NUMERICAL ANALYSIS OF A NOVEL VERTICAL-AXIS WIND TURBINE LAYOUT
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ANALIZA NUMERICĂ A UNEI NOI CONFIGURAŢII DE TURBINE EOLIENE CU AX VERTICAL

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ABSTRACT
Governmental incentives, technological progress, and lowering costs have made renewable energy more accessible and more affordable for residential areas. Switching to renewable energy sources not only reduces greenhouse gas emissions but also provides long-term financial gains, energy independence, and a cleaner environment for communities. In this study, a numerical analysis of a vertical-axis wind turbine layout that is easily adaptable to populated areas was conducted. Among the results are the variation of the torque coefficient during the course of a complete 360-degree rotation and the vorticity magnitude evolution at the nominal point. In order to validate the numerical results, a test campaign will be conducted inside the wind tunnel as part of further study. This campaign will be carried out using an experimental small-scale model.

REZUMAT
Stimulentele guvernamentale, progresele tehnologice și reducerea costurilor au făcut energia regenerabilă mai accesibilă și mai accesibilă pentru zonele rezidențiale. Trecerea la surse regenerabile de energie nu numai că reduce emisiile de gaze cu efect de seră, dar oferă și câștiguri financiare pe termen lung, independență energetică și un mediu mai curat pentru comunități. În acest studiu, a fost efectuată o analiză numerică a unei configurații de turbine eoliene cu ax vertical care poate fi, cu uşurinţă, adaptata la zonele populate. Printre rezultate se numără variația coeficientului de cuplu în cursul unei rotații complete de 360 de grade și evoluția vorticității la punctul nominal. Pentru validarea rezultatelor numerice, va fi efectuată o campanie de testare în interiorul tunelului de vânt, ca parte a studiilor viitoare. Această campanie se va desfășura folosind un model experimental la scară mică.

INTRODUCTION

Environmental concerns, technological advancement, governmental support, and market forces have all contributed to the emergence of renewable energy (*Deyu et al., 2020*). Despite the fact that there are still difficulties to be solved (*Ang et al., 2022*), the advancements made so far point to a bright future for renewable energy as a dependable and sustainable power source (*Sebestyén, 2021*). Over the past few decades, renewable energy has seen considerable change and growth and has continued to be essential to the world's energy transition (*Bhattarai et al., 2022*).

It's important to remember that wind energy is only one element in a varied mix of renewable energy sources that also includes solar, hydro, geothermal, and biomass (*Thellufsen et al., 2020*). A future energy system that is more resilient and sustainable can be built by combining these different energy sources.

Wind turbines are machinery that use the wind's energy to create electricity. Around the world, they are a well-liked and quickly expanding source of sustainable energy. A wind turbine is made up of numerous major parts (*Olabi et al., 2021*). The rotor, which frequently has three blades, absorbs the wind's kinetic energy. When the wind blows, a shaft that is attached to the blades spins (*Ramakrishnan et al., 2022*). A generator uses this spin to turn mechanical energy into electrical energy (*Drancă et al., 2019*). The turbine either uses the electricity it produces on-site or feeds it into the power grid.

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There are several sizes of wind turbines, with capacities ranging from a few kilowatts to several megawatts (*Bilgili, et al., 2022*). The available wind resource, project economics, and the particular site needs are only a few examples of the variables that affect the turbine's size (*Neshat, et al., 2021*).

Despite the many benefits of wind energy, there are a few things to think about and difficulties to overcome. These include the wind's erratic behavior, the possibility of having an effect on the region's species and ecosystems (*Nazir et al., 2020*), the aesthetic impact, and public acceptability.

A wind turbine with a main rotor shaft that is vertically oriented is known as a vertical axis wind turbine (VAWT) (*Bucur, et al., 2021*). VAWTs feature blades that spin along a vertical axis as opposed to the horizontal axis as is the case with conventional horizontal-axis wind turbines (HAWTs). Without a yaw mechanism to spin the rotor into the wind, this design enables the turbine to catch wind from any direction (*Costea, et al., 2019*).
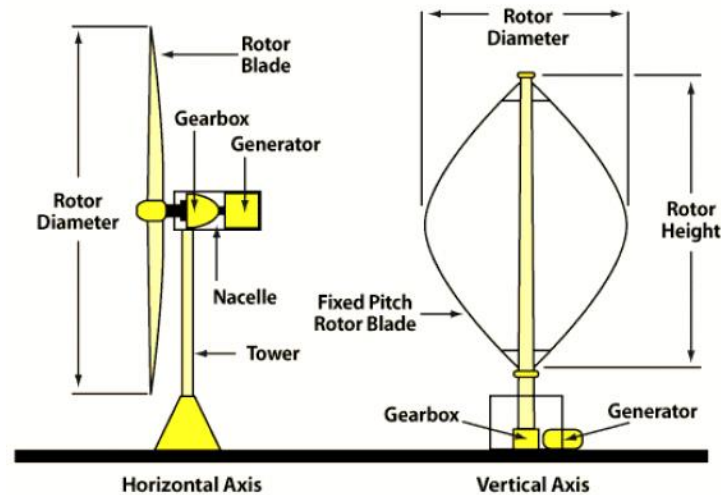

Fig.1 - VAWT vs. HAWT
(*Ahammed et al., 2021*)

Small VAWTs are often utilized in residential or small-scale applications when there is a lack of available space or where aesthetics play a significant role (*Malael, et al., 2021*). They have a smaller footprint than horizontal axis wind turbines, making them suited for locations with limited space. They may be put on roofs, in backyards, or in other urban or suburban settings (*Gall, et al., 2022*). Some compact VAWTs feature a sleek, contemporary style that is suited for applications where aesthetics are important and makes them visually appealing (*Condruz et al., 2019*).

Wind turbine integration in agriculture is an idea that blends renewable energy generation with agricultural land usage (*Skibko et al. 2021*). Wind turbines installed on fields allow farmers to create clean, sustainable power while still using the area for agriculture (*Calderon, et al., 2019*). Wind turbines can provide an extra revenue source for farmers by selling electricity to the grid or powering on-site enterprises. This diversification can aid in income stabilization during agricultural downturns (*Mostafaeipour et al., 2019*). Wind turbines have a low footprint, leaving the majority of the land open for agriculture. This allows farmers to make the most use of their land while potentially increasing their overall yield (*Bardi, et al., 2013*).

Figure 2 shows a movable platform with wind turbines and solar panels that was built as part of a research project and has a technological readiness level of 7 for producing electricity in agricultural fields in off-grid settings.

Fig. 2 - The mobile platform with wind turbines and solar panels for electric current production at agricultural farms in off-grid areas (*Preda et al., 2023*).

Energy requirements for irrigation, equipment, and other activities are frequently high for farmers (*Saputra et al., 2018*). On-site wind turbines can help offset these energy expenses, improving the profitability and sustainability of agriculture.

Farmers may reduce their reliance on unpredictable energy markets and outside energy sources by producing their own electricity (*Sampson al., 2020*). However, there are several difficulties and things to think about when incorporating wind turbines into agriculture. The main one is the high upfront cost, which some farmers may find to be prohibitive. Government assistance and financing sources can help with this issue (*Sutherland al., 2014*). A solution created for agricultural applications is shown in Figure 3. This platform is portable and may be placed in a field of crops. The energy it produces is then utilized to irrigate the crops.
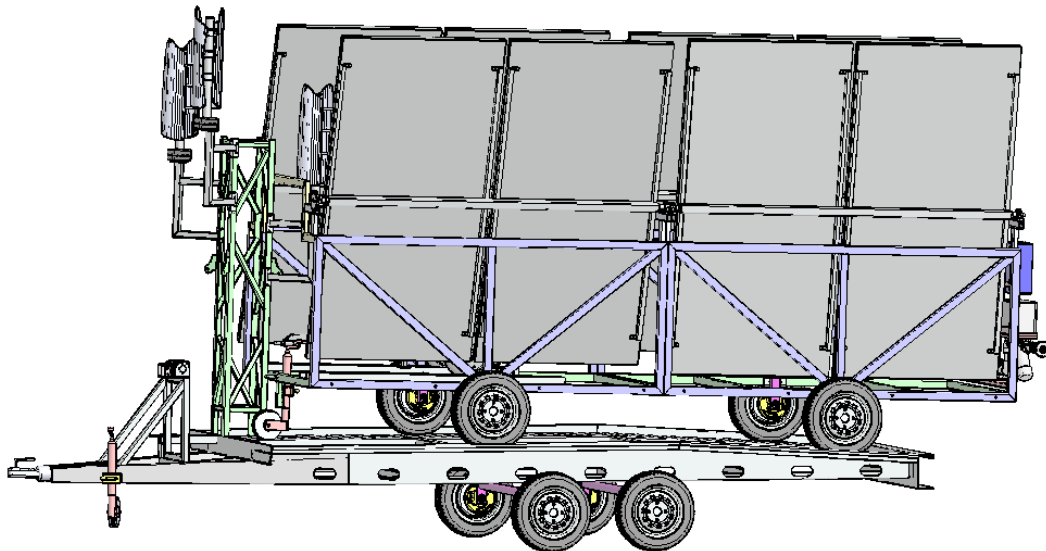

Fig. 3 - Mobile platform with wind turbines and solar panels for irrigating agricultural crops in off-grid areas
(*Preda, et al., 2023*)

While wind turbines are a clean energy source, there are still environmental challenges to be addressed, such as the possibility of noise having an adverse effect on surrounding ecosystems or bird and bat collisions (*Njiri et al., 2016*).

A viable strategy for generating sustainable energy and diversifying agricultural operations is the integration of wind turbines into agriculture (*Chel et al., 2011*). However, to guarantee successful implementation and handle possible problems, thorough planning, consideration of local conditions, and stakeholder participation are essential.

Computational Fluid Dynamics is a method used to simulate and analyze fluid flows using numerical algorithms and computer calculations. CFD is a technology that may be used to analyze and improve the performance of VAWTs (*Mălăel et al., 2014*). Engineers may evaluate a variety of VAWT design elements, such as aerodynamic effectiveness (*Dumitrescu et al., 2019*), power production, and structural stresses, by using CFD models.

In order to evaluate the lift and drag forces operating on the turbine blades at various wind speeds and angles of attack, wind tunnel testing is used to measure the aerodynamic properties of VAWTs. This information is essential for refining the design and raising the turbine's overall effectiveness (*Sunny et al., 2016*).

Researchers can use methods like smoke or dye injection, particle image velocimetry (PIV), or flow visualization methods in wind tunnels (*Edwards, et al., 2015*) to see the airflow patterns around the VAWT model. These methods offer insightful information on the flow dynamics, turbulence, and wake effects connected to VAWTs.

MATERIALS AND METHODS

Two vertical-axis wind turbine layouts were examined in this study. Both arrangements consist of three Lenz-type (*Bucur et al., 2021*) wind turbines that are the same. The distinction between the two situations is that the second turbine in case 2 spins in the opposite direction. The analyses were performed with the same operational parameters and wind speed.

Using CFD methods, researchers may optimize their designs, boost productivity, and cut costs by gaining useful insights into the aerodynamic performance of VAWTs. To achieve accurate and trustworthy results, it's crucial to keep in mind that CFD is a complicated area that calls for knowledge of both fluid dynamics and numerical techniques. By replicating the airflow surrounding the turbine, CFD models may be utilized to analyze the aerodynamics and performance of VAWTs.

Computer-aided design (CAD) software or specialist CFD preprocessing tools are used to build the geometry of the VAWT, including the turbine blades, rotor, and surrounding structures. Figure 4 shows the 3D model of the Lenz-type vertical-axis wind turbine that was utilized in this study to assess the performance of a three-turbine array arrangement.
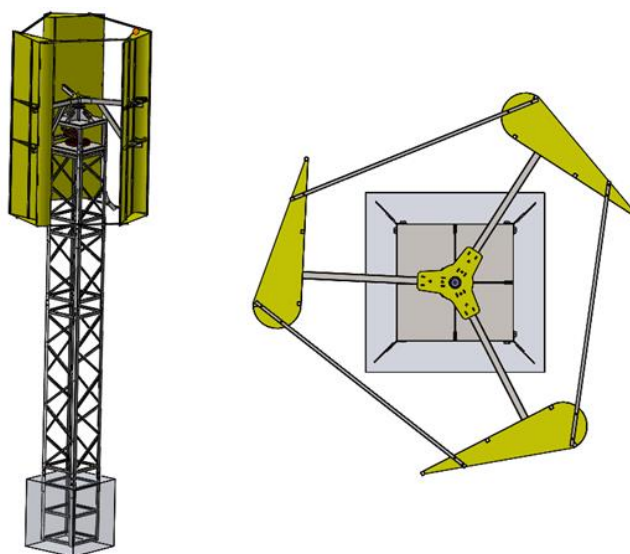
Fig. 4 - VAWT Lenz-type 3D CAD model
(*Bucur, et al., 2021*)

A computational mesh is generated around the VAWT geometry, dividing the domain into small cells or elements. The mesh should be fine enough to appropriately resolve the boundary layers and capture the key flow characteristics. The computational domain for our investigation was divided into four subdomains, with three representing the rotating domains (the turbines) and one representing the stationary domains (the environment). To achieve Yplus values less than one and apply the K-omega SST turbulence model, the initial element size was set-up at 1e-03 mm with a ratio of 1.2. The number of elements and their types for each subdomain are shown in the below table.

Table 1

Mesh statistics

No.	Subdomain	No. of nodes	No. of elements	
			Tri3	*Quad4*
1.	Turbine 1	24211	87	23473
2.	Turbine 2	24038	93	23296
3.	Turbine 3	24259	101	23513
4.	Stator	27170	82	26247
5.	**TOTAL**	**99678**	**96894**	

Knowing the fluid parameters, such as air density and viscosity, is necessary for the simulation. It is also necessary to include boundary parameters, such as wind direction and speed, input and exit conditions,

and wall characteristics. Figure 5 shows the input with blue and the outflow with red. Symmetry requirements for the domain's top and bottom were employed, and the interfaces (in yellow) between the rotors and the stator were specified.
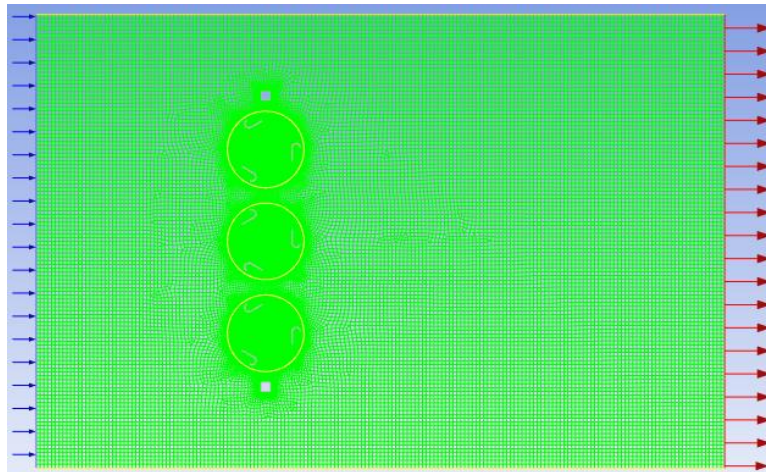

Fig. 5 - Boundary conditions

For CFD simulations, a variety of numerical techniques and solvers are available. Based on the specifics of the issue at hand and the level of precision required, the right solution is chosen. The governing equations for fluid flow are then solved by running the simulation. Table 2 lists the case parameters for the ANSYS Fluent solver.

Table 2

The ANSYS Fluent solver's case settings

Models	Solver	Pressure Based	Unsteady	2d
	Viscous Model	k-ω SST		
Materials	Air	Density, const		
Operating conditions		Pressure101325[Pa]		
Boundary Condition	Inlet	Velocity inlet; V_x=12m/s		
	Outlet	Pressure 0 [Pa]		
	Blades	wall		
	Interfaces	Interface rotors-stator		
	Rotors	Mesh motion	48[rad/s]	
	Stator	Stationary		
Solve	Controls	Solution	SIMPLE	Discretization 2nd order upwind
	Initialize	Inlet		
	Monitors	Residuals	10^{-6}	
		Force	Momentum coefficient	
	Iterate	3600 Steps	0.000364s time step size	
Report	Reference values	Inlet	Length=turbine's radius	

RESULTS

After the simulation is finished, post-processing is carried out to examine the outcomes. This might entail visualizing the flow patterns, computing aerodynamic forces, determining power output, or improving the design by changing the turbine shape or operating circumstances.

The connection between the aerodynamic forces acting on the turbine blades and the resulting torque generated by the rotor is described by the torque coefficient of a wind turbine, which is an important parameter. The torque coefficient (Ct) is defined as the ratio of the torque generated by the wind turbine to the dynamic wind pressure and the swept area of the rotor.

$$Ct = \frac{\text{Torque generated by the turbine}}{0.5 \times \rho \times A \times V^2} \qquad (1)$$

where:

ρ is the air density [kg/m³];

A is the swept area of the turbine rotor [m²](swept area is the circular area covered by the rotating blades);

V is the wind speed [m/s] at the rotor plane.

The torque generated by the turbine can be expressed in terms of the rotor's rotational speed (ω) and the power coefficient (C_p):

$$Torque = 0.5 \times \rho \times A \times V^2 \times C_p \times R \tag{2}$$

where:

C_p is the power coefficient, representing the efficiency of the turbine in converting the kinetic energy of the wind into mechanical power. It varies with the tip speed ratio (λ), which is the ratio of the blade tip speed to the wind speed. C_p is a dimensionless value between 0 and 1;

R is the radius of the rotor [m].

The power coefficient (Cp) is related to the torque coefficient (C_t) through the following equation:

$$C_p = C_t \times \lambda \tag{3}$$

where:

λ is efficiency factor in turbines (the efficiency factor is a measure of how efficiently a turbine converts the fluid's energy into power. It is defined as the ratio of the power output of the turbine to the kinetic energy of the fluid entering the turbine).

Due to different elements such blade twist, airfoil form, and aerodynamic properties, the torque coefficient is not constant over the length of the blade. The shape of the blades is tuned for wind turbines to perform at their best in a certain range of wind speeds. The torque coefficient tends to be smaller with lower wind speeds because there is less wind energy available. The torque coefficient rises with the wind speed until it reaches the peak torque coefficient, which is the highest value. The torque coefficient may begin to drop above the rated wind speed as the wind turbine starts to stall to protect itself from high loads.

Numerous design factors, such as the number of blades, airfoil profiles, and blade twist, have an impact on the torque coefficient distribution. In order to improve energy capture and overall efficiency, modern wind turbine designs strive to attain a high and smooth torque coefficient distribution.
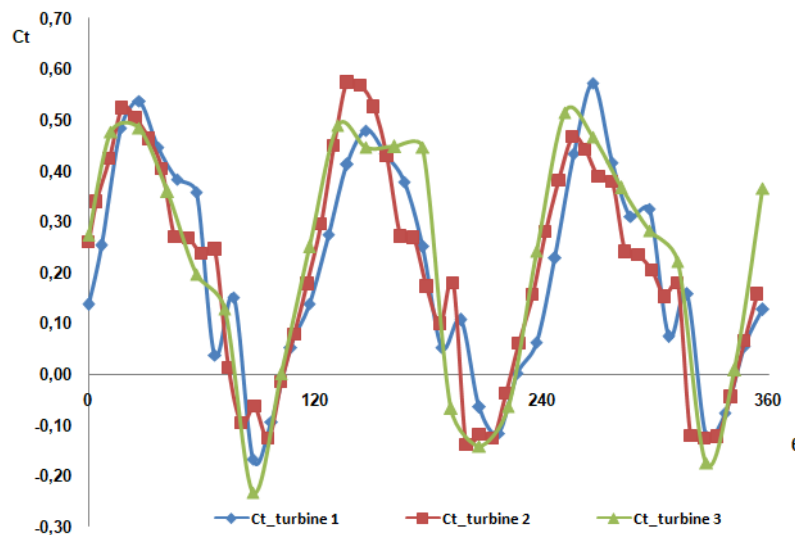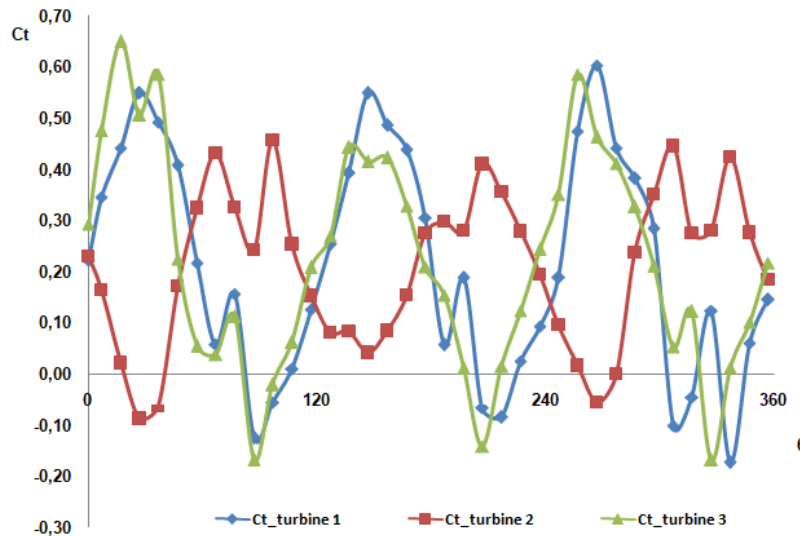

Fig. 6 - Torque coefficient case 1

Fig. 7 - Torque coefficient case 2

The figures below depict the development of vorticity magnitude (figure 8) for the two cases that were examined. The streamlines were also shown in order to better see the interactions between the three turbines (figure 9).
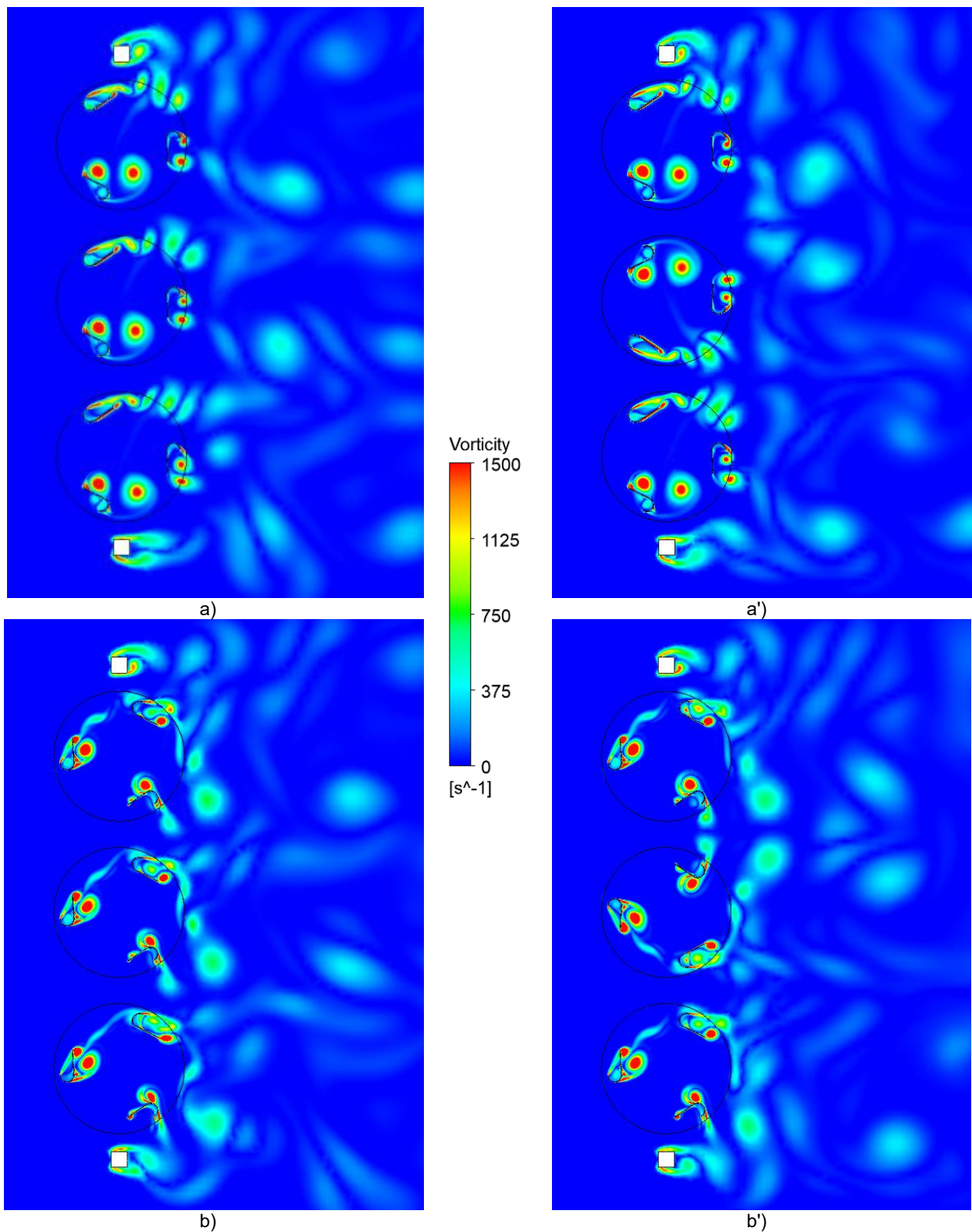

Fig. 8 - Vorticity magnitude

case 1: a) 0 degree; b) 60 degree;
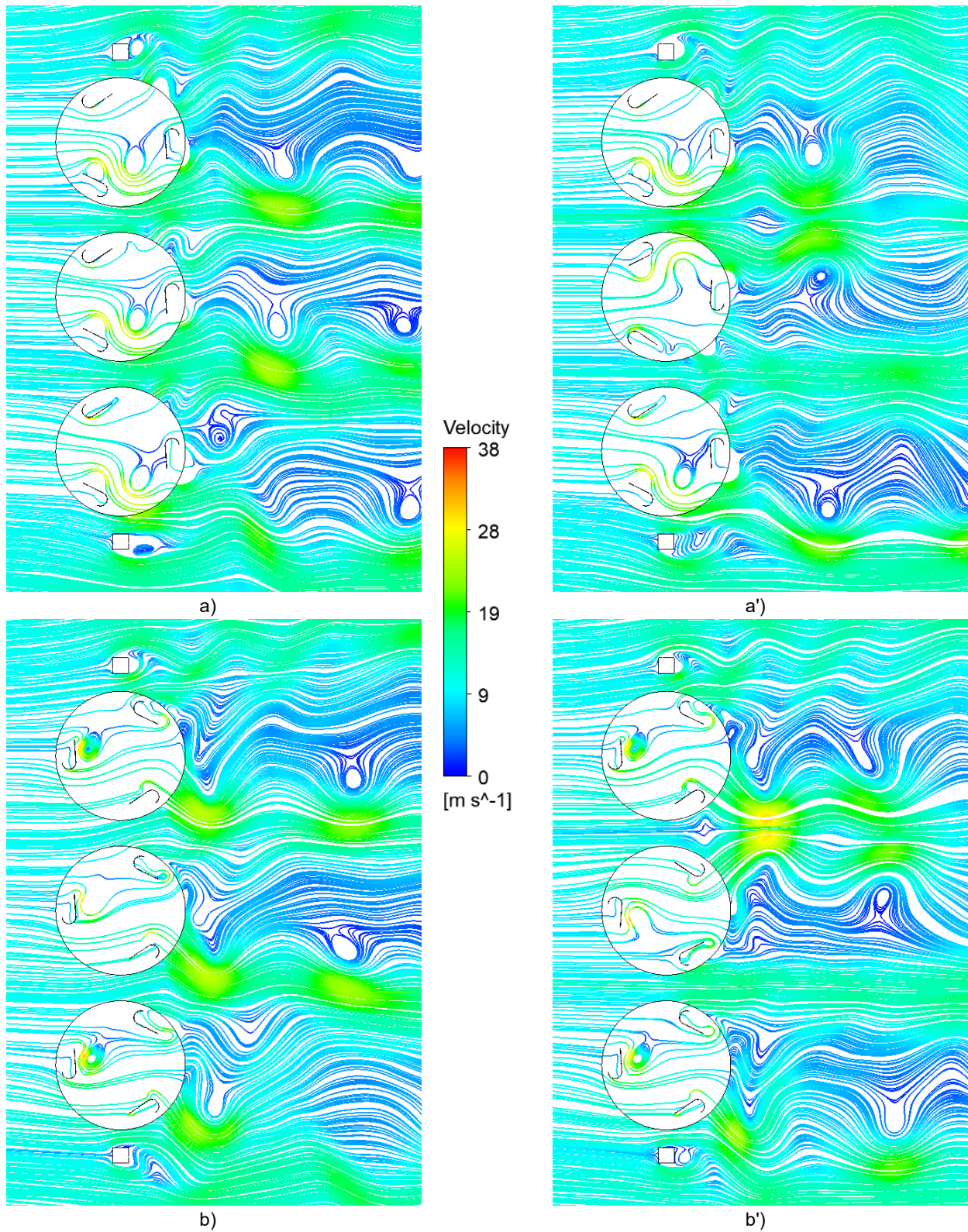case 2: a') 0 degree; b') 60 degree.

Fig. 9 - Velocity streamlines:
case 1: a) 0 degree; b) 60 degree;
case 2: a') 0 degree; b') 60 degree.

CONCLUSIONS

The main objective of this article was to quantitatively investigate a renewable energy solution that may be used in populated areas and also in agriculture. The numerical analysis was completed using CFD methods. The first example featured three wind turbines revolving in the same direction, and the second example involved the center turbine rotating in the opposite direction.

In order to investigate how the vortexes impact the operation of the wind turbines, the evolution of the vorticity magnitude and the streamlines were displayed at various locations of the blades. The arrangement from scenario 2 produced a higher power coefficient at the same rotational speed with a 1.5 percent gain in efficiency because of the high speed zones that are formed as a result of the middle turbine rotating in the opposite direction.

Future research will incorporate an experimental testing campaign in a wind tunnel where Particle Image Velocimetry technology may be used to observe the interactions between the turbines in order to verify the numerical findings.

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