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Article

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Small Wind Turbines as Partial Solution for Energy Sustainability of Malaysia

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ABSTRACT

The global market for wind turbines has kept on emerging in the former decade. The large wind turbines have all advanced over the years to such a degree, to the point that the innovation is significantly developed. Whereas, the technology for small wind turbines has not fully-fledged like the large wind turbines due to the absence of such methodical research and development. Within a short span, a base development rate of 12% is foreseen to proceed due to advanced research, and the productiveness is predicted to reach around 1.9 GW by 2020. Since, a major portion of the globe is not having sufficient wind potential, the use of small wind turbines provides the exclusive opening of entering an untapped market without any environmental degradation. As Malaysia is promoting renewable energy sources for economic and environmentally friendly energy sustainability, this research aims at introducing small wind turbine technology because of its prevailing low wind speed. The future of the small wind turbines in Malaysia depends upon the capital cost per kW of the small wind turbine installation and the energy cost per kWh of the energy produced. Hence, keeping these two factors in mind, small scale wind turbines are designed using a blade element momentum theory based on the prevailing average wind speed in Malaysia.

Keywords: Small Wind Turbine, Energy sustainability, Blade Element Momentum Theory
JEL Classifications: Q42, Q48, Q55, Q56

1. INTRODUCTION

Wind power keeps on being a standout among the most encouraging renewable energy sources. In the course of the most recent decade, the wind power industry has seen the exponential development, and wind ranches are flying up everywhere throughout the world. It's from now on the sustainable power source that can best contend with fossil fuel power plants monetarily with ecological kind disposition. Wind power's development is progressively determined through its modest pricing, and additionally in the light of the fact that it augments energy security, price solidity and through the necessity to highlight the carbon emissions which is progressively creating most part of built-up areas in the emerging world unsuitable for healthy living. The total size of all wind turbines commissioned universally up to 2017 realized 539'291 Megawatt, as per the opening statistics announced by WWEA (WWEA, 2018). Though there is an increase in added capacity compared to the previous year 2016, the annual growth rate is only 10.8%, which is the lowermost progress ever since the wind harnessing technology for electricity generation started by the end of the 20th century.

There are many challenges for the continued growth of large wind farms, though the global availability of wind resources is enormous. Earlier, some countries announced monetary supports for wind power, such as feed-in tariffs, to secure income and to reduce investor risk, have withdrawn their support recently (GWEC, 2015). Changes in the political scenario and new government policies had its own effect on the wind farm development. Hike in land price and insufficient financial provisions, and unattractive energy buyback rates are the other critical issues for the slow growth rate, especially in developing countries (IEA-ETSAP and IRENA, 2016). Besides, long and unpredictable waiting times for permission and authorization of wind farm formation, and delayed payment of the buyback energy cost to the suppliers are a further hindrance for large scale implementations (Palanichamy et al., 2014-1).

Apart from the financial, political and implementation issues of large wind turbines, there are further drawbacks to getting a large wind turbine.

- Investment: Large wind turbines result in huge investment since it costs a lot more than small ones
- Land requirement: Large wind turbine need vast land to reduce wake effect and improve energy capture
- Wind speed: Higher wind speed is foreseeable for longer hours
- Failure rate: Large wind turbine results in higher mechanical stresses due to its massive structure and the huge weight
- Risk: A failure of a single large wind turbine consequences huge energy production loss and risk of investment and system reliability, and
- Environmental impacts: Large wind turbine produces more noise, vision hindrance, and dangers for birds and bats.

The low growth rate and technical barriers of large wind turbines give space for the inception and existence of small wind turbines (SWTs). SWTs are not new and utilized all through the developed and emerging world and are essentially utilized in the countryside or remote locations in the national and international markets. The small wind industry has delivered the worldwide renewable energy segment with the affluences of energy independence for the customer, secluded electricity generation in regions without grid connections and a more expanded energy supply, which can be complemented by solar power and used by businesses and households. A noteworthy advantage of creating SWT is that they help larger wind plants overcome current market adoption hindrances that will, in the long run, lead to the development and lower energy costs. In addition, there are as yet millions of people everywhere throughout the world living in remote rural societies where access to the regional electricity grid is essentially incomprehensible. Hence, the use of SWTs provides the exclusive opening of entering an untapped market without any environmental degradation.

2. LITERATURE REVIEW

The worldwide market for wind turbines has kept on developing in the former decade. The large wind turbines have throughout the years progressed to such a degree, to the point that the innovation is considerably developed. Whereas, the technology for SWTs has not fully-fledged like the large wind turbines due to the absence of such methodical research and development (Ani et al., 2013). For trivial consumers, the curiosity in energy generation by themselves is mounting because of the hike in energy cost, specifically in developing nations and countries deprived of fossil fuel reserves (Escavador, 2017). Among the rational and efficient technologies to generate electricity for domestic or commercial consumers are SWTs.

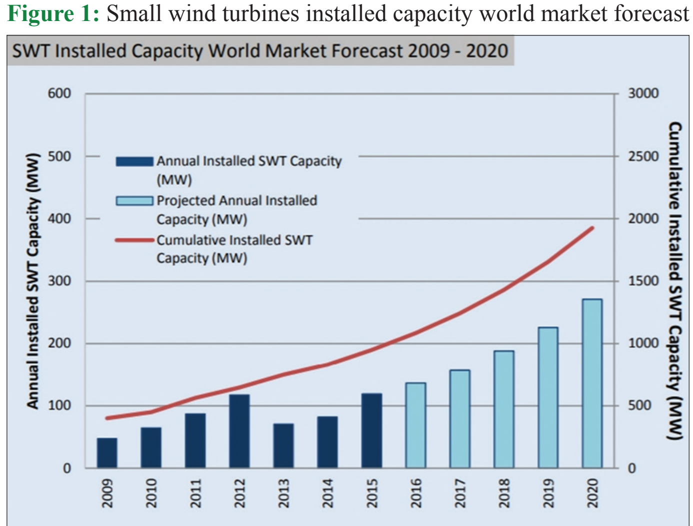
The practice of distributed generation (DG) units has developed significantly lately. As a mode to decentralize the electricity generation and transmission, DG concept offers lesser transmission losses and generation redundancy (Raffael et al., 2018). To surpass the grid-connection problems, the generators and the connected loads have loomed as subsystems of the main grid with smaller capacity power generation units mostly renewable energy sources such as small wind systems, fuel-cell, photovoltaic, ocean energy, biogas digesters, and microturbines, etc. The SWT based DG units received good interest among consumers and energy planners, primarily owing to resources obtainability, fast technical progression, and small landscape sway (Ambarnath et al., 2016). To improve efficiency, most of the SWTs use permanent magnet synchronous generators because of its greater power density, improved controllability, and greater pairs of poles, evading gearboxes.

Despite the fact that the worldwide SWT market dawdling progression during the most recent two years, it is normal that it will keep expanding. A base development rate of 12% is foreseen to proceed. The productiveness is anticipated to reach around 270MW of recently installed capacity added yearly in 2020 as in Figure 1 and accomplishes a cumulative installed capacity of around 1,9 GW by 2020 (Jean-Daniel, 2017).

The positive increase in SWT installations is due to the wind harnessing technology and the design modifications to SWT manufacturing. There are numerous studies about the improvement of wind turbine performance in the literature. Ameku et al. (2008) deliberated a 3 kW wind turbine prototype aiming at blade design. Kosasih and Andrea (2012) investigated a low power turbine with a conical configuration to speed up airflow through the wind turbine in the laboratory environment. Chong et al. (2013) presented a vertical axis SWT for tall buildings. Abdulkadir et al. (2012) advanced a new vertical axis wind turbine.

A comprehensive review of the contemporary wind turbine blade design is presented (Manoj and Anindita (2015); Navin et al., 2014; Peter and Richard (2012), Singh and Ahmed (2012), Zafar et al., 2017). The review includes hypothetical maximum efficiency, propulsion, practical efficiency, HAWT blade design, and blade loads. Further, it delivers a comprehensive wind turbine blade design and illustrates the governance of contemporary turbines.

Figure 1: Small wind turbines installed capacity world market forecast



The aerodynamic design principles for a contemporary wind turbine blade are elaborated, comprising a blade plan shape/quantity, airfoil choice, and optimal attack angles. An exhaustive analysis of design loads on wind turbine blades is offered, reciting aerodynamic, gravitational, centrifugal, gyroscopic and operational conditions.

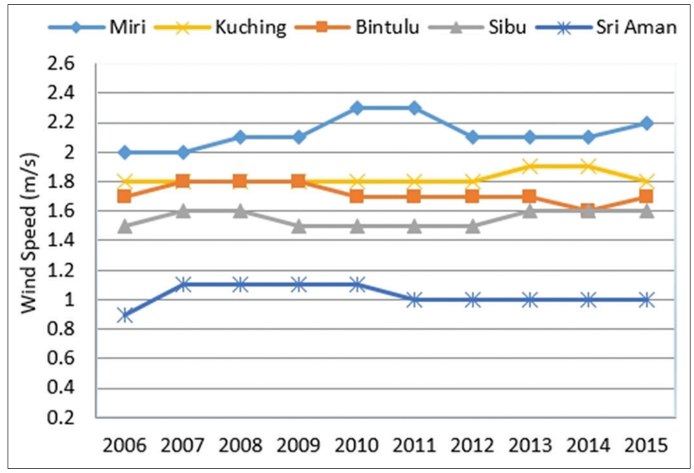
From the literature reviews, it is implied that the wind turbine blade plays a significant role since it is the most vital part of the energy absorption system. Consequently, the blade has to be designed judiciously to enable to absorb energy with its utmost efficiency. Hence, this paper focuses on the study of SWT blade design to capture low wind in urban and suburban areas.

3. MALAYSIAN WIND SCENARIO

Malaysia is situated in 1°22'N latitude and 103°55'E in Southeast Asia region. For the most part, the durable wind flow is from the Indian Ocean and South China Sea. It is comprised of thirteen states divided into two regions; Peninsular Malaysia (West) and Malaysian Borneo (East), separated by the South China Sea. October-March (Northeast monsoon) and May-September (Southwest monsoon) are the two monsoons in Malaysia. According to the Malaysian Meteorological Department statistical reports (MMD, 2016), wind speeds during the southwest monsoon are often lower than 7 m/s; however, during the northeast monsoon, steady wind speeds in the range of 5–10 m/s prevail and in the east coast of Peninsular Malaysia, wind speeds reach up to 15 m/s. While during inter-monsoons, the wind is generally light and variable. As Malaysia is for the most part an oceanic nation, the impact of land and ocean breeze on the general wind flow pattern is exceptionally critical particularly in days with clear skies. On sunny days, ocean and land breezes of 5–7.5 m/s all the time create and reach up to a few several kilometers inland or the beachfront regions (Ibrahim et al., 2014; Palanichamy et al., 2014-2). Like the land and ocean breeze, day by day wind flow happens in numerous rugged areas are called mountain and valley breeze. Normal wind speed for valley breeze is in excess of 9 m/s, though the mountain breeze for the most part more grounded than valley breeze with winds achieving velocities of 11 m/s. It also observed that wind speed is greater on the day (from sunrise to sunset) than that in times before sunrise and after sunset. Wind speed resembles a sine curve in the day, and it is constant for periods before sunrise and after sunset (Gregory, 2013).

As per the data obtained from MMD for a period of 10 years from 2006 to 2015, the average annual wind speed in the five towns of the Malaysian Borneo region is presented in Figure 2 (Woan et al., 2018). The wind speeds are practically measured at a standard height of 10 m because of the technical convenience and associated cost. Among the five towns, Miri experiences the maximum and Sri Aman the least. Malaysia experiences durable winds in the initial and late parts of the year. However, towns on the east coast of Peninsular Malaysia such as Mersing, and Kuala Terengganu experience sturdier winds. In these places, their monthly average wind speed exceeds 3 m/s. Mersing has an annual mean wind speed of 3.29 m/s and Kuala Terengganu has 2.67 m/s. Considering both east and west parts of Malaysia, the

Figure 2: Annual average wind speed in Borneo region



wind speed is not suitable for a larger wind turbine with a cut in wind speed of 3 m/s and above.

Numerous past wind potential studies in Malaysia are imprecise and inadequately extensive. Moreover, old-fashioned technologies and instruments were handled to measure the wind potential. Further, most of the measurements were made closer to the airports. For realistic data procurement, wind speed information from or close airports ought not to be utilized, especially if the information originates from low-speed zones. Besides, a couple of WTG demonstration projects implemented by the government became unsuccessful (Lip-Wah, 2016). The failure of the two wind energy demonstration projects at swallow reef and small Perhentian island reveals the fact that it is not advisable to go for promoting wind energy with the available insufficient, and short-term data obtained through outdated technologies and instruments, since Malaysia is located in an Equatorial region with low wind speed, monsoons with seasonal variability and also inter-monsoon periods with partial wind with high humidity. However, the new government is very keen on promoting renewable energy to meet out the prevailing energy challenges. Hence, to promote wind energy development in a successful manner, it is encouraging the wind potential assessments with the state of the art technologies and equipment for longer durations. Also, it is presently evaluating the probability of including wind energy in its FiT scheme.

4. SUITABILITY OF MALAYSIA FOR SWTS

SWTs contrast from large turbines in many essential ways, showing their more prominent flexibility. While larger turbines require an established grid network, the SWT has application both on and off the grid, because of their size and low power output. Their off-grid application keeps away from the substantial expense of commissioning new overhead transmission lines to the remote consumers' terminals, particularly in developing countries. Also, SWTs operate at lower wind speeds than larger wind turbines and this facilitates vast applications globally since low wind exists in larger global regions than high wind. There is a saying from SWT users (Palanichamy et al., 2014-1) that SWTs produce costlier electricity than their utility-scale counterparts (large wind turbines), which is true only in poor windy sites. However, when aimed to particular wind sites, and commissioned effectively through long-term precise wind site assessment, SWTs can be a dependable renewable energy source and socioeconomic benefit to secluded regions without electricity. As far as Malaysia in concerned whether east or west, the wind speed is in the order of 2–3 m/s with a 10 m height anemometer measurement. As it is, it is suitable for harnessing the wind by SWTs; however, it is not economically viable due to the small quantity of annual energy generation. Though it is technically possible to boost the wind speed by increasing the tower height of the SWTs and increasing the energy capture through bigger rotor diameters; again the economic viability is questionable due to the further expenses on tall tower height and larger rotor blades.

The continued economic growth of Malaysia as a developing nation stimulated a high rate of building construction in many urban and coastal regions and the proliferation of high-rise towers. These skyscrapers are symbolically associated with a fast-growing economy and a sign of progress, aiming at placing Malaysia at the forefront of the developing countries in the South East Asian region. As the global and national economy was continuously stable during the past two decades, the construction industry increased drastically not only in Malaysia but globally too. State of the art construction technologies was introduced to meet the greater urbanization demands of Malaysians more economically with environmentally friendly.

According to CTBUH (2018), there are 901 tall buildings of above 100 m height in Malaysia, and 21 buildings under proposal/vision within a height range of 190–700 m. These tall buildings favour SWT in terms of boosting the wind speed. On the ground, the wind is intensely decelerated by hindrances and ground coarseness. At approximately 5 km above the ground, the wind is not affected by the surface condition. Between these two boundaries, wind speed varies with altitude, which is known as wind shear. The wind shear coefficient is largely approximated between 0.14 and 0.2; whereas, in factual circumstances, a wind shear coefficient is not persistent and hinges on many influences, comprising atmospheric conditions, temperature, pressure, humidity, time of day, the annual seasons, the mean wind speed, wind flow direction, and nature of terrain (Zekai et al., 2012). For the Malaysian topographical conditions and man-made structural developments, the shear coefficient could be primarily categorized as class 3 and class 4. According to Swiss Federal Office of Energy (2018), class 3 (roughness length 0.3 m) refers to towns, villages, agricultural land with many or high hedges, forests and very rough and uneven terrain, and class 4 (roughness length 1.6 m) denotes large cities with high buildings and skyscrapers. Assuming an average wind speed of 2 m/s at 10 m height, the wind speeds are theoretically evaluated for a height of 100 m, in steps of 10 m for the two roughness classes as in Table 1. The maximum wind speeds at 100 m heights are enhanced by 71.5% and 125.5% respectively for class 3 and class 4. The achieved wind speeds are above the cut in wind speeds of most of the commercially available large wind turbines. Since most of the skyscrapers are above 290 m height, the energy production of large wind turbines will be of appreciable magnitude. Under such circumstances, the performance of SWT will be more prosperous and very attractive for wind harvesters.

Table 1: Wind speed at different heights

Height above ground (m)	Wind speed (m/s)	
	Roughness Class 3	Roughness Class 4
10	2.00	2.00
20	2.43	2.76
30	2.68	3.20
40	2.86	3.51
50	3.00	3.76
60	3.11	3.96
70	3.21	4.12
80	3.29	4.27
90	3.37	4.40
100	3.43	4.51

5. METHODOLOGY

The wind turbines, whether large or small becomes a dependable supply of energy when they are sized appropriately according to the site constraints and operate at their most advantageous conditions. Related to the large wind turbines, the SWTs can turn out to be a better source of environmentally friendly energy sources for most of the developing nations and remote locations in several industrialized nations. Nevertheless, the prospect of SWTs hinges on the unit cost of energy generated. The capital cost per kW of the SWT installation and the energy cost per kWh of the energy produced by these turbines are the two governing factors in the successful promotion of the SWTs. Hence, the design of the SWTs is the deciding factor for the success of renewable technology. The drive for this research is to design SWTs using a blade element momentum theory (BEMT) based on the prevailing average wind speed in Malaysia. An attempt to constant-speed horizontal-axis SWT (CS-HASWT) with induction generator has been made due to its direct grid connection support without any complex power electronics devices; besides simplicity, ease of control, sturdy, and proven cost-effective nature. Induction generators up to a certain power rating are easy to build, and more serviceable. After a certain power level (not the case with SWT), the intricacy upsurges and then it becomes a design call whether to go with them or not.

5.1. Design Wind Speed and Rotor Diameter

Initially, the design wind speed, V_{Design} is defined based on the international standard of IEC61400-2 for designing SWT. The V_{Design} for SWT is 1.4 times the mean annual wind speed (MAWS) (Tenghiri et al., 2018). To be consistent, the V_{Design} is set at 4 m/s for 2–3 m/s average wind speed in Malaysia. The V_{Design} is the wind speed at which the wind turbine rotor spins at its maximum power coefficient. The rotor diameter is set as 1.16 m, with a hub diameter of 0.16m.

5.2. Optimum Number of Blades

The more blades there are on a wind turbine, the higher will be the torque and the slower the rotational speed. In any case, turbines utilized for producing electricity need to operate at high speeds, and really needn't bother with much torque. In this way, the less the number of blades, the better suited the wind turbine is for producing power. Hypothetically, a one-bladed turbine is the most efficiently proficient setups. Still, it is not widely practiced due to stability issues. Wind turbines with two blades have better applications than one-bladed turbines; however, they are affected by wobbling phenomenon and offer greater resistance to the yawing motion. Three-bladed wind turbines have next to no vibration due to the counterbalancing action of two blades to the resistance to the yaw force of the other blade. Thus, a three-bladed turbine speaks to the best mix of high rotational speed and least burden. All around, most wind turbines work with three blades as customary. The choice to outline turbines with three blades is really something of a bargain.

5.3. Tip Speed Ratio (TSR) and Rotational Speed

The TSR is influenced by the specific wind turbine design, the airfoil profile of the rotor, and the number of rotor blades. Considering a wind turbine with 3 blades, the maximum power extracted from the prevailing Malaysian wind at the maximum power coefficient is 4π/3 (4.19). For improved enactment of the wind turbine, the airfoil is likely to have 25–30% higher TSRs than the optimal values; thus, generating more power with increased rotor speed.

$$TSR : \lambda = \frac{\omega R_{rotor}}{V_{design}} = \frac{Blade\,tip\,speed}{Design\,wind\,speed} \quad (1)$$

The TSRs of 5, 6, 7 and 8 are chosen at design wind speed 4 m/s. Equation (1) is applied to obtain the corresponding angular velocity to determine their rotational speed are listed in Tables 2 and 3 respectively. For example, the operation of wind speed from 2.5 m/s to 8 m/s TSR of 7 varies in the range of 3.5–11.

5.4. Airfoil

On wind turbine technology, the aerodynamic performance is fundamental to increase efficiency. Nowadays there are several databases (Manoj and Anindita, 2015; Navin et al., 2014; Peter and Richard, 2012; Zafar et al., 2017) with airfoils designed and simulated for different applications. The choice of an airfoil is obligatory for virtuous performance and reliability of small-scale wind turbine. Airfoil governs the design angle of attack, maximum lift to drag coefficient and Reynolds number.

In this study, National Advisory Committee for Aeronautics (NACA) 4412 airfoil (Figure 3) developed by the NACA is selected because its nearly flat bottom surface avoids the negative ground effect that happens with extreme curvature or when Venturi flow is created beneath the airfoil. According to McCosker (2012), NACA 4412 has desirable average power coefficient values of a wider range of TSR.

5.5. Reynolds Number

When planning a wind turbine for energy harvesting, the average working speed is only the underlying parameter in the analysis; it is additionally critical to consider the atmospheric pressure, air density, air viscosity and the dimensions of the electric generator. Hence, a constant which relates these parameters is expected to describe the air flow, the Reynolds number (Re) will satisfy this condition. For a given atmospheric conditions, Reynolds number is a function of the relative wind speed V_{rel}, characteristic length, C (the chord of the airfoil at the blade span location), and μ is the air viscosity as presented in Equation (2). The Reynolds number for an SWT will be much smaller than for a large turbine.

Table 2: Chosen TSR for turbine design

Item	Design wind speed, V_{design}=4 m/s			
Turbines	SWT_re0.2	SWT_re0.25	SWT_re0.3	SWT_re0.35
TSR	5	6	7	8
ω, rad/s	36.4	43.6	50.9	58.2

TSR: Tip speed ratio, SWT: Small wind turbine

$$Re = \frac{\rho V_{rel} C}{\mu} = \frac{Inertia\ force}{Viscous\ force} \quad (2)$$

The startup of horizontal-axis SWTs virtuously hinges on the torque created by the wind acting on the rotor. Small horizontal-axis wind turbines are generally constant pitch control due to its economic benefits and the simplicity of the operating mechanism.

The Reynolds numbers of all the turbines are calculated for wind speeds ranging from 1 m/s to 8 m/s; however, only the calculated values for SWT_re0.3 are presented in Table 4. There are small deviations in Reynolds numbers 270,000–320,000 and the calculated ones which is due to its constant rotational speed of the turbine. Therefore, Reynolds number of 300,000 is chosen for SWT_re0.3 turbine design.

The maximum lift coefficient decreases with decrease in Reynolds number and vice versa for the drag coefficient. Figure 4 shows lift to drag ratio (C_l/C_d) increases gradually with an increase in Reynolds number. For SWT_re0.3, the lift coefficient is 1.0 and the maximum lift to drag is 91 at an angle of attack of 5° which is the design angle of attack, α for designing the rotor blade. This is repeated for another three designed CS-HASWTs as listed in Table 3.

5.6. Blade Element Momentum Theory (BEMT)

Blade aerodynamic design and analysis is the initial step to accomplish the probable power generation performance. The

Figure 3: National Advisory Committee for Aeronautics 4412 airfoil geometry

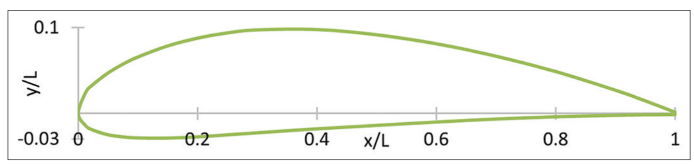
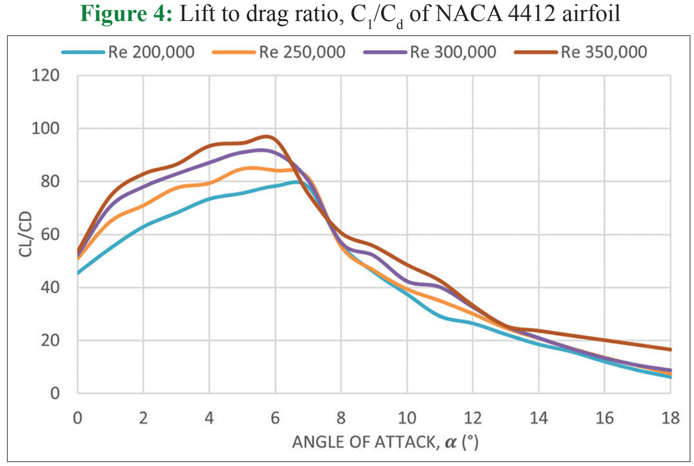


Figure 4: Lift to drag ratio, C_l/C_d of NACA 4412 airfoil



aerodynamic performance of a wind turbine is directly linked to the shape of the blade comprising of airfoils, chord and twist distribution. The choice of these blade parameters is frequently centered on BEMT. A BEMT (Tony et al., 2001; Manwell et al., 2009) is a theory that combines both blade element theory and momentum theory which is readily practicable, efficient and fast with an economic value in analyzing wind turbine aerodynamics.

In BEMT method of analysis, the blade is divided into segments (elements) along its span and two-dimensional experimental lift and drag coefficients are used to determine the aerodynamic forces on each segment. Each segment is examined individually. For each element, the thrust, dT and torque, dQ are characterized by:

$$dT = \rho V_{\infty}^{2} 4a(1-a)\pi r dr \quad (3)$$

$$dQ = 4a'(1-a)\rho V_{\infty}\pi r^{3}\Omega dr \quad (4)$$

In Equations (1) and (2), V_{∞} is free stream velocity, r is the radial location along the blade length, Ω is angular velocity, a and a' are axial and angular induction factors, respectively.

From the blade element theory, normal force, F_n and torque, Q is determined as follows:

$$dF_n = B\frac{1}{2}\rho U_{rel}^{2}(C_l \cos\varphi + C_d \sin\varphi)cdr \quad (5)$$

$$dQ = B\frac{1}{2}U_{rel}^{2}(C_l \sin\varphi + C_d \cos\varphi)cdr \quad (6)$$

Where B is the number of blades, ρ is air density, U_{rel} is the relative wind speed, C_l and C_d are lift and drag coefficients, respectively, c is the chord length of the airfoil and φ is the relative angle.

After paralleling normal force from blade element and momentum theory with the similar action for torque equations, the valuable correlation for axial and angular induction factors has resulted. They are used to govern the angle of relative wind and angle of attack which results in reading lift and drag coefficient. Subsequently, a and a' are rationalized. This process becomes repetitive till axial and angular induction factors are achieved with permissible inaccuracy. The computational flow of BEMT to obtain power performance of CS-HASWT is presented in Figure 5.

Table 3: Lift to drag coefficient at their respective angle of attack

Turbines	α (°)	C_l	C_d	C_l/C_d
SWT_re0.2	6	1.09	0.0140	78.4
SWT_re0.25	5	1.00	0.0120	84.8
SWT_re0.3	5	1.00	0.0110	91.0
SWT_re0.35	6	1.10	0.0115	96.0

SWT: Small wind turbine

Table 4: Calculated Reynolds numbers for SWT_re0.3 turbine

V∞ (m/s)ι	V_{tan} (m/s)	U_{rel} (m/s)	Reynolds number, Re
1	14	14.04	278,737
2	14	14.14	280.723
3	14	14.32	284296
4	14	14.56	289,065
5	14	14.87	295,215
6	14	15.23	302,363
7	14	15.65	310,701
8	14	16.12	320,032

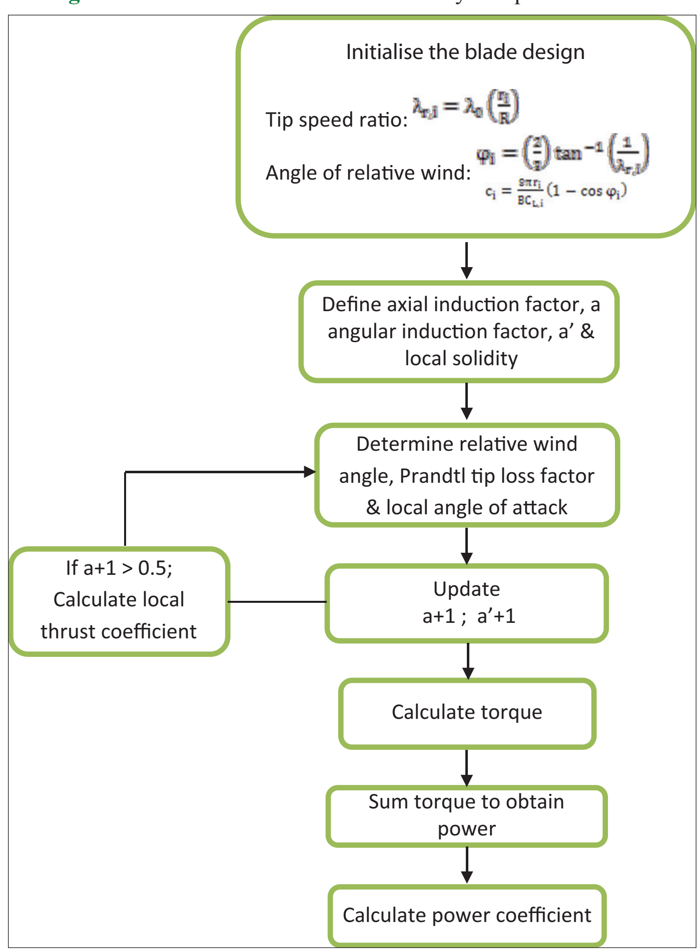
SWT: Small wind turbine

6. RESULTS AND DISCUSSION

In this study, an optimum number of 3-blades has been decided for this study due to its merits. CS-HASWT configuration is used since it has some varied benefits above other topologies for SWTs, mainly for low wind speed sites. To form a rotor blade, we have to design the blade as in Figure 6 based on the previous criteria shown. Then divide the blade into 10 elements with similar airfoil.

The power coefficients at different TSRs for the four turbines are determined as in Figure 7. From the graphs, for a particular wind turbine with known Reynolds number, it is seen that the power coefficient increases with the increase in the TSR initially, then reaches the maximum and decreases after that. This is the situation with all wind turbines; however, the TSR at which the maximum power coefficient occurs are different. Higher the Reynolds number higher will be the TSR at which the maximum power coefficient occurs. Another observation from the graphs that

Figure 5: Blade element momentum theory computational flow



optimum values of the power coefficients are different for turbines with different Reynolds numbers for their specified different TSR values. For instance, the turbine SWT_re0.2 has an optimum power coefficient of 0.50 (TSR:5) whereas SWT_re0.35 has only 0.49 (TSR:8). In other words, lesser the Reynolds number, the higher is the optimum power coefficient, and vice versa. As per the CS-HASWT logic, the power coefficient should be maximum at the design wind speed at the specified TSR. For SWT_re0.2, the design wind speed is 4 m/s and the TSR value is 5. As per the graph, SWT_re0.2 offers the maximum power coefficient at TSR value 5, SWT_re0.25 gives the maximum power coefficient at TSR value 6, and so on. For the fixed design wind speed and for other TSR values of these turbines, the power coefficients are less than the maximum value of their power coefficients.

While designing a CS-HASWT, the rotor speed is kept constant at a known value and the TSR becomes a variable according to changes in wind speed. For a specific value of design wind speed

Figure 6: Designed blade of 10 elements

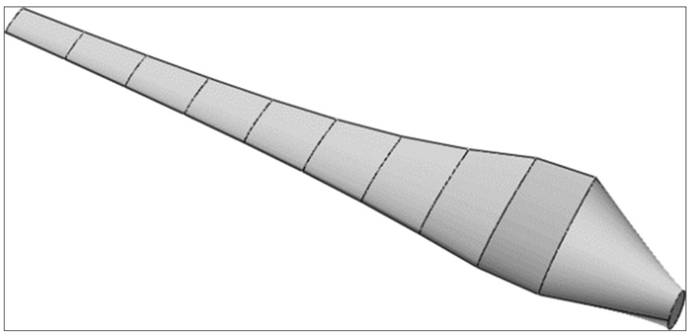
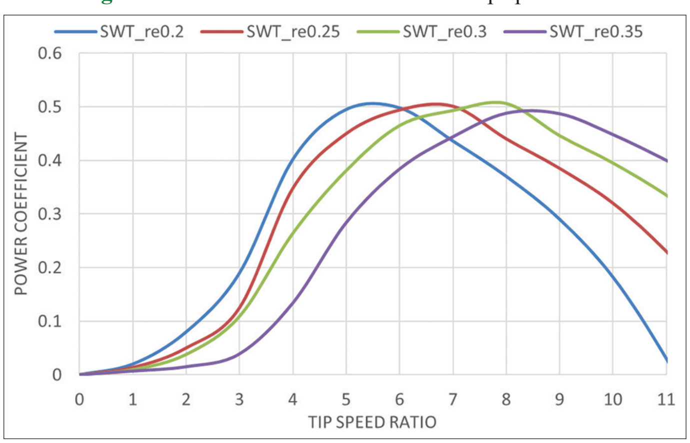


Figure 7: Power coefficients at different tip speed ratio



at a certain TSR, the power coefficient becomes maximum and for lower and higher values of the design wind speed, the power coefficient is less as depicted in Figure 7.

For all turbines, the chord length and twist distribution at various radial positions are evaluated and presented in Figure 8a-d.

It is observed that, turbines with low Reynolds number have higher twist angles for the various radial positions. For instance, SWT_re0.2 has twist angle 11° for radial position 1; whereas SWT_re0.35 has only 1° as the twist angle. Likewise, the chord length is less for turbines with low Reynolds number of varied radial positions.

Figure 9a-d depict the power output of all the turbines. For SWT_re0.2, power production starts at 1.5 m/s which is the cut-in wind speed and reaches the designed power capacity of 50 W at 6.5 m/s which is the rated wind speed. That means, the performance of this turbine is as per the designated values. In the case of SWT_re0.25, the power production reaches the rated capacity of 64.5 W at 7 m/s which is exactly the rated wind speed. For SWT_re0.3, the power production starts at 2 m/s which is the cut-in wind speed and reaches the rated power of 66 W at 7 m/s (rated wind speed); however, the power output increases to 70 W at 8 m/s rather than maintaining constant at 66 W till the cut-out wind speed. This may result in wobbling of the rotor and stress on the generator insulation. As far as SWT_re0.3 is concerned, it closely follows the power output performance of SWT_re0.2 according to its designated data.

The overall technical specifications of all the four turbines are summarised as given in Table 5. All are of horizontal axis 3-blade type with same rotor diameter and swept area. However, their cut-in and cut-out wind speeds, rated speed and power, power coefficient and rotational speeds are different. As presented power coefficients are representing at their respective turbine's design wind speed.

6.1. Annual Energy Generated

Table 6 shows the five sites of different wind conditions at their mean annual wind speed (MAWS) at 10m in Malaysia are selected, namely Kuching, Miri, Kangar, Labuan and Kudat. The 2-parameter Weibull distribution function is applied to predict the statistical wind speed probability distribution. As presented in Equation (7), it expresses the Weibull probability density function, F(v) in terms of the shape factor, k and the scale of wind regimes, c.

Table 5: Overall turbine specifications

Turbines	SWT_re0.2	SWT_re0.25	SWT_re0.3	SWT_re0.35
Number of blades	3	3	3	3
Rotor diameter, m	1.16	1.16	1.16	1.16
Swept area, m^2	1.06	1.06	1.06	1.06
Cut-in speed, m/s	1.5	2.0	2.0	2.0
Cut-out speed, m/s	7.5	9.0	9.5	10.0
Rated speed, m/s	6.5	7.0	7.0	6.5
Rated power, W	50.0	64.5	66.0	55.0
Power coefficient, Cp (%)	49.5	49.4	49.3	48.8
Rotational speed, rpm	347.2	416.7	486.2	555.6

SWT: Small wind turbine

Figure 8: (a) Chord and twist distribution for SWT_re0.2 turbine. (b) Chord and twist distribution for SWT_re0.25 turbine. (c) - Chord and twist distribution for SWT_re0.3 turbine. (d) Chord and twist distribution for SWT_re0.35 turbine

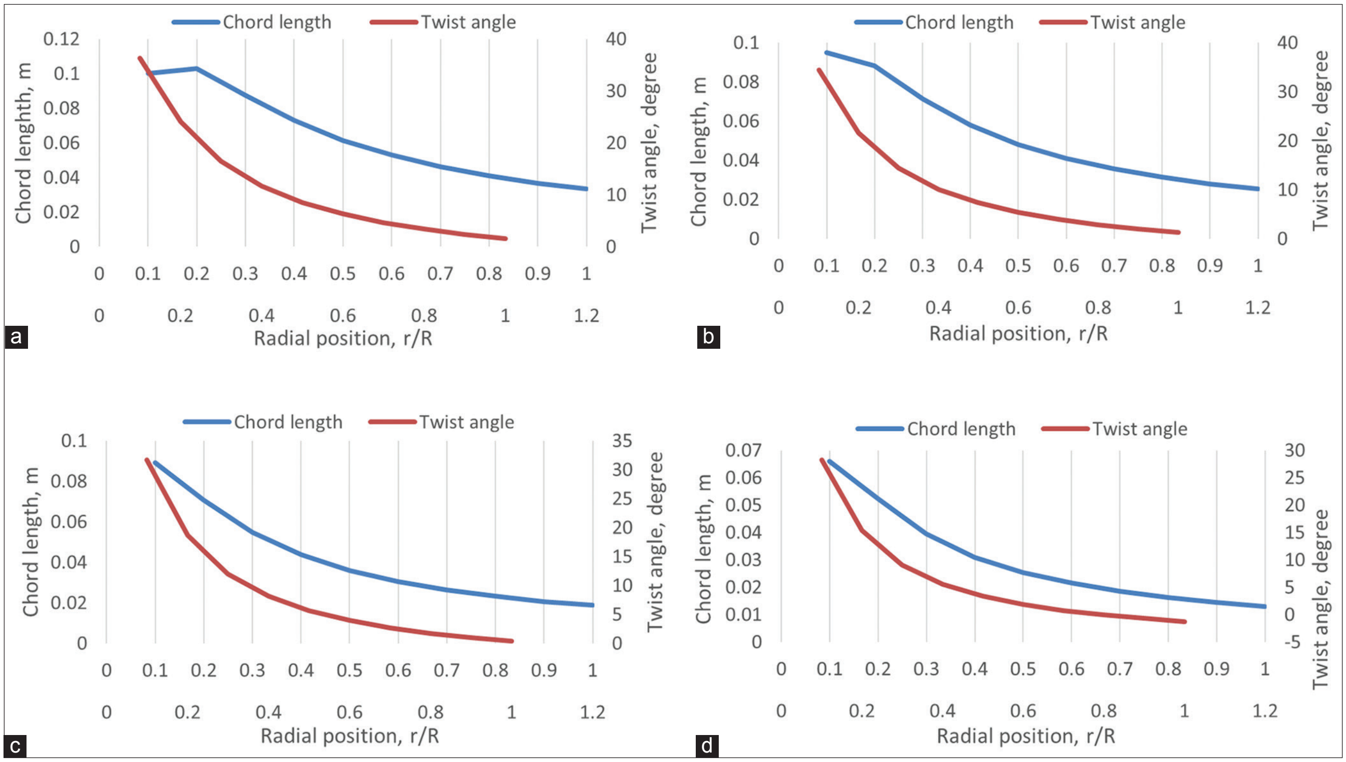
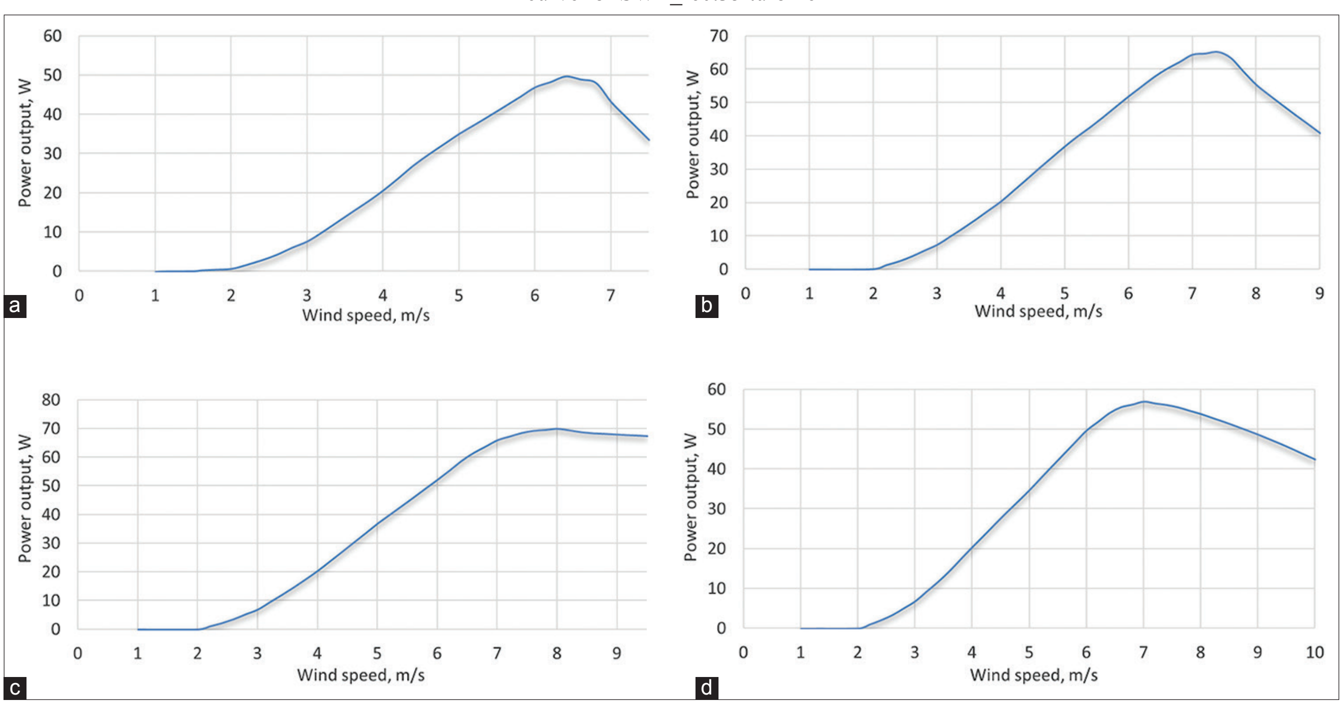


Figure 9: (a) Power curve for SWT_re0.2 turbine. (b) Power curve for SWT_re0.25 turbine. (c) Power curve for SWT_re0.3 turbine. (d) Power curve for SWT_re0.35 turbine



$$F(v) = \left(\frac{k}{C}\right)\left(\frac{k}{C}\right)^{k-1}\left(-\frac{v}{C}\right)^{k} \quad (7)$$

The power curve, P(v) of the designed CS-HASWTs are mapped with Weibull distribution function, F(v) and T refer to 8760 h, to obtain the annual energy generated, $E_{generated}$ are presented in Equation (8) and Table 7. As far as, Kuching is concerned, SWT_re0.2 performs slightly better than other turbines (cut-in wind speed 2 m/s) because of its low cut-in wind speed (1.5 m/s) compared to its MAWS. The annual energy generated in Miri is slightly higher than Kuching because of its slightly higher MAWS. In Kangar, almost all wind turbines perform equally irrespective of their

Table 6: Selected sites in Malaysia

Sites	k	c, m/s	v, m/s
Kuching	2.00	2.05	1.82
Miri	2.00	2.41	2.14
Kangar	2.01	2.86	2.00
Labuan	1.44	2.97	2.67
Kudat	1.60	3.37	3.00

Table 7: Annual energy production, kWh

Sites	Annual energy production, kWh			
	SWT_re0.2	SWT_re0.25	SWT_re0.3	SWT_re0.35
Kuching	25	24	23	22
Miri	43	43	42	40
Kangar	71	73	72	69
Labuan	90	99	102	94
Kudat	109	121	125	116

SWT: Small wind turbine

varied rated power capacities. Labuan experiences higher energy generation due to SWT_re0.25 and SWT_re0.3 because of their higher rated power capacities than SWT_re0.2 and SWT_re0.35. Finally, Kudat ranks first in annual energy generated compared to all other sites due to its greatest MAWS. At higher wind speeds, such as 3 m/s (in Malaysian scenario), higher capacity CS-HASWTs like SWT_re0.25 and SWT_re0.3 perform better than lower rated power capacity turbines like SWT_re0.2 and SWT_re0.35.

$$E_{generated} = T\int P(v)F(v)dv \tag{8}$$

The designed turbines are virtually tested with various sites in Malaysia at 10 m height above ground level. The performance is above expectation with CS-HASWTs. Since, Malaysia has a huge number of tall raised buildings, these turbines could be installed at higher heights to capture more energy. This scope is reserved for further research.

7. CONCLUSIONS

This research aimed at the optimum rotor turbine design of CS-HASWT based on the aerodynamic features of the airfoil, that is, the lift and drag coefficients, and its angle of attack. A BEMT that combines both blade element theory and momentum theory which is one among the most practical, efficient and fastest methods with low computational cost of analyzing wind turbine aerodynamics, is used for optimization as well as to obtain power performance of CS-HASWT. Four numbers of case studies by means of different design parameters are considered in the SWT blade design. The design outcomes are examined and compared to each other against the power performance of the rotor. All the designed turbines are virtually applied to five Malaysian sites and their annual energy generation are ascertained. The design outcomes of the partial design cases validate noticeably which SWT design provides the best performance in the Malaysian wind scenario.

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