# Computational Analysis of VAWT Micro Wind Farm Potential for Urban Rooftops

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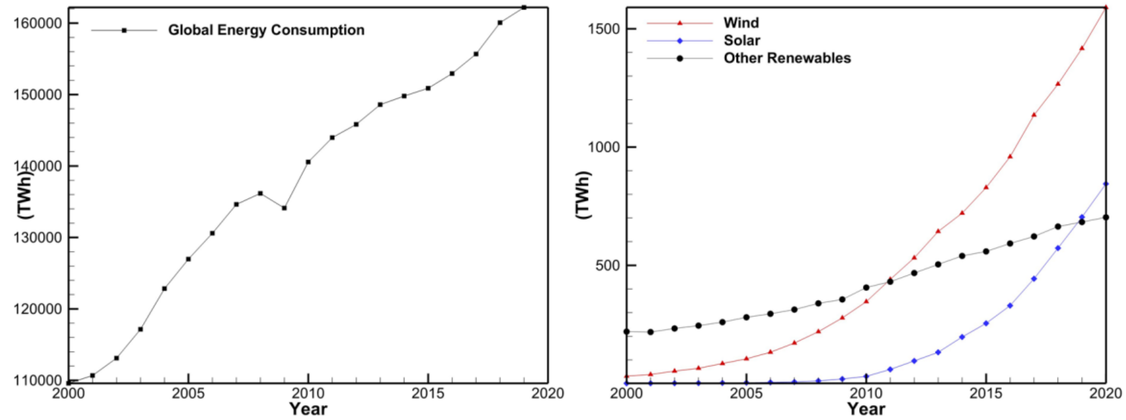
## ABSTRACT

Renewable energy resources are promising in power generation due to their sustainability aspect and environment friendliness as they are means of pollution free power production. Wind energy.y is utilized for power production with the help of wind turbines. The offshore and onshore windfarms consisting of horizontal axis wind turbines are major contributors in the wind energy. However, this type of turbine is not domestically viable mainly due to limitations of directionality and noise. Vertical axis wind turbines do not have these constraints and may blend in the urban environments. In built environments, the wind flow is quite complex due to large scale effects and turbulence. In this paper, the academic building of a university is studied as a possible platform for harnessing the wind energy resources. This case study is performed on academic blocks of University of Gujrat. These building environments were modeled and analyzed with computational fluid dynamic software to model the wind behavior on the building roof top. These results show that there is potential in setting up micro windfarms for the academic environments. The simulation for single building showed a potential for 61.8kW whereas this potential decreased substantially when terrain effects are considered using the circular arrangement for the simulation.

**Keywords:** Dynamic analysis; Riser; Thermoplastic; Offshore jacket; Wave.

## INTRODUCTION

In present age, energy is a basic necessity of life. With increase in technological development, the energy consumption is also increasing as shown in Figure 1 (a) (Energy Data Explorer - Our World in Data 2021). This leads to requirement of more energy generation. Fossil fuels have been used as the major energy replenishing means. However, there are a lot problems associated with fossil fuels such as air pollution, global warming and unsustainability. Serious environmental issues are caused by this fossil fuels-based lifestyle (Abbasi et al. 2020). The seriousness of these issues has hard-pressed human life towards the investigation of renewable resources of energy. A smooth transition should be made towards the utilization of these resources for energy production (Jauhar et al. 2021.). These renewable energy resources mainly constitute of hydropower, wind, solar and other renewables such as biomass and biofuels etc. Hydropower is the largest contributing renewable energy resource in the world energy mix (How have the world's energy sources changed over the last two centuries? - Our World in Data 2021).




(a) (b)

**Figure 1** Energy consumption of the World from (a) all sources (b) renewables.

However, it is location dependent. The second largest contributor is the wind energy that is shown in Figure 1 (b) and compared with 'Solar' and 'Other Renewables'. Wind energy on the other hand depends on the availability of wind flow (Roy and Das 2018). This study is focused with respect to Pakistan. With 64% of energy mix has been coming from fossil fuels, there has been an average shortfall of 5 GW (Ali et al. 2019; Javed et al. 2016). However, European contourites have been actively transitioning towards wind energy as their renewable energy resource (Hatziargyriou, IEEE, and 2001 2001). The global contribution of wind energy is 3540 TWh. Similarly in Pakistan, the wind energy contribution has been increasing with currently constituting the 27% of overall renewable energy as shown in Figure 2. Therefore, this study is focused on further energy harvest from wind energy.

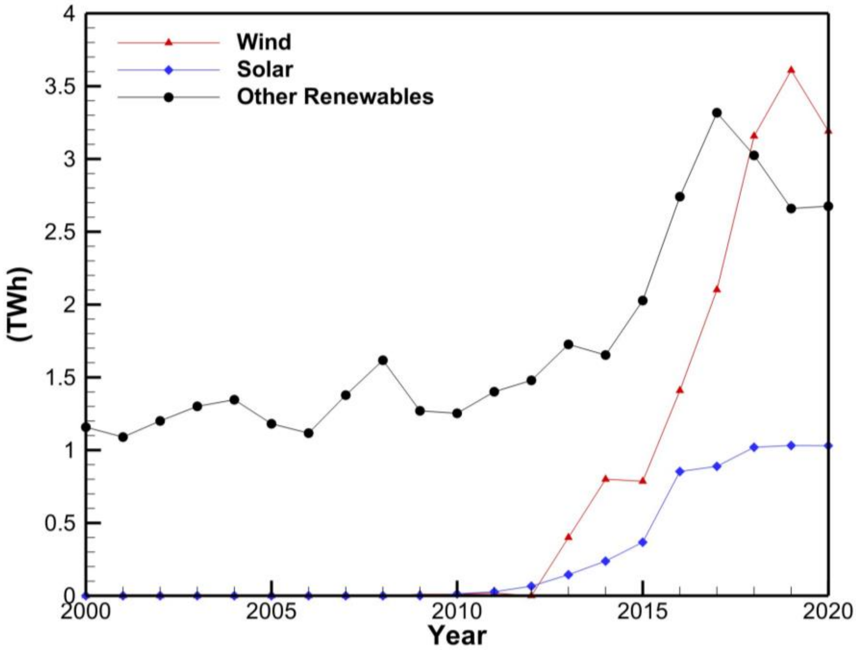


**Figure 2.** Pakistan’s renewable energy growth

World’s familiarity with wind power generation is increasing, providing means of clean energy. This pollutant that may harm the environment include carbon dioxide leading to acid rain and smog, and harmful radioactive emissions (Grieser et al. 2015). The global wind energy council predicts that 355GW capacity expansion by the year 2020–2024 (Global Wind Report 2019 - Global Wind Energy Council 2019). Majority of wind turbines consist of onshore and offshore windfarms of MW range. For these large-scale turbines, the costal and rural sites were assumed as the best sites for energy production. Nevertheless, in the recent research, it has shown that urban areas have potential for clean energy generation using wind power.

(Stathopoulos, Alrawashdeh, and … 2018; Francisco Toja-Silva, Colmenar-Santos, and Castro-Gil 2013). This idea is referred as an urban or micro wind farm. Various urban structures, such as roads, rooftops, rail-tracks, region between or around multilayer buildings have wind energy generation potential (Stathopoulos, Alrawashdeh, and … 2018; F Toja-Silva and … 2013). Therefore, the technology of micro wind farm can be explored to find solution to the present energy crisis. By integrating these micro wind turbines into the grid, the transmission losses are reduced, thereby; decreasing the power transmission costs (F Toja-Silva and … 2013). Understanding the wind flow behavior in built environment is quite difficult due to turbulence and more chaotic nature of the wind flow (Ishugah et al. 2014; Janajreh et al. 2012). The wind flow pattern is governed by the urban built environment (Pandit et al. 2017). The urban wind resource efficiency exploration is an active area of research (Stathopoulos, Alrawashdeh, and … 2018). Producing the wind maps for wind power generation is quite difficult. The patterns of wind should be assessed on the desired places to predict the available energy potential. The available wind power potential in the built environment is obstinate about determining subsequently the conventional measurement methods do not perform well in urban areas (Ishugah et al. 2014). Traditional structures of wind turbine are not suitable for the bult environment environment as well.

Wind turbines are used to harvest wind energy that are further categorized into horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) (Eriksson, Bernhoff, and Leijon 2008; Tjiu et al. 2015; Tummala et al. 2016). In HAWTs, the axis of rotation is parallel to the wind flow whereas in VAWTs, the axis of rotation is perpendicular to the wind flow. The suitability of large-scale wind turbines is questioned urban areas due to space limitations. Conventional, HAWTs are ineffective due to complicated control of yawing action and axis of rotation always be in the parallel to wind which is inefficient in an urban area. Apart from these technical shortcomings, the residents of urban areas disprove large sized HAWT installments due to noise and safety apprehensions (Johari, Jalil, and Shariff 2018).

VAWTs, on the contrary, are an excellent choice for wind power production in built environments (Frunzulica et al. 2016). VAWTs do not require a lot of space, their placement is possible in tight places such as between two buildings and rooftop. This is motivation for the development of novel wind turbines in towns (Stathopoulos, Alrawashdeh, and … 2018; F Toja-Silva and … 2013). Moreover, for VAWTs, no yawing action is required, this makes them less sensitive to the rapid changes in the wind direction. Therefore, effective harvesting of the wind energy in urban areas is quite tricky. With respect to the energy harnessing tools, the areas of research include wind energy assessment, wind mapping tools, turbine design, blade materials, aerodynamic model, airfoil design, etc. (F Toja-Silva and … 2013). In this study, research is focused on wind energy assessment.

In urban areas, there are buildings which influence the air flow behavior of the air. The terrain's high roughness length and presence of impediments of different profiles and permeability cause the wind conditions to become complex in the built environmentas. The real adaptability of wind turbines in these areas is to be tested. Due to these reasons, the wind profile in urban locations does not follow the classical log-law based profile (Mertens 2006) rather it becomes quite complex as shown in Figure 3. In this case the zero-velocity high is shifted upwards by a displacement d which is function of average height of the surrounding buildings.

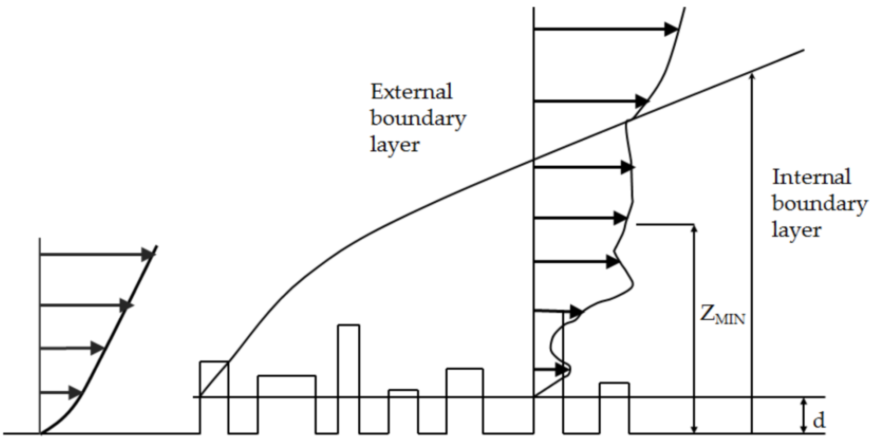



**Figure 3.** Wind profile in build environment

From theoretical perspective, the wind turbines placement requires those buildings that are at a sufficient height from the surrounding buildings to take advantage of the deflection and accelerations (Mertens 2006). However, this requires the fulfillment of geometric proportions between the buildings.

In this study, the buildings of same features are analyzed for the flow behavior. The academic region of the University of Gujrat (UOG) is studied. The academic block is shown in Figure 3 (a) and the circular arrangement of the academic blocks is shown in Figure 3 (b). The dimensions for the model are extracted from Google Earth. The single academic building and the whole academic area both are analyzed in the digital wind tunnel.

(a) (b)

**Figure 3** UOG Building (a) 3D rendering order (b) Circular arrangement.

## NUMERICAL METHODOLOGY

For the complete turbulence capturing by numerical modeling, the equations of motions for fluid flow should be solved on all spatial and temporal scales. This approach is called direct numerical simulations (DNS). The computational resources required to solve DNS far exceed the capacity of the most powerful supercomputers currently available. Instead of DNS, there is another method in which flow variables are decomposed into mean components and fluctuation components. The governing equations of fluid motion are averaged in order to remove the small scales, resulting set of the modified equations is less computation intensive. These equations are referred as “Reynolds-averaged Navier-Stokes equations” (RANS). In order to solve RANS, the k-ε turbulence model is used (Launder, transfer, and 1974 1974). In this model two transport equations are used for turbulence properties. Equation (1) is the transport equation of the turbulence kinetic energy $k$, and the Equation (2) governs the transport of dissipation rate $\varepsilon$ of $k$. This method is widely used and tested model for CFD calculations. The standard k-ε turbulence model works well for building simulations as well (Balduzzi et al. 2012).

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij}E_{ij} - \rho\,\varepsilon \;\ldots (1)$$

$$\frac{\partial(\rho\,\varepsilon)}{\partial t} + \frac{\partial(\rho\,\varepsilon\,u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}\,2\mu_t E_{ij}E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \;\ldots (2)$$

Snappyhex mesh technique (OpenFOAM: User Guide: snappyHexMesh n.d.) was used for meshing. In this meshing technique the meshing is started from pure hex mesh, prismatic layers are generated. It works well with non-watertight surfaces. To scale model is placed in a virtual wind tunnel comprising of 458×381×191 meters. The snappyhex mesh created is shown in Figure 4 (a). For various values of y coordinate, the grind is present in the Figure 4 (b) to (f). With figure (b) starting from far side of the wind tunnel, figure (c) is the inner domain, figure (d) is near the building, figure (e) is on one side of the building and figure (f) is in the center of the building.

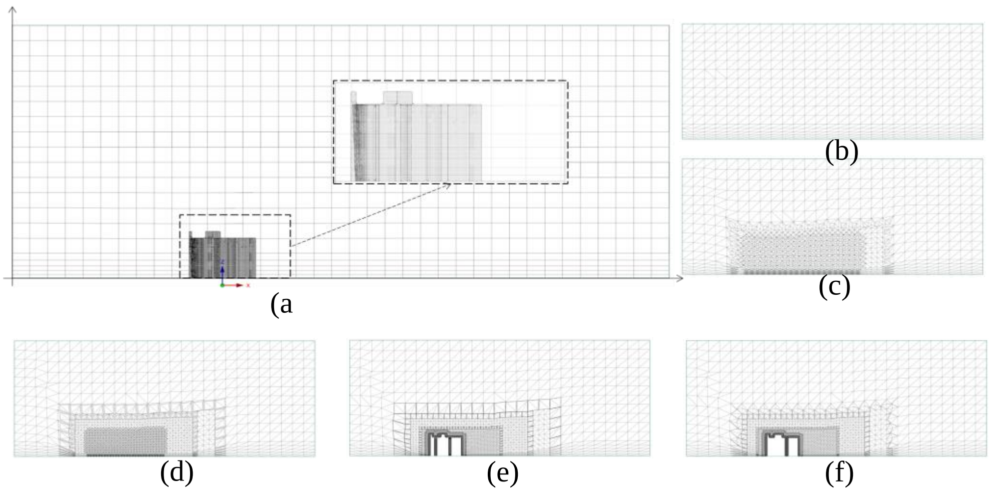
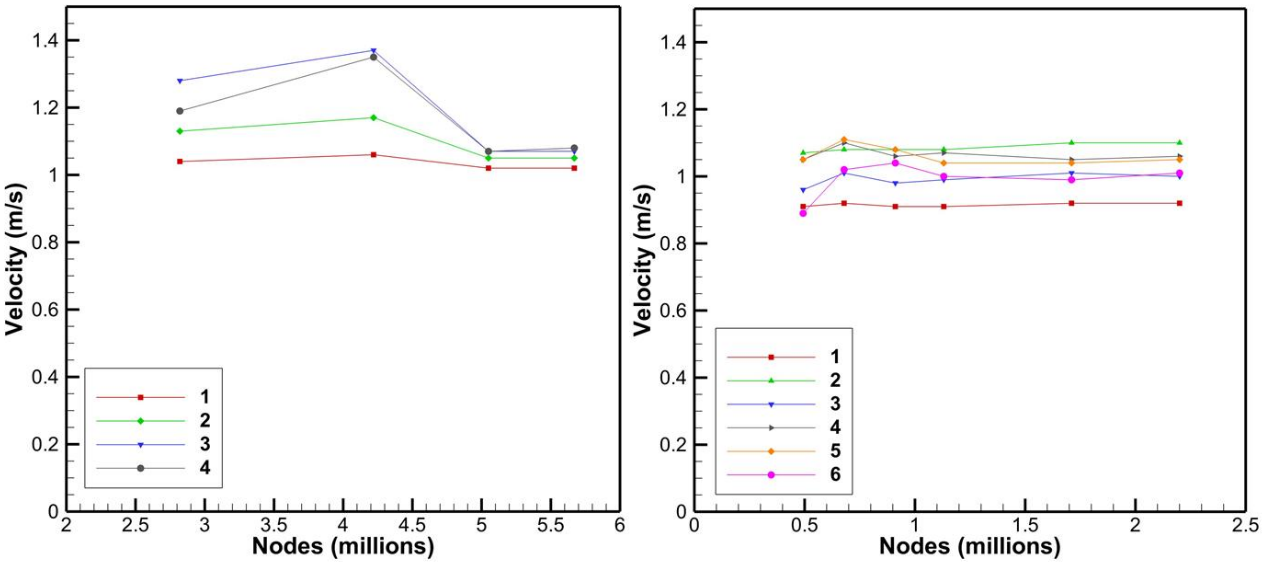



**Figure 4.** Mesh at various locations in the digital wind tunnel

In this study, natively compiled OpenFOAM (OpenFOAM | Free CFD Software | The OpenFOAM

Foundation n.d.) version from CFD Support (Download OpenFOAM® Software n.d.) called "OpenFOAM® for Windows", version 17.10 is utilized. The numerical solver is called "RWINDSimulationSolver" and it is related to the family of a steady-state solver for incompressible, turbulent flow, using the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm.

A number of simulations with 1 m/s free stream velocity were performed with varying cells and nodes out of which convergent runs at 0.001 residual pressure were selected. It was found that grind independence was achieved at 5.6 million nodes for the case of single building and 2.2 million nodes for the circular arrangement of the seven buildings however, the ventilation spaces left open for the actual building were remove for the circular arraignment simulations due to non-convergent solutions and this is the reason for the mesh independence at much lower number of nodes.




(a) (b)

**Figure 5** Grind Independence Study (a) Single Building (b) Circular Arrangement

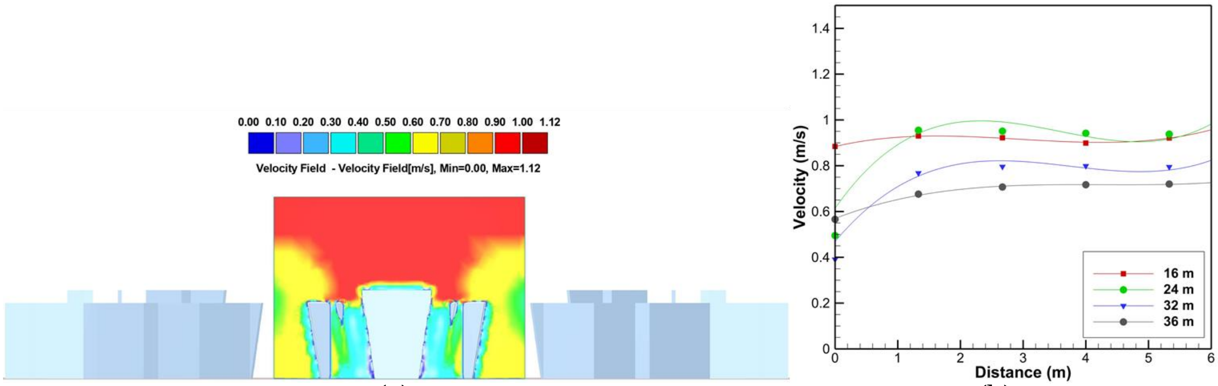
## RESULTS AND DISCUSSION

From the simulation of the single building, the velocity contours were plotted for the XZ plane as it is the front side of the building and shows that the maximum velocity augmentation is available on the rooftop away from the center of the building and on the extreme sides of the building. The velocity profile is extracted at a distance of 4 meters from the center of the building to the far end of the building that is 36 meters from the center. Figure 6 shows that the high velocities exist on the rooftop the single building. The velocity profiles were measure eight meters apart because a 10.3 kW wind tree is 8 m in diameter, thus possible installation sight 61.8 kW wind trees. These trees will produce energy with free stream velocity of 2 m/s.

(a) (b)

**Figure 6** Single Building Velocity (a) Contours in YZ (b) Profile from center of building

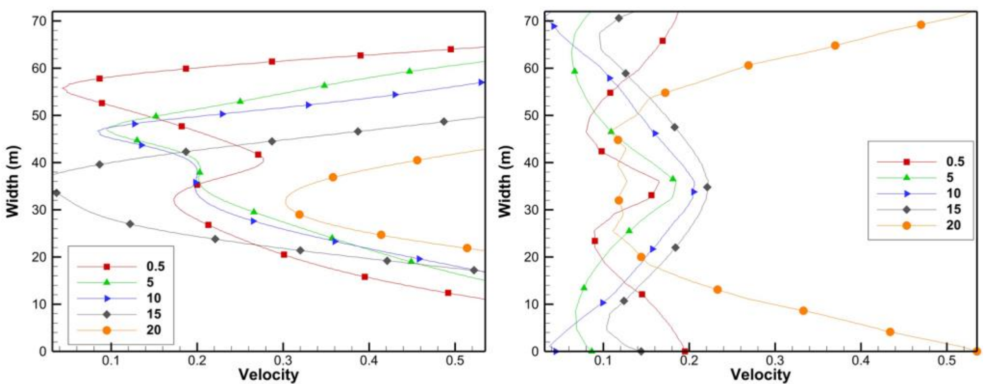
However, when compared to the velocity contours for the circular arrangement, the results prohibit the installation of the wind trees. This is because of the terrain effect that are remaining six buildings in this case as shown in Figure 7 (a) and (b).




(a) (b)

**Figure 7** Terrain Effect on Velocity (a) Contours in YZ (b) Profile from center of building

From the Figure 7 (a), the velocity profile is greatly affected which hinders the placement for the wind turbines.



(a) (b)

**Figure 8** Flow past building (a) Single Building (b) Circular Arrangement

The difference of the wind flow behavior is evident from the wind profiles past the building at various heights. For the single building analysis in Figure 8 (a), the wind profile follows a close to the logarithmic function with maximum velocity increasing with increase in height whereas this is not the case for the circular arrangement, in the Figure 8 (b), the maximum value of velocity is rather in a close range with decreasing effect on the top of the building. Moreover, the velocity at the maximum height of the building is decrease for the circular arrangement when compare to the single building analysis. This shows that terrain plays a major role in assessing the possible arrangement of the wind turbines placement on the roof top. The pressure contours of the circular arrangement are shown in the Figure 9, that support the velocity profile past the building. The regions under direct impact from the wind show high pressure zones where as low-pressure zone are created past the built environment. That leads to decreased air low thus reducing the extract able wind energy. However, this configuration of the buildings shows another aspect of the built environment i.e. local high velocity zone in the region formed the geometric placement of the buildings. This shows a local high velocity region that may be used as a potential sight for wind turbine placement for energy extraction in Figure 10.

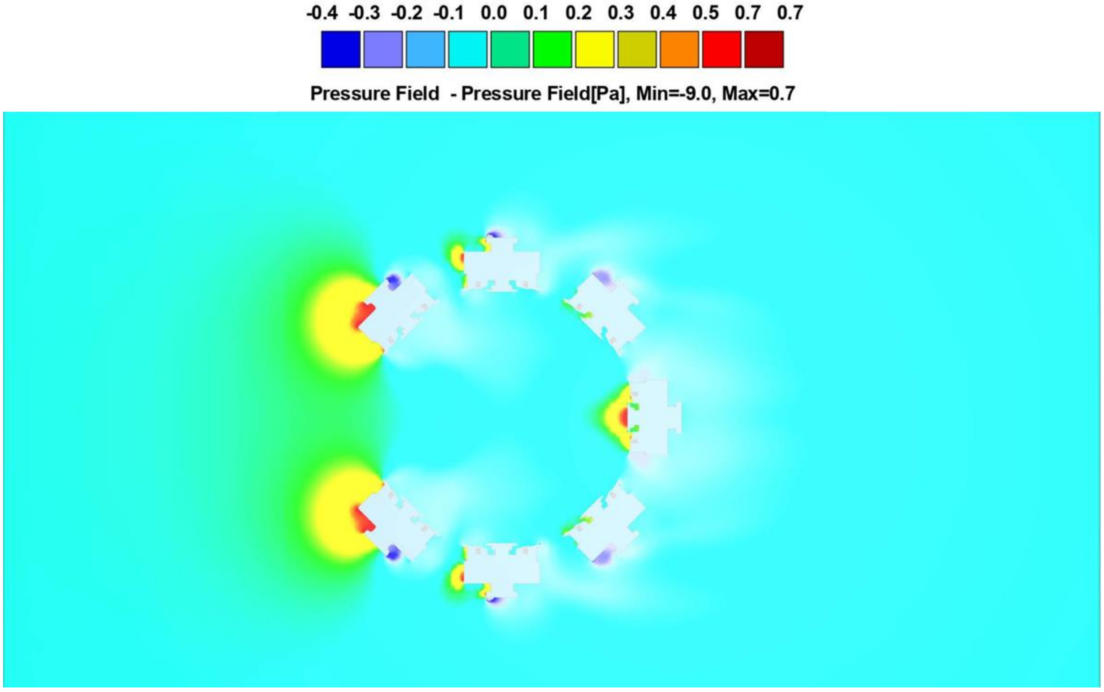



**Figure 9.** Pressure Field Around the circular arrangement.

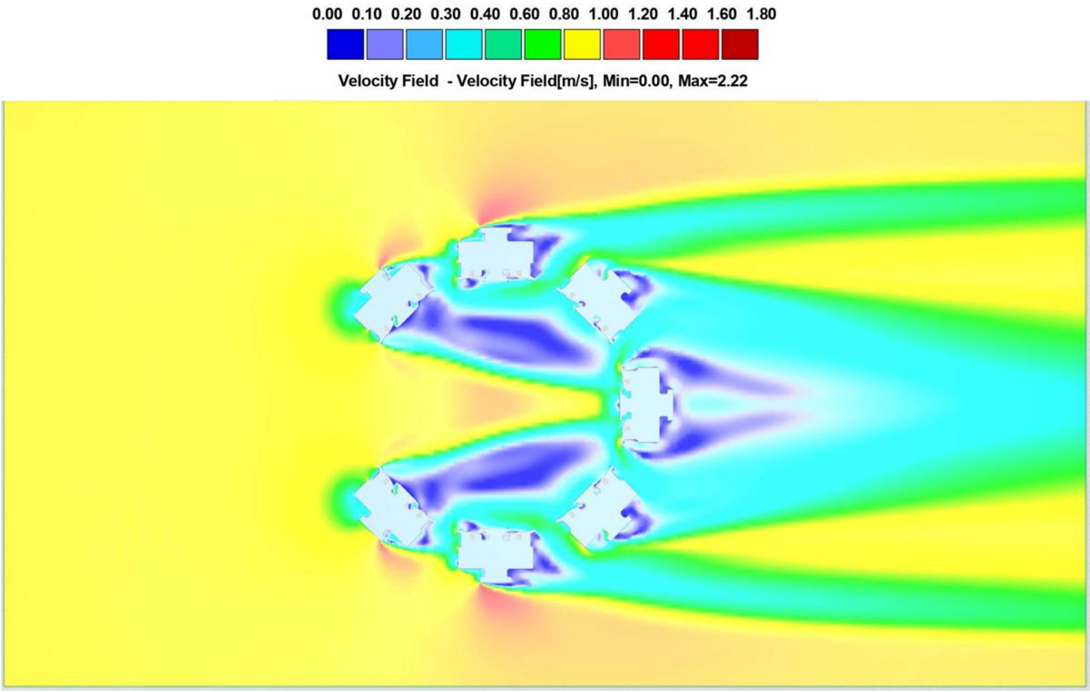
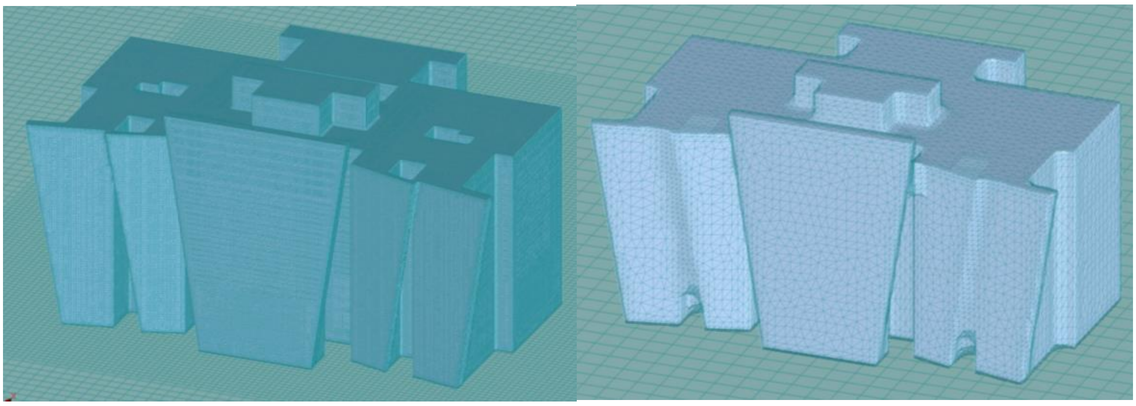



**Figure 10.** Velocity Field Around the circular arrangement.

In this study, analysis is performed using wind only in one direction that limits possibility of to evaluate the effect of wind coming from other directions other than the mentions one. The model simplifications were applied which also limit the when considering the circular arrangement. The snappyhex meshing technique was used, the simplifications were applied based on the minimum edge length and smaller edges compared to the model's dimensions were simplified. This is shown in the Figure 11 (a), where a very fine mesh is generated for the single building analysis whereas in the Figure 11 (b), the vents were removed and small empty regions were also removed in order to have convergent solutions.



(a) (b)

**Figure 11** Sanppyhex Mesh (a) Single Building (b) Circular Arrangement

## CONCLUSION

In this study, CFD analysis of academic blocks of the UOG has been performed using the k-ε turbulence model with the SIMPLE solver. The analysis performed for the single building and the circular arrangement of the building as they are standing in the built environment. Although results from the single building show promising results and can possibly support wind trees ranging to 60 kW power, however, the terrain effect greatly reduces this potential by blocking the incoming flow. The terrain affect disrupts the wind turbine placement to the center of the blocks and away from the rooftops that was originally intended. Moreover, due to the recent constructions, the terrain affect should be modelled by modeling the whole university buildings to have a clear look at the wind flow and possible sites where wind turbines may be placed.

To conclude, there is potential available for wind power extraction, however it is greatly affected by terrain. Therefore, in the future study, various levels of details for the built environment will be considered. Moreover, the CFD analysis will be performed for the whole environment with wind coming from different directions to map the three-dimensional affect of terrain on the wind profile and that will help in specifying the overall possible wind energy extraction sites.

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