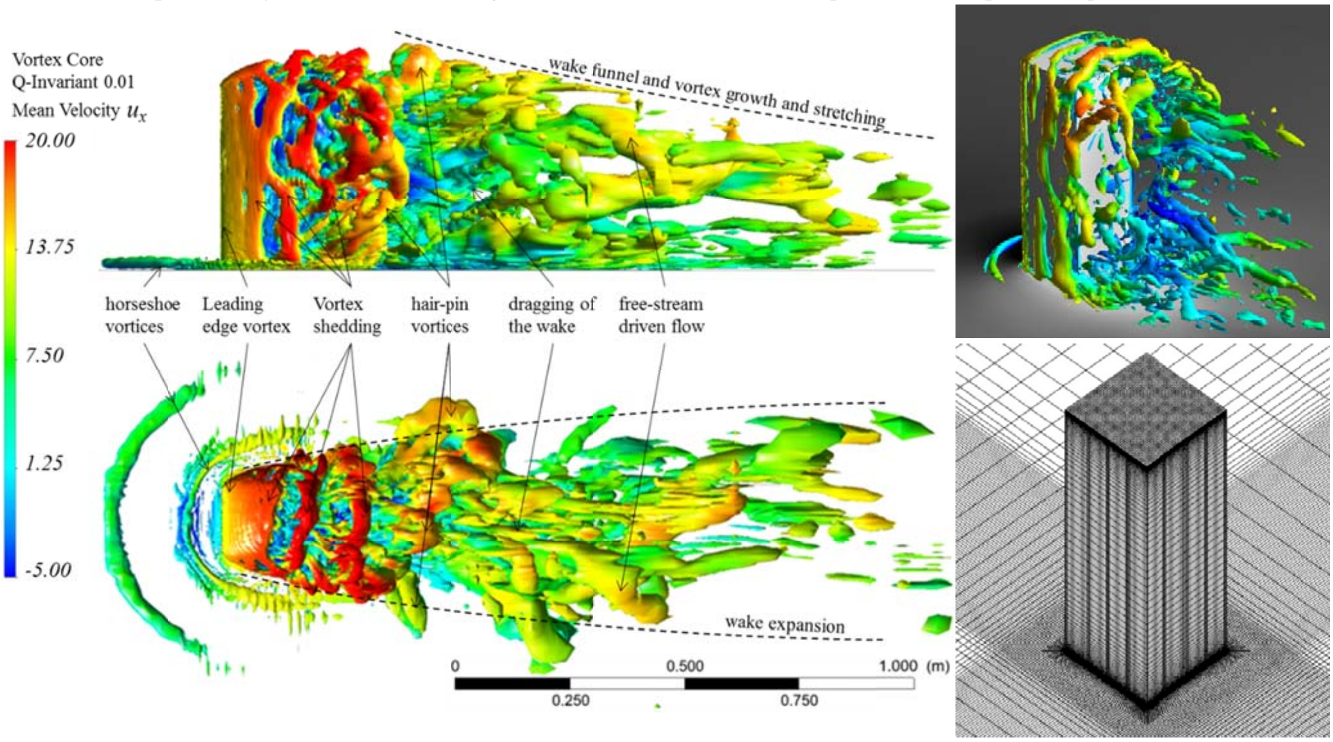

Figure 5 a), b) Vortex core visualisation (Q invariant $1/s^2$), with flow pattern identification; c) vortex core visualisation (swirling strength $1/s$) and d) structured block grid of the high-rise building model.

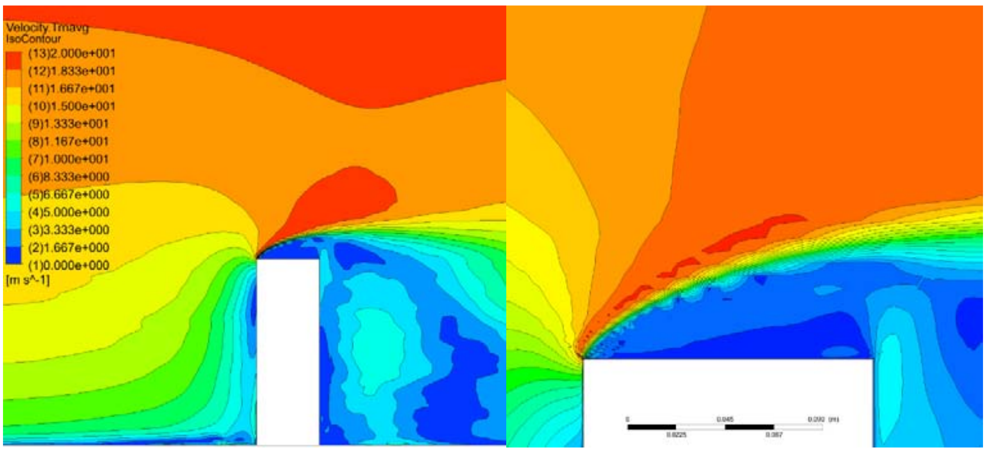

Figure 6 Iso-contours of the mean velocity field for the LES simulation.

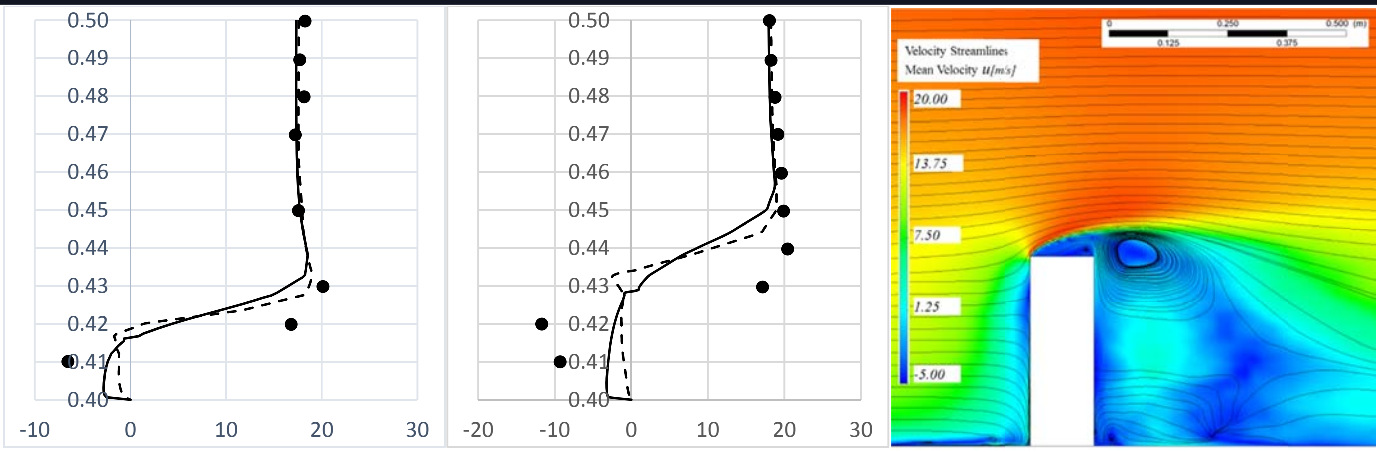

Figure 7 Mean Velocity respectively at position 1 a) and 2 b), with experimental results (line for k-omega, dashed for LES); c) streamlines of averaged velocity field for LES model.

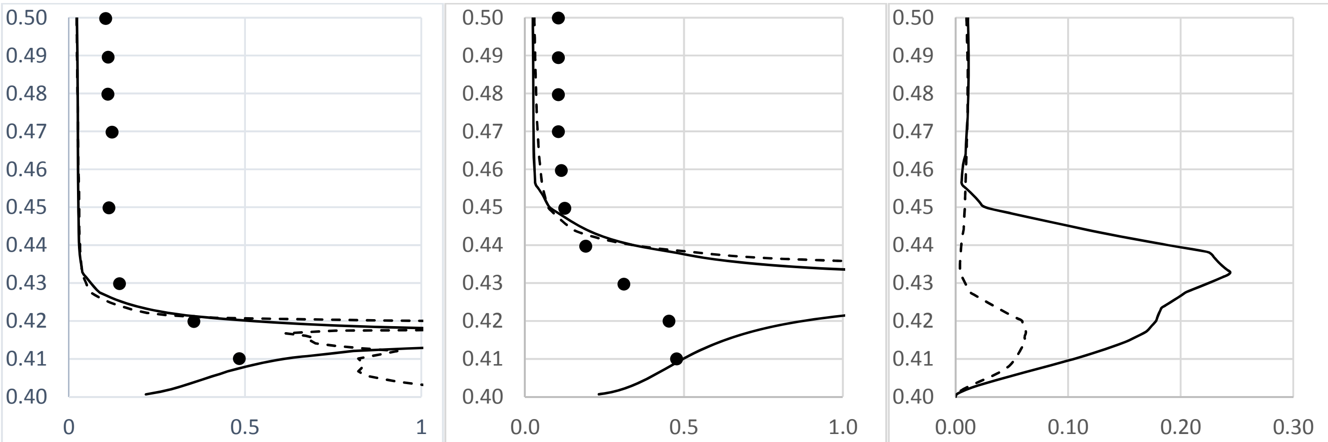

Figure 8 Turbulence intensity (respectively at position 1 and 2, with experimental results, line for k-omega, dashed for LES) and turbulent length scale for Position 1 (dash) and 2 (line), relative to RANS k omega, in cm.

Results show that LES simulation provides little improvement with respect to the steady RANS simulation. This is due to the insufficient averaging time which has been so far simulated: improved data will provide a longer time domain to be modelled. Fig 6 shows that the flow field still is affected by the instantaneous flow. It can also be noticed though, that the flow pattern experiences a steep acceleration of the flow in the area above the separation bubble.

However, the turbulence intensity shows that the simulation needs improvement and that high turbulence occurs in the accelerated flow region. The effect of turbulence is important because of the turbulent length scale (shown in Fig. 8c, as evaluated using the kinetic energy of turbulence). Such values are much smaller than the expected length scales in the atmospheric boundary layer, and such a pattern is almost unexplored regarding the expected effect of turbulence on the aerodynamics of a hypothetical device placed in the immediate vicinity of a building, even if an accelerated zone is looked at.

5 CONCLUSIONS AND NEXT STEPS

This preliminary results show the need of a high-fidelity approach for the modelling of the turbulence pattern around building for wind energy harvesting.

The flow pattern around a building has been modelled and validated using both the RANS and the LES approach, showing little difference in the results. In fact, the quality of an LES simulation strongly depends on the actual averaging time used, which is confirmed by the whole totality of the literature.

A brief critical literature review has been made, showing the necessity of more studies about the physical phenomena involving the interaction of turbulence with bluff bodies, especially for practical applications involving the urban environment.

Future work will provide more averaging time to the LES simulation to validate the fluctuating pattern, in the scope of understanding the actual turbulence pattern at the inflow of a supposedly nearly place wind energy converter.

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