Three Windstar 530G VAWTs among HAWTs in the San Gorgonio Wind Resource Area, California

Dramatically increase wind farm output while protecting wildlife

How to safely harvest high speed, near-ground wind in existing wind farms

This paper will be submitted for peer review to Renewable Energy Focus after receiving comments from the publication of excerpts in the April issue of Windpower Engineering. Send comments and suggestions to Kevin Wolf, Chief Operating Officer, Wind Harvest International, *kwolf@windharvest.com* Last updated – *4 February 2018*

Introduction

Wind farms in California and other regions of the world exist only in relatively small geographic regions.[1] Most of these resource areas have reached their physical or political[2] limits in their ability to install additional propeller-type, horizontal axis wind turbines (HAWTs).[3] Nonetheless, many have topographies that create excellent near-ground wind speeds.

To profit from the energetic wind below their HAWTs, wind farm owners need cost-effective vertical axis wind turbines (VAWTs) that operate efficiently in high turbulence and that do so without wake[4] from the added rotors negatively impacting their existing turbines. They also need turbines that are wildlife friendly.

Turning the best near-ground wind into energy should eventually result in lower priced power than solar technologies or new wind farms, less habitat developed, and thousands of MWs of additional power produced well after the sun sets[5]

Near-Ground Turbulence

The good-to-excellent average annual wind speeds (6-9 m/s, 14–20 mph) found at 10–25m above ground level in wind farms in California[6] and other regions are well known to wind industry meteorologists.[7] Passes and ridgelines accelerate near-ground wind and cause wind shears to decrease, often significantly. Meteorological data also document that thermal and obstacle-induced turbulence in the high-energy, near-ground wind is found in many wind farms, including in four of California's five Wind Resource Areas.

One reason near-ground wind resources haven't been developed is that HAWTs have increased failure rates when their blades pass through turbulence.[8] As a result, rows of

HAWTs are hundreds of meters downwind of each other, and the bottom tips of their blades range between 20m and 50m above ground level.

HAWT turbulence-loading problems arise primarily from their long blades connecting to the drive shaft at only one end and their large rotor having to operate in changing wind speed and direction. The blades and bearings used in modern HAWTs would have to be substantially strengthened to withstand the high peak and cyclic loads from the near-ground layer of extreme turbulence.[9]

Why VAWTs Now

VAWTs are intrinsically less sensitive to turbulence than HAWTs because their blades are attached to the rotating shaft at two or more locations. Another beneficial outcome from their geometry is that VAWTs don't have to yaw and turn into the changing wind direction.

At least one such wind turbine (i.e., Wind Harvest International's (WHI) Harvester VAWTs[10]) is ready for certification and operation underneath HAWTs.[11] Other turbines could also soon be capable of achieving a 20+ year service life in high turbulence and be ready for industry-scale sales(e.g., Stanford/Dabiri's VAWTs), once they can comply with the IEC 61400 certification process and become UL listed.

Historically, VAWTs have had trouble with mechanical design and durability because they lacked field-validated, aeroelastic modeling that HAWT engineers use. That has been resolved by building on VAWT modeling developed by Sandia National Labs and advanced at Delft and Danish Technical University. The engineers of the WHI Harvester used a suite of prototype-validated finite element, frequency response, and fatigue analysis models that together function as an aeroelastic model.[12]

Aerodynamic modeling funded by a 2010 California Energy Commission (CEC) EISG grant[13] to WHI proved that modern VAWTs, when placed close together would also create the "coupled vortex effect". The one meter close spacing and counter rotations let them produce 20–30% more energy per pair than from two VAWTs operating separately. This offsets the problem VAWTs face that HAWTs don't: their blades create drag as they return into the wind. Historically, this increase in drag prevented them from realizing more than a 45% efficiency,[14] whereas HAWTs can achieve 50%. With the coupled vortex effect, VAWTs in arrays can theoretically realize the efficiencies of HAWTs.

Another problem hindering VAWT development is that smaller VAWTs like WHI's Harvesters use more steel and material per rotor-swept area and MW of installed capacity than do large HAWTs. However, with large-scale use possible in wind farms:

- The mass manufacture of the smaller VAWTs offer significant savings.[15] For example, VAWTs with straight blades can be extruded or pultruded and avoid the expensive hand work involved in making the blades of large HAWTs.
- Their shorter towers use less material[16] and are easier to make and install. WHI's Harvester 70 VAWTs' foundations are 1/2 meter deep, and their rebar cages can

be mass manufactured. In contrast, HAWT foundations require twelve to twenty, 35 to 50-feet long anchors, and even more on larger machines[17].

- They make dual use of valuable land and infrastructure[18] when installed in existing wind farms.

An additional benefit modern inverter-based VAWTs have for repowering wind farms is that they can help solve the grid harmonics and reactive power problems that are caused by older HAWTs using "induction generators". These problems harm the efficiency and quality of energy transmission. A megawatt of VAWTs like WHI's Harvester 70 with inverters similar to the ones in Northern Power Systems' 100kW HAWTs can, independently of wind speed instantaneously source or sink 450 KVARs[19] of the problematic reactive power, and thus make a significant difference in improving the power quality of older wind farms.

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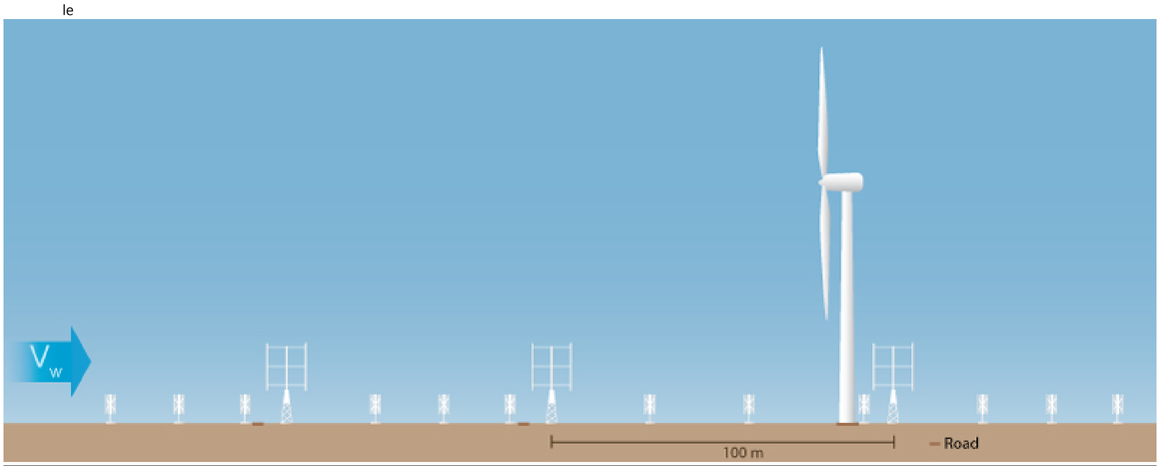

***Figure 1**. This graphic shows a vertical and horizontal staggering of VAWTs upwind and downwind of a 2MW HAWT. The distances between VAWTs and their heights are described in Table 1 with the exception that the Harvester 70 VAWT distance immediately upwind of the HAWT is 100m and not 70m. The faster-moving wind that is upwind and above the HAWT will be drawn down toward the ground by the vertical mixing and energy extraction of the VAWTs below.*

VAWT Impacts on HAWTs

Aerodynamics predict that the wake from VAWTs won't harm HAWTs, and may in fact help them. The wake and vortices shed from an array of tightly spaced VAWTs should stay in the same wind layer that passes through their vertically spinning rotors. Modeling shows that downwind by five rotor heights[20] or ~eight rotor diameters[21] , the wake of VAWTs is gone, their vortices have disintegrated, and the wind speed has recharged, in part due to the vertical mixing that their spun-off vortices create.

VAWT placements are theorized to increase the wind speeds entering the rotors of the HAWTs above them in two major ways.

Lowering the wind shear

A growing body of field data and research, led in large part by Dr. John O. Dabiri, has demonstrated how the vertical mixing created by counter-rotating VAWTs lowers wind shears by bringing higher, faster-moving wind toward the ground and replenish the wind speeds lost to the energy and turbulence the VAWTs produce.[22] As a result, faster moving wind from above will drop down into HAWT rotors and increase their energy output.[23].

Stanford University doctoral candidate Anna Craig led a study that modeled various VAWT arrangements. Their results[24] indicate that VAWTs can interact positively when placed in close proximity to one another. Craig noted that “We think that the VAWTs can have blockage effects causing speedup around the turbines that help downstream turbines. They can also have vertical wind mixing in the turbine's wake region, which assists in the wind velocity recovery.”

In *Benefits of collocating vertical-axis and horizontal-axis wind turbines in large wind farm*s, the authors stated, “Because of the presence of the VAWT layer, the turbulence in the wind farm is increased, which enhances the wake recovery of the HAWT. The faster wake recovery more than compensates for the additional momentum loss in the wind because of increased effective surface roughness associated with the VAWTs.”[25]

Porous Wind Fence Effect
Dr. Marius Paraschivoiu’s modeling shows that there will be a few meters of high turbulence directly above an array of VAWTs. Above that is a zone where the wind speeds increase above ambient. This is caused by the blockage effect of the VAWTs.

A row of VAWTs could be placed upwind of a HAWT at just the right height so that the HAWT blade enters a zone of higher wind speed with no significant increase in turbulence. Arrays of VAWTs placed a short distance downwind of a HAWT can also create a speed-up effect for the upwind HAWT, but the physics are different. The wind speeding up over the VAWTs decreases the pressure there, which increases the pressure difference between the front and back of the HAWT rotor. This in turn would increase the wind speed through the HAWT rotor and thus its energy output.

Just how much this effect could benefit HAWTs was to be a significant focus of the LiDAR studies WHI proposed as part of its R&D proposal to the CEC EPIC Program.

VAWTs Potential to Increase Wind Farm Energy Output
HAWTs in wind farms are placed substantial distances apart. Below is a table comparing wind farm land use in California’s Wind Resource Areas to other means of estimating the amount of land a HAWT wind farm needs.

Modeling and field testing show that the relative distances between rows/arrays of VAWTs can be much shorter than with rows of HAWTs without the downwind row losing wind speed and energy.[26] The table below shows the VAWT energy densities that can be developed with the following assumptions:

- One-third meter between 3kW VAWTs in a four-turbine array
- One meter between WHI’s Harvester 70 VAWTs in a four-turbine array
- Two rotor diameters (6m and 24m) between arrays in a row
- 5 times rotor height between Harvester 70 rows (70m)
- 8 times the rotor diameter between rows of 3kW VAWTs (24m)

Table 1. Comparing Densities of HAWTs to VAWTs

HAWTs	Turbine Size (kW)	Turbine Swept Area (m2)	Swept Area (m2) per sq. km	MWs per sq. km	Turbines per sq. km
NREL[27]	1000	2.289	9,156	4.0	4.0
6 x 7 Rule of Thumb [28]	1000	2,289	18,690	8.2	8.2
3 x 10 Rule of Thumb[29]	1000	2,289	26,167	11.4	11.4
Mountain. View Power Partner [30]	750	1,809	60,795	25.2	33.6
Shilo III, Solano, CA	2050	6,644	34,073	9.5	5.1
VAWTs					
4m x 3m rotor [31]	3	12	105,820	26	8,818
WHI Harvester 70[32] - 14m x 12m rotor on ~9m tower	70	168	124,444	52	741
Combined layers			230,265	78	9,559

The layouts in Figures 1, 2 and 3 would lead to ~150-200 MWs of VAWTS on the same land on which 32 MWs of HAWTs now operate in one of the best near-ground wind resources[33] in the San Gorgonio Pass. Dabiri's research on VAWTs predicts a 5-10 times increase in energy density is possible from VAWTs compared to HAWTs. This seems to be eminently doable with two layers of VAWTs set among the same MWs of HAWTs.

__Figure__ 2. The Mountain View Power Partner LLC wind farm at the junction of the Whitewater River and Interstate 10 (33° 54' 35.6" -116° 37' 44.4") in the San Gorgonio Pass has 44 750 kW HAWTs (33 MWs) in the ½-square mile outlined in yellow. Rows of Harvester 70 VAWTs are envisioned to be along red lines, each row roughly 70m apart. The blue square at the bottom right of the red rows shows the area of Figure 3, below.

In the Mountain View Power Partner LLC wind farm, the wind is unidirectional from the west. In Figure 3:

- A row of small VAWTs (3kW) maximizes the porous wind fence effect increasing the wind speed into the taller Harvester VAWTs a few meters downwind.
- The Harvester are a short distance (10-25m) downwind of a HAWT such that the bottom blade tips of the HAWT pass at just the right height above the VAWTs to safely maximize pressure difference the downwind VAWTs create.
- More rows and arrays of small- and medium-sized VAWTs are placed upwind and downwind at roughly a 7-rotor diameter distance apart.

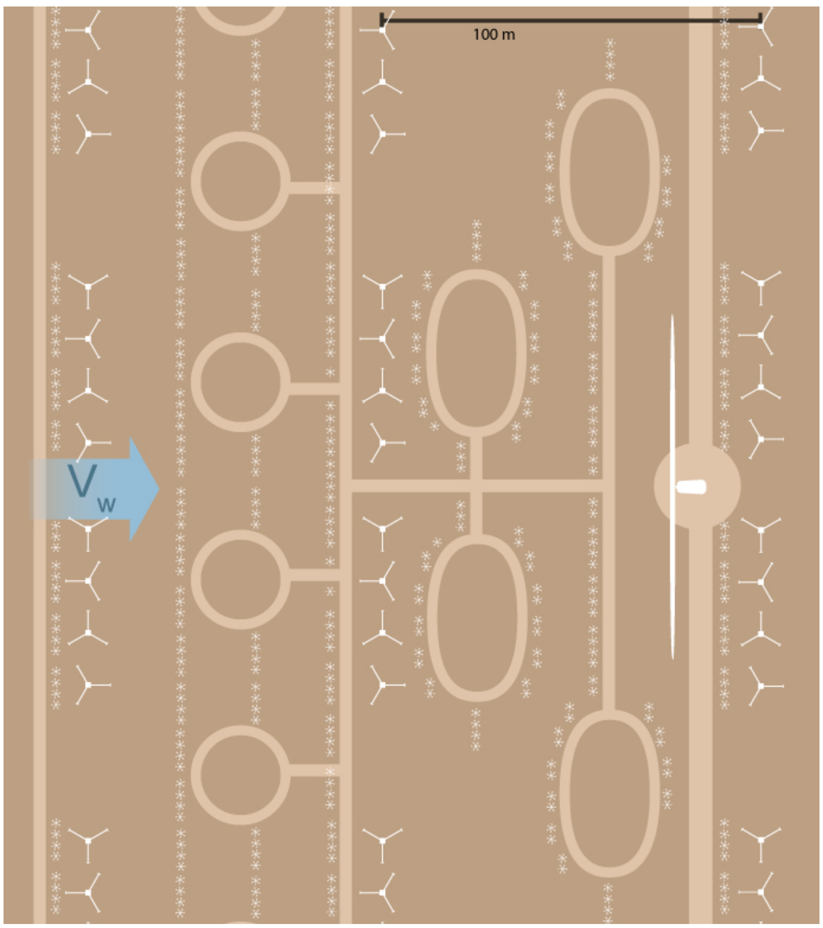

__Figure 3__ This 250 X 250 sq. meter slice of the Mountain View Power Partner wind farm in Figure 1 shows one way in which VAWTs of different heights could be placed around a newly installed 2 MW HAWT on a 65m tower. In this graphical representation, there are 428 of the 3kW VAWTs and 39 of the WHI's 70kW VAWTs and one 2 MW HAWT.

<u>Next Steps to Adding VAWT Layers to Wind Farms</u>

In the last round of wind energy grants through the CEC's EPIC Program, there were three applications to advance the development of VAWTs toward installation in existing wind farms. All three were either disqualified or failed to score enough points to qualify. The main objections from reviewers included the following misunderstandings:

- Near-ground wind resources won't be developed because wind shear causes the wind speed to be too low to ever be competitive with simply adding new wind farms of HAWTs.[34] *(Note: High wind shear occurs in wind farms in the Great Plains but not in California or other areas with passes and ridgelines).*
- VAWTs have such a terrible history of commercialization that grants should not be made for their development until after they have been certified.[35] *(Note: Grants should be available to help renewable energy technology get through the most difficult part of the commercialization process – certification.)*
- Funding should not be spent on how VAWTs can best be sited in a wind farm because R&D on HAWT placement is already commercialized.[36] *(Note: Very little is known about how VAWT wakes will interact with HAWT wakes in different topographies and wind conditions.)*

WHI's proposal to the EPIC Program called for the use of its Harvester 70 VAWTs in a 140-280 kW project on ranch land in the Solano Wind Resource Area. There, San Jose State University LiDAR and its transportable meteorological mast with sonic anemometers would have been used to collect wake data from the VAWT array. Modeling would have been done with the help of Stanford University's Large Eddy Simulation CFD model. WHI committed to placing the resulting data into the public domain, so other universities and companies could begin to validate their own modeling codes for VAWT wakes.

More field data on arrays of VAWTs is needed. LiDAR is the key to measuring the changes in wind speeds and turbulence created from different ways of linking together counter-rotating VAWTs. Then data will be needed on how those VAWT wakes interact with HAWT wakes. Given the capabilities of modern wake and topography modeling, it shouldn't take long to confirm basic "rules of thumb" for how vertical turbines can be safely and effectively installed along ridgelines and among the wind turbines in rich resource areas like the flat desert lands of the San Gorgonio Pass.

<u>Wildlife</u>

VAWTs will eventually enter the wind farm market. Before large numbers are installed, their potential impact on birds and bats needs to be evaluated and mitigated through the California Environmental Quality Act (CEQA) and other land use planning processes. Both Dabiri's and WHI's most recent EPIC proposals included new ways of documenting how birds and bats react to VAWTs. Biologists[37] theorize that these animals evolved to fly around three-dimensional objects, such as trees and VAWTs, and will have an easier time avoiding their blades than they do those of two-dimensional HAWTs. Producing field data to try to disprove this hypothesis is a fundamental first step.

VAWT development in existing wind farms reduces the pressure to develop new HAWT projects and their longer transmission lines in more pristine and wildlife rich areas.

The fastest way to produce bird and bat impact data would be for all 100+kW VAWT projects like the one WHI proposed to use 24/7 motion detection and recording systems with binocular, high-definition cameras. Such tools can be field validated and then relied upon to capture far more animal-turbine interactions than traditional field observation methods. In-field, mortality studies should accompany the camera data analysis to compare the two methodologies until the mortality studies are no longer needed to accurately count fatal interactions.

Given the potential for VAWTs to be safely installed in valuable wind resource lands containing endangered species' habitat, grant funding of VAWT wildlife research would be a wise investment. This is especially so if it helps commercialize the VAWTs

Benefits to Ratepayers and Slowing Climate Change

Installing thousands of megawatts of new VAWT capacity in existing wind farms with good near-ground wind resources promises to be of significant help to ratepayers and local economies, especially if some of the VAWT components can be manufactured near the new installations.

Layering VAWTs among HAWTs in high-value wind resources should result in a lower Levelized Cost of Energy than any other renewable energy option. In land with 40% Capacity Factors and after a 14% "learning curve" for price reductions in the technology, by 2025, the LCOE of VAWTs installed among HAWTs should drop to $.05 per kWh, which is less than the wind energy alternatives for places like California, where it is very difficult to permit new wind farms, and the alternatives are expensive offshore projects or installing new transmission lines to large projects in places like Wyoming.

According to Project Drawdown, the second-best way to meet carbon reduction goals is with on-shore wind development. Making double use of existing wind farm infrastructure to harvest the lower wind layers of some of the best wind resources in a region *should be a priority on the world's road map for achieving carbon and pollution-reduction goals while keeping ratepayer costs low*.

Summary

- Approximately 20% of the world's wind farms, including all in California, have good-to-excellent, but turbulent, near-ground wind resources that presently cannot be harvested by traditional horizontal axis wind turbines (HAWTs).

- Vertical axis wind turbines (VAWTs) can handle the turbulence, but it is only recently that VAWT designers have had available aeroelastic modeling similar to what HAWT engineers use to ensure 20-plus-year fatigue life in wind farm-strength winds.

- VAWTs may now use the coupled vortex effect which occurs when VAWTs are placed very close together in arrays, bringing their efficiencies to the levels of modern HAWTs.

- In large-scale installations in existing wind farms, VAWT projects will eventually achieve a lower cost per MW and MWh than new HAWT projects can realize, primarily because they are able to use land and infrastructure that has already been paid for.

- Wind farm capacities and energy densities can be dramatically increased with layers of VAWTs.

- The theory that VAWTs can enhance the energy output of HAWTs when placed around and beneath them needs more field testing and modeling before layers of VAWTs can be safely and effectively installed in existing wind farms.

- Human field observation, along with motion-detection technology, must be done before the hypotheses can be proven that birds and bats will avoid the three-dimensional VAWTs better than they do the blades of the two-dimensional HAWTs.

- Government agencies need to become aware of the value of topographically enhanced near-ground wind resources and the potential contribution VAWTs can make to developing these valuable renewable resources.

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Key Research Questions

1. Rows of VAWTs will enhance recovery of the mean wind speed above, but the turbulence fluctuations in the wind layer above will likely increase significantly[38].
    - How far above and downwind of a field of VAWTs do HAWTs have be so that the higher turbulence doesn't harm the lifetime of the HAWTs' blades and drive trains?
    - How problematic is the turbulence created by different types and placement patterns of VAWTs?
    - Does the shape of the VAWT blade tips matter to the turbulence that might impact HAWTs?

2. VAWTs and HAWTs layered in the densities of Figures 1, 2 and 3 could increase the ~650 MWs of wind turbines in the San Gorgonio Wind Resource Area to more than 3000 MWs and rotor-swept area by a similar percentage. Could this more-intense extraction of energy and lowering of the boundary layer have either positive or negative impacts for regional and even distant weather patterns and intensities?

3. Families of species often have similar attributes, behaviors and physiologies. How much field research needs to done before scientists can accurately predict whether a species that has never seen a VAWT will be able to avoid being hit by its rotating blades? For example, if research proved that vultures were able to consistently avoid arrays of VAWTs with carrion placed underneath, would studies

still be needed on whether condors in Chile were always able to avoid VAWT blades before VAWTs were allowed in condor habitat in the U.S. where the bird is an endangered species?

End Notes:

[1] In 2014, WHI conducted a cursory review of wind farms around the world to evaluate them for topographies and roughness that were conducive to creating good near-ground wind speeds. At that time, approximately 20-25% of wind farms had the topographies, wind shears and wind speeds that should produce 15-20 mph average annual wind speeds at 10-20m above ground level.

[2] The politics of zoning and permitting are influenced by concerns over views, habitat, aviation and wildlife impacts. There are many peer reviewed articles documenting this. Here is one that covers many of the issues - https://journal.gnest.org/sites/default/files/Submissions/932/932_published.pdf

[3] The large setback requirements needed by rows of HAWTs are well documented. New HAWTs cannot be installed within most existing wind farms without reducing the wind speeds or increasing the turbulence realized by their neighbors.

[4] The rotating blades of wind turbines create wake and turbulence in the wind in a similar way that a boat and its propeller create wake and waves in the water. The wake created by VAWTs is very different from the wake created by HAWTs. HAWTs with their blade tip speeds often exceeding 150 mph create circular wakes extending and mixing together long distances downwind..

[5] "Land-Use Requirements for Solar Power Plants in the United States" states that an average of 2.8 acres is required to produce 1 GWh of solar energy from ~550kW of solar panels. According to Southern California Edison, 1 kW of PV will produce 1500-1800kWh per year. In comparison, each kW of capacity from VAWTs like the WHI Harvester 70s will result in 3500 kWh per year. Four Harvester 70s (280kW) would produce 1 GWh on 1.3 acres (per Table 1) with farming, grazing and other activities possible beneath and around them, which is not possible in large commercial solar projects. Hardware, installation and project costs for VAWTs are expected to drop over time at similar rates as prices dropped for HAWTs. For more discussion on this, see Benefits to Ratepayers. In addition, wind in places like California's wind resource areas blow well into the night reducing the intermittent energy supply limitations associated with photovoltaic projects.

[6] Almost all the data used to produce the "*Wind Atlas*" published by the CEC in April 1985 was derived from reports written in part by some of the consultants below from 1980-1984 who collected and found near-ground wind data, most often at 30' above ground level. For example, it shows seven sites in the Altamont Wind Resource Area have average annual wind speeds varying between 15.4 – 19.7 mph and averaging close to 17 mph at 30' above ground level (agl). The Atlas also shows six sites in the Solano Wind Resource Area with wind speeds averaging ~15-18.5 mph at ~33' agl. One of the reasons for collecting near ground wind data in the 1970s and 1980s is shown on the inside back cover of 1983 CEC Report – *Wind Energy, Investing in our Future*. There is a photo of a DAF-Indal Darrieus-type VAWT with hub height of around 30' agl. At that time, VAWTs were expected to be major players in the future of wind energy production and data collection for potential wind farms was oriented to their hub heights.

[7] The following wind industry meteorologists and companies will confirm that there are good to excellent average annual speeds and high turbulence in the near-ground wind in California's Wind Resource Areas. Note that titles and associated organizations are used for identification purposes only:

Allen Becker, Consulting Meteorologist
John Bosche, President and Principal Engineer at ArcVera Renewables
Neil Kelley, Applied Meteorologist (retired)
Pep Moreno, CEO, Vortex
Ron Nierenberg, Consulting Meteorologist
Lucile Olszewski, General Manager, Ensemble Wind
Richard Simon, Consulting Meteorologist
John Wade, Senior Meteorologist, Ensemble Wind
ArcVera Renewables, Wind Prospecting and Resource Assessment
WindSim, CFD Wind Resource Assessment

[8] Turbulence problems created in HAWT blades, gearboxes, and bearings HAWTs are documented in multiple places in this wind engineering textbook, "Wind Energy Explained: Theory, Design and Application," J.F. Manwell, J.G. McGowan, A.l. Rogers; John Wiley, U of Mass Amherst, 2002.

[9] David Malcolm, PhD, structural engineer, retired from Det Norske Veritas/Gemanischer Lloyd

[10] WHI's Harvester VAWTs have ~170 square meters of rotor swept area and 50-100kW+ generators, which vary based on the wind resource. For specifications see: http://windharvest.com/harvester-vawt/

[11] WHI's Harvester 70 design files have been sent to the Small Wind Certification Council, which follows the IEC 61400-2 certification requirements for small wind turbines under 100kW in size.

[12] WHI used a Frequency Response and Fatigue Model first created and validated by Sandia National Labs on its Darrieus-type VAWTs. Using strain gauge data from the Harvester 70 prototype in Denmark, WHI validated the loads predicted in its Midas FEA model and these other two models.

[13] "Modeling Blade Pitch and Solidity in Straight Bladed VAWTs", Iopara Inc, Bob Thomas and Kevin Wolf, February 12,2012, Final Report to the California Energy Commission's Energy Innovations Small Grant Program.

[14] Sandia National Labs' field research on a Darrieus-type VAWT showed it was capable of achieving a maximum of a 45% efficiency or Cp max. See "A Retrospective of VAWT Technology", Herbert J. Sutherland, Dale E. Berg, and Thomas D. Ashwill, SANDIA REPORT (SAND2012-0304), January 2012 and "The Sandia Legacy VAWT Research Program."

[15] WHI's Harvester VAWTS are made of extruded, aircraft quality (6061-T6) aluminum. Bob Thomas, a founder of the Wind Harvest Company and the inventor and lead engineer of their Windstar turbines determined that a NACA 0018 blade profile to be effective and easy to extrude with internal walls.

[16] HAWT towers not only use more material because they are taller but they have to be strengthened further to handle the oscillations that come from their offset rotors. VAWT blades rotating evenly around the top of its tower (discussion with Herb Sutherland, retired Sandia National Laboratory engineer who worked on the mechanical aspects of wind turbines.

[17] http://www.conteches.com/Markets/Wind-Turbine-Foundations/Anchor-Deep-Foundation

[18] For a full build-out of a wind farm's understory, new transmission lines and substations will be needed. For a "capacity factor enhancement" project where VAWTs are added to the wind farm but are turned off as the substation reaches capacity, no new transmission lines or substations are needed.

[19] "Reactive Power Compensation - Using a Northern Power® NPS 100TM or NPS 60TM wind turbine to manage power factor", NPS Engineering Bulletin

[20] In Dr. Marius Paraschiviou's letter to the CEC in support of WHI's grant application, he stated "…after the CEC Innovations grant was completed, we conducted additional aerodynamic modeling on downwind wakes that showed VAWTs like WHI's Harvesters will be able to be placed about six rotor heights downwind of an upwind VAWT array and realize the full wind speed that entered the rotors of the upwind array."

[21] A number of Dr. John O. Dabiri's papers show that VAWTs when placed as in their field studies can regenerate ~95% of the full wind speed at 7 rotor diameters downwind. (Kinzel M, Mulligan Q, Dabiri J., Energy exchange in an array of vertical-axis wind turbines. *Journal of Turbulence* 2012; 13: 1–13). Note that in his field studies, Dabiri's placement of VAWTs are as close together as they are in Paraschivoiu's modeling. The tighter spacing and the resulting increase in wind speed in the gaps between the VAWTs that were used in Paraschivoiu's modeling probably is the reason for the difference

[22] "Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays". John O. Dabiri, *Journal of Renewable and Sustainable Energy* 3, 043104 (2011) and Benefits of Co-locating Vertical-Axis and Horizontal-Axis Wind Turbines in Large Wind Farms.

[23] The energy in the wind is the cube of the wind speed so a small increase in wind speed results in a significant increase in the energy available for the turbine to convert to electricity.

[24] "Low order physical models of vertical axis wind turbines", Anna E. Craig[1,a)], John O. Dabiri[2], *and* Jeffrey R. Koseff[3], *Journal of Renewable and Sustainable Energy, Feb. 2017*

[25] Page 15, "Benefits of collocating vertical-axis and horizontal-axis wind turbines in large wind farms" Shengbai Xie, Cristina L. Archer, Niranjan Ghaisas and Charles Meneveau, *Wind Energy*, 2016

[26] See footnotes 11 and 12.

[27] "Land-use Requirements for Wind Turbines in the U.S.", Paul Denholm, Maureen Hand, Magdalena Jackson, and Sean Ong, NREL, August 2009. Note that NREL's study covers "Total Wind Plant Area" which is considered the "footprint of the project as a whole" and includes more land than the Rule of Thumb methods of determining land use per MW of wind turbines.

[28] Six rotor diameters between turbines in a row and 7 rotor diameters between rows.

[29] Three rotor diameters between turbines in row and 10 rotor diameters between rows.

[30] Satellite imagery of the 750kW NEG Micon turbines. Mountain View Power Partners LLC, Riverside County, California. *Note that this specific location might not be appropriate for many more VAWTs because of their roughness impact on flood events from the Whitewater River. A hydrological modeling analysis would be needed before CEQA requirements could be met.*

[31] Assumes four VAWTs in a 13m long array with two rotor diameters between each 12kW array in a row.

[32] The blade tips of and vortices shed from the VAWTs create turbulence, vertical mixing and roughness should bring faster-moving wind into the taller Harvester 70 arrays. An array of the 9m tall VAWTs only meters upwind of Harvester VAWTs on 8-10m tall towers would create a blockage effect, and if positioned

correctly send more into the VAWTs above and downwind. Together, the field of VAWTs could have a greater positive impact on the wind speed increases realized by the HAWTs.

[33] WHI operated its Windstar 1066 and a Windstar 530 VAWTs in this section of the San Gorgonio Pass for years and recorded average annual wind speeds of 16mph at 10m above ground level.

[34] Jocelyn Brown Saracino, Wind Energy Manager with the US DOE in her critique of WHI's grant proposal states, "(WHI's) proposal suggests that VAWTs might be used as an understory below HAWTs and suggests that the primary driver for the height of HAWTs is that near-ground wind is too turbulent. Wind resource is much greater at height and this calls into question the resource potential for VAWTs deployed in this fashion."

[35] In Jocelyn Brown Saracino's comments on WHI's CEC EPIC proposal, which were similar to her critique of Dabiri's proposal, she stated "To date no VAWT has received certification in the US due to technical challenges associated with their performance (energy production on average lower than predicted and also due to issues associated with reliability and maintenance). I do not recommend providing funding for VAWT turbine installation until after certification has been obtained"

[36] The Technical Review of WHI's proposal disqualified it because "In the questions and answers for the solicitation, answer #30 states that "Projects focused mainly on siting or optimally locating wind turbine including wind pattern modeling, are outside of this solicitation."

[37] The author has talked with numerous ornithologists who hypothesize that birds, especially many birds of prey, will see and avoid the shorter, vertically rotating turbines. Hawks, raptors, vultures and similar soaring and hunting birds have their eyes focused close to the earth, often in the 10m zone above the ground. Above that they haven't evolved the need to see the fast moving, two dimensional HAWT blades. Because VAWTs have horizontal arms with wide fairings that attach to their vertically aligned blades and because they are close to the ground, these birds should easily see VAWTs as obstacles similar to trees but on which they cannot land because the "branches" are moving.

[38] Communication with Dr. John Dabiri.