California North Coast Offshore Wind

Transmission Alternatives

Schatz Energy Research Center

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Schatz Energy Research Center
Cal Poly Humboldt
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Offshore Wind Research for CA's North Coast

Project Sponsor

Bureau of Ocean Energy Management

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Schatz Center Team Members

Team lead: Arne Jacobson; **Project manager**: Jim Zoellick; **Team members**: Zach Alva*, Charles Chamberlin, Greg Chapman, Ian Guerrero, Andrew Harris, Amin Younes*

*participated as student researchers

Partners

Motivation for Analysis

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1. **Large Wind Resource:** The California north coast offshore wind resource is very large and has great potential to contribute to California's climate and clean energy goals.
2. **Limited Transmission:** Transmission capacity is a barrier for developing offshore wind at scale on California's north coast. Substantial investment in transmission upgrades is needed to develop a large-scale project. Development of transmission capacity will take time.
3. **Objective of Current Analysis**: Identify options for developing offshore wind ***within the bounds of existing regional transmission infrastructure*** (or with modest investment in transmission upgrades). Assess the economics (costs and revenue) of initial project options.

Overview of Key Findings

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1. **Cost for transmission upgrades**: In cases where the wind farm size exceeds the available transmission line capacity, the cost of transmission upgrades is significant.
2. **Possible initial project**: A small commercial offshore wind farm could be developed in the Humboldt Wind Energy Area (e.g., 140 – 170 MW) without upgrading existing transmission infrastructure if modest curtailment is accepted.
3. **Sizing an initial project:** To maximize revenue, the ideal wind farm size may be ~140-150 MW. This result is sensitive to the size of the regional electric load.
4. **Wind farm economics:** The economics of developing a small commercial offshore wind farm in the Humboldt Wind Energy Area are challenging, especially in the absence of federal tax incentives (PTC or ITC).
5. **Potential for integrating storage:** Adding storage to an offshore wind farm in the Humboldt Wind Energy Area can improve project economics.
6. **Potential for hydrogen generation:** Hydrogen generation from curtailed and low-cost power is potentially viable for some local applications.

Enormous Wind Resource

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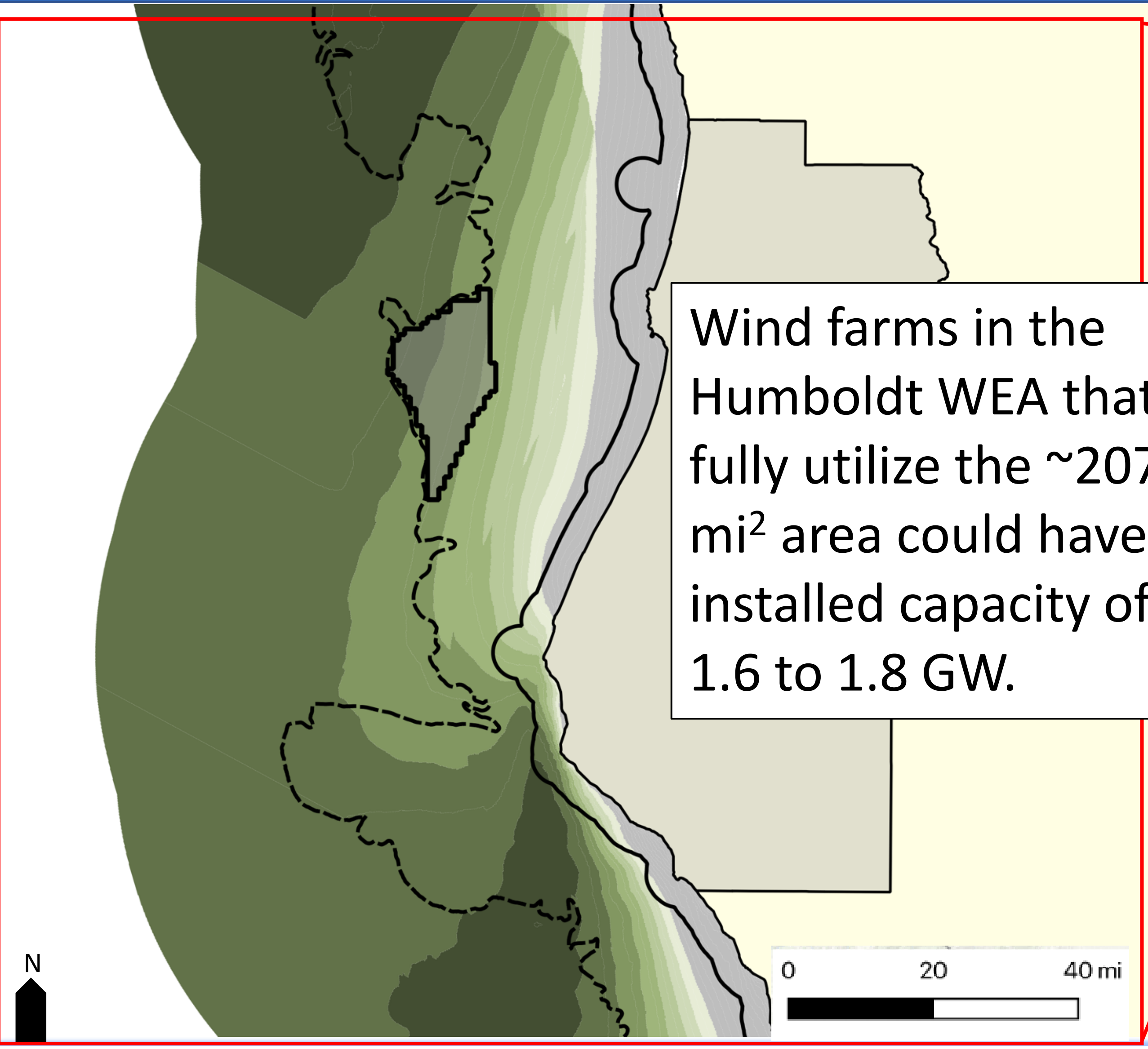
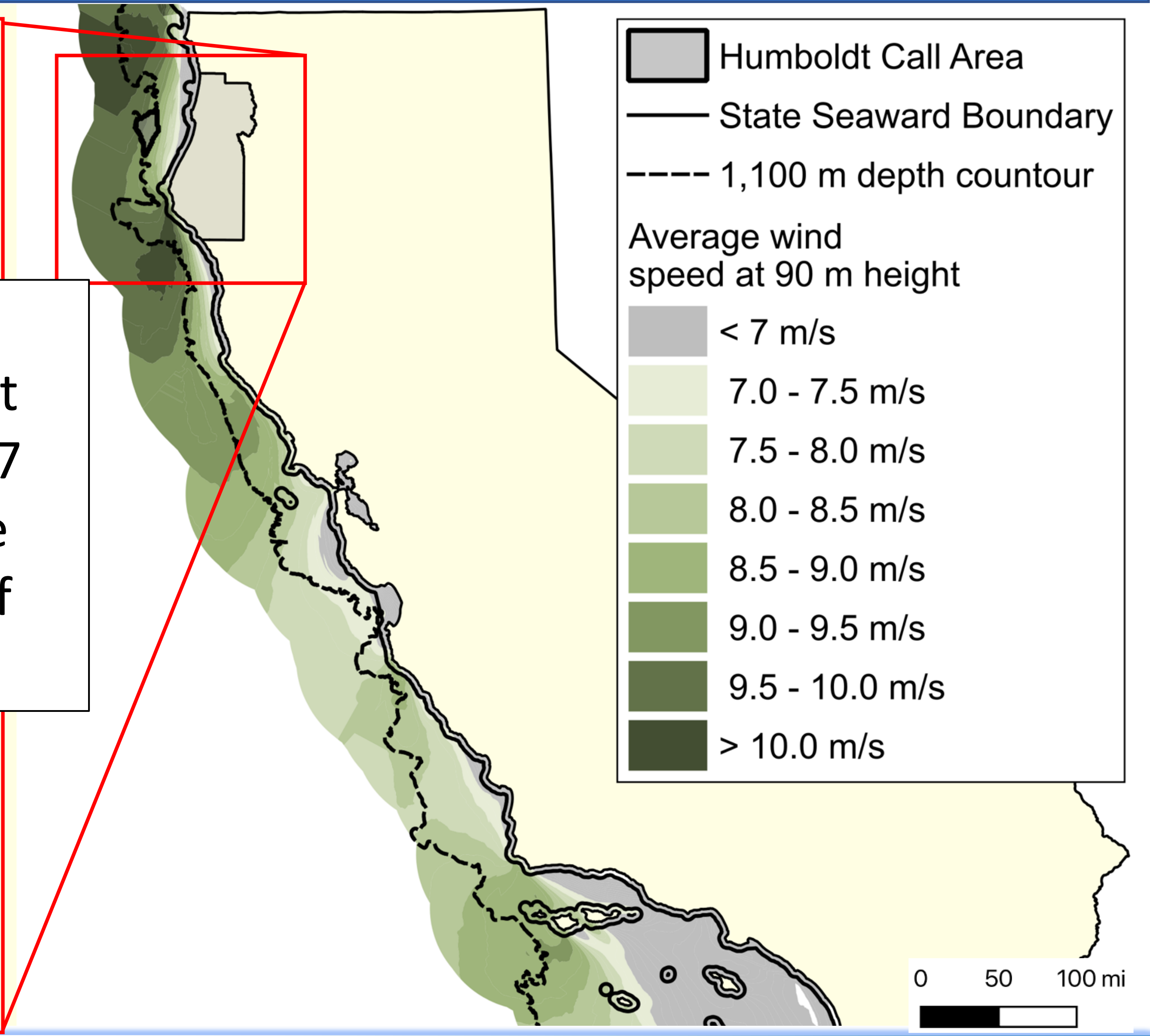


Wind farms in the Humboldt WEA that fully utilize the ~207 mi^2 area could have installed capacity of 1.6 to 1.8 GW.



Transmission Infrastructure is a Constraint on the North Coast

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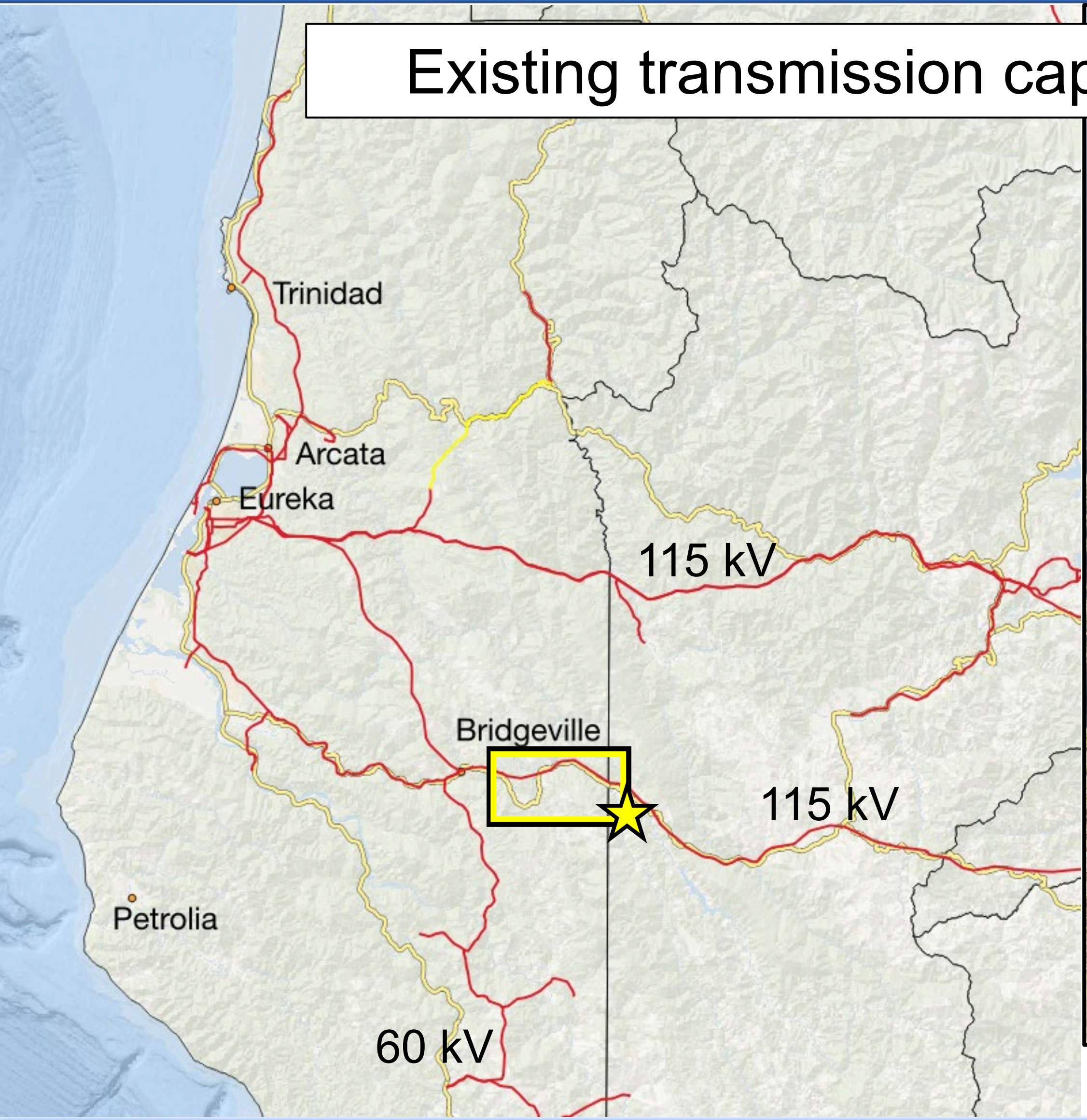
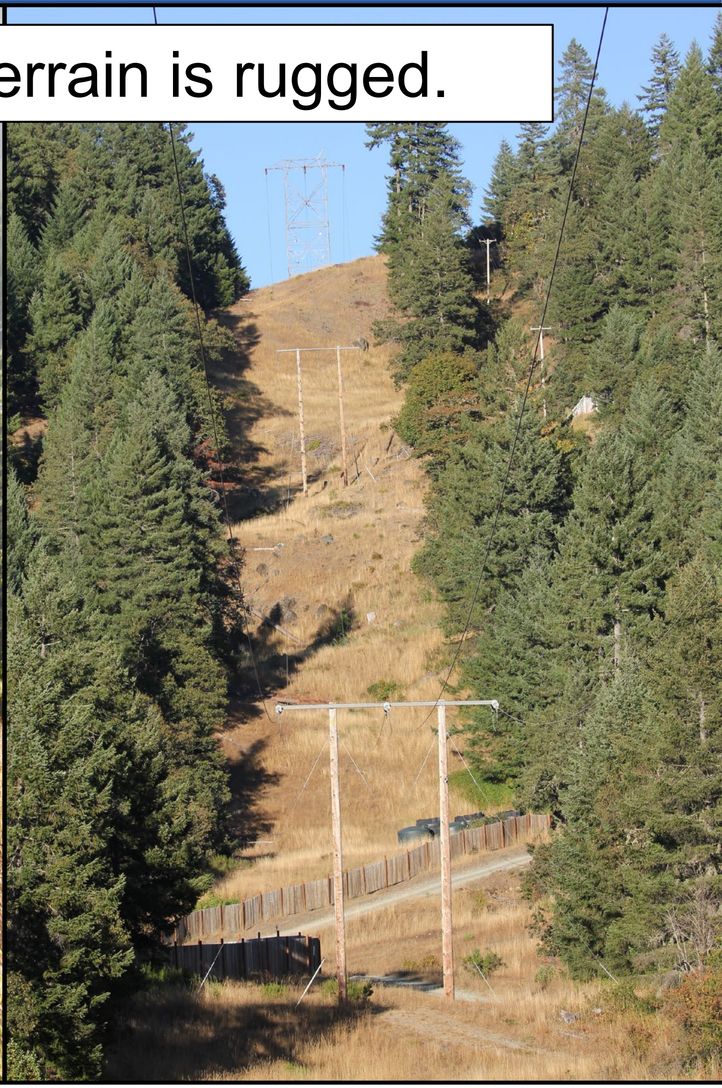
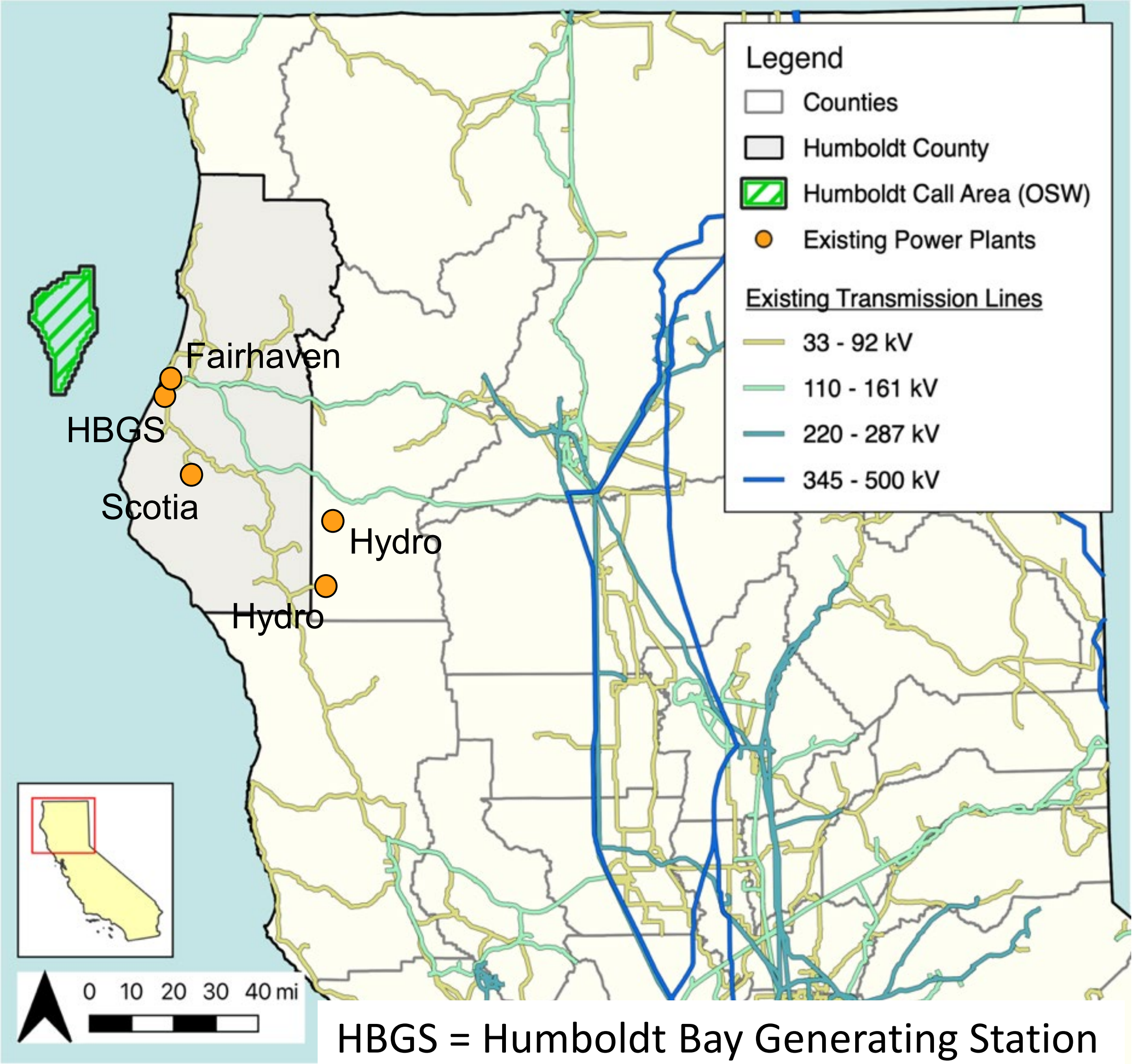
Existing transmission capacity is limited, and the terrain is rugged.





★ Photos taken outside Bridgeville on Highway 36

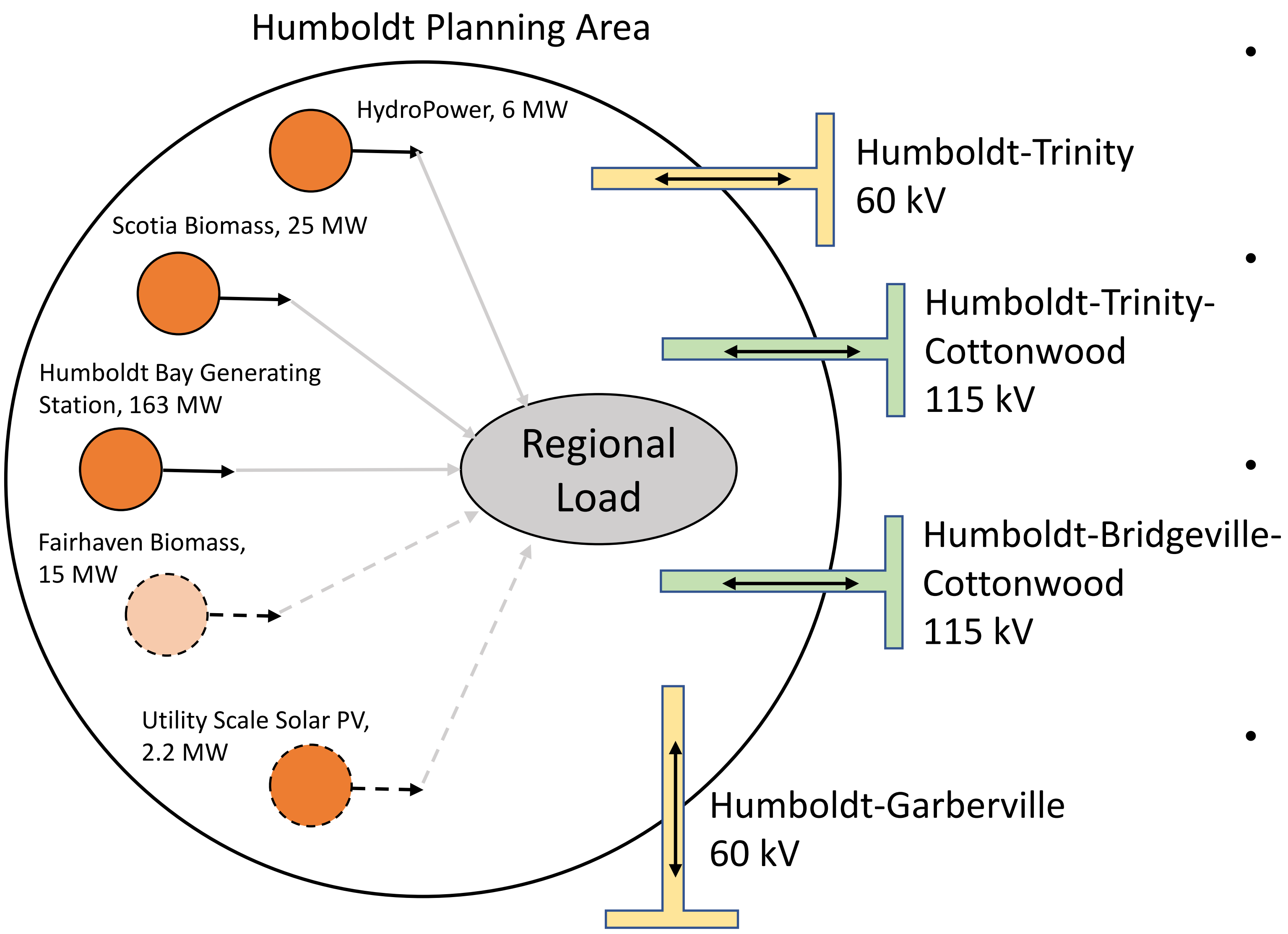
Humboldt County Electricity System (Circa 2021)



HBGS = Humboldt Bay Generating Station

- Humboldt County's electrical system is relatively isolated from the main CA grid.
- The regional load is concentrated in the Humboldt Bay area (avg load ~100 MW).
- Local generation is needed to power the region. The 163-MW natural gas fired Humboldt Bay Generating Station plays this role.
- Major transmission corridors run north and south in California, connecting large generators and load centers.

Humboldt County Electrical System (Circa 2021)



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Required Transmission for a Full Humboldt WEA Buildout

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- Analysis published in 2020 by PG&E and the Schatz Center identified several overland and undersea transmission alternatives for a 1.8 GW wind farm in the Humboldt WEA.
- In 2022, the CAISO published a draft Transmission Planning report that included analysis of transmission alternatives for offshore wind in California. This included an estimate of requirements for 1.6 GW of offshore wind in the Humboldt WEA.
- Cost estimates for transmission upgrades to enable a full buildout of the Humboldt WEA were similar for the two studies.

PG&E / Schatz Center Analysis of Transmission Alternatives (1.8 GW)

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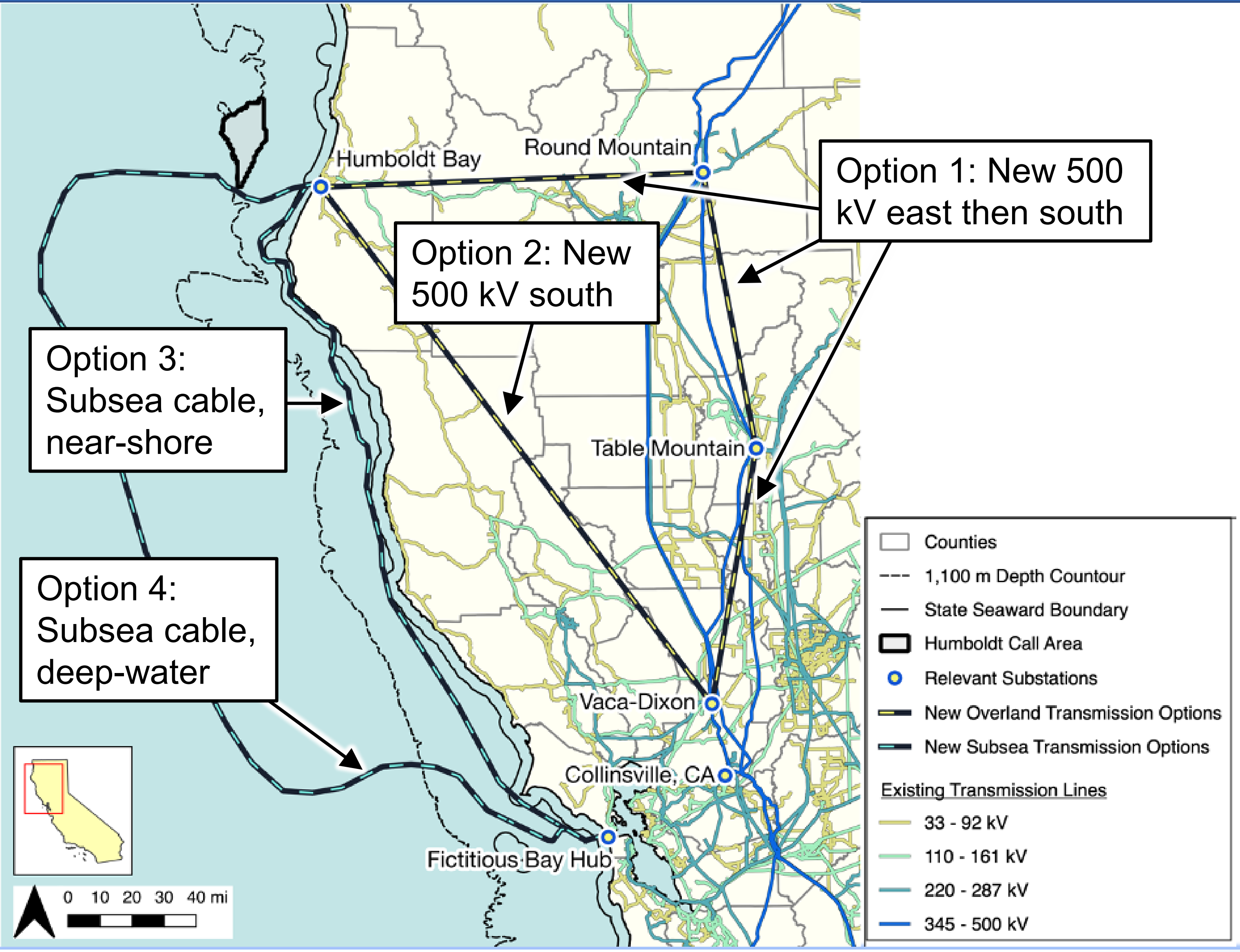

- Large scale offshore wind developments have several options for transmission upgrades including overland or undersea routes.
- Costs for upgrades to accommodate 1.8 GW of wind capacity were estimated at $1.7 to $3 billion for overland alternatives and $2.4 to $4.4 billion for undersea cable routes.

Source: Severy, et al., 2021: schatzcenter.org/pubs/2020-OSW-R12.pdf

CAISO Analysis of Transmission Alternatives (1.6 GW)

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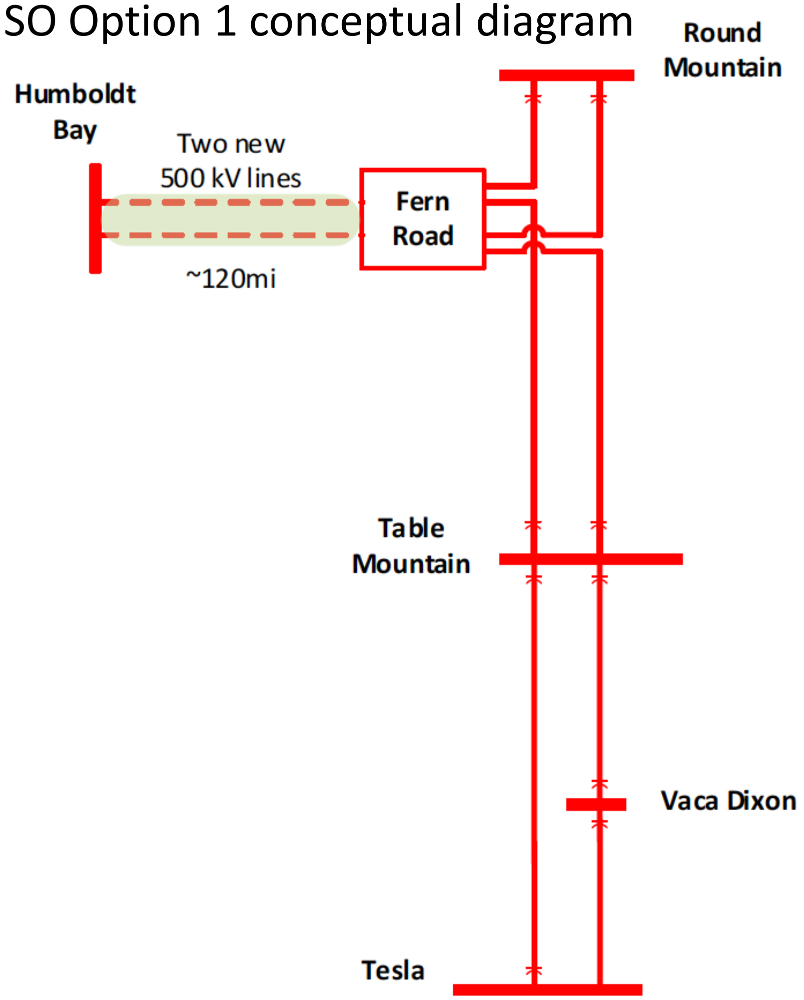
CAISO Option 1 conceptual diagram



Source: California ISO 2021-22 Transmission Plan (draft from January 31, 2022)
http://www.caiso.com/InitiativeDocuments/Draft-2021-2022TransmissionPlan.pdf

California ISO

- The California Independent System Operator (CAISO) analyzed three options for connecting 1.6 GW of wind generation capacity in the Humboldt WEA.

- **Option 1**: 500 kV AC line to Fern Road substation (near Round Mountain substation) – estimated cost: $1.2 billion
- **Option 2**: High voltage DC undersea cable to the SF Bay Area – estimated cost: $4 billion
- **Option 3**: High voltage DC overland transmission line to the Collinsville substation (Solano County) – estimated cost: $3 billion

Timeline for Large Scale Transmission Upgrades

- The process for completing a large-scale transmission upgrade is complex and involves steps related to planning, financing, land acquisition, permitting, and construction.
- The timeline to complete these processes is hard to estimate and is beyond the scope of our current analysis.
- Some prior GW-scale transmission projects in California have taken a decade or more.

Motivation and Scope for Current Analysis

Objective of Current Analysis: Identify options for developing offshore wind within the bounds of existing regional transmission infrastructure (or with modest investment in transmission upgrades). Assess the economics (costs and revenue) of initial project options.

Scope of Work

- Analyzed transmission requirements for multiple offshore wind development scenarios in the Humboldt WEA, with wind farms up to ~500 MW. The analysis included high-level cost estimates using a System Impact Study approach as per CAISO guidelines.
- Conducted offshore wind revenue analysis for selected scenarios.
- Assessed wind farm economics for the selected scenarios.

Humboldt Wind Energy Area Study Scenarios

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- Wind farm scenarios involved rated capacity ranging from 30 MW to 480 MW and assumed 12 MW turbines mounted on semi-submersible floating platform systems.
- Estimates of the wind generation for the respective cases was based on NREL's CA20 wind data set.
- For the purposes of understanding transmission requirements and expected project revenues, we considered both "full capacity deliverability" and "energy only" cases

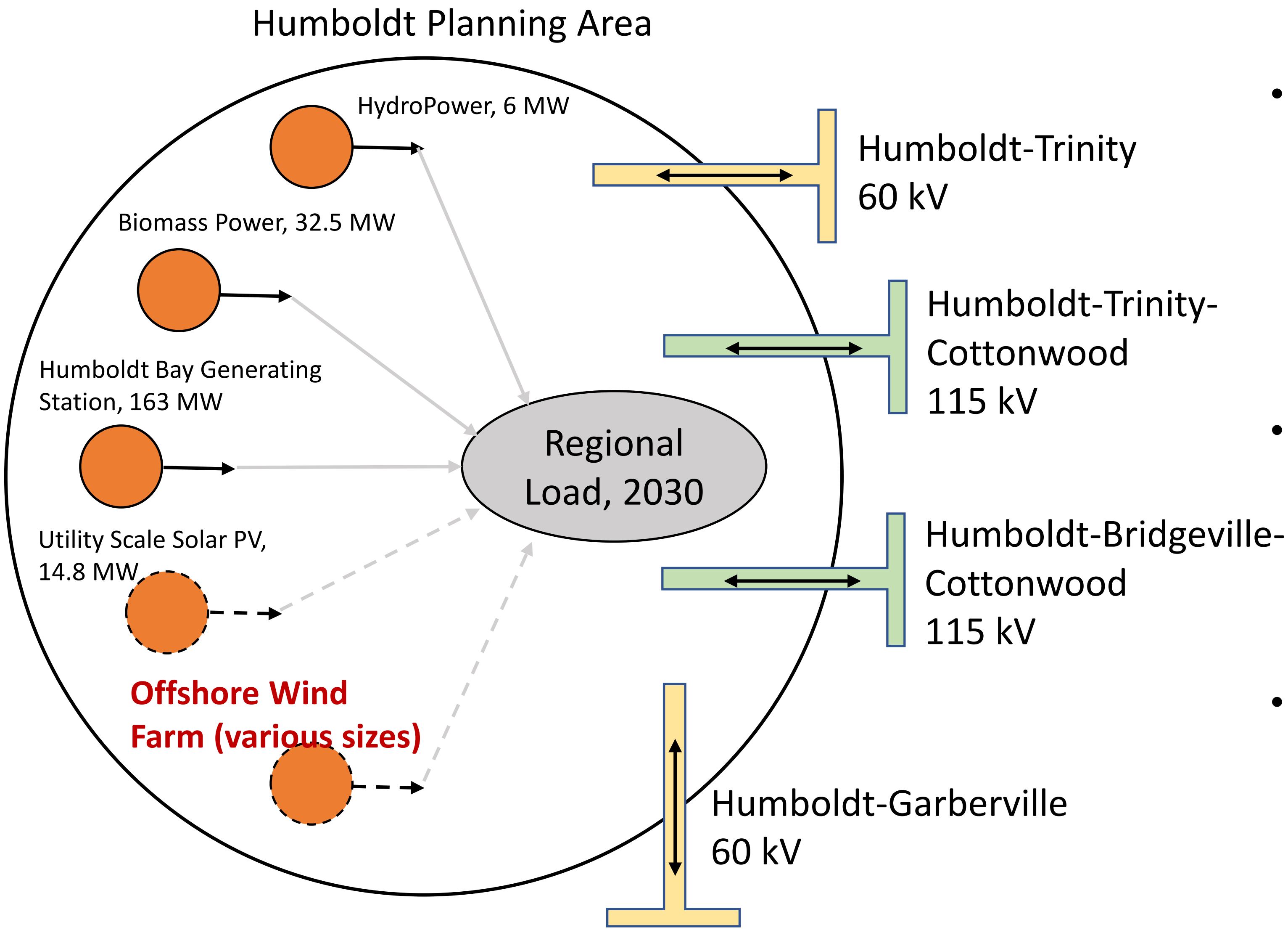
Image source: Wikipedia Commons (https://upload.wikimedia.org/wikipedia/commons/7/76/Agucadoura_WindFloat_Prototype.jpg

Grid Interconnection Vocabulary

- **Full capacity deliverability interconnection**: In cases where projects are connected on a "full capacity deliverability" basis, ***the transmission system must be capable of accepting power generated by the project under a wide variety of conditions***. If the existing transmission infrastructure is not able to do this, upgrades are needed to ensure transmission system reliability and deliverability***. If a generator is connected on a full capacity deliverability basis, it will not need to curtail for the purpose of congestion management***.

- **Energy only interconnection**: If projects are connected on a "energy only" basis, the transmission system is assessed to determine if reliability upgrades are needed, but the system does not need to be upgraded to ensure that the power from the generator can be accepted in cases where the system is congested. ***If a generator is connected on an energy only basis, it may be required to curtail to enable transmission system congestion management.*** Moreover, the system would not qualify for resource adequacy and would forego associated capacity payment revenue.

Humboldt County Electrical System, Projected to 2030



- Our team's analysis is based on integrating offshore wind into a system that includes projected local generation sources and loads for the year 2030.
- The projected regional load for 2030 was based on data provided by the Redwood Coast Energy Authority (RCEA).
- Generation sources for 2030 were based on CAISO data and information from RCEA.

Analysis of transmission infrastructure requirements, upgrade costs, and offshore wind revenue generation.

QUANTA TECHNOLOGY

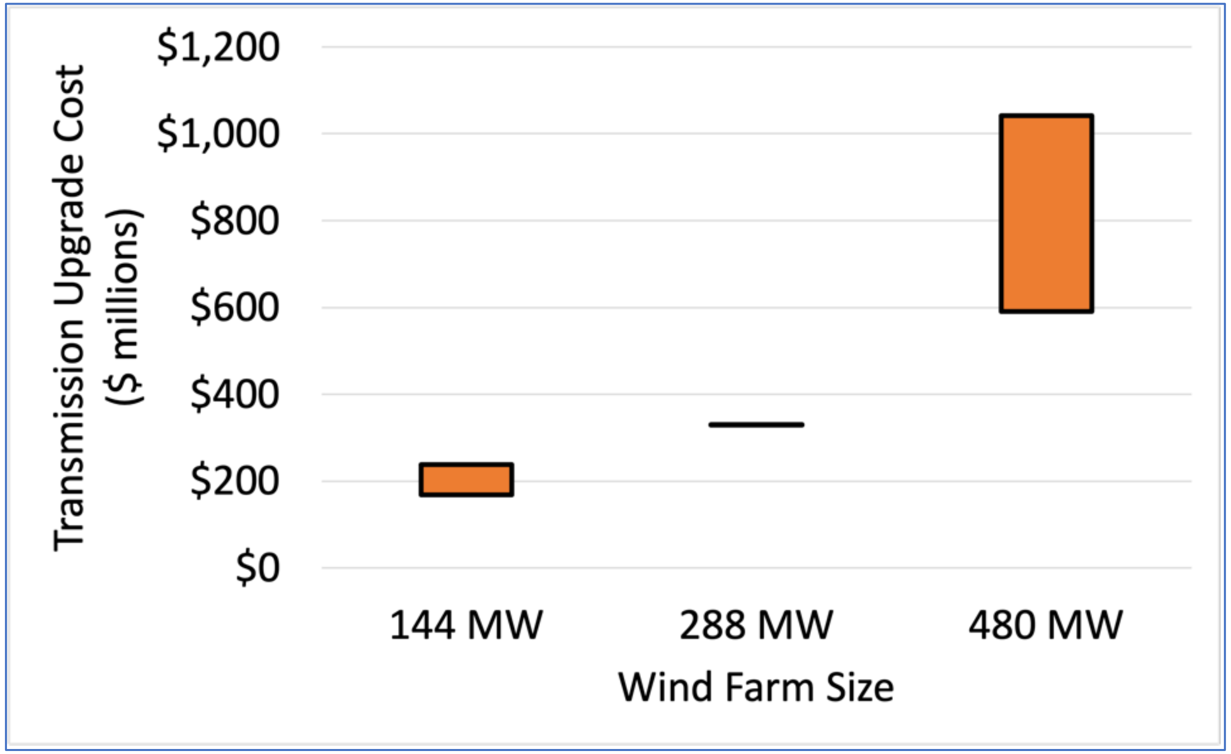
Photo credit: Nancy Stephenson of the Redwood Coast Energy Authority

Transmission Upgrade Costs

1. **Cost for transmission upgrades**: In cases where the wind farm size exceeds the available transmission line capacity, the **cost of transmission upgrades is significant**.

- If offshore wind projects are connected with full capacity deliverability, transmission upgrades would be required for projects exceeding ~30 MW.
- A range of costs are included for the 144-MW and 480-MW cases, as there is some uncertainty regarding the upgrades that would be triggered by an offshore wind farm and the costs that would be borne by the developer.

Transmission Upgrade Costs for Three Cases (Full Capacity Deliverability)



Maximum Project Size with Existing Infrastructure

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2. **Possible Initial Project**: A small commercial offshore wind farm could be developed in the Humboldt Wind Energy Area (e.g., 140 – 170 MW) without upgrading existing transmission infrastructure if some curtailment is accepted. This would involve "**energy only" interconnection**. The result is **sensitive to assumptions about load growth**.

- With the projected 2030 base case load, a wind farm up to 174 MW with "energy only" deliverability could be developed without transmission upgrades.
- Somewhat larger wind farms could be built without upgrades if load growth exceeds the base case.

Wind Farm Maximum Size	Load Case	Peak Regional Load
174 MW	Base Case	136 MW
225 MW	Augmented Load	170 MW
231 MW	Aug. Load + 20 MW	190 MW

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3. Optimal initial project size w/ existing transmission infrastructure

To **maximize net revenue**, the recommended size for an initial wind farm may be **~140-150 MW**. This assumes the 2030 base case load.

With larger wind farm size:

- Capex goes up
- Wind energy generation goes up
- Gross revenue goes **down**
- Net revenue goes down

Note: This is a unique situation where the OSW farm is interconnecting to a regionally constrained transmission grid.

Image source: Senu Sirnivas / NREL

Offshore Wind Revenue Generation

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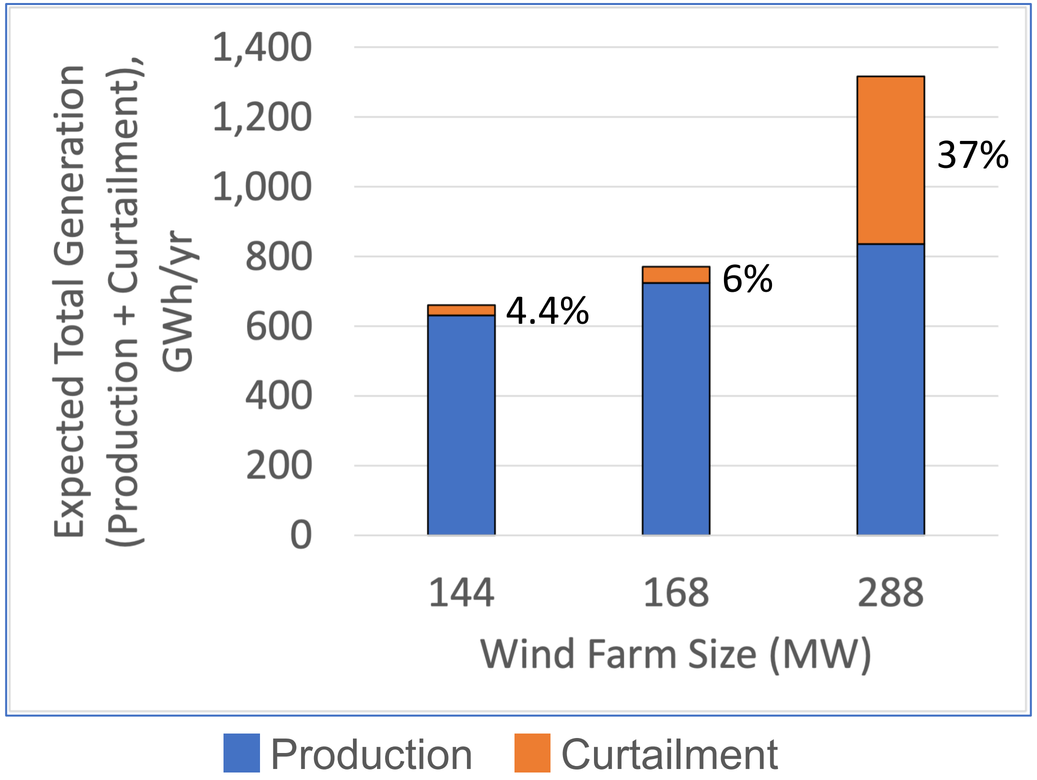
3. **Initial project size and revenue:** To maximize revenue, the recommended size for an initial wind farm may be ~140-150 MW. This assumes the 2030 base case load.



- Energy production from wind farms increases with size, but **curtailment limits** the total that can be delivered by larger wind farms.
- In addition, the **electricity price declines** for larger wind farm sizes due to **supply and demand** in situations when the transmission system approaches congestion limits.

Offshore Wind Revenue Generation

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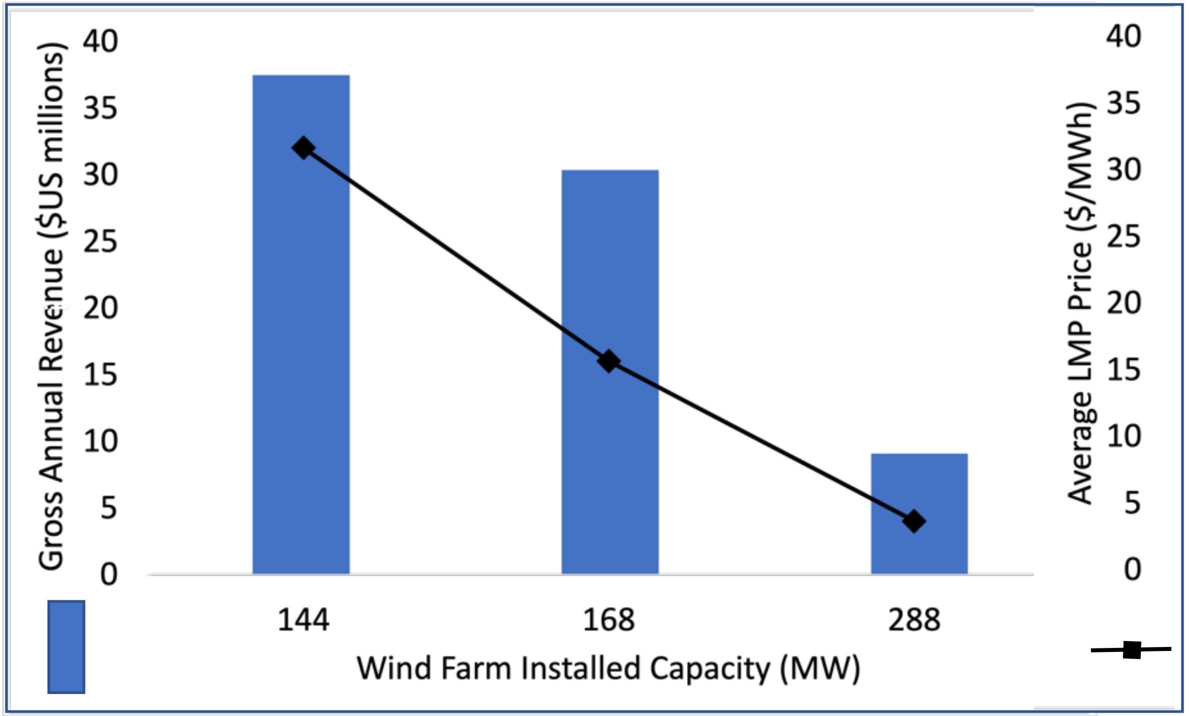
3. **Initial project size and revenue:** To maximize revenue, the recommended size for an initial wind farm may be ~140-150 MW. This assumes the 2030 base case load.

- Because of the decline in the local marginal price (LMP) at the Humboldt Substation node for larger wind farm sizes, a 144 MW wind farm generates more annual revenue than larger projects.



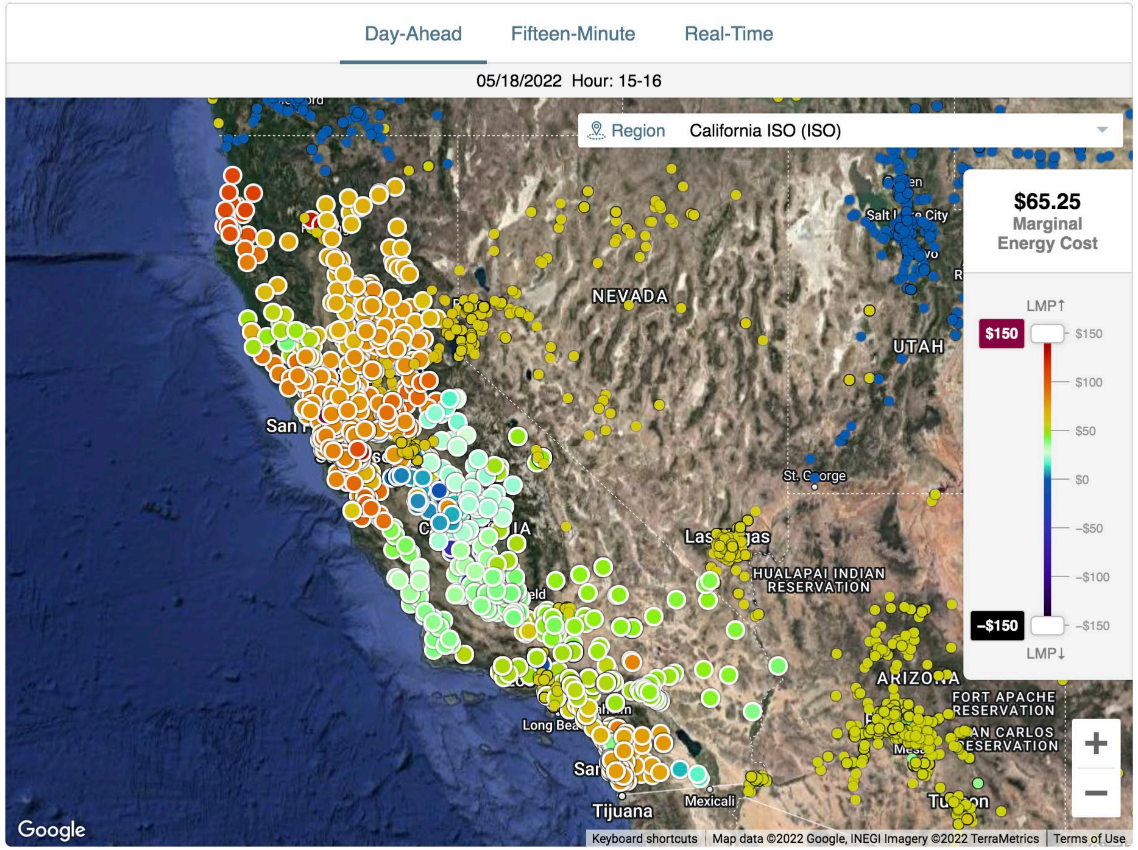
Note: The presented revenue estimates assume participation in the CAISO market. Revenue values assume a $25/MWh Production Tax Credit (PTC).

Notes about Electricity Pricing (energy sales)

What is the local marginal price (LMP) and how does this vary by region?

California ISO

- The California Independent System Operator (CAISO) manages markets for electricity sales in much of California, including wholesale electrical energy ($/MWh).
- The local marginal price is the electrical energy price at a particular point of sale on the grid.
- Prices vary regionally according to local supply and demand.



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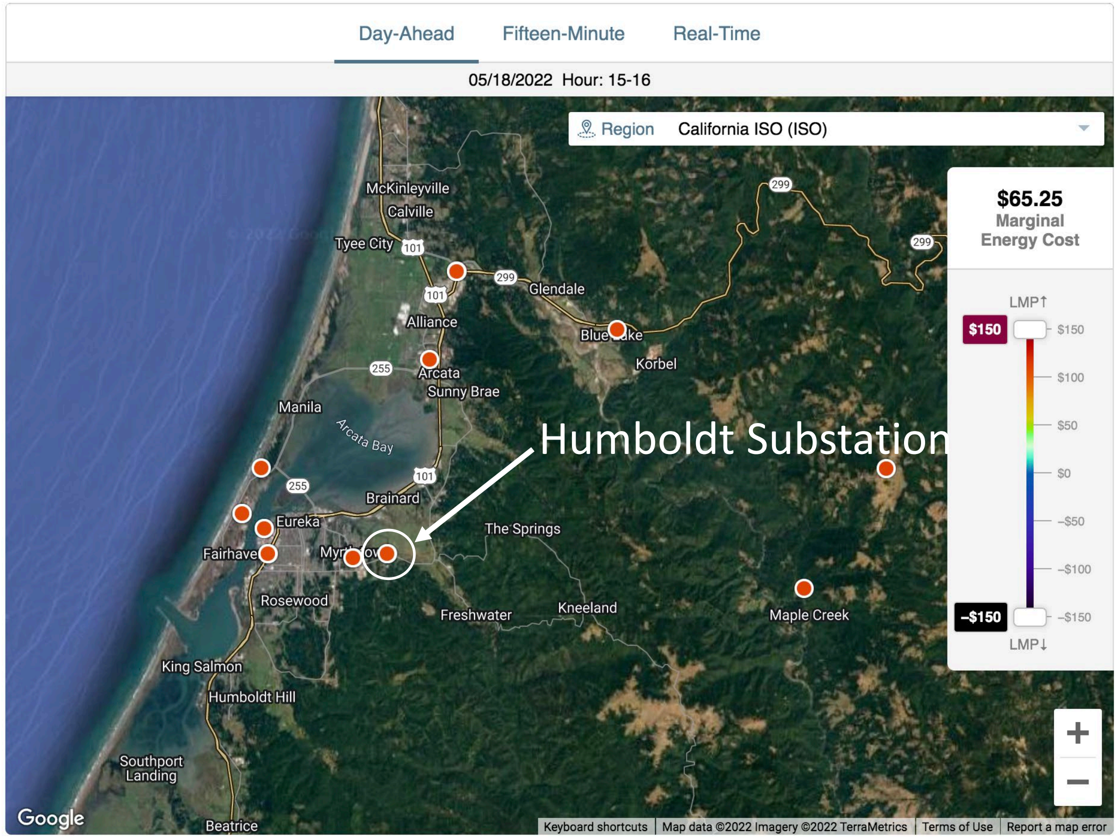

The price used for this analysis was the projected LMP for the year 2030 at the Humboldt Substation (marked on the map). Revenue estimates also considered ancillary services market participation and a $25/MWh PTC.

Offshore Wind Revenue Generation

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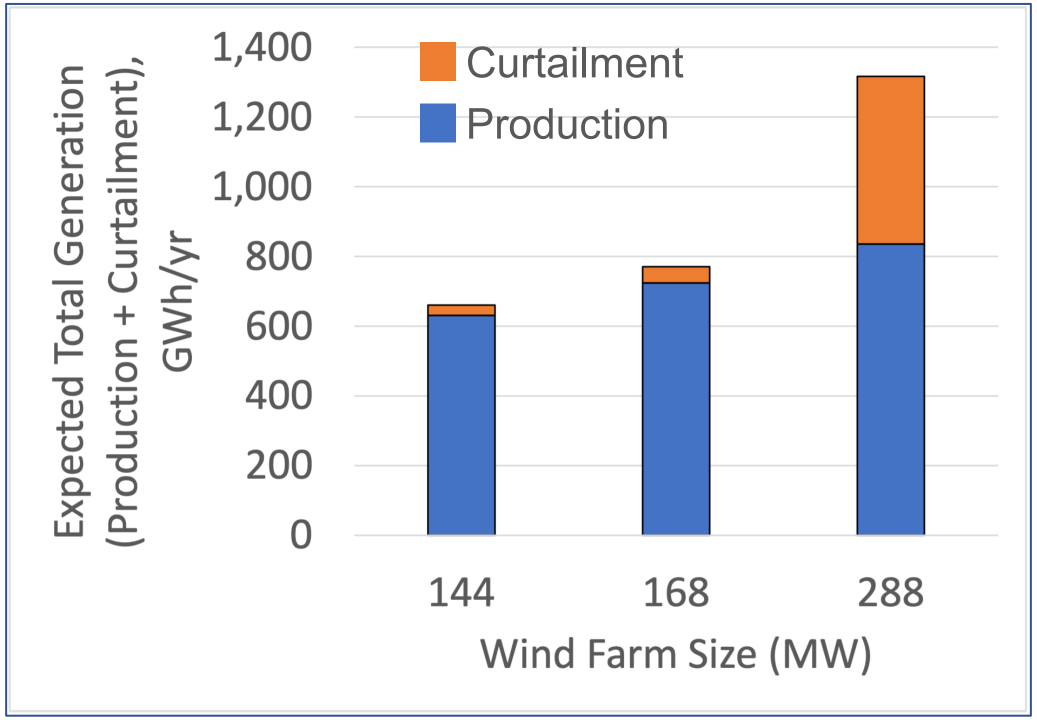
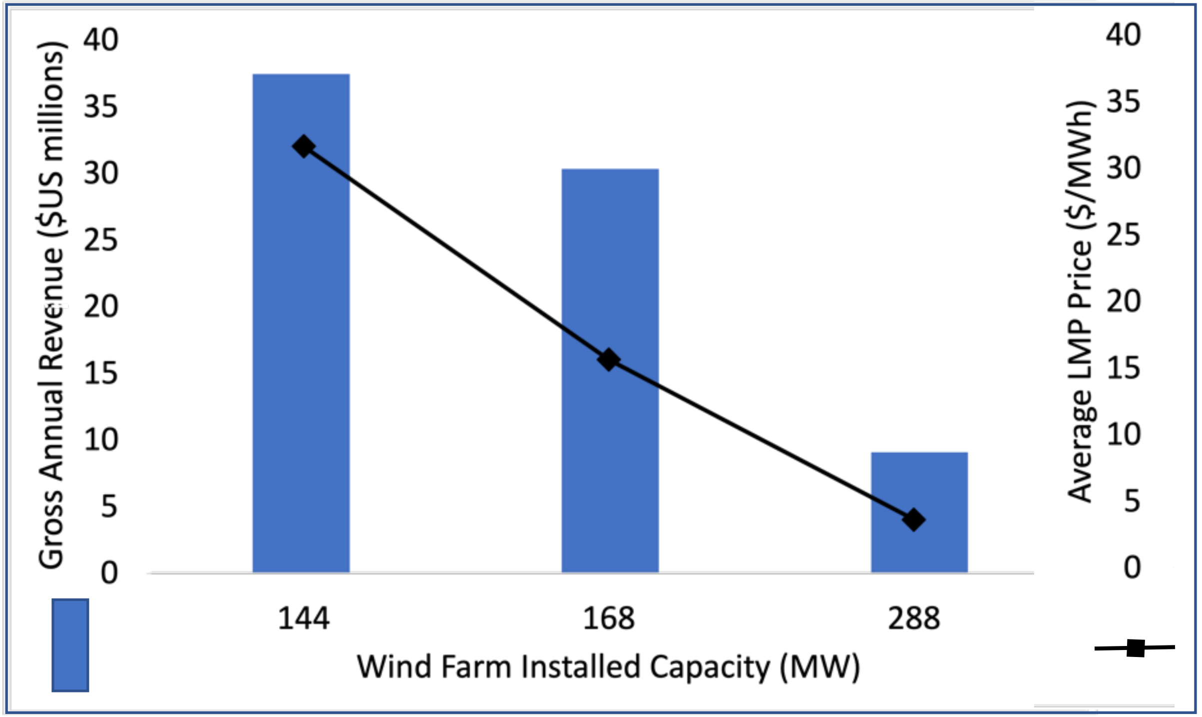
3. **Initial project size and revenue:** To maximize revenue, the recommended size for an initial wind farm may be ~140-150 MW. This assumes the 2030 base case load.





Note: The presented revenue estimates assume participation in the CAISO market. Revenue values assume a $25/MWh PTC.   Revenues would differ if based on power purchase agreements, depending on the PPA terms.

Offshore Wind Revenue Generation

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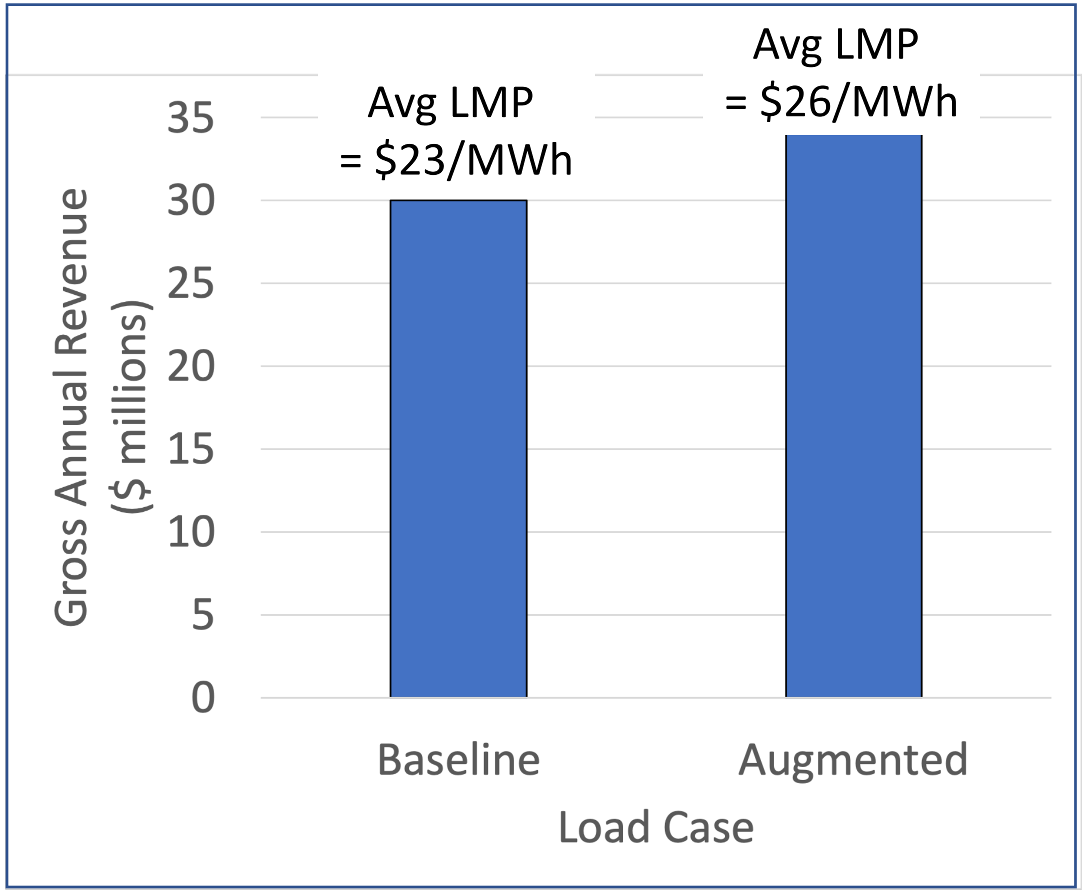
3. **Initial project size and revenue:** The **ideal size** to maximize revenue is **sensitive to** the growth of the regional electric load. Accelerated **load growth** could allow a somewhat larger wind farm.

- The graph shows estimated gross annual revenue for a 168 MW wind farm for two electric load cases for the year 2030 (baseline and augmented load).
- Gross revenue increases as the regional electric load increases because the average LMP is higher with a larger load for a given wind farm size.



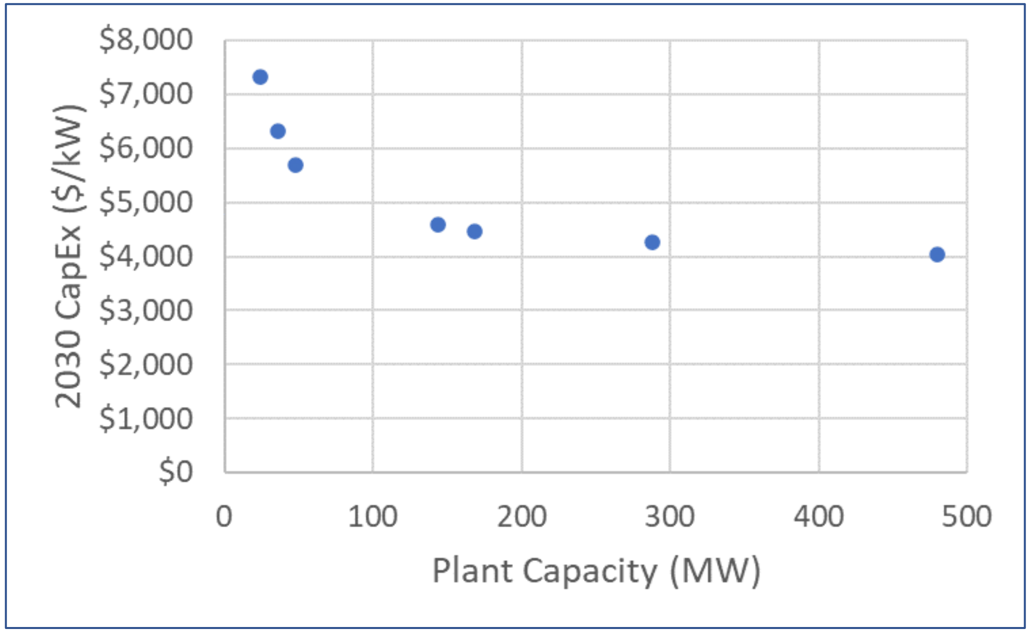
168 MW Wind Farm (Energy Only)

Economic analysis of offshore wind development costs and revenues

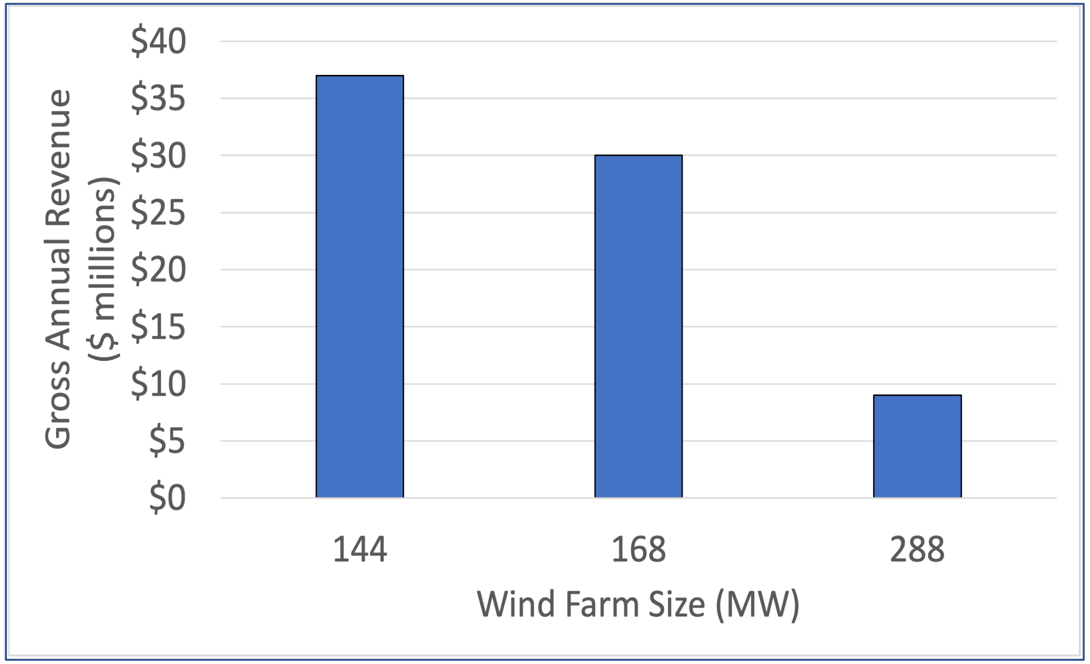
(includes levelized cost of energy (LCOE) and levelized cost of transmission (LCOT))

What are project economics if both costs and revenues are considered?

- Wind farm costs per unit of installed capacity decline as the project size increases. This highlights the benefit of increasing the wind farm size.
- However, we have also seen that gross annual revenue for <u>energy only</u> wind farms in the Humboldt Wind Energy Area declines with larger wind farms due to local price dynamics in a constrained transmission system.



Floating Wind Farm CapEx per Installed kW (NREL analysis)



Gross Annual Revenue for Wind Farms in the Humboldt Wind Energy Area (Quanta Technology Analysis)

Levelized Cost of Electricity (LCOE)

Cost of electricity from a project where the total capital cost and operating costs are amortized over the life of the project ($/MWh).

Net Electricity Value

Net Electricity Value ($/MWh) = amortized lifetime revenue – LCOE

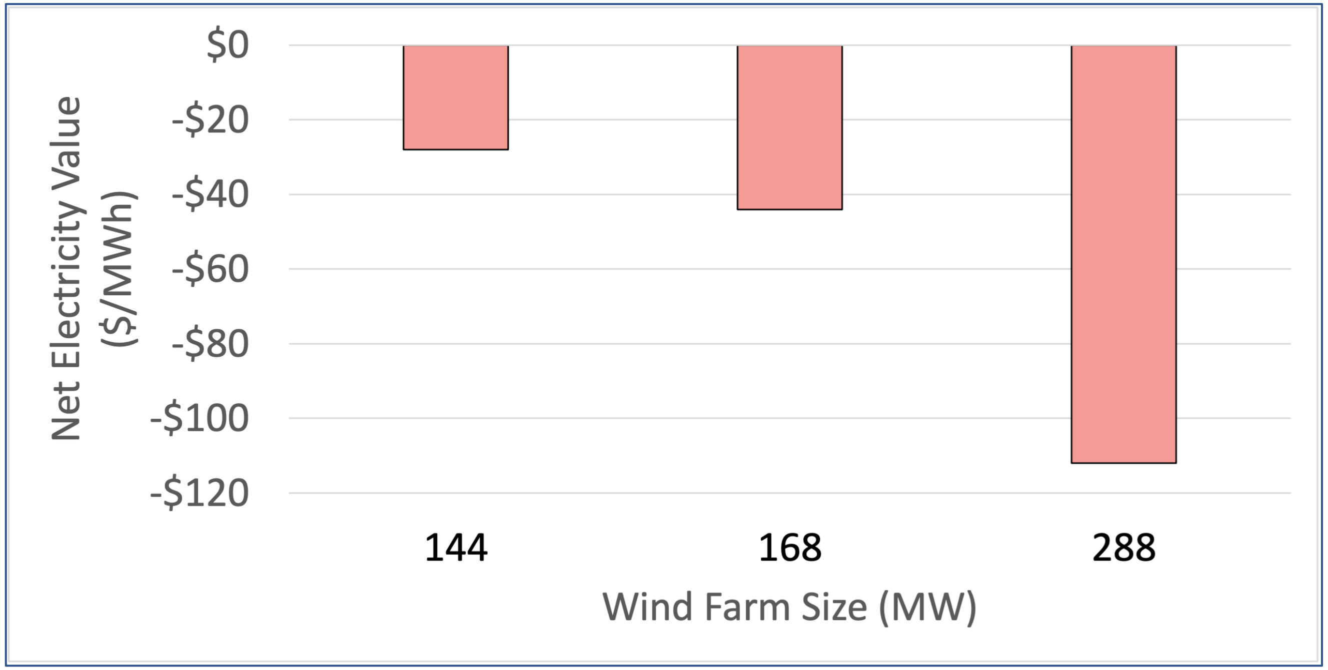
- If the Net Electricity Value is positive, the project is in the black
- If the Net Electricity Value is negative, the project is in the red

Image Source: Vestas Wind Systems

What are project economics if both costs and revenues are considered?

- The estimated **cost** of developing the wind farm **exceeds the revenue** generated over the 30-year life of the project for **all cases considered**, even with a product tax credit in place. The net value of the electricity is higher (less negative) for the 144-MW project due to greater revenue generation and lower project costs.

Wind Farm Size	CapEx	Curtailment	Levelized Cost of Energy (LCOE)	Gross Annual Revenue
144 MW	$661M	4.4%	$84/MWh	$37M
168 MW	$748M	6%	$83/MWh	$30M
288 MW	$1,225M	37%	$119/MWh	$9M



*The net electricity value results assume that a $25/MWh PTC is in place.

Relative Significance of the Cost of Transmission

- For full deliverability projects, the levelized cost of transmission adds 15% to 34% to the levelized cost of offshore wind projects between 144 MW and 480 MW in the Humboldt Wind Energy Area.*

	144 MW	288 MW	480 MW
OSW CapEx (million $)	$661	$1,225	$1,935
Transmission CapEx (million $)	$168 - $238	$329	$591 - $1,040
OSW OpEx (million $/yr)	$10	$20	$33
Net Annual Energy Production (GWh)	660	1,317	2,160
LCOE ($/MWh)	$80	$75	$73
LCOT ($/MWh)	$12 - $17	$12	$13-$25
LCOE + T ($/MWh)	$92 - $97	$87	$86 - $98

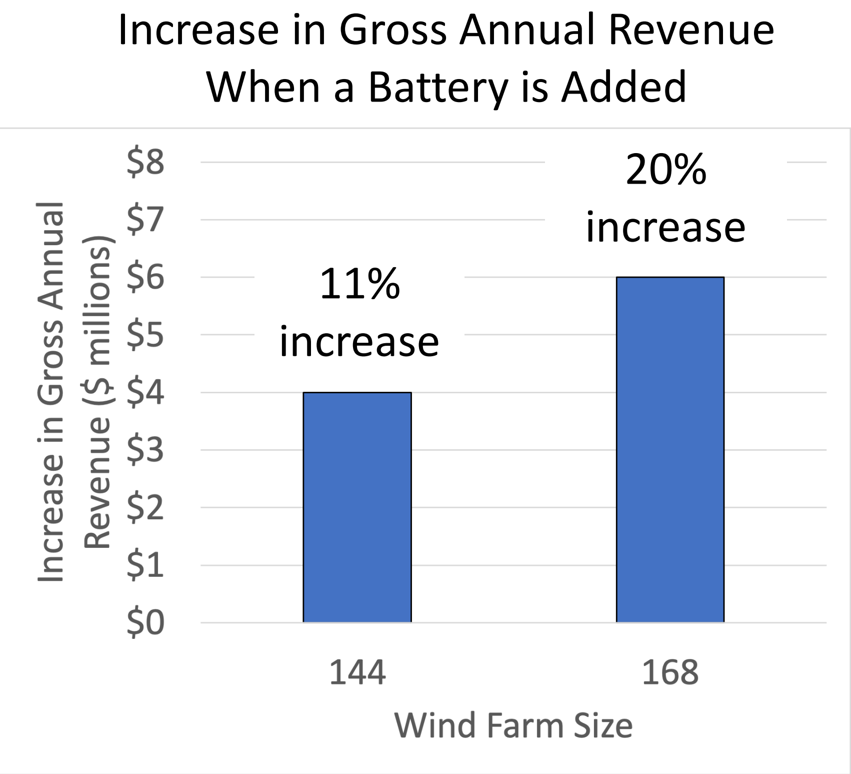
*Note that this analysis assumes that the life of the transmission infrastructure is 60 years, which is twice the assumed wind farm life of 30 years. In addition, the investment for an offshore wind farm would be made by the developer, while nearly all state-approved transmission upgrade costs would likely be covered by rate payers or public financing.

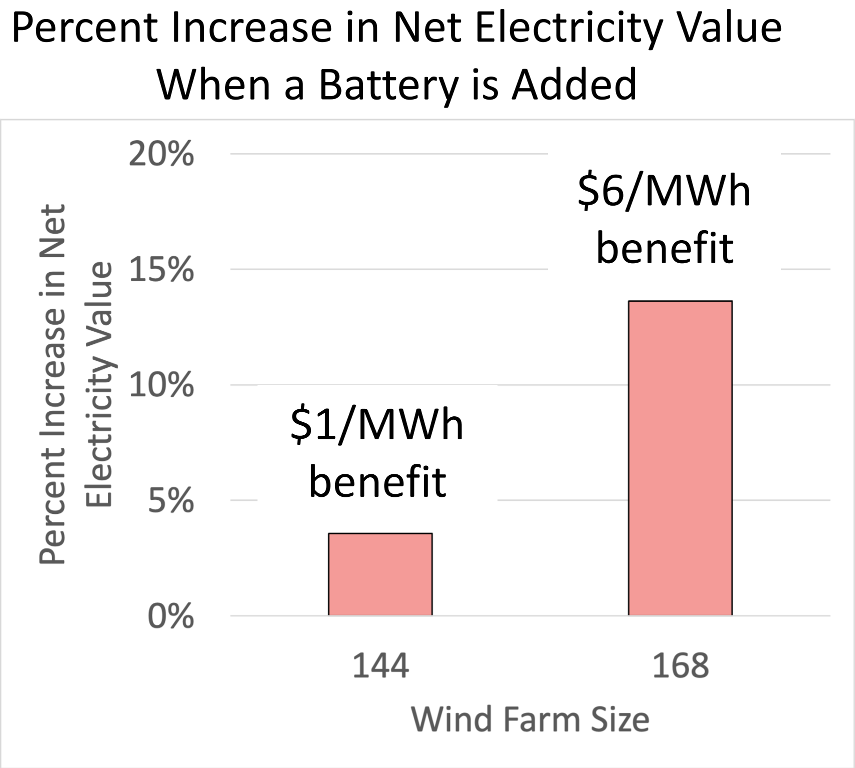
Can addition of storage improve project economics?

- As a preliminary evaluation of the value of coupling storage with a wind farm, we added a 15 MW, 4-hour battery energy storage system (BESS) to the 144 MW and 168 MW wind farm cases. The analyses assumed the 2030 base case load.
- We assumed commercial scale lithium-ion BESS technology costs, projected to 2030 (source: NREL, 2021).

Can addition of storage improve project economics?

- The results show that adding a battery increases revenue and overall value in both the 144 MW and 168 MW cases.



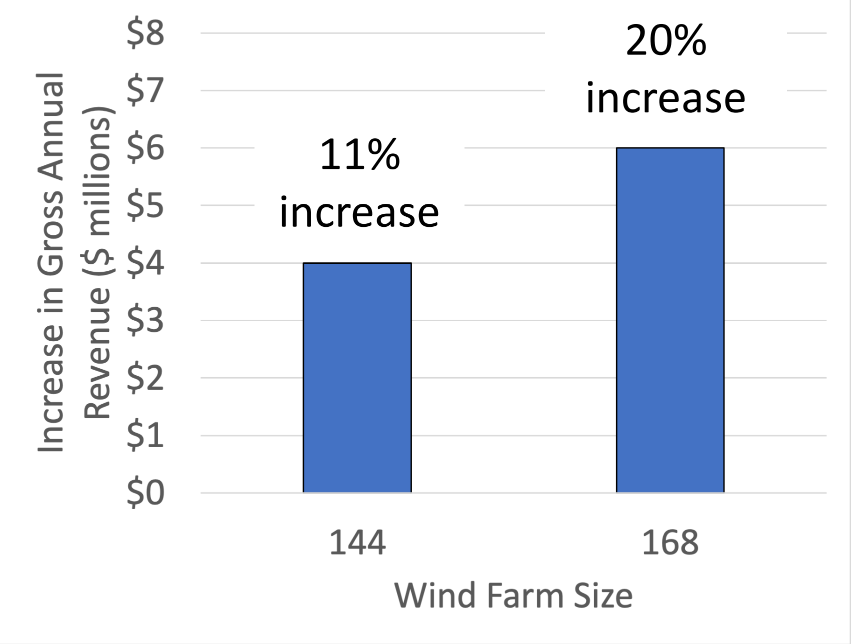


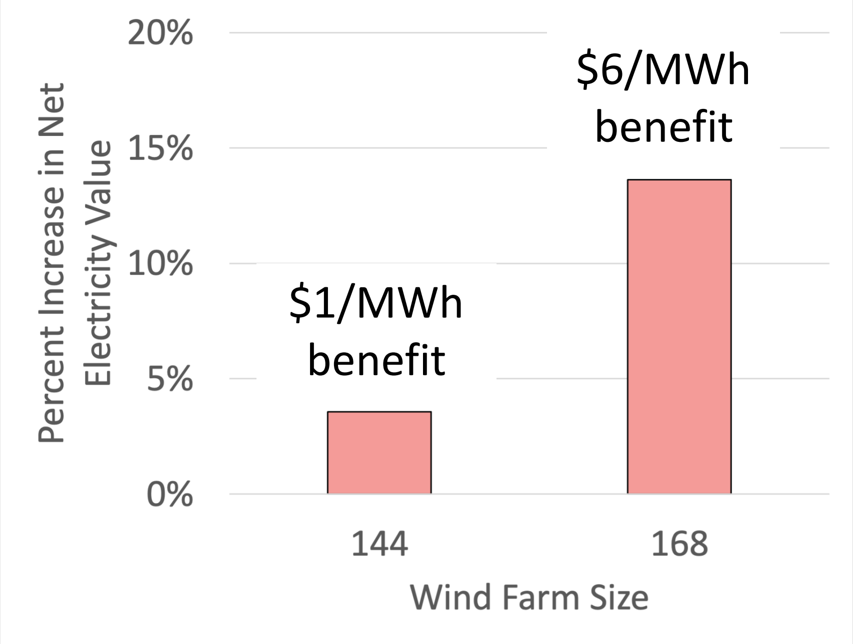
*Results assume a $25/MWh PTC is in place.

Can addition of storage improve project economics?


Photo: Maia Cheli

- The incremental benefit is larger for the 168 MW wind farm case because the battery can be used to reduce the LMP price suppression, which is more significant for the larger wind farm.





*Results assume a $25/MWh PTC is in place.

Can addition of storage improve project economics?

Suggested additional research includes:

- Additional analysis to better understand the value of coupling battery storage with an offshore wind farm.
- Analysis that considers a wider range of storage system sizes (in terms of power and energy storage), wind farm sizes, regional electric load profiles and market participation strategies.

Can hydrogen generation reduce the impact of curtailment?

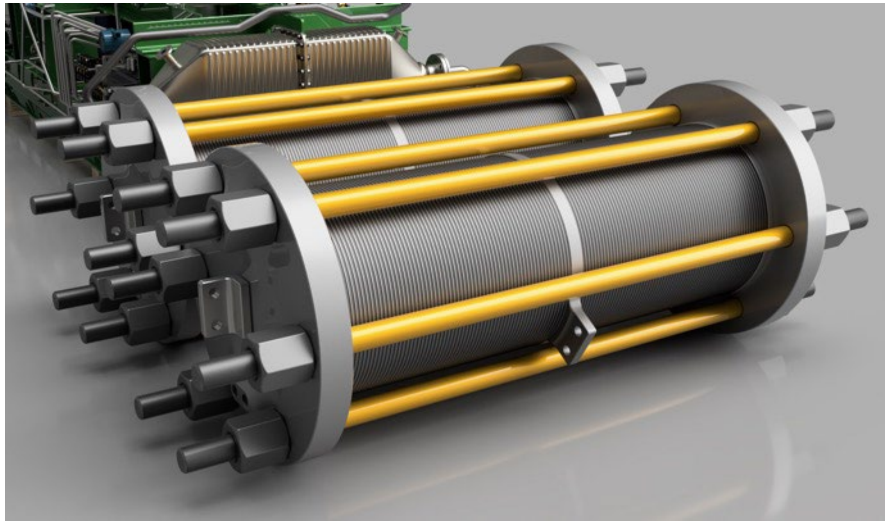


Image source: https://pocharitechnologies.com/2021/06/15/reduced-capex-alkaline-electrolyzers-using-commercial-off-the-shelf-component-cots-design-philosophy/

- Green hydrogen generation from curtailed and other very low-cost electricity from a wind farm could be cost competitive with H_2 delivered from outside the region.
- A potential near-term opportunity is to use H_2 as a transportation fuel to supply the projected regional demand (~1200 kgH_2/day) for zero-emission vehicles.
- Curtailed energy from a 168 MW wind farm could meet this demand 60% of the time. H_2 generation from higher cost power would be needed to fill the deficit.

Conclusions

- CA's north coast offshore wind resource is very large
- Transmission challenges vary depending on the scale of development.
  - *A small commercial project can be built in the Humboldt Wind Energy Area without transmission upgrades if interconnected as "energy only."*
  - *Larger projects require significant investments in transmission infrastructure.*
  - *The recommended project size for an initial "energy only" project may be on the order of 140-150 MW (this result is sensitive to assumptions about load growth).*
  - *Small project economics are challenging, especially in the absence of federal tax incentives (PTC or ITC).*
  - *Storage can help improve project economics.*
  - *Hydrogen generation from curtailed and low-cost power is potentially viable for some local applications.*

Potential Future Research

It would be valuable to conduct additional analysis in the following areas:

- **Coupling storage with offshore wind projects** (our analysis considers two cases, and it would be valuable to examine additional cases)
- **Integrating hydrogen production into offshore wind projects** (we conducted preliminary analysis related to this topic, but additional work is needed to understand the opportunity more fully)
- **Assessing transmission requirements for a group of GW-scale project scenarios** for sites in northern CA and southern OR

Contact Information

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Photo credit: Maia Cheli

www.schatzcenter.org/wind

Annex Slides

Cost analysis method and assumptions

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FCR: Fixed Charge Rate
6.9% (nominal) based on financing parameters from NREL's Annual Technology Baseline

CapEx: Capital Expenditures
Computed for each OSW plant size using NREL's Offshore Renewables Balance-of-system and Installation Tool (ORBIT) to simulate the installation process and estimate costs

$$Levelized\ Cost\ of\ Energy: \quad LCOE = \frac{(FCR * CapEx) + OpEx}{AEP_{net}}$$

OpEx: Operational Expenditures
Computed for each OSW plant size based on NREL's Offshore Regional Cost Analyzer (ORCA)

AEP_{net}: Annual Energy Production
varies with plant capacity and incorporates downtime, electrical losses, and wake effects

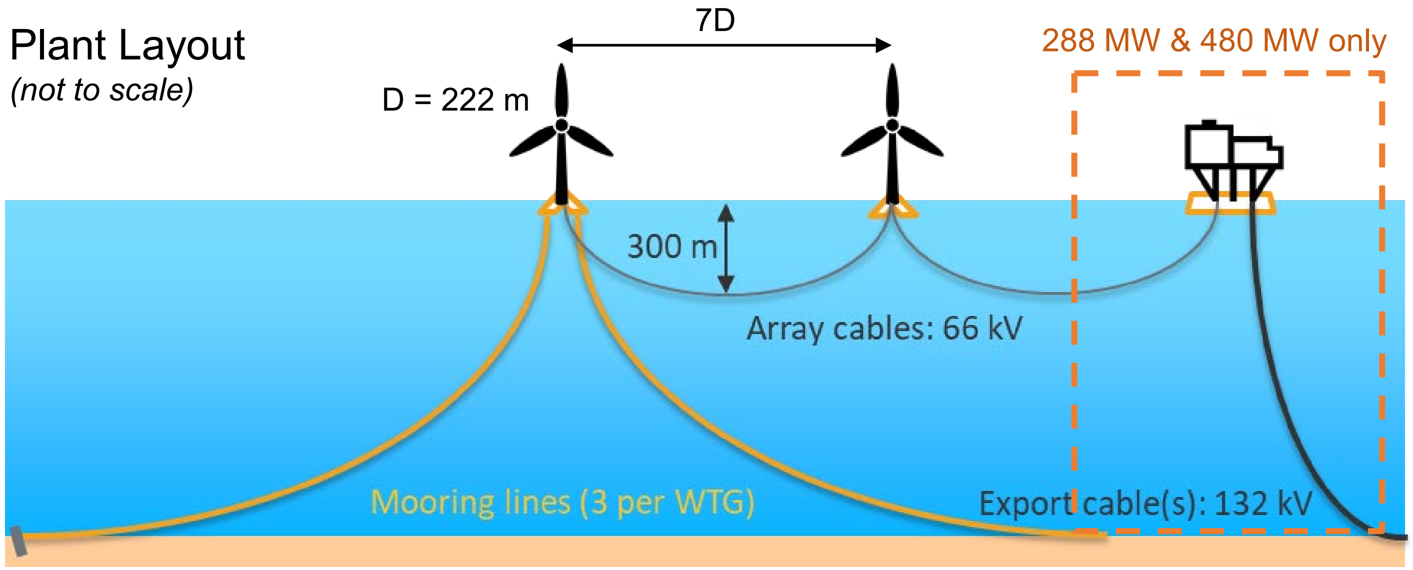
C = capital cost of transmission investment
r = discount rate (4.4%)
n = transmission asset lifetime (60 years)

$$Levelized\ Cost\ of\ Transmission: \quad LCOT = \frac{C * r}{AEP_{net} * [1 - (1 + r)^{-n}]}$$

Offshore wind CapEx method & assumptions

Mean wind speed at 100 m	10.8 m/s
Water depth	686 m
Distance to port	45 km
Turbine rated capacity	12 MW
Number of turbines	Up to 40 (480 MW)
Rotor diameter [D]	222 m
Hub height	138 m
Substructure technology	Semisubmersible
Subsea export cable length	45 km
Onshore cable length	2 km

Plant Layout
(not to scale)



Wind Farm CapEx Sensitivity Analysis

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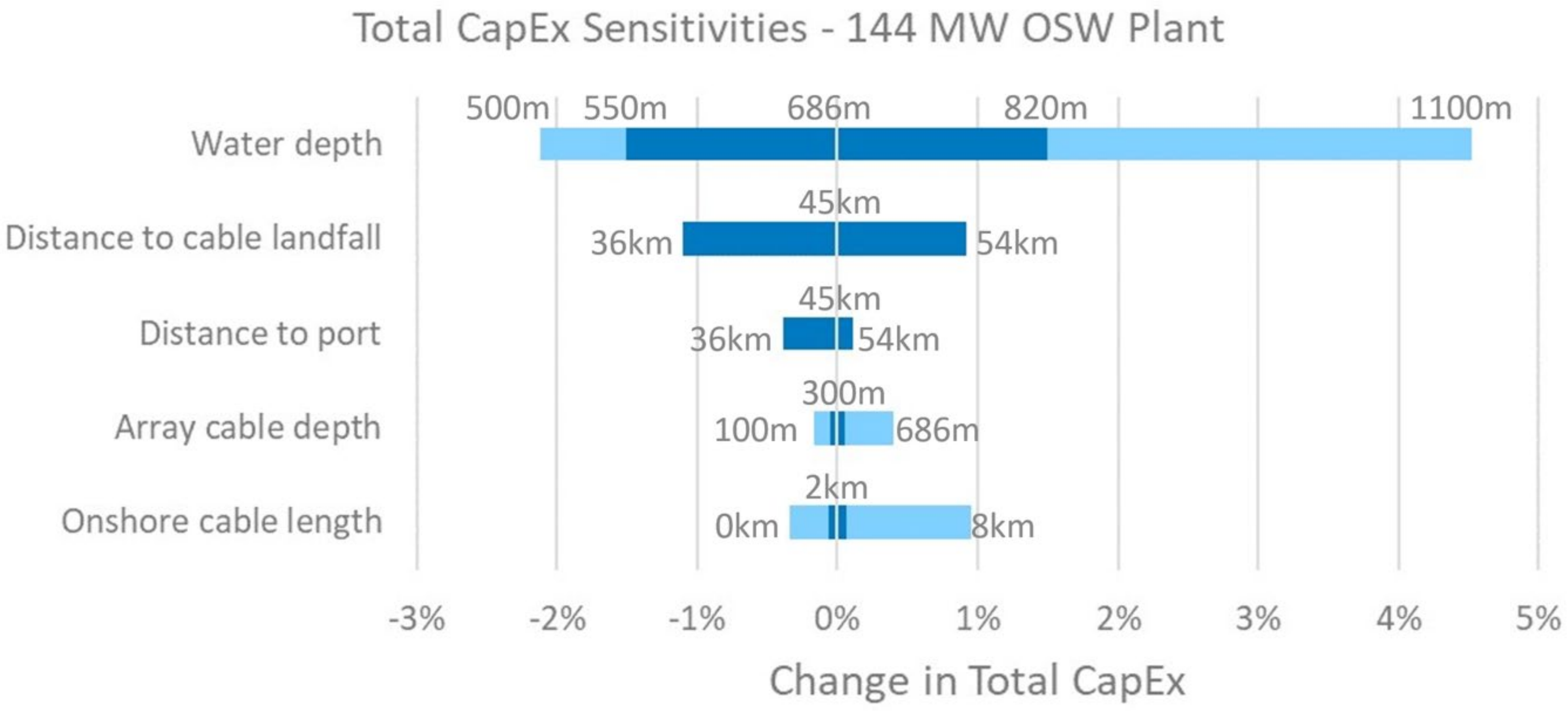
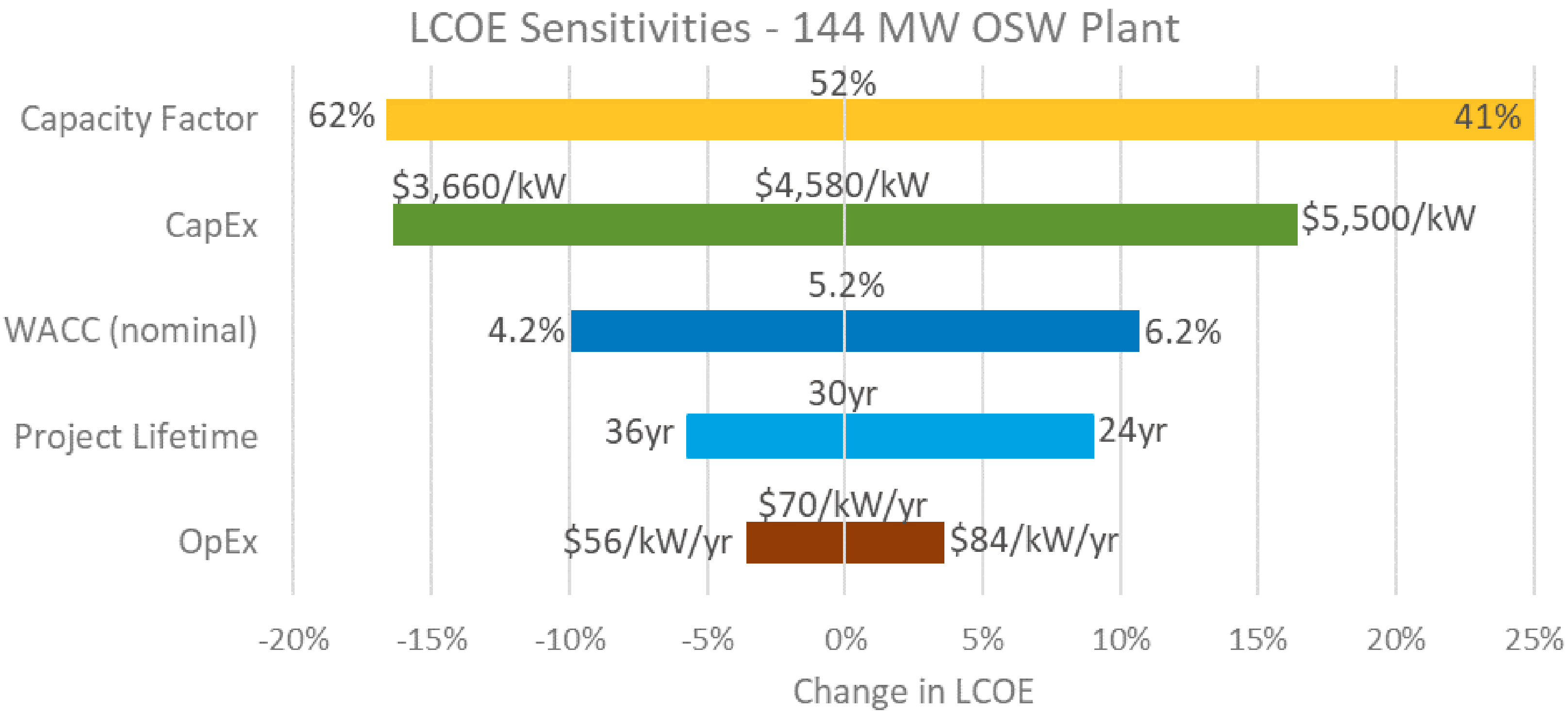
- The capital expenditures (CapEx) associated with wind farm development are sensitive to multiple factors, including especially water depth and distance to landfall.



The values presented here are relative to the baseline value for a 144-MW offshore wind power plant when varying physical site parameters by ±20% (dark bars) or across the full range of possible values within the Humboldt WEA (light bars). Labels by each bar indicate the value of the parameter corresponding to the baseline (center), low, and high CapEx results.

Wind Farm LCOE Sensitivity Analysis

- The levelized cost of energy (LCOE) values are especially sensitive to capacity factor, CapEx, and the weighted average cost of capital (WACC).



The value presented here represent the change in LCOE relative to the baseline value for a 144-MW offshore wind power plant when varying financial parameters by ±20%. Labels on each horizontal bar indicate the parameter values that produce the baseline (center), low, and high LCOE.