UNIVERSITY OF TECHNOLOGY SYDNEY

Feasibility and Energy Output of Wind Turbines in New South Wales

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Dr. Ali Altaee
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June 2021

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.

Signature of Student: Production Note: Signature removed prior to publication.

Date: 23/05/2021

Acknowledgements

Pursuing a doctoral degree can be a long and challenging journey. Fortunately, I received a lot of help and support through this journey from the following wonderful people who made doing this thesis enjoyable and fruitful.

Primarily, I would thank God for being able to complete this project with success. I would like to say a special thank you to my supervisor, Dr Ali Altaee; His support, guidance, and overall insights in this field have made this an inspiring experience for me. The door to, Dr Ali Altaee office was always open whenever I ran into a trouble spot or had a question about my research or writing. He steered me in the right direction whenever he thought I needed it. Also, I would like to thank my supervisory committee, Prof. John Zhou, for his enthusiasm for the project, support, guidance, and patience; the thoughtful comments and recommendations on this dissertation. Without the supervisory panel's assistance and dedicated involvement in every step throughout the process, this research would have never been accomplished.

I would like to sincerely thank Isra University, Jordan, for its doctoral scholarship. I gratefully acknowledge the University of Technology Sydney (UTS) for awarding me the “FEIT Women in Engineering Top-up Scholarship.” I am also thankful to the Faculty of Engineering and its staff for all the considerate guidance. I would like to acknowledge the Australian Government Bureau of Meteorology for supplying wind data.

I would like to thank my parents, family, daughter, and son, who have been very supportive and helpful in various stages of my Ph.D. research study.

Finally, To my soulmate husband – it would be an understatement to say that, as a family, we have experienced some ups and downs in the past four years. You did not let me every time I was ready to quit, and I am forever grateful. This dissertation stands as a testament to your unconditional love and encouragement.

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 wields 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-ε, k-ω 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-ε 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
$\overrightarrow{v_r}$	Velocity seen from the moving frame
$\overrightarrow{V_{sta}}$	Velocity seen from the stationary frame
$\bar{\bar{\tau}}_r$	Viscous stress
$\acute{u}_i$	Fluctuating velocity
$\bar{u}_i$	Mean velocity
ρ	Air density
$\cap$	Magnitude of the vorticity
ε	Turbulent dissipation rate
k	Turbulent kinetic energy
v_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

Cp	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
X^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_O	Free wind speed
a	Axial induction factor
$Cpower$	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