ATTACHMENT 12
Costs and Benefits Calculations

1. Levelized Cost of Energy (LCOE)

The major reasons why the research and development in this grant proposal can lead to a projected lower Levelized Cost of Energy (LCOE) for new VAWT wind farm capacity in CA are:

- The new VAWT capacity would be in existing wind farms near major regions of electrical demand.
- By being in existing wind farms, their projects make double use of existing wind farm assets (e.g. roads, security, met masts, maintenance crews)
- VAWTs can achieve the energy efficiencies and the combined manufacturing, assembly and installation costs of HAWTs especially when HAWT manufacturers start making VAWTs
- VAWTs can increase the energy output of HAWTs with strategic placement

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

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[1]. 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 25% with some "learning curve" improvements already identified.[2] Using this 100 turbine order of $2550/kW as a base price and then applying the 10% "learning curve", less than the 14.4% that HAWTs achieved in their early years of development,[3], then VAWTs would be selling for an average $1100/kW in 2028. This should be close to the HAWT price is expected to be then and recognizes that mature technologies like HAWTs have a much lower cost reduction curve than new technology.[4]

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

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

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

[3] The 1982-2004 period for HAWTS had a 14.4% learning curve. Wind Technologies Market Report, LBNL, Ryan Wiser, Mark Bollinger pp. 35

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

G168 VAWTs used in this research project cost $12,500,[5] which is about half the cost of a HAWT tower per MW installed.

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[6], 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.

7. Electrical costs average 9%[7] 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 2025, the cost for VAWT projects added into the understory of HAWTs will produce less expensive energy for ratepayers than can be realized by any HAWT alone project

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 MWs of existing wind farms with Class 6 and 7 winds and with

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[5] Report to WHI from Patriot Modular, June 2016. No price reduction for future costs reductions when mass manufactured.
[6] 2014 Cost of Wind Energy Review, NREL pp
[7] Ibid

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. [8]

The average CF for a CA wind farm was 25%[9] according to the most recent report. New wind farms on wind speeds at hub height of 18+ mph are achieving 40% CFs while sites with very old turbines have been lowering the state average. For the purpose of this exercise, high CFs are assumed for HAWTs and more moderate CFs for new wind farm developments for both HAWTs and VAWTs.

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[10] 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.

HAWT Projects	Cost ($/kW)	O&M ($/kWh)	Capacity Factor	LCOE ($/kWh)
Repower HAWTs 2016	$1,900	$0.02	40%	$0.06
Repower w/ VAWTs 2016	$1,900	$0.02	41%	$0.062
Greenfield HAWTs 2016	$2,000	$0.02	30%	$0.075
Greenfield w/ VAWTs 2016	$2,000	$0.02	32%	$0.070
Repower HAWTs 2021	$1,750	$0.02	41%	$0.058
Repower w/ VAWTs 2016	$1,750	$0.02	42%	$0.057
Greenfield HAWTs 2025	$1,850	$0.02	30%	$0.070
Greenfield w/ VAWTs 2025	$1,850	$0.02	32%	$0.064

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[8] See Table in Attachment 4, Section

[9] "Estimated Cost of New Renewable and Fossil Generation in California", Draft Staff Report to the CEC, May 2014 "5,900 MW of wind farms in CA, spread among 130 generation projects. These projects generated about 13,000 gigawatt-hours (GWh)" (which results in a CF of 25%)

[10] http://windharvest.com/library/whi-g168-vawt/

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VAWT Projects	Capital Cost ($/kW)	O&M ($/kWh)	Capacity Factor	LCOE ($/kWh)
Repower w/ HAWTs 2016	$3,150	$0.02	40%	$0.08
Greenfield 2016	$3,350	$0.02	29%	$0.11
HAWT-VAWT C.F. 2016	$2,850	$0.02	40%	$0.08
Repower w/ HAWTs and VAWTs 2025	$1,700	$0.01	41%	$0.05
Greenfield 2025	$1,800	$0.01	30%	$0.07
HAWT-VAWT C.F. 2025	$1,500	$0.01	41%	$0.05

Comparing the true LCOE of energy technologies is difficult, especially for renewable technologies where the “fuel” is free but the upfront Capital Expenditures (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.

Notes and assumptions on Table:

1. The data was calibrated so that the LCOE of a HAWT greenfield project in 2016 matched the LCOEs on the CEC’s March 2016 slides on the Cost of Generation Model. Total Capital Cost for a HAWT project was assumed to $1100/kW plus tax and average costs for shipping and installation and project development expenses.

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 projects 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% that of HAWT costs and will also reduce at the same rate in the future. The higher 2 cents per kWh as in O&M vs. the standard 1 cent in the NREL LCOE default is done based on what seems to be consensus by most experts.[11]

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[11] “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

4. The NREL Simple LCOE calculator[12] was used with no other changes made to its standard assumption but the above. The numbers in this table can be replicated there.

5. For HAWT wind speed augmentation from both the porous wind fence and/ or from planform kinetic flux, a conservative 2% increase in CF was used to show how the HAWT CF could increase with VAWTs beneath.

Summary

The lowest cost projects that will be built out with VAWTs first. Capacity Factor Improvement Projects that require no new transmission lines, little or no new grading, and where the near ground wind resources are excellent will have the lowest LCOEs of around $0.05/kWh. These types of project should be profitable in a few years and would drive the early growth projected in the table in Section 3 below.

The price of VAWT alone projects will reach the prices of HAWT alone projects by 2025. They won't be a s profitable as VAWT – HAWT projects.

Every project that can add VAWTs into the understory will result in lower energy costs for ratepayers.

2. Energy Returned for Energy Invested

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 [13]	26,000	104,000
Aluminum[14]	2400	7200
Concrete foundations[15]	50,000	50,000
Total	**78,400**	**161,200**

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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).

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

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

[14] Ibid

[15] "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/

One MW of G168 VAWTs (14.3 turbines) using the CVE will produce approximately 2.7 GWh of electricity per year in a 7.0m/s wind resource. At a conversion rate of 1.22 lbs. of CO2 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 CO2 produced in the making of a VAWT. [16]

3. Greenhouse Gas Emission Avoidance

Each GWh of energy produced by new VAWT wind farms will not necessarily replace a fossil fuel source so the table below is inherently optimistic in terms CO2 avoidance. Other key assumptions in the table include:

- Average annual wind speed at VAWT hub height is 15.7 mph (7m/s)
- Turbine power performance – only as good as WHI's G168 VAWT
- A Capacity Factor increase of 1% (e.g. 30% to 31%) in existing HAWTs equalized to the MWs of VAWTs installed.
- Greenhouse gas avoidance at 771 tons per GWh of energy produced[17].
- Assume a doubling of wind energy produced by VAWTs in CA starting with 1 MW installed in 2020,
- Assume the doubling continues until 500 MWs are installed per year starting in 2029. Then assume at 105% increase per year until 2040 results in around 8600 MWs of VAWT capacity in the state.

Summary

- By 2025, around 63 MWs of VAWTs would be installed and would have produced171 GWhs of electricity and avoided 120,000 metric tons of CO2 emissions.
- By 2040, 150,000 GWhs of cumulative energy will have been produced with over 8000 MWs of capacity installed
- By 2040, over 100 million metric tons of CO2 could be avoided by VAWT wind farms installed in CA.

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[16]

[17] US Environmental Protection Agency. Clean Energy: Calculations and References https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (703 metric tons of CO2 per GWh of electricity produced)

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	Installed per year (MW)	Cumulative Installed (MW)	Energy added per Year (GWh)	Cumulative Energy (GWh)	Annual Avoided CO2 (metric tons)	Cumulative Avoided CO2 (metric tons)
2020	1	1	2.7	2.7	1,908	1,908
2021	2	3	5.4	11	3,816	7,633
2022	4	7	11	30	7,633	20,990
2023	8	15	22	71	15,265	49,612
2024	16	31	43	155	30,530	108,764
2025	32	63	87	326	61,061	228,977
2026	64	127	174	670	122,121	471,311
2027	128	255	347	1,363	244,242	957,888
2028	256	511	695	2,750	488,485	1,932,949
2029	512	1,023	1,390	5,526	976,969	3,884,979
2030	538	1,561	1,459	9,762	1,025,818	6,862,827
2031	564	2,125	1,532	15,530	1,077,108	10,917,783
2032	593	2,718	1,609	22,907	1,130,964	16,103,703
2033	622	3,340	1,689	31,973	1,187,512	22,477,135
2034	653	3,994	1,774	42,813	1,246,888	30,097,455
2035	686	4,680	1,862	55,515	1,309,232	39,027,007
2036	720	5,400	1,955	70,172	1,374,694	49,331,253
2037	756	6,157	2,053	86,883	1,443,428	61,078,927
2038	794	6,951	2,156	105,750	1,515,600	74,342,201
2039	834	7,785	2,264	126,880	1,591,380	89,196,854
2040	876	8,661	2,377	150,388	1,670,949	105,722,457

CO2 Avoided by CEC funded R&D project in Solano County:

Assumptions:

1. 280 kW, four turbine project
2. Starts operating in 2018 and continues to operate until 2040
3. Realizes and annual wind speed of 15.7 mph (7m/s) and 95% up time

Summary:

1. 12,288 metric tons of CO2 emissions avoided
2. 17.5 GWhs of energy produced