COMPUTATIONAL FLUID DYNAMICS ANALYSIS AND OPTIMIZATION OF HIGHWAY SAVONIUS WIND TURBINE INTEGRATED WITH GUIDE VANES

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ABSTRACT

Substantial efforts have been made by researchers to study the interaction between vortices produced by moving vehicles and wind turbines as a renewable energy source. The speeding vehicles produced a scattered and non-uniform wind flow. A curtain system was placed in front of the wind turbine blade to reduce the negative torque. However, it has limitation where high wind energy losses occur when passing through the curtain system arrangement. The aim of this study was to improve further the performance of wind by designing a capable Highway Savonius Wind Turbine (HSWT) integrated with a curtain system. It consists of a row guide vane with an aerofoil shape of National Advisory Committee for Aeronautics (NACA) 4412. In addition, a Computational Fluid Dynamics (CFD) modelling of a reliable HSWT integrated with guide vanes was also employed. Three factors, namely, the distance between the guide vanes (d_{GV}), the guide vanes angle (α), and the moving car speed (V_C) were selected to evaluate their influence on the HSWT power coefficient (C_p). Taguchi Method with an orthogonal array of $L_9(3^3)$ was used to plan and conduct the simulations. The CFD simulations with one degree of freedom were performed using k-ω SST turbulence model to observe the effects of the wind velocity induced by the moving vehicle in real-life situation. The influence strength of each factor was $V_C > \alpha > d_{GV}$ where the ranks were 3.53, 8.86 and 9.33, respectively. It was found that, the performance of HSWT was sensitive to the car speed and the guide vanes angle, but insensitive to the distance between the guide vanes. The signal to noise ratio showed that combination of $d_{GV} = 0.4$m, $\alpha = 30^o$, and $V_C = 30$m/s produced the maximum power coefficient. This optimum condition increased the power coefficient by 26% compared to without the installation of the guide vanes. In addition, the observation of streamline and velocity contours showed that guide vanes demonstrate a positive effect on the wind turbine performance by redirecting and distributing the turbulence wake flow uniformly to the convex surface of the advancing turbine blade. Hence, the proposed guide vanes system improved the self-starting abilities of HSWT by reducing negative torque.

ABSTRAK

Banyak usaha telah dilakukan oleh penyelidik untuk mengkaji interaksi antara kenderaan bergerak dan turbin angin sebagai sumber tenaga boleh diperbaharui. Kenderaan dipandu laju menghasilkan aliran angin yang tersebar dan tidak seragam. Satu sistem tirai diletakkan di hadapan bilah turbin angin untuk mengurangkan daya kilas negatif. Walau bagaimanapun, ia mempunyai kelemahan yang mana terdapat kehilangan tenaga angin yang tinggi berlaku apabila angin melalui susunan sistem tirai. Tujuan kajian ini adalah untuk meningkatkan lagi prestasi turbin angin dengan merekabentuk Turbin angin Savonius lebuhraya (HSWT) bersama sistem tirai. Ia terdiri daripada satu baris panduan angin yang mempunyai bentuk aerofoil *National Advisory Committee for Aeronautics* (NACA) 4412. Sebagai tambahan, model Pengkomputeran Dinamik Bendalir (CFD) bagi HSWT yang boleh dipercayai serta panduan angin telah juga digunakan. Tiga faktor, iaitu jarak antara panduan angin (d_{GV}), sudut panduan angin (α), dan kelajuan kereta bergerak (V_C) telah dipilih untuk menilai pengaruhnya kepada pekali daya (C_p) turbin angin. Kaedah Taguchi dengan susunan ortogonal $L_9(3^3)$ telah digunakan untuk merancang dan menjalankan simulasi. Simulasi CFD dengan satu darjah kebebasan dilakukan menggunakan model gelora k-ω SST untuk melihat kesan kelajuan angin yang disebabkan oleh kenderaan bergerak dalam situasi sebenar. Urutan kekuatan pengaruh setiap faktor adalah $V_C > \alpha > d_{GV}$ yang mana nilai pangkat masing-masing adalah 3.53, 8.86 dan 9.33. Didapati bahawa, prestasi turbin angin sensitif terhadap kelajuan kereta dan sudut panduan angin tetapi tidak sensitif terhadap jarak sesama panduan angin. Nisbah isyarat kepada hingar menunjukkan bahawa kombinasi $d_{GV} = 0.4$ m, $\alpha = 30^o$, dan $V_C = 30$m/s menghasilkan pekali kuasa yang maksimum. Keadaan optimum ini meningkatkan pekali kuasa sebanyak 26% berbanding dengan tanpa pemasangan sistem panduan angin. Di samping itu, pemerhatian kontur aliran dan halaju menunjukkan bahawa sistem panduan angin mempunyai kesan positif terhadap prestasi HSWT dengan mengarahkan dan menyebarkan aliran bergelora secara seragam ke permukaan cembung kemaraan bilah turbin. Oleh itu, sistem panel panduan yang dicadangkan meningkatkan kemampuan permulaan sendiri HSWT dengan mengurangkan daya kilas negatif.

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LIST OF ABBREVIATIONS

1DOF	-	One degree of freedom
2D	-	Two dimensional
3D	-	Three dimensional
ABS		Acrylonitrile Butadiene Styrene
CAD		Computer Aided Design
CFD	-	Computational Fluid Dynamics
DOE	-	Design of Experiment
GBT	-	Guide Box Tunnel
GIT	-	Grid Independent Test
HAWT	-	Horizontal axis wind turbine
HSWT	-	Highway Savonius Wind Turbine
SSWT	-	Small Savnoius Wind Turbine
NACA	-	National Advisory Committee for Aeronautics
OA	-	Orthogonal Array
PC	-	Personal Computer
PIV	-	Particle Image Velocimetry
PLA	-	Polylactic Acid
RAM	-	Random-access memory
RNG	-	Re-Normalisation Group
RPM	-	Revolutions per minute
SST	-	Shear-Stress Transport
SWT	-	Savonius Wind Turbine
S/N	-	Signal to noise ratio
TSR	-	Tip speed ratio
UDF	-	User-Define Function
VAWT	-	Vertical axis wind turbine

LIST OF SYMBOLS

C_d	-	Drag coefficient
C_m	-	Torque coefficient
C_P	-	Power coefficient
e/2	-	Overlap ratio for three bladed Savonius wind turbine
D	-	Wind turbine rotor diameter
D_o	-	End plate diameter
d	-	Wind turbine single blade diameter
d_{GV}	-	Distance between guide vanes
d_{shaft}	-	Wind turbine shaft diameter
h_{ideal}	-	Ideal cell height
h_{min}	-	Minimum cell height
k-ε	-	K-epsilon
k-ω	-	K-omega
n	-	Number of samples
R	-	Radius
Re	-	Reynolds number
s/d	-	Overlap ratio for two bladed Savonius wind turbine
V	-	Velocity
V_C	-	Car speed
y_i	-	Statistical sample
y+	-	Wall function
α	-	Angle of guide vanes
α_s	-	Cell layer split factor
λ	-	Tip speed ratio
ω	-	Angular velocity

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Presently, the world in general and Malaysia in particular are facing energy crisis. The main energy consumption in all sectors is in form of electricity. The consumption of electricity energy is increasing parallel with human population growth (“Malaysia - Electricity - production - Historical Data Graphs per Year,” 2018). New area being develop into new town means more electrical energy is needed to supply for suitable living condition. Currently, Malaysia’s trend on electricity generation is coming from the high dependency on fossil fuels consists of natural gas and coal. As stated by Chong *et al.*, (2015), major fuel in power plants was natural gas and secondly is coal to generate electricity, but coal can easily replace natural gas in the next 20 years due to natural gas depletion and national energy security. Massive use of coal may result in higher CO_2 emissions which will cause negative implications to our climate and pollution level.

One of the major contributors of accident on Malaysian road is due to insufficient illumination by 48.6% compared to other road defects (Darma *et al.*, 2017). During the 10th Malaysian plan (2011–2015), the government has spent approximately MYR 19.5 billion on improving the road infrastructure which includes providing reliable lighting for the highway network in order to decrease the accident rates in the country. However, the connection of a robust lighting system on such network to the national electricity grid will definitely increase the load on the power generation stations, which are mainly fuelled by natural gas, coal and diesel. Along with the persisting increase in global oil price, and the uprising political instability in the major oil producing countries, a country such as Malaysia would definitely consider sustainable energy resources as successful alternatives to support its rapidly developing economy.

There is a need to resolve the crisis as they are directly affecting all spheres of life. The government is trying to explore economical renewable energy resources. One such renewable energy resource available in abundance is wind. Different potential sites for harnessing wind energy in Malaysia have already been identify by researchers (Al-Aqel *et al.*, 2017). This study aims at identifying the additional wind energy generation sites alongside the highways due to natural wind and vehicular generated vortices produce by speeding vehicles.

The work has included a numerical modelling and simulation for characterizing the aerodynamic of both the guide vanes, the Highway Savonius Wind Turbine (HSWT), the velocity induced from the speeding vehicles, predicting the wind data and later determine the HSWT performance potential at various operating conditions. The optimum guide vanes configuration located at the highway medians has been identified and HSWT performance through the optimization process using Taguchi's method as a Design of Experiment (DOE) tools.

The significance of the output from this research project was beneficial for developing a dependable Highway Savonius Wind turbine (HSWT) in combination with guide vanes for harvesting and recapturing the maximum amount of wind energy from the automobiles running on the highways. The energy produced is to provide electric power to supply highway lighting and digital sign system which is in line with the government policy related National Renewable Energy Policy and Action Plan (2009).

1.2 Problem Background

Currently, Malaysian Government seeks out the most potential renewable energy to be develop in coming years which are solar and biomass energy. Implementation of methods to generate electricity by wind and tidal based renewable energy percentages are too small and negligible due to their potential resource problems. For instance, wind turbine farm method is not applicable in Malaysia because of its low average wind speed ranging between 2 and 3.7 m/s only (Kadir *et* *al.*, 2018). On the other hand, the average velocity of aerodynamic wake of cruising vehicles is approximately 34 m/s near the car body and depending on wind turbine position it can strike wind turbine blades at speeds up to 6 m/s (Saqr and Musa, 2011; Hegde *et al.*, 2016). Therefore, with a highway network of 49,935 km in total length, the turbulent wind induced by the speeding passenger vehicles on highway seems not negligible and is highly potential wind energy resource towards sustainable and renewable energy.

Relatively, wind speed induced by moving vehicles can reach up to 5 to 6 m/s (Al-Aqel *et al.*, 2017). From here, a suitable type and design of wind turbine need to be developed so that it can operate under low wind resources. Other challenges are non-uniform and unpredictable wind flow on highway. Speeding vehicles produce scatter wind flow with disturbance from crosswind and other external wind source. As studied by Santhakumar (2018), moving vehicles in opposite direction affecting the rotational speed and causing negative drag force to their wind turbine. Therefore, an alternative arrangement of curtain system can be place in front of wind turbine blades to prevent negative torque (Altan *et al.*, 2008). There are many types of curtain system such as 'wind booster', 'wind tunnel', 'deflecting panel', 'wind curtain' and 'guide vane nozzle' that are discussed thoroughly in the literature review.

The proposed curtain system for this study is wind panel or referred as 'guide vanes' to concentrate turbulent wind flow to the wind turbine blades and increase wind speed with suitable operating factor. Figure 1.1 shows the concept of having guide vane panels to direct vehicles' wake energy to the wind turbine rotor when fast moving vehicles pass through. Main concern is the losses of wind energy from leading edge to trailing edge when traveling pass the rectangular shape panel. Guide vane shape plays an important role to reduce air drag of the incoming wind flow (Wahba *et al.*, 2012). Hence, to reduce wind energy losses and further increase wind velocity, rectangular panel shape is changed to an aerofoil NACA 4412 shape (Albers *et al.*, 2019). The guide vanes angle and distance between it need to be identified to determine the effectiveness of having the proposed curtain system.

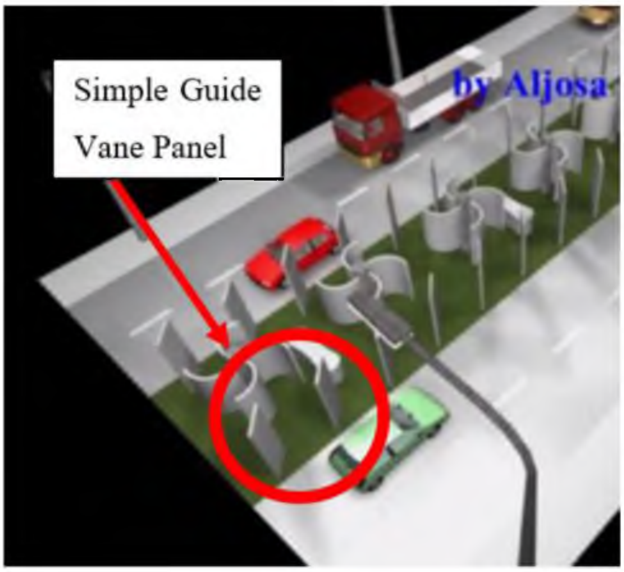

Figure 1.1 Electricity Generation by Highway Wind Energy Concept (Dimitrijevic. A. 2008, 0:18)

Many existing literatures in Computational Fluid Dynamics (CFD), regarding moving vehicle cases was done in static state where the vehicle was set still in one place and wind speed was inserted at inlet as an input variable to observe the flow pattern such as the studies done by Lapointe *et al.*, (2016), Hegde *et al.*, (2016) and Patel, (2017). However, this simplification does not represent real-life situation where vehicle should be moving instead of being stationary. In addition, many studies towards understanding behaviour of wind turbine performance at highway setting whether experimental or numerical were using uniform wind velocities instead of unsteady non-uniform wind velocities such as the researches done by Hosseini and Goudarzi, (2019), Tian *et al.*, (2015) and Cai *et al.*, (2019). This practice does not combine moving vehicle and wind turbine in one computational domain.

Considerable effort has been exerted by researches to study the interactions between moving vehicles and wind turbine. Tian *et al.* (2017) and Tian *et al.* (2020), focused on numerical studies on the possibility of using wind turbines on the highway to generate power from the induced wakes of cruising vehicles. Their studies provided detailed information on the aerodynamic forces and separation flows on the moving vehicle and wind turbine. Although, inflow velocity was not fixed because wind flows changed respective to the moving vehicle but the rotational speed was already set on the wind turbine rotor. Therefore, wind turbine was already rotating when vehicle model start moving before it reached the wind turbine rotor. Hence, in this study, to observe the effect of wind velocity induced by moving vehicle on wind turbine rotor, the one degree of freedom (1DOF) approach was used (Jaohindy *et al.*, 2014). Furthermore, finding the wind turbine rotational speed based on the incoming flow can be done computationally and time expensive.

Besides that, the methods for moving object mechanism were diverse and complex to setup in CFD software. Furthermore, the mesh grid cell type and size generation would affect the method for moving vehicle. To have a moving vehicle instead of static vehicle in simulation, lengthened the time for mesh generation and solver setup for numerical calculation and surely additional knowledge and good understanding were required for using moving object method in CFD. This would complicate the numerical modelling study to have a real situation such as speeding vehicles at highway during modelling development. Hence, the numerical modelling needed to be simplified accordingly as well as to meet the real-life situation for simulation-wise purposes.

Hence to address these issues, this study aimed to recover the moving vehicles wake at highway using a wind turbine that could operate under low wind speed and under turbulent wind flow. In addition, to improve the performance of the wind turbine, a curtain system consisted of guide vanes with aerofoil NACA 4412 shape were placed near the HSWT blades. Parametric study of guide vanes arrangement was investigated to find the optimum guide vanes configuration by using design of experiment Taguchi Method. The geometry models were designed using SolidWorks CAD software and for numerical domain modelling and the analysis was done in ANSYS CFD software. This research approach was dynamic simulation instead of stationary vehicle simulation to resemble real moving vehicle on the road and also wind turbine would only rotate after the induced wind flow form moving vehicle reached its rotor.

(e) Only one side of the highway was considered in CFD domain modelling

(f) Dynamic mesh layering technique was used for translational zone and sliding mesh for rotating zone

(g) One degree of freedom (1DOF) was set at wind turbine at vertical axis

(h) Turbulence model was k-omega Shear Stress Transport (k-ω SST)

(i) Taguchi Method was used to analyse and optimize the wind turbine performance.

1.5 Hypothesis

The wind energy produced from cruising vehicles was considerably small. However, with a reliable design of HSWT, it was highly expected to operate effectively at low wind speed. Besides, with a better curtain system using NACA 4412 aerofoil shape guide vanes, the wind flow would be guided and accelerated toward wind turbine blades which would reduce the negative torque effect, thus enhancing the performance of HSWT. Moreover, DOE tool Taguchi Method used a fractional of full factorial design by mixing the levels of the control variables and selected limited number of experiments from all the possibilities to generate most information in more practical way as well as reducing the number of simulations or experiments. In summary, the goal of this research was applying dynamic simulation and Taguchi Method to analyse new wind turbine design integrated with proposed curtain system performance.

REFERENCES

Ahmad Abu-Baker. (2020, June 10). Aircraft basic Aerodynamics (part 1). PILOT AHMAD PERSONAL BLOG RELATED TO AVIATION INDUSTRY. Retrieved September 23, 2021, from https://pilotahmad.com/2020/06/10/aircraft-basic-aerodynamics-part-1/.

Akwa, J. V., Alves Da Silva Júnior, G. and Petry, A. P. (2012) 'Discussion on the verification of the overlap ratio influence on performance coefficients of a Savonius wind rotor using computational fluid dynamics', *Renewable Energy*, 38(1), pp. 141–149.

Al-Aqel, A. A., Lim, B. K., Noor, E. E. M., Yap, T. C. and Alkaff, S. A. (2017) 'Potentiality of small wind turbines along highway in Malaysia', *Proceedings of 2016 International Conference on Robotics, Automation and Sciences, ICORAS 2016*.

Alam, F. and Golde, S. (2013) 'An aerodynamic study of a micro scale vertical axis wind turbine', *Procedia Engineering*. Elsevier B.V., 56, pp. 568–572.

Albers, M., Meysonnat, P. S. and Schröder, W. (2019) 'Influence of airfoil shape on active drag reduction efficiency', *11th International Symposium on Turbulence and Shear Flow Phenomena, TSFP 2019*, (August).

Ali, M. H. (2013) 'Experimental Comparison Study for Savonius Wind Turbine of Two & Three Blades At Low Wind Speed', 3(figure 1), pp. 2978–2986.

Altan, B. D., Atilgan, M. and Özdamar, A. (2008) 'An experimental study on improvement of a Savonius rotor performance with curtaining', *Experimental Thermal and Fluid Science*, 32(8), pp. 1673–1678.

Asmanissa, D., Osman, A., Rosmin, N., Hatib, A. and Hussin, S. M. (2018) 'Performance of a Small-sized Savonious Blade with Wind Concentrator', 10(3), pp. 1227–1233.

Bani-hani, E. H., Sedaghat, A., Al-shemmary, M., Alshaieb, A. and Kakoli, H. (2018) 'Feasibility of Highway Energy Harvesting Using a Vertical Axis Wind Turbine F easibillity of Highway Energy Harvesting Using a Vertica [Axis Windl Turbine', 8595.

Bao, Z., Yang, F., Wu, Z., Nyallang Nyamsi, S. and Zhang, Z. (2013) 'Optimal design of metal hydride reactors based on CFD-Taguchi combined method', *Energy Conversion and Management*. Elsevier Ltd, 65, pp. 322–330.

Cai, C., Ming, T., Fang, W., de Richter, R. and Peng, C. (2020) 'The effect of turbulence induced by different kinds of moving vehicles in street canyons', *Sustainable Cities and Society*, 54(1037).

Cai, X., Zhang, Y., Ding, W. and Bian, S. (2019) 'The aerodynamic performance of H-type darrieus VAWT rotor with and without winglets: CFD simulations', *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. Taylor & Francis, 00(00), pp. 1–12.

Chan, C. M., Bai, H. L. and He, D. Q. (2018) 'Blade shape optimization of the Savonius wind turbine using a genetic algorithm', 213(August 2017), pp. 148–157.

Chen, W., Chen, C., Huang, C. and Hwang, C. (2017) 'Power output analysis and optimization of two straight-bladed vertical-axis wind turbines', *Applied Energy*. Elsevier Ltd, 185, pp. 223–232.

Chong, C., Ni, W., Ma, L., Liu, P. and Li, Z. (2015) 'The use of energy in Malaysia: Tracing energy flows from primary source to end use', *Energies*, 8(4), pp. 2828–2866.

Darma, Y., Karim, M. R. and Abdullah, S. (2017) 'An analysis of Malaysia road traffic death distribution by road environment', *Sādhanā*. Springer India, 42(9), pp. 1605–1615.

Davis, R. and John, P. (2018) 'Application of Taguchi-Based Design of Experiments for Industrial Chemical Processes', *Statistical Approaches With Emphasis on Design of Experiments Applied to Chemical Processes*.

Deisadze, L., Digeser, D., Dunn, C. and Shoikat, D. (2013) 'Vertical Axis Wind Turbine Evaluation and Design', *Engineering*, 1, pp. 1–81.

Dewan, A., Gautam, A. and Goyal, R. (2021) 'Savonius wind turbines: A review of recent advances in design and performance enhancements', *Materials Today: Proceedings*. Elsevier Ltd, (xxxx).

Dimitrijevic, Aljosa. (2008, October 20). *Highway wind energy* [Video]. YouTube. https://www.youtube.com/watch?v=GBRyVjWfUdY

Elvik, R. (2002) 'Optimal speed limits: Limits of optimality models', *Transportation Research Record*, (1818), pp. 32–38.

Fei, N. C., Mehat, N. M. and Kamaruddin, S. (2013) 'Practical Applications of Taguchi

Method for Optimization of Processing Parameters for Plastic Injection Moulding: A Retrospective Review', *ISRN Industrial Engineering*, 2013, pp. 1–11.

Fujisawa, N. (1992) 'On the torque mechanism of Savonius rotors', *Journal of Wind Engineering and Industrial Aerodynamics*, 40(3), pp. 277–292.

Ghosh, A., Biswas, A., Sharma, K. K. and Gupta, R. (2015) 'Computational analysis of flow physics of a combined three bladed Darrieus Savonius wind rotor', *Journal of the Energy Institute*. Elsevier Ltd, 88(4), pp. 425–437.

Gray, A., Singh, B. and Singh, S. (2021) 'Low wind speed airfoil design for horizontal axis wind turbine', *Materials Today: Proceedings*. Elsevier Ltd., 45, pp. 3000–3004.

Guilmineau, E. (2008) 'Computational study of flow around a simplified car body', *Journal of Wind Engineering and Industrial Aerodynamics*, 96(6–7), pp. 1207–1217.

Guo, F., Song, B., Mao, Z. and Tian, W. (2020) 'Experimental and numerical validation of the influence on Savonius turbine caused by rear deflector', *Energy*, 196.

Hegde, S. S., Thamban, A., Bhai, S. P. M., Ahmed, A., Upadhyay, M., Joishy, A. and Mahalingam, A. (2016) 'Highway mounted horizontal axial flow turbines for wind energy harvesting from cruising vehicles', *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, 6B-2016, pp. 1–9.

Hosseini, A. and Goudarzi, N. (2019) 'Design and CFD study of a hybrid vertical-axis wind turbine by employing a combined Bach-type and H-Darrieus rotor systems', *Energy Conversion and Management*. Elsevier, 189(November 2018), pp. 49–59.

Irabu, K. and Roy, J. N. (2007) 'Characteristics of wind power on Savonius rotor using a guide-box tunnel', *Experimental Thermal and Fluid Science*, 32(2), pp. 580–586.

Jaohindy, P., Ennamiri, H., Garde, F. and Bastide, A. (2014) 'Investigation of the root flow in a Horizontal Axis', *Wind Energy*, (March 2013), pp. 1–20.

Jeon, K. S., Jeong, J. I., Pan, J. K. and Ryu, K. W. (2015) 'Effects of end plates with various shapes and sizes on helical Savonius wind turbines', *Renewable Energy*. Elsevier Ltd, 79(1), pp. 167–176.

Johari, M. K., Jalil, M. A. A. and Shariff, M. F. M. (2018) 'Comparison of horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT)', *International Journal of Engineering and Technology(UAE)*, 7(4), pp. 74–80.

Kadir, E. A., Miskon, M. T., Rashid, N. A. and Yunus, M. Y. (2018) 'A Study of Vertical Wind Turbine for Application in Low Wind Speed Condition in UiTM Terengganu, Malaysia', *Journal of Power and Energy Engineering*, 06(08), pp. 38–48.

Korprasertsak, N. and Leephakpreeda, T. (2015) 'CFD-Based Power Analysis on Low Speed Vertical Axis Wind Turbines with Wind Boosters', in *Energy Procedia*. Elsevier B.V., pp. 963–968.

Kumar, R., Raahemifar, K. and Fung, A. S. (2018) 'A critical review of vertical axis wind turbines for urban applications', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 89(February), pp. 281–291.

Kumar Rathore, M., Agrawal, M. and Baredar, P. (2020) 'Energy production potential from the wake of moving traffic vehicles on a highway by the array of low economic VAWT', *Materials Today: Proceedings*. Elsevier Ltd, 46(xxxx), pp. 5272–5277.

Lapointe, C., Hall, S., Street, U., Gopalan, H., Hall, S. and Street, U. (2016) 'Numerical Investigation of Mini Wind Turbines Near Highways', 138(April), pp. 1–4.

Loganathan, B., Mustary, I., Chowdhury, H. and Alam, F. (2017) 'Effect of sizing of a Savonius type vertical axis micro wind turbine', *Energy Procedia*. Elsevier B.V., 110(December 2016), pp. 555–560.

Lye, G. (2016, September 29). DRIVEN: 2016 Proton Saga first impressions review – meet the true challenger to the Perodua Bezza. Retrieved May 25, 2020, from https://paultan.org/2016/09/24/driven-2016-proton-saga-review/

Menet, J.-L. J., Bourabaa, N. and Bouraba, N. (2004) 'Increase in the Savonius rotors efficiency via a parametric investigation', *EWEA - 2004 European Wind Energy Conference*, (January 2004).

Meri, S., Absi, A., Salleh, H. B., Maseer, M. M., Abbas, M. A. and Al-quraishi, B. A. (2019) 'Experimental Study of the Performance of the Elliptical Savonius Turbine and New Design for Blade Shape Using A 3D Printing Technology', (August).

Micha Premkumar, T., Sivamani, S., Kirthees, E., Hariram, V. and Mohan, T. (2018)

'Data set on the experimental investigations of a helical Savonius style VAWT with and without end plates', *Data in Brief*. Elsevier Inc., 19, pp. 1925–1932.

Mohamed, M. H., Janiga, G., Pap, E. and Thévenin, D. (2010) 'Optimization of Savonius turbines using an obstacle shielding the returning blade', *Renewable Energy*. Elsevier Ltd, 35(11), pp. 2618–2626.

Molnár, B. (2014) 'Comparison of structured and unstructured meshes for the computations of an H-type darrieus wind turbine', pp. 61–62.

Nasef, M. H., El-Askary, W. A., AbdEL-hamid, A. A. and Gad, H. E. (2013) 'Evaluation of Savonius rotor performance: Static and dynamic studies', *Journal of Wind Engineering and Industrial Aerodynamics*. Elsevier, 123, pp. 1–11.

Patel, H. V (2017) 'A CFD Investigation into the Transient Aerodynamic Forces Induced by Passing Maneuvers of a Truck and a Car', 1(3), pp. 68–75.

Payambarpour, S. A., Najafi, A. F. and Magagnato, F. (2020) 'Investigation of deflector geometry and turbine aspect ratio effect on 3D modified in-pipe hydro Savonius turbine: Parametric study', *Renewable Energy*, 148, pp. 44–59.

Promdee, C. and Photong, C. (2016) 'Effects of Wind Angles and Wind Speeds on Voltage Generation of Savonius Wind Turbine with Double Wind Tunnels', in *Procedia Computer Science*. The Author(s), pp. 401–404.

Ricci, R., Romagnoli, R., Montelpare, S. and Vitali, D. (2016) 'Experimental study on a Savonius wind rotor for street lighting systems', *Applied Energy*. Elsevier Ltd, pp. 143–152.

Roy, S. and Saha, U. K. (2013) 'Review of experimental investigations into the design , performance and optimization of the Savonius rotor', 227(4), pp. 528–542.

Saad, A. S., El-Sharkawy, I. I., Ookawara, S. and Ahmed, M. (2020) 'Performance enhancement of twisted-bladed Savonius vertical axis wind turbines', *Energy Conversion and Management*. Elsevier, 209(December 2019), p. 112673.

Rumsey, C. (2019, December 31). 2D NACA 4412 Airfoil Trailing Edge Separation. Retrieved May 25, 2020, from https://turbmodels.larc.nasa.gov/naca4412sep_val.html

Salleh, M. B., Kamaruddin, N. M. and Mohamed-kassim, Z. (2020) 'The effects of deflector longitudinal position and height on the power performance of a conventional Savonius turbine', *Energy Conversion and Management*. Elsevier Ltd, 226(October), p. 113584.

Santhakumar, S. (2018) ‘An experimental study on the rotational behaviour of a Savonius wind turbine for two-lane highway applications’, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. Springer Berlin Heidelberg, 9.

Saqr, K. M. and Musa, M. N. (2011) ‘A perspective of the Malaysian highway energy consumption and future power supply’, *Energy Policy*. Elsevier, 39(6), pp. 3873–3877.

Sarath Kumar, R., Micha Premkumar, T., Seralathan, S., Dominic Xavier, D., Elumalai, E. S., Hariram, V. and Sabapathi, S. (2020) ‘Simulation studies on influence of shape and number of blades on the performance of vertical axis wind turbine’, *Materials Today: Proceedings*. Elsevier Ltd., 33(xxxx), pp. 3616–3620.

Selvaraju, P. N., Parammasivam, K. M., Shankar, G. and Devaradjane (2015) ‘National Conference On Recent Trends And Developments In Sustainable Green Technologies ANALYSIS OF DRAG AND LIFT PERFORMANCE IN SEDAN CAR MODEL USING CFD’, *Journal of Chemical and Pharmaceutical Sciences* , (7), pp. 429–435.

Son, S., Singh, P. M. and Choi, Y.-D. (2013) ‘Influence of guide vane shape on the performance and internal flow of a cross flow wind turbine’, *Journal of the Korean Society of Marine Engineering*, 37(2), pp. 163–169.

Sonawane, C. R., Sasar, Y., Shaikh, M., Kokande, Y., Mustafa, M. and Pandey, A. (2021) ‘Numerical simulation of Savonius rotors used for low wind speed application’, *Materials Today: Proceedings*. Elsevier Ltd, (xxxx).

Tasneem, Z., Al Noman, A., Das, S. K., Saha, D. K., Islam, M. R., Ali, M. F., R Badal, M. F., Ahamed, M. H., Moyeen, S. I. and Alam, F. (2020) ‘An analytical review on the evaluation of wind resource and wind turbine for urban application: Prospect and challenges’, *Developments in the Built Environment*. Elsevier Ltd, 4, p. 100033.

Tian, W., Mao, Z., An, X., Zhang, B. and Wen, H. (2017) ‘Numerical study of energy recovery from the wakes of moving vehicles on highways by using a vertical axis wind turbine’, *Energy*. Elsevier Ltd, 141, pp. 715–728.

Tian, W., Song, B. and Mao, Z. (2020) ‘Numerical investigation of wind turbines and turbine arrays on highways’, *Renewable Energy*. Elsevier Ltd, 147, pp. 384–398.

Tian, W., Song, B., Vanzwieten, J. H. and Pyakurel, P. (2015) 'Computational Fluid Dynamics Prediction of a Modified Savonius Wind Turbine with Novel Blade Shapes', pp. 7915–7929.

Torresi, M., De Benedittis, F. A., Fortunato, B. and Camporeale, S. M. (2014) 'Performance and flow field evaluation of a Savonius rotor tested in a wind tunnel', *Energy Procedia*. Elsevier B.V., 45, pp. 207–216.

Toudarbari, S., Maghrebi, M. J. and Hashemzadeh, A. (2021) 'Evaluation of Darrieus wind turbine for different highway settings using CFD simulation', *Sustainable Energy Technologies and Assessments*. Elsevier Ltd, 45(April 2020), p. 101077.

Uli Kaiser, Publisher at AutoBook International Follow. (2016, May 22). Malaysia Automotive Statistics Full Year 2015 by Model. Retrieved January 09, 2017, from http://www.slideshare.net/ulikaiser/malaysia-automotive-statistics-full-year-2015-by-model

Wahba, E. M., Al-Marzooqi, H., Shaath, M., Shahin, M. and El-Dhmashawy, T. (2012) 'Aerodynamic drag reduction for ground vehicles using lateral guide vanes', *CFD Letters*, 4(2), pp. 68–79.

Wang, Q., Fang, W., de Richter, R., Peng, C. and Ming, T. (2019) 'Effect of moving vehicles on pollutant dispersion in street canyon by using dynamic mesh updating method', *Journal of Wind Engineering and Industrial Aerodynamics*. Elsevier Ltd, 187(November 2018), pp. 15–25.

Wang, Z., Wang, S., Ren, J., Meng, X. and Wu, Y. (2020) 'Model experiment study for ventilation performance improvement of the Wind Energy Fan system by optimizing wind turbines', *Sustainable Cities and Society*. Elsevier, 60(May), p. 102212.

Wang, Z., Wang, Y. and Zhuang, M. (2018) 'Improvement of the aerodynamic performance of vertical axis wind turbines with leading-edge serrations and helical blades using CFD and Taguchi method', *Energy Conversion and Management*. Elsevier, 177(September), pp. 107–121.

Wenehenubun, F., Saputra, A. and Sutanto, H. (2015) 'An experimental study on the performance of Savonius wind turbines related with the number of blades', *Energy Procedia*. Elsevier B.V., 68, pp. 297–304.

Yahya, W., Ziming, K., Juan, W., Qurashi, M. S., Al-Nehari, M. and Salim, E. (2021) 'Influence of tilt angle and the number of guide vane blades towards the

Savonius rotor performance’, *Energy Reports*. Elsevier Ltd, 7, pp. 3317–3327.

Yiğit, C. (2018) ‘Improving the Horizontal Axis Wind Turbine Blade Profiles’, *Sakarya University Journal of Science*, 22(5), pp. 1–1.

Yoon, S. H., Lim, H. C. and Kim, D. K. (2013) ‘Study of several design parameters on multi-blade vertical axis wind turbine’, *International Journal of Precision Engineering and Manufacturing*, 14(5), pp. 831–837.

Yossri, W., Ben Ayed, S. and Abdelkefi, A. (2021) ‘Airfoil type and blade size effects on the aerodynamic performance of small-scale wind turbines: Computational fluid dynamics investigation’, *Energy*, 229.

Zahraee, S. M., Rohani, J. M., Firouzi, A. and Shahpanah, A. (2015) ‘Efficiency Improvement of Blood Supply Chain System Using Taguchi Method and Dynamic Simulation’, *Procedia Manufacturing*. Elsevier B.V., 2(February), pp. 1–5.

Zhang, Qingqing, Feng, J., Zhang, Quanquan and Peng, X. (2019) ‘Performance prediction and evaluation of the scroll-type hydrogen pump for FCVs based on CFD–Taguchi method’, *International Journal of Hydrogen Energy*. Elsevier Ltd, 44(29), pp. 15333–15343.

LIST OF PUBLICATIONS

1. Mazlan, M. Z., Mohd Zawawi, F., Tahzib, T., Ismail, K., & Samion, S. (2021). Performance Analysis of Highway Wind Turbine Enhanced with Wind Guide Vanes Using the Taguchi Method. CFD Letters, 13(3), 25-42. https://doi.org/10.37934/cfdl.13.3.2542