ATTACHMENT 12
Costs and Benefits Calculations

Predicted Costs and Benefits for VAWTs installed in Wind Farm understories

Wind Harvest International's proposal to the CEC's EPIC Program 2016-00_GFO-16-301

The three major factors leading to a projected lower Levelized Cost of Energy (LCOE) for VAWT created wind energy in CA than the alternatives are:

- They make double use of existing wind farm assets
- They can be installed in high energy land where HAWTs can't
- They can achieve the efficiencies of horizontal axis wind turbines (HAWTs)

The LCOE Table below varies only these three factors when comparing VAWTs in existing wind farms to the other options.

IOPARA's modeling of VAWTs using Coupled Vortex Effect predicts that VAWTs will realize the close to the 50% efficiencies achieved by the best HAWTs[1]. One of the outcomes of the proposed research will be to field test this prediction with arrays of WHI's G168 VAWTs. Though WHI only predicts its G168 VAWT will achieve a 30% Capacity Factor (CF) in a 15.7 mph (7m/s) wind resource when operating alone, it should realize a 35.4% CF when operated as closely spaced pairs of VAWTS in the Coupled Vortex position. With better aspect ratios, Reynolds numbers and fairings, VAWTs should achieve the higher efficiencies predicted by IOPARA's modeling[2].

The LCOE prediction assumes that over the next five years, as major wind turbine developers enter the VAWT market[3], the costs and efficiencies of the technology will continually improve and eventually achieve those of modern HAWTs.

The instant and installed costs to take a project from an idea to operations (installed or instant costs) can have the biggest impact on the LCOE. For a traditional wind farm, the cost of the HAWTs nacelle (41%), rotor (17%) and tower (13%), consume the highest percentages of the investment[4]. Understory VAWTs promise to come in at lower costs than HAWTs in the years to come for the following reasons:

1. While the four 70kW VAWTs in this research proposal will have Cost of Goods Sold plus a 17% margin equaling $3.40 per W ($240,000 each), the manufacturer Patriot Modular has quotes for an order of 100 that reduces this by

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[1] M. Paraschivoiu, C. X. Zhang, S. Jeyatharsana, N. V. Dy, F. Saeed, R. N. Thomas and I. Paraschivoiu, "CFD Analysis of Vertical Axis Wind Turbines in Close Proximity," October 2010.

[2] Personal communication Dr. David Malcolm, formerly a senior engineer with Det Norske Veritas

[3] This research project will make publicly available the date that could prove VAWTs can be safely installed under HAWTs thus validating the large market that exists in CA and around the world.

[4] C Moné, T Stehly, B Maples, and E Settle, 2014 Cost of Wind Energy Review, NREL

25% with some “learning curve” improvements already identified.[5] Using this $2550/kW as a base and then applying the 14.4% “learning curve” for HAWTs,[6], then VAWTs would be selling for an average $1172/kW in 2021. This should be close to the HAWT price in 2021 given that mature technologies like HAWTs have a much lower learning curve than new technology.[7]

2. The towers of short VAWTs under HAWTs will cost significantly less than the 13% of the project costs that HAWT towers create. The VAWT tower for the G168 VAWTs used in this research project cost $11,000,[8] which is less than half the percent of project cost of a HAWT tower.

3. VAWT blades can be mass manufactured using pultrusion or extrusion techniques for fiberglass or aluminum because the blades are symmetrical across their entire length. HAWT blades are hand made and thus are more expensive than blades that can be made by machines running 24/7.

4. Shipments of understory VAWTs with their shorter blades can be made in standard land sea containers and don’t have to use the expensive transportation logistics needed for HAWT blades and towers.

5. Understory VAWT installation doesn’t require the tall, expensive cranes needed for HAWTs, nor does it need the highly skilled labor force.

6. Site access and staging costs of a HAWT project average 3% of total costs[9], and wont be needed in VAWT understory project as this infrastructure has already been paid for with the development of he original wind farm. The 2% cost of developing a site will likely be offset by the ~$40/kW cost of adding the DT Bird units to VAWT arrays. With proof that this technology keeps VAWTs from harming birds, the costs of permitting an understory should not raise a repower project’s development cost.

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[5] Report to WHI from Adam Kreft, Patriot Modular, June 2016

[6] We use the 1982-2004 period 14.4% learning curve because this better matches the early years of VAWT commercialization to HAWTs. Wind Technologies Market Report, LBNL, Ryan Wiser, Mark Bollinger pp. 35

[7] The HAWT learning curve in recent years has dropped from the 14.4% of 1982 to 2004. Now the 1982-2014 learn curve averagies 6.7%. According to the LBNL Market Report, HAWTs average $1221/kW in 2015.

[8] Report to WHI from Patriot Modular, June 2016

[9] 2014 Cost of Wind Energy Review, NREL pp

7. Electrical costs average 9%[10] of a greenfield project. A Capacity Factor Improvement project with enough VAWTs in the understory to allow problematic HAWTs to rest in high wind events without adding any new substation or transmission line capacity will increase the CF of a wind farm. This should save almost all of the costs of connecting a greenfield wind farm to the grid.

For the reasons stated above, WHI predicts that by 2021, the cost for VAWT understory builds and CF Improvement projects will be produce less expensive energy for ratepayers than can be realized by any other options for significantly increasing wind energy in the state.

A project's Capacity Factor has the second largest impact on the LCOE. Most of California's windiest and easy-to-access sites have been developed already. According to the 2014 CEC draft staff report entitled *Estimated Cost of New Renewable and Fossil Fuel Generation in California,* "The majority of the most consistent (Class 4 and 5) sites in California already have extensive development. Future development is most likely to occur at Class 3 sites." So while most new greenfield wind farms in the state will have average wind speeds of 14-15 mph at 50m above ground level (agl), there are thousands of MMs of existing wind farms with Class 6 and 7 winds and with topographies that lead to a lower or zero wind shear and thus Class 6 and 7 wind speeds at the hub heights of VAWTs beneath HAWTs. [11]

Not included in the preliminary LCOE calculations is the expectation that VAWTs will be able to realize a longer fatigue life than HAWTs. WHI's fatigue life analysis using strain gauge data from the G168 prototype and the Sandia National Lab's based LIFE modeling, predicts that the foundations, rotor, blades, drive shaft and tower should last 40+ years. Generators, bearings, brakes and other components would be periodically replaced at the same rate as for HAWTs, but the long life expectancy of the blades, rotor, drive shaft, and tower would increase their value to ratepayers.

Comparing the true LCOE of energy technologies is difficult, especially for renewable technologies where the "fuel" is free but the upfront CapEx costs and land development costs are high. To create a fair comparison between different future options of wind farm development in CA, the assumptions for the different scenarios used in NREL LCOE calculator were the same except for changes to the CF, the project and O&M costs across the different scenarios of HAWT greenfield projects, HAWT repower without VAWTs, VAWT / HAWT CF Improvement projects, and full a VAWT build out in a HAWT repower project.

[10] Ibid

[11] See Table in Attachment 4, Section

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Table 1 and 2: Projected LCOEs of HAWT and VAWT projects in CA in 2016 and 2021

HAWT Projects	Cost ($/kW)	O&M ($/kWh)	Capacit y Factor	LCOE ($/kWh)
Repower HAWTs 2016	$1,900	$0.020	40%	$0.063
Repower w/ VAWT Augmentation 2016	$1,900	$0.020	41%	$0.062
Greenfield HAWTs 2016	$2,000	$0.020	35%	$0.072
Greenfield w/ VAWT Augmentation 2016	$2,000	$0.020	36%	$0.070
Repower HAWTs 2021	$1,750	$0.018	41%	$0.058
Repower w/ VAWT Augmentation 2016	$1,750	$0.018	42%	$0.057
Greenfield HAWTs 2021	$1,850	$0.018	36%	$0.065
Greenfield w/ VAWT Augmentation 2016	$1,850	$0.018	37%	$0.064

VAWT Projects	Capital Cost ($/kW)	O&M ($/kWh)	Capacit y Factor	LCOE ($/kWh)
Repower w/ HAWTs 2016	$3,150	$0.015	40%	$0.082
Greenfield 2016	$3,350	$0.015	29%	$0.113
HAWT-VAWT C.F. 2016	$2,850	$0.015	40%	$0.077
Repower w/ HASTs 2021	$1,700	$0.014	41%	$0.053
Greenfield 2021	$1,800	$0.014	30%	$0.069
HAWT-VAWT C.F. 2021	$1,500	$0.014	41%	$0.049

Notes and assumptions:

1. The data was calibrated so that the LCOE of a HAWT greenfield project in 2016 and 2021 matched the LCOEs on the CEC's March 2016 slides on the Cost of Generation Model. This plus the cost of $1100/kW plus tax for a HAWT less project cost was the basis for the project costs.

2. Talking with experts led to different estimates of HAWT greenfield vs. repowering project costs. Small repowering projects seem to cost more per MW than large greenfield even though they don't require new land costs. But larger repowering projects should be less expensive because of the less infrastructure investments needed in land acquisition, site access and grid connection.

3. O&M reflects the trend of lowering costs per kWh with the assumption that VAWT O&M will be 75% of HAWT costs and will also reduce at the same rate in the future.

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The higher 2 cents per kWh as use vs. the standard 1 cent in the NREL LCOE default because of comments from experts in the field and other reviews.[12]

4. The NREL Simple LCOE calculator[13] was used with no other changes made to its standard assumption but the above.

5. For HAWT wind speed augmentation from both the porous wind fence and/ or from planform kinetic flux, only a 1% increase in CF was used to show how the HAWT CF could increase with VAWTs beneath.

Greenhouse Gas Emission

There are three basic materials that go into the construction of a G168 VAWT: steel for the rotor, drive train and support tower; concrete for the foundation and aluminum for the blades. Based on the EPA's website, the following Greenhouse Gas Emissions can be estimated for a single turbine:

Material	**Total Weight in lbs**	**CO2 emissions (lbs)**
Steel [14]	26,000	104,000
Aluminum[15]	2400	7200
Concrete foundations[16]	50,000	50,000
Total	**78,400**	**161,200**

A MW of G168 VAWTs (14.3 turbines using the CVE will produce approximately 3,250,000 kWh per year in a 7.5m/s wind resource. At a conversion rate of 1.22 lbs. of

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[12] "Significantly, the two wind power projects for which Berkeley Lab has the most complete information showed annual operation costs averaging over $21 per MWh, about twice the $11 average employed by NREL. If a more reasonable estimate of the installed cost of capital is $88 per MWh and operating costs are $21 per MWh, we can estimate a reasonable LCOE for wind power near $109 per MWh rather than NREL's estimate of $72 — a more than 50 percent increase" (Giberson, 2013: p. 7).

[13] http://www.nrel.gov/analysis/tech_lcoe.html?print

[14] Solid Waste Management and Greenhouse Gases: A life cycle assessment of emissions and sinks, NREL, (www.epa.gov/climatechange/wycd/waste/downloads/chapter3.pdf

[15] Ibid

[16] "Producing a ton of cement requires 4.7 million BTU of energy, equivalent to about 400 pounds of coal, and generates nearly a ton of CO_2. http://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/

CO_2 per kWh produced from natural gas which is the fuel that wind energy most likely replaces in CA, it would take 0.57 years to offset the total amount of CO_2 produced in the making of a VAWT.

Predictions:
There are many reasons to anticipate that VAWTs will become part of the future of wind energy in CA to the benefit of ratepayers and the state's economy. Given the modeling and work done by Dabiri and Paraschivoiu, there are strong reasons to predict that only VAWTs wont harm HAWTs and will augment the wind speeds realized by their rotors.

We predict that as soon as WHI's G168 begins sales and the results are back from the CEC funded research, HAWT original equipment manufacturers will bring VAWTs into this large and potentially lucrative market. This will further drive down prices and increase VAWT efficiencies and CFs, all to the benefit of CA ratepayers.