

**Feasibility and Energy Output of Wind Turbines in
New South Wales**

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the degree of

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under the supervision of Dr. Ali Altaee

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Certificate of Original Authorship

I, *NOUR KHLAIFAT* declare that this thesis is submitted in fulfilment of the requirements for the award of *Doctor of Philosophy*, in the *School of Civil and Environmental Engineering/Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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List of Publications

Journal articles

- [1] **N. Khlaifat**, A. Altaee, J. Zhou. Assessment of wind energy potential at Yanco, New South Wales, Australia. *International Journal of Industrial Electronics and Electrical Engineering*. 8 (2020) 26-30.
- [2] **N. Khlaifat**, A. Altaee, J. Zhou, Y. Huang, A. Braytee. Optimization of a Small Wind Turbine for a Rural Area: A Case Study of Deniliquin, New South Wales, Australia. *Energies*. 13 (2020) 2292.
- [3] **N. Khlaifat**, A. Altaee, J. Zhou, Y. Huang. A review of the key sensitive parameters on the aerodynamic performance of a horizontal wind turbine using Computational Fluid Dynamics modelling. *AIMS Energy*. 8 (2020) 493-524.
- [4] **N. Khlaifat**, A. Altaee, J. Zhou, Y. Huang. Evaluation of wind resource potential using statistical analysis of probability density functions in New South Wales, Australia. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. (2020) 1-18.
- [5] **N. Khlaifat**, A. Altaee, J. Zhou, Y. Huang. Statistical analysis of wind characteristic in Yanco agricultural institute, Australia. *International Journal of Smart Grid and Clean Energy*. 10 (2021) 1-7.

Abstract

The horizontal axis wind turbine (HAWT) is considered as the forefront of modern technology due to its reliability and cost-effectiveness. However, the efficiency of wind turbines is sometimes not at the desired level due to inefficient extraction of power from the wind by the turbine blades. Small wind turbines have emerged as a popular renewable energy source for remote sites and rural areas. Critical parameters influence the aerodynamics performance of small-sized HAWT, such as atmospheric conditions and the wind blade's geometry. The location also yields a significant effect on the annual energy production of wind turbines. When designing the HAWT for a specific area or region, accounting for environmental conditions could improve the power produced.

This study aims to optimize the performance of a small HAWT with 20 kW capacity under local wind conditions in rural New South Wales (NSW). Five rural locations in NSW have been selected for this study according to wind data availability. This study addresses the gap in our knowledge of combining wind turbine shape design and the available wind resources in Australia using updated and refined methodologies to maximize the annual energy production (AEP). One of the key objectives of this study is to understand the aerodynamics performance of small-scale HAWT under different conditions. The topic was investigated using computational fluid dynamics (CFD) modelling to understand the main aerodynamics characteristics of each section along the blade. Ansys Fluent (version 18.2, Canonsburg, PA, USA) was used to examine the aerodynamics performance of the HAWT. Four Reynolds Averaged Navier-Stokes (RANS) turbulence models, namely the Realizable $k-\varepsilon$, $k-\omega$ SST, Spalart-Allmaras and Transition SST models, are specifically researched. This is done to assess the ability to predict the flow over the wind turbine under different wind velocities where the flow varies from the attached to separated flow conditions. The CFD model was validated using the NREL CER measurement data. The results demonstrate that all RANS models expect Realizable $k-\varepsilon$ can well predict the pressure coefficient in the area where the flow is still attached. The differences between turbulence models become significant as wind speed increases. The Transition SST model does agree with the experimental data on the prediction of pressure coefficient airfoil. The best performing CFD model will examine the mechanical output with different rotational speeds and variable pitch angles for the baseline wind turbine based on this numerical validation.

This study also highlights the feasibility of wind potential at five rural sites in NSW,

specifically Ballina, Merriwa, Deniliquin, Yanco, and Bega areas. The local wind conditions can fluctuate daily in many rural environments, and seasonal variations are significant. Therefore, accurate wind data models are necessary to find the best possible location for a wind turbine in an urban environment. The types of wind speed distribution function dramatically affect the output of the available wind energy and wind turbine performance at a particular site. Consequently, the accuracy of applying the four probability density functions was evaluated, namely Rayleigh, Weibull, gamma, and lognormal distributions. The outcomes showed Weibull provided the most accurate distribution.

Several numerical methods are applied to estimate the Weibull parameters depending on wind data measurement at the five sites. The accuracy and performance of numerical models have been evaluated using statistical indicators. The results showed that Deniliquin employed the maximum scale and shape parameters, while the minimum scale and shape parameters were utilized at the Bega area. Assessment of power density indicated that Deniliquin had a marginal wind speed resource, while Ballina, Bega, and Merriwa had poor wind resources. The wind data model of shape and scale parameters of 2.096 and 5.042 m/s, respectively, were used to improve the overall optimization process. The aerodynamics shape of the rotor was optimized to maximize the AEP in the Deniliquin region. The HARP_Opt (National Renewable Energy Laboratory, Golden, CO, USA) specifically enhanced the design variables concerning the shape of the blade, rated rotational speed, and pitch angle. The pitch angle remained at 0° while the rising wind speed improved rotor speed to 148.4482 rpm at rated speed. This optimization improved the AEP rate by 9.068% when compared to the original NREL design.

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Definitions and Abbreviations

Acronyms

| | |
|----------|--|
| AEP | Annual energy production |
| AIC | Akaike information criterion |
| BEM | Blade element momentum |
| BIC | Bayesian information criterion |
| CER | Combined experiment rotor |
| CFD | Computational fluid dynamics |
| DES | Detached-eddy simulation |
| DNS | Direct numerical simulation |
| HARP_Opt | Horizontal axis rotor performance optimization |
| HAWT | Horizontal axis wind turbine |
| GA | Genetic algorithm |
| LES | Large eddy simulation |
| LIDAR | Light detection and ranging |
| MPPT | Maximum power point tracking |
| MRF | Moving reference frame |
| NACA | National Advisory Committee for Aeronautics |
| NREL | National Renewable Energy Laboratory |
| NSW | New South Wales |
| PMSG | Permanent magnet synchronous generator |
| RANS | Reynolds Averaged Navier-Stokes |
| RMSE | Root mean square error |
| SEDA | Sustainable Energy Development Authority |
| SMI | Sliding mesh interface |

| | |
|-------|--|
| SST | Shear stress transport |
| VAWT | Vertical axis wind turbine |
| URANS | Unsteady Reynolds Averaged Navier-Stokes |
| WRSG | Wound rotor synchronous generator |

Symbols

| | |
|-----------------|---|
| Re_{θ} | Reynolds number |
| y^+ | Dimensionless wall distance |
| y | First layer thickness |
| u_t | Friction velocity |
| \vec{v}_r | Velocity seen from the moving frame |
| \vec{V}_{sta} | Velocity seen from the stationary frame |
| $\bar{\tau}_r$ | Viscous stress |
| \acute{u}_i | Fluctuating velocity |
| \bar{u}_i | Mean velocity |
| ρ | Air density |
| Ω | Magnitude of the vorticity |
| ε | Turbulent dissipation rate |
| k | Turbulent kinetic energy |
| ν_t | Turbulence eddy viscosity |
| ω | Turbulent dissipation rate |
| μ_t | Turbulence eddy viscosity |
| $Re_{\theta t}$ | Transition momentum thickness Reynolds number |
| γ | Intermittency |
| V_{inelt} | Inlet velocity |
| A_{inelt} | Inlet area |
| V_{outlet} | Outlet velocity |
| A_{outlet} | Outlet area |

| | |
|----------------|---|
| C_p | Pressure coefficient |
| P_{static} | Local static pressure |
| P_{rel} | Free stream pressure |
| Ω | Rotational wind speed |
| V_{rel} | Relative wind speed |
| \bar{U} | Mean wind speed |
| U_i | Wind speed at i number of observations |
| N | Number of observations |
| σ_U | Standard deviation |
| s | Skewness |
| $f(U)$ | Probability density function |
| $F(U)$ | Cumulative distribution function |
| c | Scale parameter for Weibull distribution |
| K | Shape parameter for Weibull distribution |
| σ_c | Scale parameter for Rayleigh distribution |
| α_{sh} | Shape parameter for lognormal distribution |
| β_c | Scale parameter for lognormal distribution |
| ξ | Shape parameter for gamma function |
| β_G | Scale parameter for gamma function |
| ψ | Digamma function |
| Γ | Gamma function |
| Q | Number of parameters in the model (dimension θ) |
| $\hat{\theta}$ | Maximum likelihood estimate |
| $erf(U)$ | Error function |
| R^2 | Coefficient of determination |
| χ^2 | Chi-square |
| KS | Kolmogorov–Smirnov |
| $X_{observed}$ | Frequency of observations |

| | |
|------------------|--|
| $X_{predicted}$ | Frequency of predicted value from probability density function |
| E_{pf} | Energy pattern factor |
| $\overline{U^3}$ | Mean of wind speed cubes |
| A | Area of actuator disc |
| P | Output power |
| V_0 | Free wind speed |
| a | Axial induction factor |
| C_{power} | Power coefficient |
| $c(r)$ | Chord length |
| $\beta(r)$ | Twist angle |
| φ | Flow angle |
| a' | Tangential induction factor |
| α | Angle of attack |
| θ_p | Pitch angle |
| F_n | Projected normal aerodynamics force on the rotor blade |
| F_t | Projected tangential aerodynamics force on the rotor blade |
| l | Lift force |
| d | Drag force |
| C_t | Tangential force coefficient |
| dT | Thrust force |
| C_T | Thrust coefficient |
| B | Number of blades |
| $\sigma(r)$ | Local solidity |
| $U_{cut,in}$ | Cut-in wind speed |
| $U_{cut,out}$ | Cut-out wind speed |
| $X_{i min}$ | Lower limit for the chord length and the twist angle |
| $X_{i max}$ | Upper limit for the chord length and the twist angle |
| PD | Wind power density |

| | |
|------------------|------------------|
| h_0 | Reference height |
| α_{power} | Power exponent |
| h_y | Desired height |