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Floating axis wind turbines for offshore power generation—a conceptual study

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Abstract
The cost of energy produced by offshore wind turbines is considered to be higher than land based ones because of the difficulties in construction, operation and maintenance on offshore sites. To solve the problem, we propose a concept of a wind turbine that is specially designed for an offshore environment. In the proposed concept, a floater of revolutionary shape supports the load of the wind turbine axis. The floater rotates with the turbine and the turbine axis tilts to balance the turbine thrust, buoyancy and gravity. The tilt angle is passively adjustable to wind force. The angle is 30° at rated power. The simplicity of the system leads to further cost reduction of offshore power generation.

Keywords: floating axis wind turbine, offshore wind power, wind energy conversion, economic performance

1. Introduction

The recent accidents at nuclear reactors triggered by the earthquake and tsunami in Japan have raised new disputes on energy policies all over the world. We have to reassess the costs of renewable energy and explore new possibilities of energy generation which can be substituted for a part of the present share of nuclear power. In Japan, wind power is one of the prospective candidates. However, in Japan, flat land and shallow water area available for the construction of new wind farms is very limited. Therefore, there is an urgent need for low-cost offshore wind turbines that are applicable to deep water regions.

At present, most offshore wind turbine concepts are marinized versions of land based ones. The major concept is the horizontal axis wind turbine (HAWT). The tower of the HAWT is constructed on the base foundation fixed on the sea bottom or on a floating platform. It significantly increases the cost of the total system. Recently, vertical axis wind turbines (VAWTs) have been proposed for offshore applications [1–6]. VAWTs do not require yaw control mechanisms and their main mechanics are installed near the ground/sea level. They have potential in offshore applications where firm ground foundations are not available.

Conversions of land based wind turbines are reasonable in some aspects. They utilize the accumulated knowledge on land based turbines and benefit from lower R&D costs. However, these concepts require firm foundations as they are used on ground sites. Providing sub-sea structures or floating platforms increases the cost of energy from the baseline costs of land based ones.

To solve the problem, the authors propose an alternative solution for offshore wind turbines. It uses the buoyancy of the turbine's float as the supporting mechanism of the turbine axis. The concept is a floating axis wind turbine (FAWT). This letter describes the concept and preliminary estimation of its economic performance in comparison with other offshore wind turbines.

2. Floating axis wind turbine

2.1. Vertical axis wind turbines

Although offshore wind turbines receive merits of scale in comparison to land based ones, construction of their tall towers

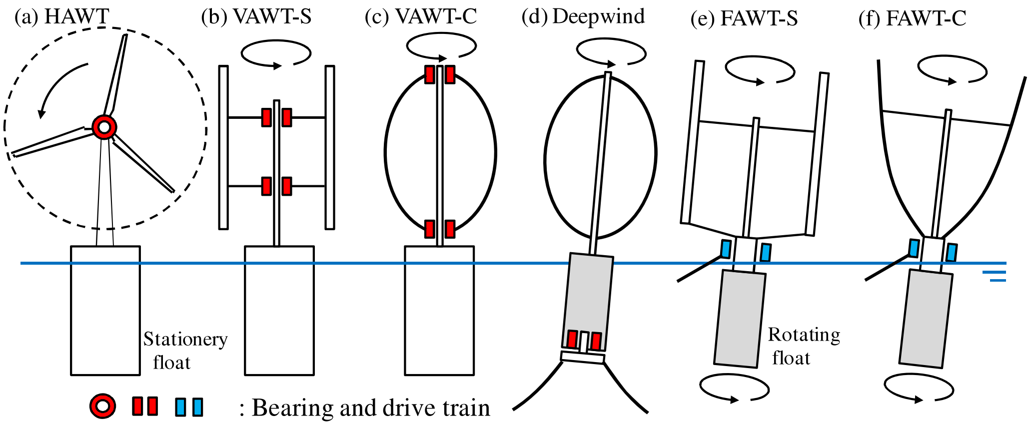

Figure 1. Floating wind turbine concepts (a), (b) and (c) floating wind turbines, (d) Deepwind concept, (e) and (f) floating axis wind turbines.

and operation and maintenance costs of high-mounted turbines in an offshore environment are severe problems. Since the main mechanisms of a VAWT are simple and installed near the base structure, it leads to a lower cost of supporting structures. Known disadvantages of VAWTs are low starting torque, aerodynamic stability of blades and fatigue strength. However, the potential of VAWTs in offshore use has not been fully discussed because successful development of land based HAWTs drove out the R&D into large VAWTs in the exploration of wind power.

In recent years, some companies have been working on offshore VAWTs (VERTAX wind [1], Vertical Wind [2]). These use straight blade turbines placed on floaters. Nenuphar [3] proposed a straight blade floating offshore VAWT with direct drive configuration. NOVA [4] proposed a large V-shaped arm design VAWT. The V-shaped arm supports a series of winglets and provides a large rotation radius to them. Deepwind [5, 6] proposed a VAWT design mounted on a rotating and floating spar buoy which has an electric generator at its lower end. It allows inclination of the tower for low-cost structures. However, the generator installed at the lower end of the rotating buoy is a new challenge. At present, comparative studies on the economics of VAWTs and HAWTs in an offshore environment are very limited. Blonk [7] compared cantilevered and guyed VAWTs with a floating HAWT. It showed that the economic performance of VAWTs is comparable to that of HAWTs in offshore applications. However, since it is a cooperative research effort between TU Delft and a company, some important design procedures are concealed as confidential.

2.2. *Floating axis wind turbine*

In both offshore HAWT and VAWT concepts, major challenges are on how to provide firm support of the turbine axis in an unstable sea environment without a significant increase in cost. Also, the sea environment is not a suitable place for seeking firm foundations. To solve this problem, the authors propose a different approach to offshore wind turbines. The concept is the FAWT. It allows large inclination of the turbine axis and its major mechanisms including generators are installed above the water surface. The inclination angle of the turbine axis is passively adjustable to wind speed. It simply denounces the idea that the turbine axis should be stable around the upright position.

Figure 1 shows the schematic image of the floating wind turbine concepts. Figures 1(a)–(d) illustrate HAWT, the straight blade VAWT, carved Darrieus blade VAWT and the Deepwind concept respectively. Figures 1(e) and (f) are FAWTs with straight blades (FAWT-S) and with curved blades (FAWT-C) respectively. Although a FAWT looks like a spar buoy VAWT, its bearings for the turbine axis are not on its central tower. A cylindrical float rotates with upper structures of the turbine. The tilt angle of the turbine axis is passively determined in the balance of turbine thrust, buoyancy of the float and gravity. The torque of the turbine is converted to electricity by bearing rollers and generators above the sea surface. The major merits of FAWT can be stated as follows.

(1) The float supports the weight of the turbine and most of its axial load. The bearing rollers swivel like swivel casters of a desk chair. It allows relative heave motion of the rotating float to the bearing mechanism so that only the thrust force of the turbine is on the bearing mechanism. The thrust force of a wind turbine is less than $1/10$ of the weight of the VAWT mechanism.
(2) Power output from the turbine is obtained from torque of the rotating float by rollers contacting on the cylindrical surface of the float. Since the drive train is not in a limited space like the nacelle of a HAWT or the shaft of a VAWT, restrictions on the weight and size of the mechanism are lighter than those in other turbine concepts.
(3) Non-firm support of the turbine axis avoids concentration of the load. Since the weight and bending moment of the turbine are not directly on the drive train, the configuration leads to lighter structural requirements. Gyroscopic moment of the turbine and the float stabilizes the direction of the turbine axis in wind fluctuation.
(4) FAWTs inherit the simple mechanism and low maintenance cost of VAWTs.
(5) Installation of FAWTs does not require floating cranes and other specifically designed service vessels.

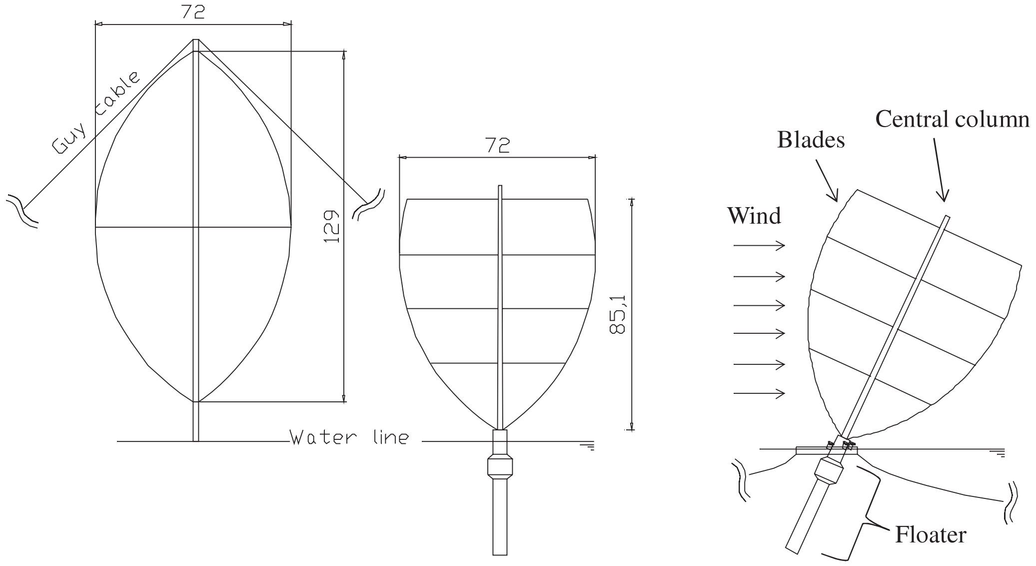

Figure 2. Sweep area dimensions of a 5 MW VAWT [7] and the derived 3 MW FAWT.

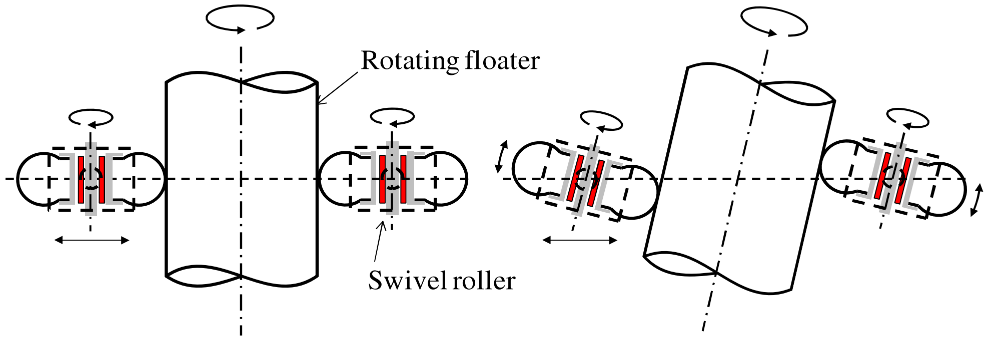

Figure 3. Sample design of the inclined rotor support.

As is the case with all emerging technologies, there are many unknown factors and possible problems. The structure and concept must be checked by model tests and numerical simulations for its realization. The authors recognize that there will be many challenges in vibration treatment of the lightly supported rotating structure, fatigue strength and the complex flow field. For example, we have to consider the time-dependent gyration moment and the Magnus effect caused by wind and water current. These will be checked in our future work.

2.3. Example of FAWT dimension

At present, cost information of offshore VAWTs is very limited in comparison to that of HAWTs. Since most research on floating VAWTs is still ongoing, dependency relations of the size parameters of floating VAWTs to their performance and construction are not publicly available yet. Therefore, for preliminary evaluation of the concept, we derive the dimensions of a 3 MW FAWT from the guyed 5 MW VAWT design of Blonk [7] by trimming the sweep area of the turbine. Figure 2 shows the schematic images of the guyed 5 MW VAWT and the trimmed sweep area of the present 3 MW FAWT. Since, in this conversion, local aerodynamics and loads on blades are basically unchanged, we can partially reuse the analysis of Blonk [7] for a rough estimation. The selected power rating of 3 MW is for the comparison of economic performance with the baseline cost of 3 MW HAWTs of the National Renewable Energy Laboratory (NREL), USA [9] in section 3.

The trimmed FAWT of 85.1 m height receives 60% wind power of the original VAWT with the assumption that the vertical shear wind distribution is $U(z) \propto z^{1/7}$ and the wind power is proportional to the cube of local wind speed. Here, $U(z)$ is the mean velocity at the altitude z. The maximum rotor diameter of the turbine is $R = 72$ m. The 3 MW FAWT inherits the wing section, rotational speed and solidity of the 5 MW VAWT. They are summarized in table 1. The blades are made of GFRP using a vacuum assisted resin transfer molding (VaRTM) [10] process. The clearance of blades from the sea surface is an important parameter for the survivability of the system in heavy seas. However, this matter is not discussed in the present conceptual study.

It should be noted that these parameters are only to use the existing VAWT design of Blonk [7]. They are not optimal for economic performance. In this estimation, the weights of

Table 1. Particulars and component masses of the VAWT (5 MW) [7] and FAWT (3 MW).

	VAWT-C (5 MW)	FAWT(3 MW)
Rated wind speed (m s^{-1})	15	15
Equator height/max. radius height (m)	78	63
Rotor diameter (m)	72	72
Rotor height (m)	129	82
Blade chord length (m)	2.2	2.2
Solidity	0.18	0.18
Total weight	785	602
Blades (ton)	123	81
Generator (ton)	141	84
Central column (ton)	247	122
Cables (ton)	86	86
Floater (ton)	188	188
Ballast (ton)	—	41

the blades and central column of the FAWT are downscaled linearly according to the length of blades (61% of base VAWT). Also we assume that the weight of the generator is proportional to the rated power (60% of base VAWT). These are preliminary estimations for the present conceptual study. The weights of the floater and supporting cables (catenary loose mooring system) are the same as those in the VAWT because we do not yet have reliable information on their estimation. The shape of the floater is a circular cylinder with radius $r = 2.5$ m and depth $d = 40$ m. It has a bulge near the sea surface to increase the height of the buoyancy center and the ballast of heavy concrete for stability enhancement. Water displacement of the total system in operation is 602 ton including ballast weight. The wave load on the bulge should be estimated in a future study. The tilt angle of the turbine axis is 30° at rated power. Since the righting moment is proportional to the sine value of tilt angle, the large allowable tilt angle provides sufficient stability. The rotation speed of the FAWT at rated wind speed is 17 rpm (angular velocity $\omega = 17.9$ rad s^{-1}).

2.4. *Inertial moment and frictional loss on the float*

The approximate inertial moment of blades is $I_{\mathrm{blades}} = (1/3)m_{\mathrm{blades}}R^2$ and that of the float is $I_{\mathrm{float}} = (1/2)m_{\mathrm{float}}r^2$. Here, R, r, m_{blades} and m_{blades} are the turbine radius, floater radius, mass of blades and mass of float respectively. In the present FAWT, the resultant inertial moments are $I_{\mathrm{blades}} = 3.5 \times 10^7$ kg m^2 and $I_{\mathrm{float}} = 8.6 \times 10^5$ kg m^2. Since the radius of the floater is significantly smaller than that of the turbine, the inertial moment of the float is only 2.5% of the inertia of the blades. The large inertial moment of the total system might cause problems in the concept. For example, the high rotational kinetic energy of the turbine increases the extent of damage in accidents. However, it works as a large flywheel. It has a leveling effect on power output and also stabilizes the turbine axis in the fluctuating natural wind.

The tangential velocity on the floater surface is $v_{\mathrm{t}} = 4.45$ m s^{-1} at 17 rpm rated rotation. The Reynolds number of the flow is $Re = rv_{\mathrm{t}}/\nu = 9.85 \times 10^6$ (3.5% salinity, 15 °C). Frictional loss P_{fric} in the turbulent boundary layer on the floater surface is approximately

$$P_{\mathrm{fric}} = C_{\mathrm{f}}\tfrac{1}{2}\rho_{\mathrm{water}}v_{\mathrm{t}}^2 2\pi r d v_{\mathrm{t}}. \tag{1}$$

Here C_{f} is the frictional drag coefficient on the floater surface. Using the experimental result of Theodorsen and Regier [8], we use $C_{\mathrm{f}} = 2.00 \times 10^{-3}$ at the given Reynolds number. The estimated frictional loss of floater P_{fric} is 113 kW on the submerged surface including the bulge part. It is 3.7% of the rated 3 MW power.

2.5. *Supporting mechanism of the turbine axis*

The supporting mechanism of the inclined rotating turbine requires new engineering tasks. Figure 3 shows an example of possible designs. Swivel rollers contacting on the cylindrical surface of the float bear the horizontal and fluctuating components of turbine load and derive torque from the surface. The rollers have multiple swivel axes for adjustment to the motion of the turbine. The high torque of a VAWT-type turbine can be shared by multiple sets of roller-generator units. The ratio of roller and floater diameters determines the speed increasing ratio at the generator axis. Direct rim-driven generator design on the floater rim is also possible. The wave induced motion of the floater and roller supports can be reduced if their water plane areas are small and the fluctuation of buoyancy is not significant to the total weight as in a spar buoy. In the present configuration, the fluctuation of buoyancy in a 3 m height wave is 5.2% of the total weight. In the following sections, the authors assume that the efficiency of the new drive train is equivalent to that of conventional ones and that the loss by blade supports is insignificant. It should be noted that the resultant economic performance contains uncertainty about the new technology.

3. Economic performance of FAWTs

At present, it is difficult to find comparative studies of the economics covering both offshore HAWTs and VAWTs. Therefore, we conduct two comparisons separately in this section.

First, we compare the hardware cost of the present model with two floating 5 MW turbines of the VAWT and HAWT in Blonk [7]. Note that the fairness of the following comparison is limited because the data source of the reference HAWT is not open as it is confidential information.

Table 2 shows the comparison of levelized expenditure cost (LEC) [7] among three offshore wind turbines. The definition of LEC is

$$\mathrm{LEC} = \sum_{t=0}^{T}(I_t + M_t + F_t)(1+r)^{-t}. \tag{2}$$

Here T is the lifetime of the system and r the interest rate. I_t, M_t and F_t are annual expenditures of investment, maintenance & operation and fuel cost in the year t, respectively. In the present case, T is 20 yr and r is 0.05.

In the estimation, we assumed that the floater and anchoring cost of the 3 MW FAWT is the same as that of the 5 MW VAWT. It is an upper side estimation of the float

Table 2. Estimated hardware costs of floating wind turbines (M Euro).

Concept	Guyed VAWT (5 MW)[a]	HAWT (5 MW)[b]	FAWT (3 MW)
Floater	2.06	—	2.06
Anchoring	2.05	—	2.05
Cables	0.29	—	0.29
(Subtotal)	(4.41)	(9.50)	(4.41)
Drive train	2.37	1.76	0.00
Power equipment	0.95	0.73	0.44
Blades	2.83	1.37	1.87
Blade supports	—	—	45
Tower/central column	0.86	1.18	0.57
Bearings	2.08	0.23	0.23
Brake	1.10	0.12	0.66
Yaw and pitch mech.	0	0.71	0.00
Miscellaneous	1.42	1.42	0.85
Maintenance	4.01	5.94	2.41
Other	4.06	4.06	4.06
Total LEC (20 yr)	20.0	22.9	11.8
LEC/rated power (Euro W^{-1})	4.01	4.59	2.36
(LPC[b] (Euro kWh^{-1}))	(0.089)	(0.101)	(0.087)

[a] Data source [7]. [b] Assumed capacity factor is 38.13%.

cost. The costs of blades and the central tower were linearly downscaled with the shorter blade length of the FAWT in comparison to the base 5 MW VAWT. The cost of blade supports is 20% of the blade cost. Since these blades are supported by arms connected to the central column, we do not require integral molding of each long blade. Each blade is divided into shorter straight blade units for low production costs. Therefore, the long blade length does not lead to rapid increases in production cost. The costs of power related components are reduced from that of a 5 MW VAWT in proportion to rated power. The merit of scale in 5 MW turbines on 3 MW is not included in this preliminary estimation. The result shows that the installed cost per rated power of FAWT is 50% and 57% of those in the reference HAWT and guyed VAWT respectively. It indicates the potential economic performance of the proposed FAWT in offshore applications.

The total cost of energy can be shown in the form of levelized production cost (LPC) defined as

$$\mathrm{LPC} = \mathrm{LEC} \Big/ \sum_{t=0}^{t=T} E_t (1+r)^{-t}. \tag{3}$$

Here E_t is the electricity generation in the year t. For reference, LPCs of these turbines are shown in the last line of table 2 with the assumption that the capacity factors (energy production/rated power) of them are equal to 38.13% as in the offshore HAWT example of NREL [8].

The second comparison is between the present FAWT and an offshore HAWT fixed on a shallow sea bottom. The offshore HAWT is an output example of the NREL [9]. It is a 3 MW rated turbine with 90 m rotor diameter and 80 m hub height. the foundation of the tower is a monopile. Comparison of their component costs are shown in table 3.

The longer blades of the FAWT increase the cost of rotor parts in comparison to the HAWT design. However, the cost reduction of the drive train yields lighter rotor and tower costs. The cost of the float is 54% higher than those of a monopile foundation and supporting structure of HAWT. In the estimation of float cost, we assumed that the cost ratio between blades and floater is the same as in the previous comparisons of floating wind turbines. For operation and maintenance (O&M) cost, we assumed that the cost reduction ratio is the same as that between the HAWT and VAWT in Blonk [7] and is proportional to the rated power. Other parameters are the same as those of the reference HAWT so that they lead to higher cost estimations. Although the present FAWT is not for shallow water areas, the cost of longer electric transmission to the shore has not yet been considered. The estimated cost of energy in the FAWT (0.071 USD kWh^{-1}) is 25% lower than that of the base HAWT. Although the present estimation contains uncertainties in the new concept, the result showed that the economic performance of the FAWT is comparable to the baseline of the HAWT and that it might be superior to the existing wind turbine concepts.

Table 3. Cost estimation of the 3 MW shallow water HAWT and FAWT (1000USD).

	3 MW HAWT [9]	3 MW FAWT
Rotor	477	871
Drive train, nacelle	1425	659
Control, safety system, monitor, pitch mech. and bearings	60	60
Tower/central column	415	221
Marinization (13.50% of turbine and tower cost)	321	244
Monopile foundation/support structure/float	1114	1712
Transport, installation, electrical interface, assessment	1835	1835
Scour protection	204	0
Surety bond (decommissioning—3.0% of ICC)	180	168
Offshore warranty premium (15.00% of turbine and tower system)	357	272
(Subtotal: initial capital cost ICC)	(6386)	(6042)
Levelized replacement cost (LRC) (USD yr^{-1})	55	55
O&M (USD per turbine/yr)	215	145
Bottom lease cost (USD yr^{-1})	12	12
(Subtotal: annual operating expenses (USD yr^{-1}))	(282)	(212)
Cost of energy (USD kWh^{-1})	0.095	0.071

4. Concluding remarks

The authors proposed the concept of an offshore wind turbine with a floating tilted axis. The tilt angle varies according to the balance of turbine thrust and stability of the float. By allowing a large tilt angle, we can reduce the total weight of the system. Electric generators are installed above the water surface at a low altitude to provide easy maintenance access. Preliminary estimation and comparisons indicate that economic performance of the new concept can be higher than those of horizontal and vertical axis offshore wind turbines. There are many items that are not discussed in this letter. These include optimum stability of the floater, bending moment and fatigue strength of the blades, dynamic fluid–structure interactions and the minimization of viscous loss. Though the merits and demerits of the proposed concepts have not yet been examined fully, the authors think it will be a breakthrough in the present high energy cost of offshore wind power generation.

References

[1] P C Hunter of VertAx Wind Ltd 2009 Multi-Megawatt vertical axis wind turbine *Presentation Slides for GL How Conf. 2009*

[2] Vertical Wind AB www.verticalwind.se/en/index.html (accessed 21 May 2011)

[3] Nenuphar *Nenuphar Technology Benefits* www.nenuphar-wind.com/technology (accessed 11 May 2011)

[4] Wind Power Ltd 'NOVA' *Project Description* www.nova-project.co.uk/ 2009 (accessed 21 May 2011)

[5] Vita L *et al* 2010 A novel concept for floating offshore wind turbines: recent developments in the concept and investigation on fluid interaction with the rotating foundation *(OMAE2010): Proc. ASME 2010 29th Int. Conf. on Ocean, Offshore and Arctic Engineering (Shanghai)* pp 389–96

[6] Paulsen U S *et al* 2011 Deepwind-an innovative wind turbine concept for offshore *Proc. EWEA Annual Event 2011 (Brussels)* p 9

[7] Blonk D L 2010 Conceptual design and evaluation of economic feasibility of floating vertical axis wind turbines *MSc Thesis* Delft University of Technology

[8] Theodorsen T and Regier A 1944 *Experiments on Drag of Revolving Disks, Cylinders and Streamline Rods at High Speeds (Technical Report 793)* (Langley Field, VA: National Advisory Committee for Aeronautics)

[9] Fingersh L, Hand M and Laxson A 2006 Wind Turbine Design Cost and Scaling Model *NREL Technical Report No.* TP-500-40566

[10] Rigas E J, Walsh S M and Spurgeon W A 2001 Development of a novel processing technique for vacuum assisted resin transfer molding (VARTM) *Proc. 46th Int. SAMPE Symp. and Exhibition (Long Beach, CA)* pp 1086–94