Utilization of Vertical Axis Wind Turbines on Remote Islands

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Abstract— **Wind turbine (W/T) installation in coastal regions is highly beneficial for green electricity production. Even though the high velocity of air flow in these areas is a crucial factor, there are also issues in the design and construction of the W/T that have to be examined in order to obtain a high level of energy efficiency. Two major issues are: a) the erosion of the W/T's construction material due to the moisture content and salinity and b) the high and volatile loads at the rotor blades caused by the high velocity of air flow.**

The purpose of this paper is first to assess the durability of Vertical Axis Wind Turbines (VAWTs) and secondly to calculate and evaluate, with the use of numerical and analytical models, the renewable energy produced. The materials used in the modeling of the rotor blades and the tower of the VAWT are fiberglass-reinforced polyester (GFRP) and anodized aluminum respectively. These materials have been selected due to their resistance in erosion and their mechanical strength in high dynamic loads.

The results of the effects of air flow velocity and pressure on the rotor blades have been calculated through Computer Fluid Dynamics (CFD) code in Ansys Fluent while the effects of dynamic mechanical loads on the rotor, through Finite Element Method (FEM) in Ansys Mechanical. Finally, the electrical energy of the VAWTs' network is calculated with the use of an analytical model.

Index Terms— **CFD, FEM, VAWT, Green Energy**

I. INTRODUCTION

ACCORDING to the assessment report of IPCC, the increase in GHG (Greenhouse Gases) concentration in the atmosphere over the last 50 years is the greatest factor of global warming. It is also mentioned that there is a need for significant drop to the CO_2 emissions in order to assist the stabilization of the atmospheric CO_2 concentration [1].

In compliance with European Union's CO_2 emissions reduction internal commitment, EU's 28 aim to achieve a 20% reduction until 2020, while the EU's GDP grew 45% between 1992 and 2012. A major factor for this achievement is the implementation of structural policies in the fields of climate and energy [2].

Also, the concept of local energy production is a factor of energy independence and cost reduction, applied to facilities with vast requirements of electricity [3].

Under these findings, there is a profound need to explore the ability to provide electricity with a more ecological, cost-effective and sustainable strategy. In this case, the implementation of renewable energy sources to the energy equilibrium of an island is to be considered.

II. AVAILABLE WIND POTENTIAL

According to the European Environment Agency's (EEA) No 6/2009 Technical Report (with the aid of the European Centre for Medium-Range Weather Forecasts), most of the Northern Sea countries and the eastern part of the Mediterranean Sea experience winds with a speed ranging from 4 m/s to 8 m/s or more. Furthermore, the same report states that the previously described areas can provide anywhere from 1000 to more than 3000 full load-hours of potential annually. These areas include some of the most highly populated areas of Europe, where the energy demands are high. They also include some remote islands (particularly in the eastern part of the Mediterranean Sea) where energy independence is crucial for the seamless operation of these communities, therefore harvesting the wind potential-in some cases in a combination with solar energy solutions-promotes energy sustainability, particularly in cases of energy shortage [3]. These findings promote the need to investigate further for efficient ways to harvest the energy provided, especially in areas where the energy demand is high.

A. *Implementation of Wind Energy Solutions in remote islands*

Due to the higher than average wind energy density and consistent wind potential of coastal areas and in particular (for the current study) islands, the actual utilization of wind energy solutions, as for example wind turbines, becomes a growing need in order to achieve green energy production along with a level of energy sustainability and independence. On-shore wind turbines, according to a research sponsored by the US Department of Energy, achieve one of the lowest levelized costs of energy production in $/kWh, which is lower than the equivalent for photovoltaic systems, which in both cases includes the payback of initial investment and operation cost [4].

Especially, the integration of Vertical Axis Wind Turbines (VAWTs) instead of Horizontal Axis Wind Turbines (HAWTs) is to be considered a more practical solution in urban and industrial environments. Small and

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medium scale VAWT's show better performance in turbulent wind, greater energy density and smaller CO_2 emission footprint than equivalent HAWT's [5], [6].

III. SIMULATIONS

For the evaluation of the capability to integrate a wind turbine structure in a remote island, a certain project of simulations is set. This certain project is a combination of two different sets of analyses: a Computational Fluid Dynamics (CFD) analysis and a Structural analysis. Theses analyses are coupled in a One Way Fluid - Structure Interaction (FSI) in order to input the results of the CFD part to the Structural analysis.

A. Gorlov Helical Wind Turbine (GHWT)

The examined VAWT design is a Helical Wind Turbine, as shown in Figure 1, credited to the Russian professor and inventor Alexander Gorlov, as the evolution of Darrieus Wind Turbine. The S-shaped blades are designed to work on the lift-based concept and they create a unidirectional wind turbine [7]. The current design contains a NACA 0020 airfoil. The design involves 3 blades of 5 m (16.40 ft) in length and a total diameter of 3.85 m (12.63 ft). The estimated power output is 1.9 kW at 8 m/s with C_p=0.31 (coefficient of power).

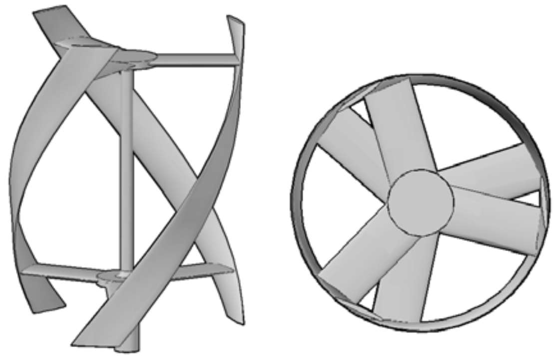

Fig. 1 Vertical Axis Wind Turbine Model Visualization.

B. CFD Analysis

A Computational Fluid Dynamics (CFD) analysis with the aid of the Ansys Fluent solver is used as a tool to extract a computational estimation of the pressure field applied to the structure. For the current study, a set of CFD scenarios are built: a hurricane-scale wind flow of 50 m/s (≈112 mph), a top operational speed wind flow of 20 m/s (≈45 mph) and a mean operational speed of 8 m/s (≈18 mph). These three scenarios will cover a wide spectrum of operational and load conditions for the examined GHWT, as shown in Table I.

TABLE I
CFD SIMULATIONS - SCENARIOS OF WIND SPEED

Case	Wind speed SI (m/s)	Wind speed I-P (mph)	Notes
Extreme wind Hurricane Cat. 2	50	111.86	Wind Turbine locked with brakes
Maximum Operational wind speed	20	44.74	Limitation for safety reasons
Average operational speed	8	17.90	Average of maximum speed in coastal areas

The fluid domain of the designed CFD analysis, as shown in Figure 2, is a volume of 10 m (32.81 ft) in height, 10 m (32.81 ft) in width and 20 m (65.62 ft) in length. An internal rotational fluid domain is created in order to simulate the estimated rotational speed of the VAWT.

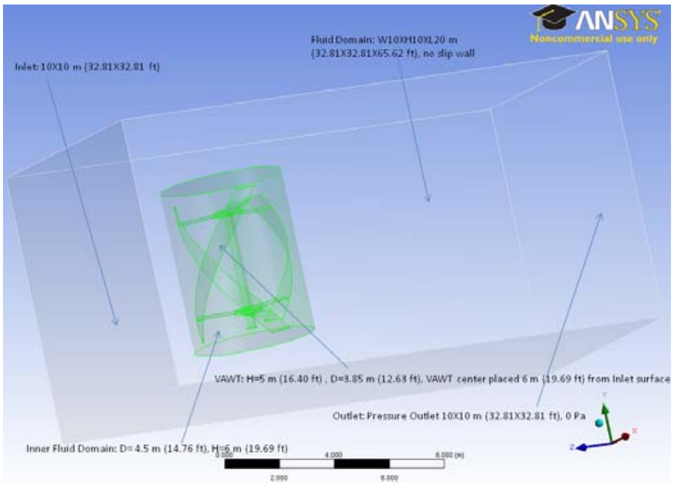

Fig. 2 Fluid Domain Setup for CFD Analysis.

The analysis is based on a Fluent solver with the following settings: Viscous-Laminar Model, SST k-ω equation, Turbulent Intensity: 0.1 %, Turbulent Viscosity Ratio 10, as indicated by previous researches in the same topic [8].

The internal rotating mesh is rotating with a speed of 10.38 rad/s for the 8 m/s (≈18 mph) case and 18.70 rad/s for the 20 m/s (≈45 mph) case. These calculations are a result of the estimated $\lambda \approx 2.5$ and $\lambda \approx 1.8$ perpetually and the:

$$\lambda = {}^{\Omega R}\!/_{V} \qquad (1)$$

where:
V = wind speed
Ω = estimated rotational speed of the VAWT
R = radius of the VAWT

C. Structural Analysis

The second part of the project involves a Structural analysis, where the generated pressure fields of the CFD scenarios described above are applied to the structural model of the VAWT for a series of different material properties. The structure of the blades and the upper and lower support wings is a shell fabricated with Glass Fiber Reinforced Polyester (GFRP) Matrix of initial thickness of 10 mm (0.394 in), involved in every case of composite material on Table II. The central supporting rod of the wind turbine is manufactured by anodized aluminum.

TABLE II
LIST OF THE GFRP MATERIALS

Material Type	Percentage of Fiberglass (%)	Direction of fibers	Fabrication Technique
GFRP 30% SMC	30	Unidirectional	Compression Moulding
GFRP 50% SMC	50	Unidirectional	Compression Moulding
GFRP 50% Woven Roving	50	0/-45/90/+45/0	Lay-up

These three different composite materials, with their mechanical properties illustrated on Table III, will be tested under the resulting pressure fields of the CFD analyses, in order to eliminate those that are proven insufficient for the case loads and define the optimum one. In case that all three materials fail, the procedure will be restarted with increased blade thickness.

TABLE III
MECHANICAL PROPERTIES OF VAWT BLADE MATERIALS

Properties	GFRP 30% SMC	GFRP 50% SMC	GFRP 50% Woven Roving
Density (kg/m^3, lb/ft^3)	1850, 115.63	2000, 125	1640, 102.5
Tensile Yield Strength (MPa, psi)	83, 12038	160, 23205	190, 27556
Compressive Yield Strength (MPa, psi)	83, 12038	160, 23205	190, 27556
Modulus of Elasticity (GPa, kpi)	12, 1740	15.7, 1280	15.5 , 2250
Flexural Strength (MPa, psi)	180, 26100	310, 45000	320, 46400
Flexural Modulus (GPa, kpi)	11, 1600	10, 1450	15.5 , 2250

The estimations on the material properties shown above are based on average values of commercial products.

D. *Analyses Results*

From the first set of CFD analyses, a series of pressure fields was extracted, in order to be exerted in the VAWT model. An example of volume rendering of pressure fields is illustrated in Figure 3.

Material Eliminations

With the application of the pressure-load field resulting from the CFD analyses, we managed to eliminate the GFRP 30% SMC composite material and GFRP 50% SMC, due to poor mechanical behavior during the simulation, showing extreme total deformation. The GFRP 50% Woven Roving composite material came under the resulting maximum total deformation of 73 mm (2.87 in) in 20 m/s (≈45 mph) as the most appropriate material of the study. Figure 4 shows the resulting total deformation for all the wind speed cases for each material. An interesting note is that, the maximum total deformation for all three materials occurs in the wind speed case of 20 m/s (≈45 mph), which is the upper operational limit of the VAWT, underlining the effect of centrifugal force in higher rotational speeds. The Visualization of Total Deformation per revolution in the average operational speed of 8 m/s (≈18 mph) is illustrated in Figure 5

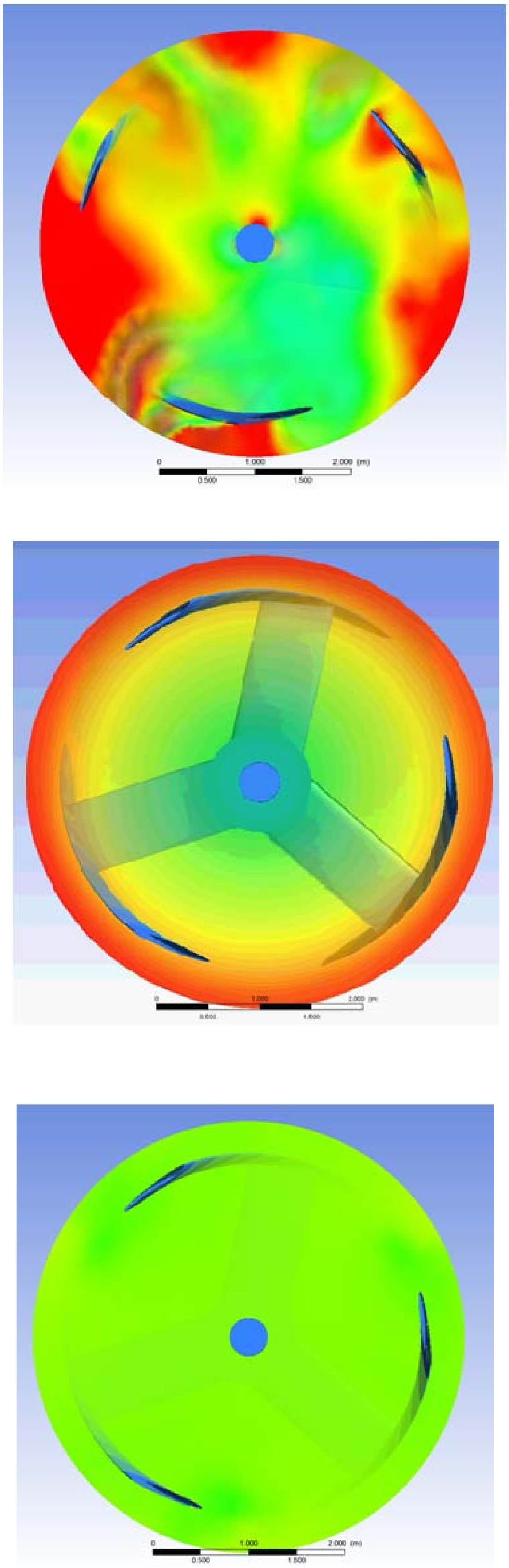

Fig. 3 Volume Rendering of Pressure Fields in the middle of the structure for 50 m/s, 20 m/s and 8 m/s.

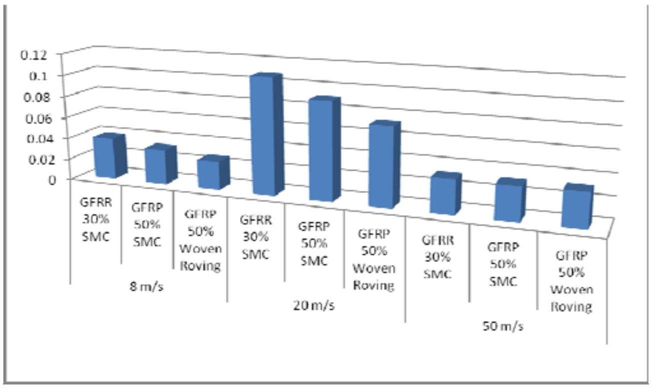

Fig. 4 Total Deformation Data for different wind speeds and materials.

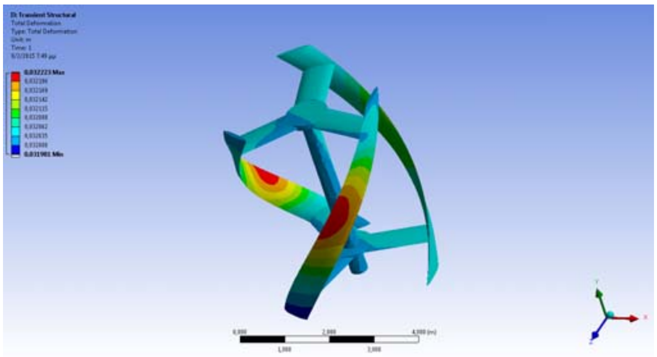

Fig. 5 Total Deformation Visualization per revolution on 8 m/s for GFRP 50% Woven Roving.

Under these finding, that the installation of a VAWT on an island is considered to be a wind resistant solution as it can also be a safe one. The factor of chloride-induced corrosion and subsidence of the composite material is not considered because of the polyester matrix of the composite [9].

E. Discussion

By the application of the studied GHWT in a coastal area, under the assumption for an estimated average wind speed of 8 m/s, which is indicated by relevant bibliography [10];[11] and the maps from the Centre for Renewable Energy Sources of Athens for coastal areas in Greece (specifically islands in the Aegean Sea) [12], a production of more than 6,500 kWh per year is estimated, using a Weibull distribution calculation for the probability of occurrence of a certain wind speed as below:

$$p_{(v)} = \frac{k}{v}\left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\} \quad (2)$$

where $p_{(v)}$ is the frequency of occurrence of wind speed (v), c is the scale factor which is closely related to the wind speed for the location and k is the dimensionless shape factor which describes the form and width of the distribution. The Weibull distribution is therefore determined by parameters c and k [13]. This amount of energy production is typical for commercially applied VAWTs with similar power output and design.

The average cost for the commercial application of the simulated rotor model and an equivalent generator is estimated to approximately USD 4,700 per unit, depending on the raw materials prices and the fabrication process. A pilot installation project of 5 units of GHWTs connected to the grid, but with the ability to power facilities off-grid in cooperation with a battery array in case of a power outage, comes to an estimated cost of USD 23,500 for the set of 5 GHWTs, USD 45,000 for a 50 kWh Li-Ion battery array and USD 5,000 for the inverter and various components. The cost for an on-grid project is reduced to USD 25,000 for the set of 5 units and various components. The costs presented are derived from current market prices. The price for electricity produced by wind turbines in Greece is set to USD 270 per MWh, according to the Hellenic Transmission System Operator [14]. These prices lead to an annual reduction of energy cost by approximately USD 8700 and CO_2 emissions by 11,700 kg (25,800 lb) in lignite combustion equivalent. The reimbursement of the on-grid project is calculated to less than 5 years for a 20-year lifespan of the VAWTs.

IV. CONCLUSION

By the application of the studied GHWT in a coastal area with an average wind speed of 8 m/s, a production of more than 20000 kWh per year is estimated. The use of a grid of GHWT's installed in non-functional areas of an island, such as remote hills or on top of existing buildings that can support their weight, is able to achieve a production capable of covering a fraction of the energy demands of an island. Furthermore, the CO_2 emissions saved by the integration of such a system in an island increase by a fraction the effort to reduce the GHG emissions and formulate an eco-friendly image and a sense of environment responsibility.

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