5 GW of Short Turbines Could be Added to the greater Solano Wind Resource Area (SWRA)[1]

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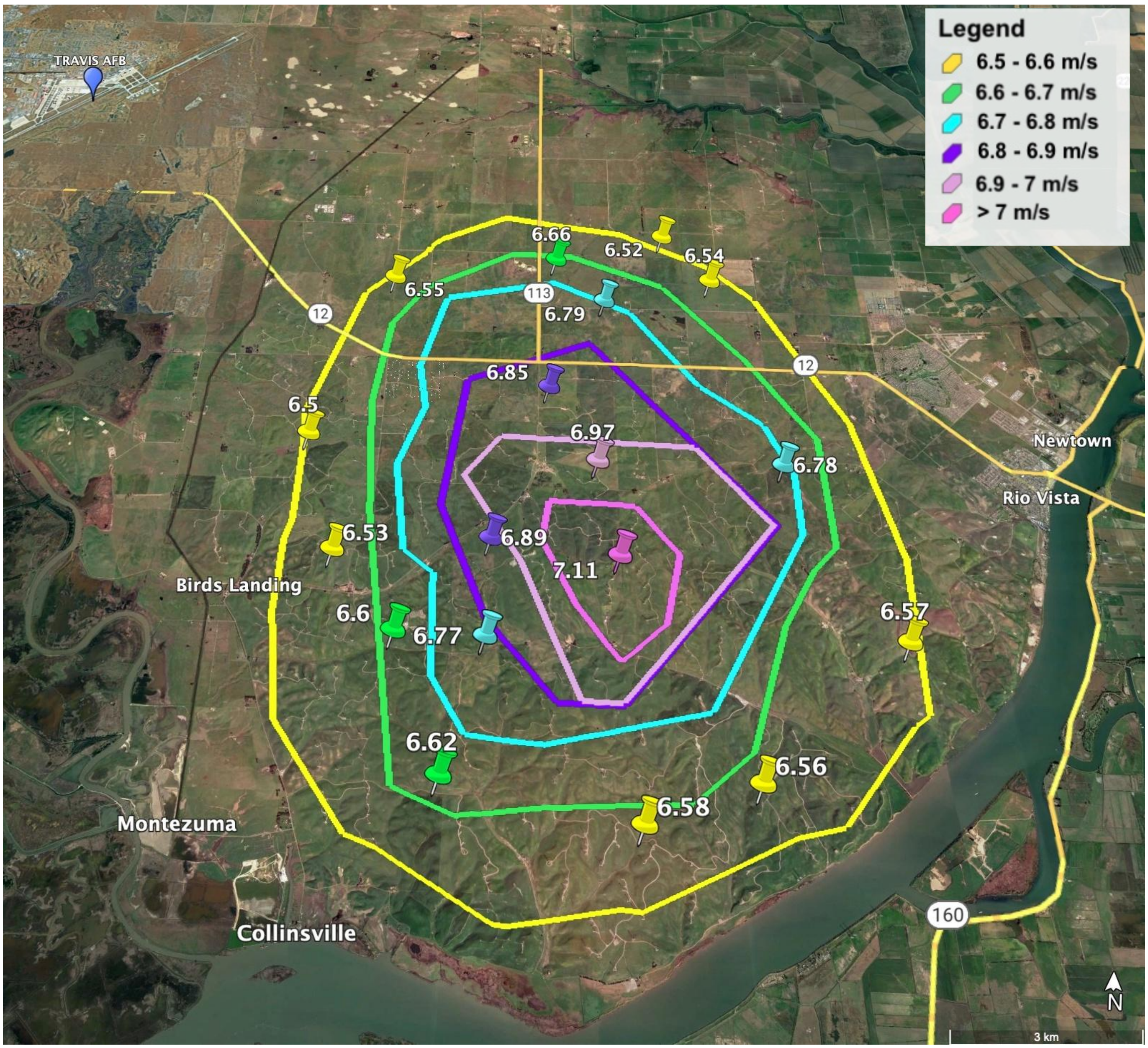


Image 1. Wind speed zones >6.5m/s (14.5mph) in the Solano Wind Resource Area at 66' (20m)

[1] Land in and outside of wind farms in Solano County, CA where the average annual wind speed exceeds 6.5m/s (14.5 mph) at 66' (20m) above ground level. See Methodology for more information.

Executive Summary and Background

The Solano Wind Resource Area is the second biggest in the state with over 1 GW of horizontal axis wind turbines (HAWTs) operating in its 13 wind farms. These turbines produce over 3000 GWh of renewable electricity each year but no more can be installed without changes in Solano County's zoning laws. This report shows that an **additional 5 GW and 13,500 GWh** can be produced in the windy parts of Solano County with short vertical axis wind turbines (VAWTs) and meet zoning laws.

In the winter, storms bring high-speed wind into the Wind Resource Area. But it is the temperature difference between the Pacific Ocean outside the Golden Gate Bridge and the heat in the Sacramento Valley in spring through fall that drive most of the wind that makes this area renowned for its excellent average annual wind speeds.

The actual boundaries and acreage of the SWRA are defined differently by different sources. The area inside the 6.5m/s (at 66' or 20m above ground level) boundary in the map on page one encompasses 38,000 acres. The wind farms south of Highway 12 use 35,000 acres.

The wind generation capacity of the SWRA would have increased but the County prohibits turbines taller than 100' (30m) from being installed north of Highway 12 and within six miles of Travis Air Force Base. Radar and flight patterns are impacted by nearby tall, two-dimensionally spinning rotors. The land south of Hwy 12 already has all the HAWTs that can fit. Adding more would create turbulence problems for their neighboring turbines. HAWTs are raised high above the ground and installed far apart from one another because wind turbulence creates too much wear and tear on their horizontally aligned bearings 200' above the ground.

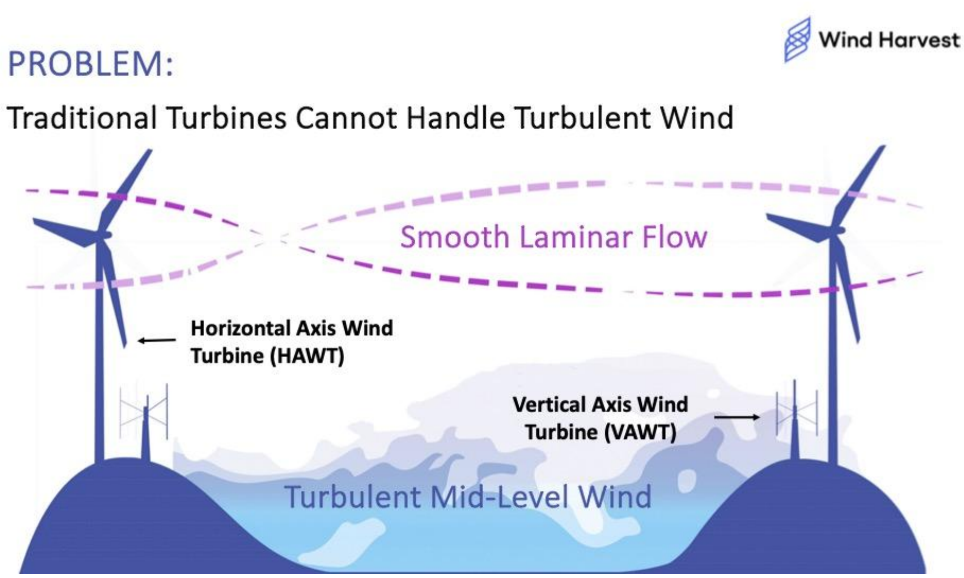


Image 2: Turbulence and Turbine Types[2]

[2] How VAWTs like *Wind Harvesters* operate in turbulent wind

The wind shear in southern Solano County is low which means wind speeds stay strong much closer to the ground. Physics and topography are the reasons why this and the other California Wind Resource Areas have excellent mid-level wind speeds. The colder ocean air funnels through the Carquinez Straits and then squeezes together *again* as it rises up and over the Montezuma Hills as it is pulled into the hot Sacramento Valley. The funneling of wind into a narrower area causes it to speed up[3].

Table 1. Total Capacity and GWh with HAWTs and VAWTs in the SRWA

	Capacity (GW)	Annual Energy Production (GWh/yr)
HAWT	1.02	3,827
VAWT	4.99	13,527
Combined Potential	**6.01**	**17,354**

Table 2. Existing HAWT Annual Energy Production (AEP) by Wind Speed in the SWRA

Wind speed		HAWT Existing	HAWT Existing
m/s	MPH	Capacity (GW)	AEP (GWh/yr)
7.5	16.8	0.01	32
7.75	17.4	0.79	2,925
8	17.9	0.22	870
Total		**1.02**	**3,827**

2.9 GW of H-type VAWTs Could be Added to Existing Wind Farms

On the same properties on which horizontal axis wind turbines (HAWTs) generate power, short H-type vertical axis wind turbines (VAWTs) can be installed in such a way that they don't cause turbulence that could harm the tall turbines under which they would operate. Because the HAWTs are spread far apart from one another to avoid the wake and gusts generated by their neighbors' blades, a great deal of open space is available below 100 feet above the ground. In this way, VAWTs can safely and effectively operate below rows of existing HAWTs adding energy capacity without sacrificing the capacity of HAWTs.

[3] Bernoulli's Principle

The windiest parts of the Resource Area are where wind funnels over the Montezuma Hills and speeds up. Since these hills are prone to erosion, this analysis assumes only 50% of HAWT capacity can be increased there with VAWTs operating underneath.

Still, much of the land in the Resource Area is flat. There, VAWTs could quadruple capacity. In total, an estimated 2.9 GWs of VAWTs could be added to the properties on which the HAWTs currently operate.

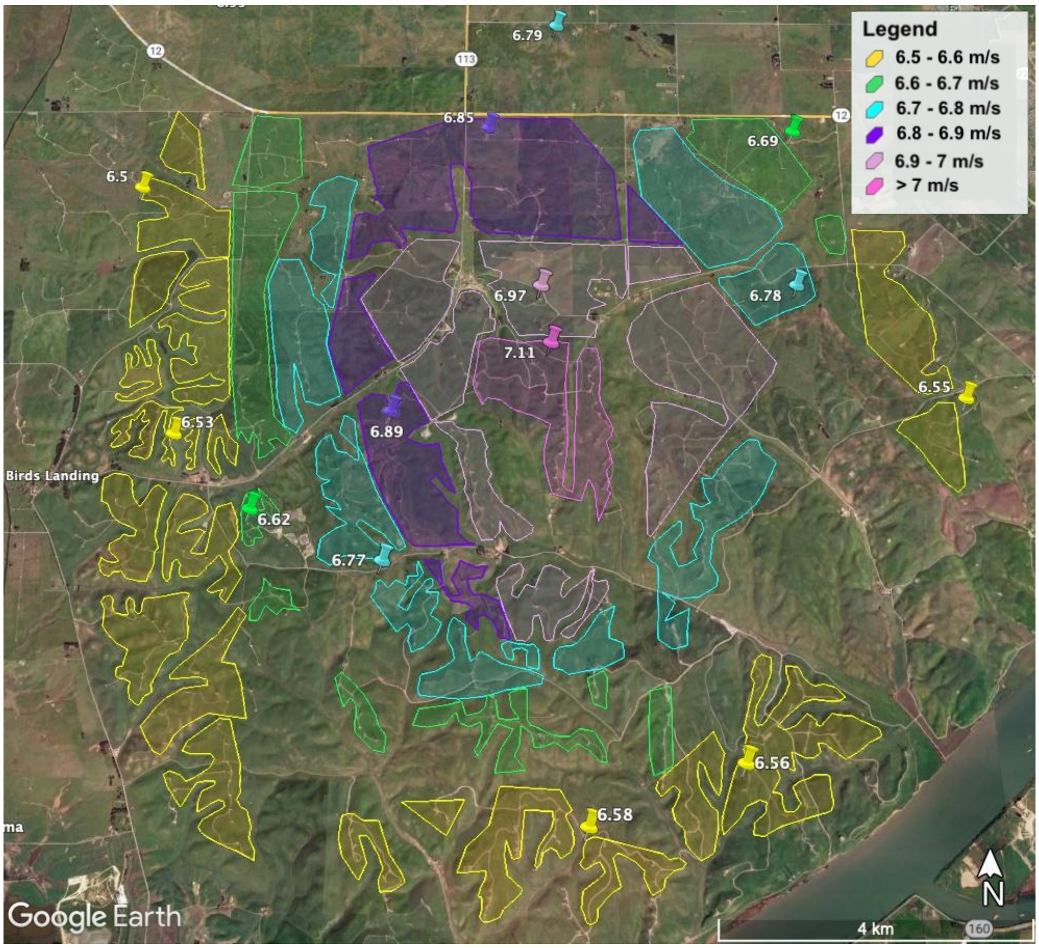


Image 3. Wind speed zones >6.5m/s (14.5 mph) in Existing Wind Farms, Solano Wind Resource Area at 66' (20m) above ground level

Based on the simple calculation of MWs over the almost 28,000 acres[4] (11,331 hectares) of wind farms in the Solano Wind Resource Area, the existing energy density of HAWTs is 9 W/m^2 or 0.036 MW per acre. This is a very high energy density given that research shows small wind farms can achieve 10 W/m^2 and most large wind farms only achieve 1 W/m^2. A validation of this density comes from the Shiloh II Wind Farm analysis. In this calculation, HAWTs have a capacity of 6W/m^2.[5]

[4] See the Appendix for a discussion on the density calculation of HAWTs in the wind resource area.
[5] Spatial constraints in large-scale expansion of wind power plants

The methodology used a conservative assumption that VAWTs are grouped in arrays of four, with 85’ (26m) gaps between each array to allow for bird and bat passage. This spacing would produce a density of 49W/m^2 or 0.2 MW per acre. If VAWTs were placed in arrays of seven rather than four, capacity density could be 57W/m^2 or 0.23 MW per acre. This would increase annual energy production by an additional 1,219 GWh.

The analysis shows that on average, VAWTs can increase the capacity in existing Solano wind farms from 1,021 MW to 3,970 MW. Energy production in terms of GWh per acre varies based on wind speed and type of technology. When VAWTs are placed close together and can utilize the “coupled vortex effect”[6], they can achieve the 45% or greater efficiencies that large HAWTs realize. This analysis assumes that HAWTs are 5% more efficient than VAWTs at the same wind speeds.

Table 3. Potential H-type VAWTs to Existing Wind Farms in the SWRA

Wind speed	Wind speed	VAWT Area		VAWT Potential Buildout	VAWT Potential Annual Energy Production
m/s	MPH	Hectares	Acres	(MW)	(GWh/yr)
6.5	14.5	1,620	4,004	801	2071
6.6	14.8	704	1,739	348	928
6.7	15.0	1,193	2,948	590	1622
6.8	15.4	975	2,410	482	1366
6.9	15.7	1,107	2,735	547	1596
7	16.8	369	911	182	547
Total		**5,968**	**14,747**	**2,949**	**8,129**

Because this land is already zoned for wind turbines, and access roads and security fences have already been installed, it should take less time and effort to secure a permit to install an understory of VAWTs into existing wind farms than it takes to develop new wind farms in the state. This is especially true for “capacity factor enhancement” projects which don’t require additional substations and transmission lines.

Based on the mid-level wind speeds in the resource area and the assumed annual energy production of VAWTs, a buildout of VAWTs under existing HAWTs would produce an additional **7,962 GWh** of electricity per year to the 3,827 GWh of electricity generated now.

[6] The Coupled Vortex Effect occurs when two H-type VAWTs are placed very close to each other. Blockage by the blades forces wind to around turbines. The diverted wind enters the gap and speeds up and also speeds up through the neighboring rotors.

Note: *Research*[7] *from Stanford, CalTech, and other universities predict that vertical mixing from understories of VAWTs will bring faster-moving wind into the rotors of the HAWTs in wind farms and increase their energy output by 10%. The additional expected output by HAWTs by adding VAWTs to wind farms was not included in this analysis.*

2 GW of H-type VAWTs Could be Added Outside of Existing Wind Farms

We found that areas outside of existing farms with average annual wind speeds greater than 6.5m/s at 66' (20m) above ground level could also hold **2.1 GWs of VAWTs**. Most of this additional area is north of Hwy 12 where zoning prevents turbines taller than 100' (30m) from being installed. VAWTs can easily stay under that height restriction.

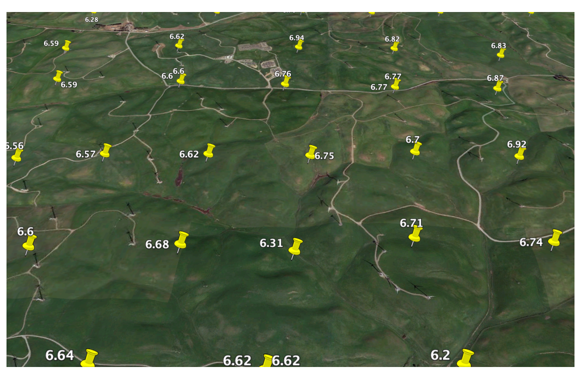
Based on the zones of mid-level wind speeds, the additional 2.1 GWs of VAWTs with the efficiencies of *Wind Harvester*s (see Appendix 2), would produce 5,398 GWh of electricity per year, enough to power over 770,000 California homes[8].

Table 4. VAWTs that Could be Added Outside of Existing Wind Farms

Wind speed		Area		Potential	Annual Energy
m/s	MPH	Hectares	Acres	Buildout (MW)	Production (MWh/yr)
6.5	14.5	2,118	5,235	1,047	2,707
6.6	14.8	1,073	2,652	530	1,416
6.7	15.0	903	2,232	446	1,228
6.8	15.4	34	84	17	47
Total		**4,129**	**10,202**	**2,040**	**5,398**

Methodology: How was VAWT density calculated?

1. Wind Harvest analyzed **66 feet** (20 meters) above ground wind speeds in the Solano Wind Resource Area using publicly available location information and predictions from UL Solution's Windnavigator. This image shows a subset[9] of the wind speed predictions at the proposed hub height of VAWTs.

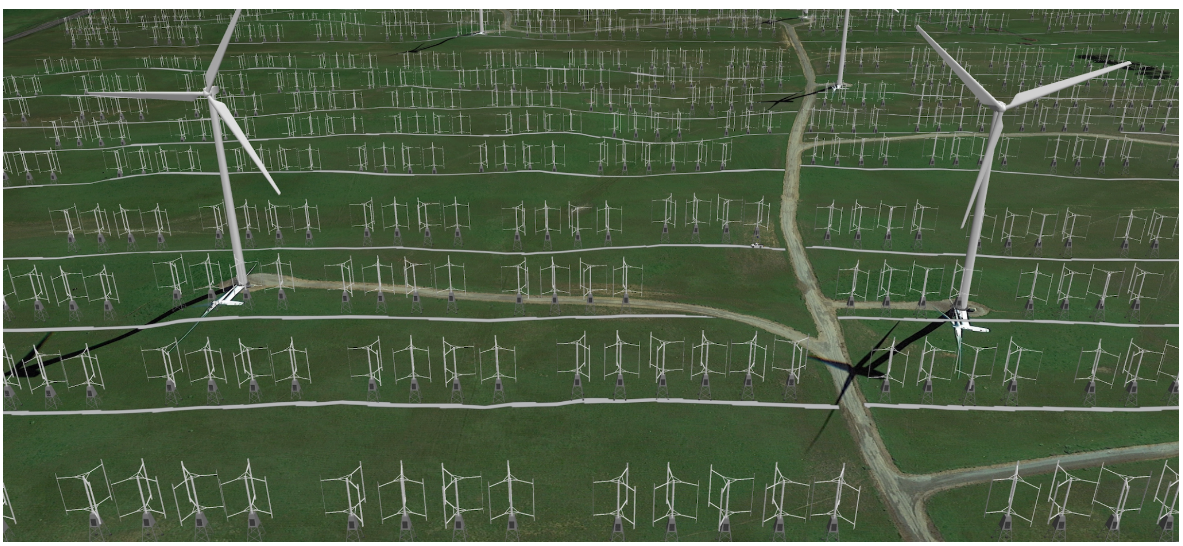


[7] Benefits of collocating vertical-axis and horizontal-axis wind turbines in large wind farms
[8] The average annual electric consumption per Californian household is ~7,000 kWh.
[9] For all the wind speeds included in this report, please contact us for the kmz file with all the wind speed pins.

2. The topography and existing infrastructure were analyzed using Google Earth to determine the feasible areas for H-type turbines within each wind speed area.

3. The potential VAWT buildout is calculated to be 49W/m^2 or 0.2 MWs per acre based on these factors:
   a. The distance between rows of H-type VAWTs is set at 5X their rotor height. For this analysis, 43' (13m) tall rotors were used. This scales so if the rotors were 66' (20m) tall, the rotor swept area of VAWTs per acre would be roughly the same.
   b. In a row of VAWTs, it is assumed that neighboring turbines are installed 3.3' (1m) apart from each other. Arrays of four VAWTs in a row are separated by an 85' (26m) gap to allow for bird passage if needed.[10]

4. This report assumes that VAWTs are only installed:
   i. 98' (30m) away from roads
   ii. 492' (150m) away from residences
   iii. 348; (100m) away from facilities and freeways
   iv. In areas with wind speeds greater than 6.5m/s (14.5mph) at 66' (20m) above ground level.



Recommendations

1. The California Energy Commission should immediately fund meteorologists who already have collected wind speed data to analyze and estimate how much acreage in the wind resource area exceeds 6.5m/s at 66' (20m) above ground level.

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[10] VAWTs are 3 dimensional with slower tip speeds than HAWTs. Ornithologists predict they will cause fewer impacts on birds and bats than the 2d HAWTs with tip speeds often over 67m/s (150 mph).

2. The CEC in conjunction with the wind industry should determine which wind farms would be best to install pilot projects. Topography matters. To accurately determine the best locations of VAWTs in the SWRA will require the use of LiDAR to collect wake data from strategically placed VAWT pilot projects and sophisticated modeling.

3. The DOE and CEC should fund the evaluation of how harvesting mid-level wind in the resource area could:
    a. Increase capacity factors from wind farms with and without new transmission lines.
    b. Extend the life of HAWTs under which the VAWTs are installed.
    c. How motion detection technology with VAWT pilot projects could speed up the environmental review of bird and bat impacts from large-scale installations.
    d. How much can fields of VAWTs increase the energy output of HAWTs when installed together.

4. The venture capitalist backed Flannery Group has bought 50,000 acres in the south county where it wants to build new “sustainable” cities. The wind resource under 100’ above the ground in this area could be used to help supplement the increased energy demand the new cities would create. Wind blows at night from April through September and would significantly reduce the land that would need to be covered with solar panels as well as the amount of battery storage. [11]

Conclusion

California and Solano County, its citizens, and businesses would benefit greatly from the buildout of even a small fraction of the 5GWs of mid-level wind energy in the Solano Wind Resource Area. New short VAWTs will soon be available to handle the turbulent, high-energy winds. When turbines are installed to tap the Wind Resource Area’s excellent mid-level wind speeds, more jobs, property and other taxes, and lower cost energy could soon benefit the region and the state. The size of the mid-level wind resource is so large, it could become a source of energy for green hydrogen production for Northern California.

[11] Solano County Diurnal Wind Speeds

Appendix

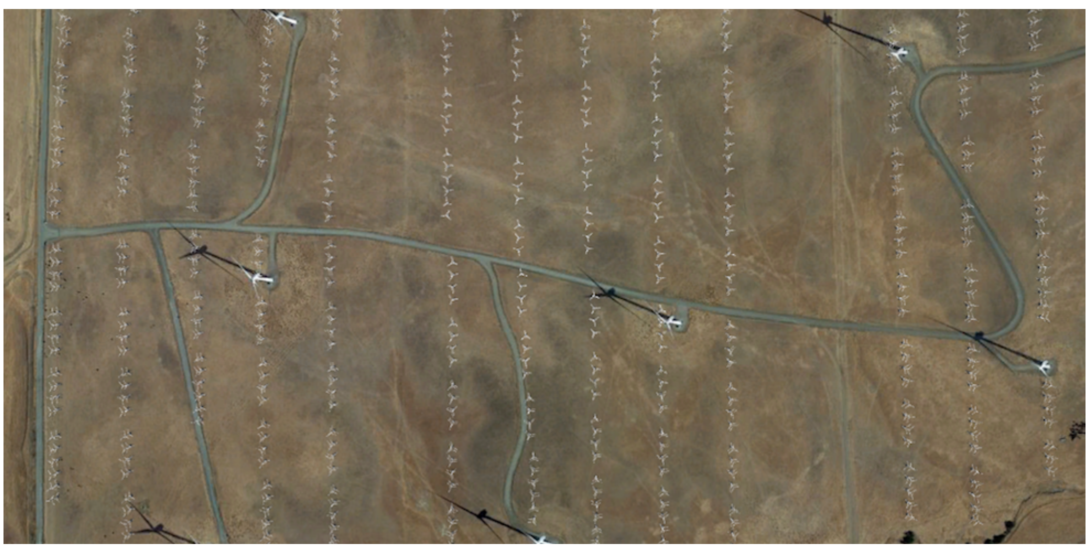
1. Estimating Wind Turbine Capacity Density

Sacramento Municipal Utility District's Solano 4 Wind Project[12] will have 92 MW of HAWTs over 2,271 acres of land in the Collinsville-Montezuma Hills area. This would result in a capacity density of 10W/m^2 or 0.04 MW/acre.

	Capacity Density	
	W/m^2	MW/acre
Existing HAWTs	6	0.03
Potential VAWTs	49	0.20
Potential Combined	55	0.23

The Shiloh II wind project is one of the largest wind farms in the Solano Wind Resource Area. It currently has 150 MWs of HAWTs on its 6,100 acres. This is a capacity density of 6W/m^2 or 0.025 MW per acre. An understory of VAWTs would increase this by 1205 MW for a total of 1355 MW. The density of VAWTs would be 49W/m^2 or 0.2 MW per acre for a combined project density of 55W/m^2 or 0.225 MW per acre.[13]

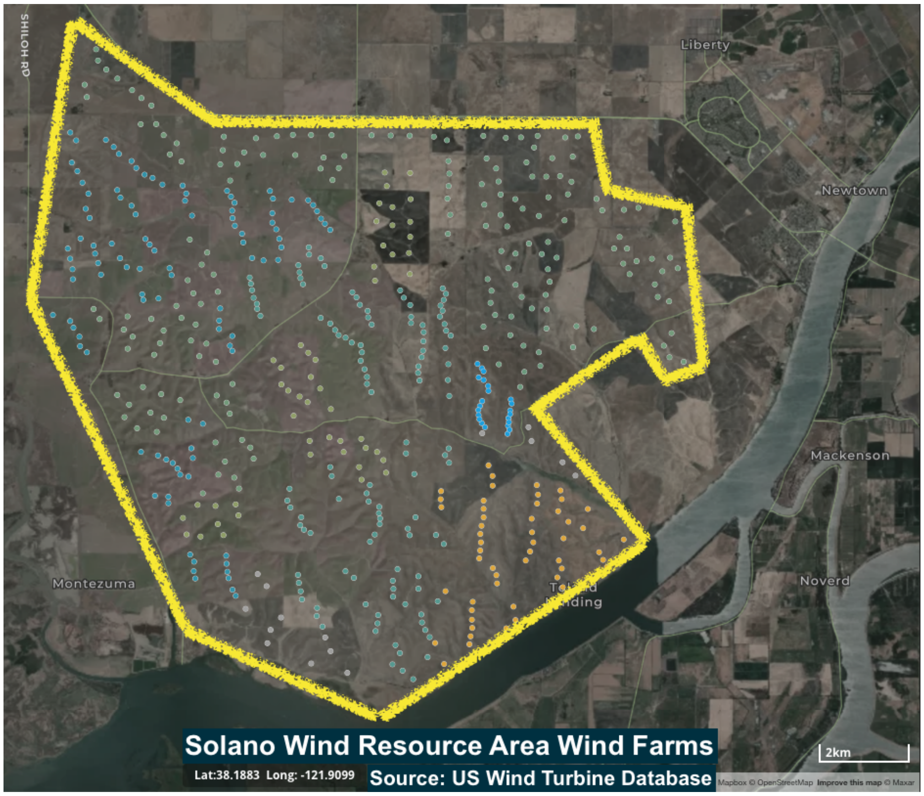
The image below shows a section of the Shiloh II Wind Farm with a potential buildout of VAWTs. The existing 2 MW HAWTs (75 REpower MM92 turbines) are seen between rows of VAWTs.



The distance between rows of VAWTs is five times their rotor height as modeling shows at this distance, wind speeds return to full strength and the wake from the VAWTs is gone[14]. In this analysis, 230' (70m) between rows was used.

For this analysis, we assumed VAWTs would be arranged in arrays of four to allow for bird and bat passage between each set of four. If we did 7 turbine arrays, the density would be 57W/m^2 or 0.23MW per acre. Total capacity potential of VAWTs in the entire wind resource area would increase from 5,000 MW to 5,400 MW.

[12] Solano 4 Wind Project
[13] Note that little land is lost to grazing by adding an understory of VAWTs to these wind farms.
[14] Dr. Marius Paraschivoiu, Concordia University



The existing wind farms in the Solano Wind Resource Area cover about 35,000 acres of land (pictured to the left, area outlined in yellow). For our analysis, we assumed that 28,000 acres of this total area could be categorized as actual wind farm land.

Holding a total of 1,021 MW of turbines, this area then has a capacity density of 9W/m^2 or 0.036 MW per acre.

2. H-type VAWT Annual Energy Production (AEP)

This table uses power performance data from the *Wind Harvester* Model 3.1 prototype at the UL Advanced Wind Turbine Testing Facility in Texas. It assumes a 15% increase in AEP because pairs of H-type VAWTs placed close together gain the benefit of the coupled vortex effect. All H-type VAWTs of this size when installed 3 feet apart should realize the same power performance and annual energy production.

Wind speed		Turbine	Per MW	Capacity
m/s	MPH	MWh/yr	MWh/yr	Factor
6.5	14.5	181	2,586	29.5%
6.6	14.8	187	2,669	30.5%
6.7	15.0	193	2,751	31.4%
6.8	15.2	198	2,834	32.4%
6.9	15.4	204	2,917	33.3%
7.0	15.7	210	3,000	34.2%
7.5	16.8	235	3,357	38.3%

3. *Wind Harvester* Sized VAWT - Theoretical Density Calculation[15]

Generator size	0.07	MW	70	kW	
Rotor diameter	13	meters	43	feet	
Rotor height	13	meters	43	feet	
Rotor Swept Area	169	m2	554	ft2	0.41 kW per m2 or 0.13 kW per ft2
Center of Rotor	20	meters	66	feet	Above ground level
Distance between turbines in array	1	meter	3.28	feet	
Length of array	55	meters	180	feet	4 H-type VAWTs each 43’ (13m) wide with 3’ (1m) between turbines
Distance between arrays in row	26	meters	85	feet	The space between arrays assumes that it is needed for bird passage. The gap between arrays is 2 turbines wide.
Distance between rows	70	meters	230	feet	Rows of VAWTs can be installed as close as 5X the rotor height and realize the same wind speed as the upwind row.
Theoretical density assumption	49	W/m^2	15	W/ft2	Estimated average VAWT capacity by surface area, which may vary ± 25% based on terrain.
	0.08	MW/hectare	0.2	MW/acre	

[15] Density of VAWTs scales. For example, a VAWT with a 2x rotor height would have half the number of rows.