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The Offshore Report: California

Plummeting offshore wind (OSW) costs can accelerate a diverse net-zero grid

Working Paper #1

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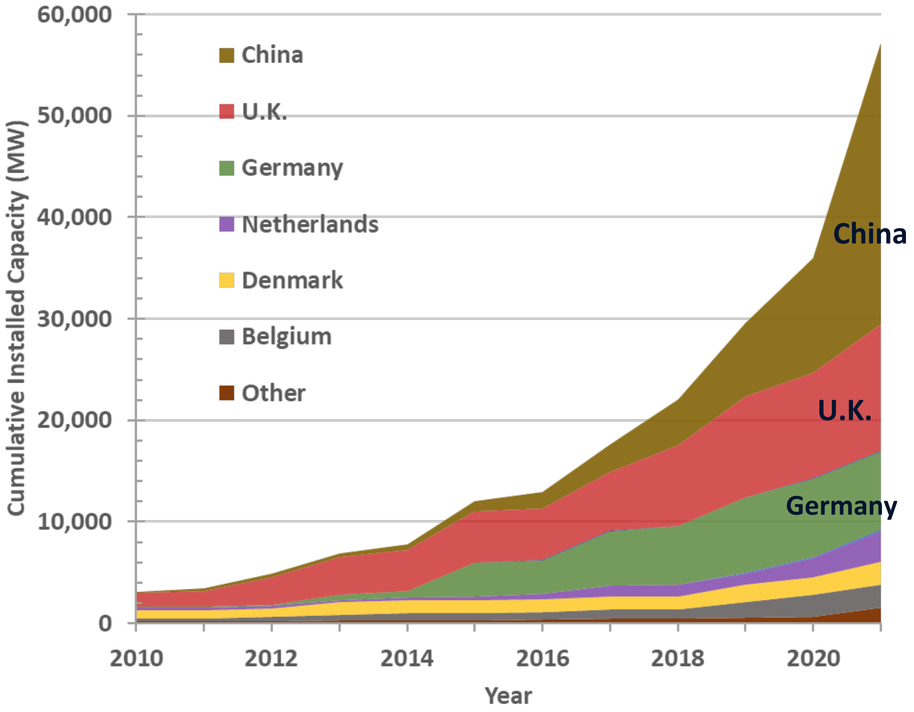
This working paper is circulated for discussion and comments. The paper although has been reviewed by internal experts, has not been fully peer-reviewed or been subject to review by any editorial board.

Summary of Recommendations

- **Consider a planning goal of ~15-20 GW by 2035 and ~50 GW by 2050**
  - Critical to ensure sufficient and diverse clean power supply to support net zero economy by 2045. Current plans (SB 100 Joint Report) appear to be missing ~ 100 GW PV equialent electricity that maybe required for green H2 and CDR as proposed in the scoping plan
  - More assessment needed to indentify strategies for the required infrastructure and environmental safeguards
- **Evaluate a procurement target/mandate to provide market certainty and economies of scale to further drive down floating OSW costs**
- **Evaluate a backbone multi GW sub-sea transmission that reduces interconnection and transmission timelines and costs**
- **Support floating OSW RD&D**

Globally, offshore wind installed capacity has reached about 60GW



Note: Most of the existing installations are fixed-bottom.

CA OSW planning goals in context

CA: 3 GW by 2030; 10-15 GW by 2045

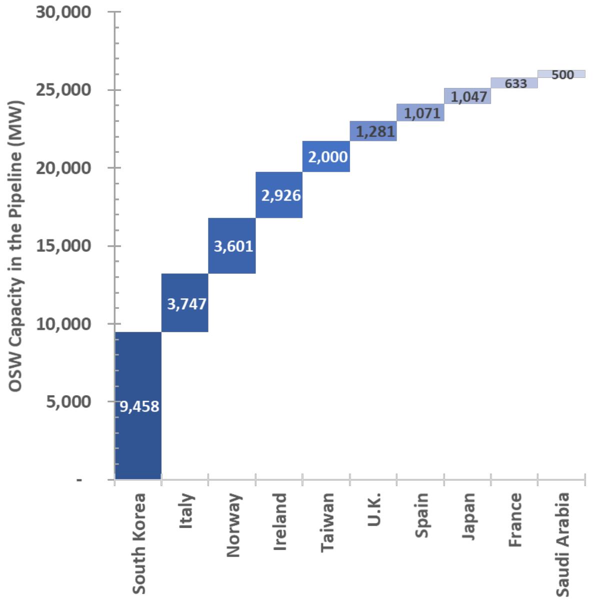
UK: 50 GW by 2030 (similar electricity demand as CA)

China: 17GW installed in 2021 alone

Poland & India: GW scale deployment by 2025-2027

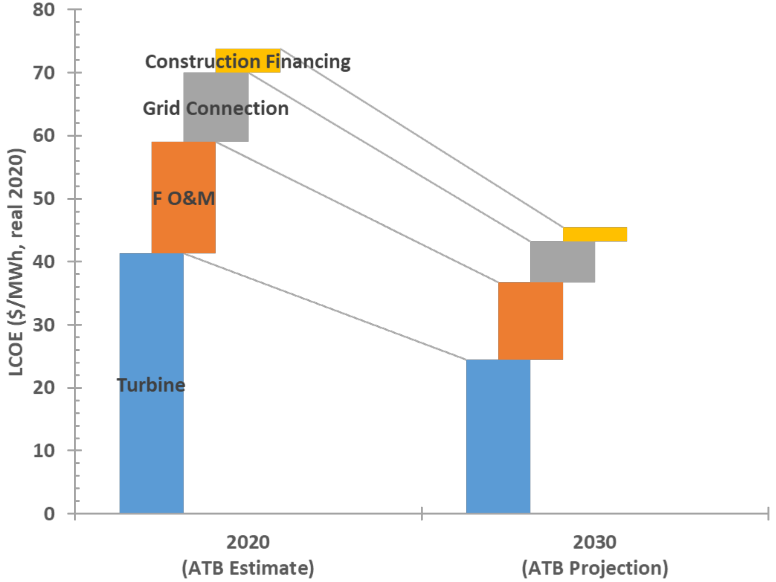
Globally, >25 GW of floating OSW is in the pipeline, while 40% cost reductions are projected by 2030

Floating OSW pipeline (Global)



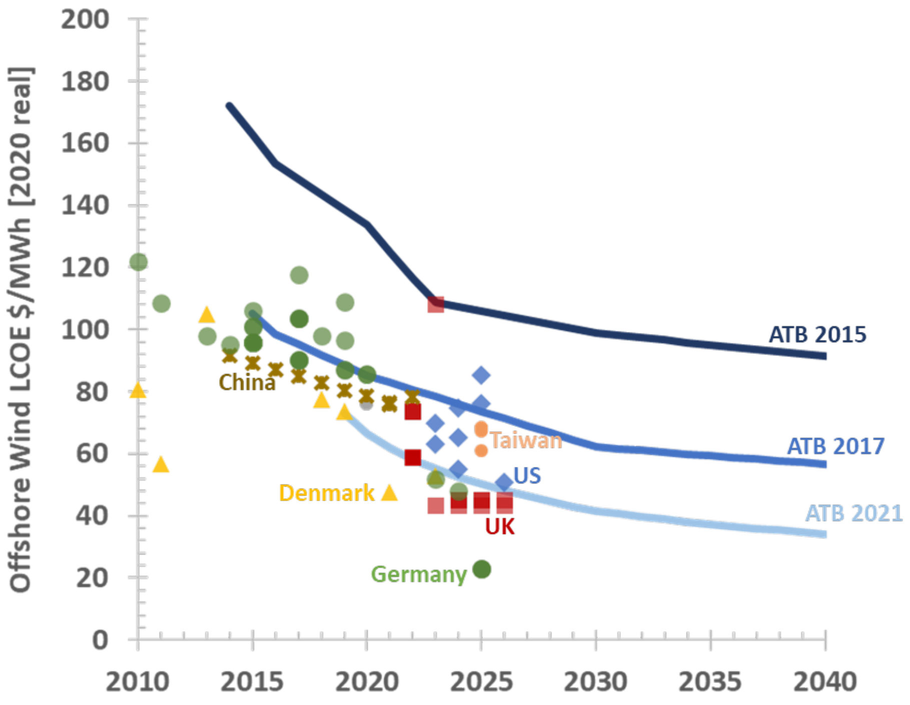
Data source: DOE's Offshore Wind Market Report (2021)

Floating OSW LCOE (US)



Data source: NREL Annual Technology Baseline (2021) - Advanced case
See also Beiter et al. 2020 (NREL)

Offshore wind costs have dropped much faster than anticipated; Several auction prices are ~$50/MWh



Solid blue lines

NREL Annual Technology Baseline (ATB) Low/Advanced-case cost projections made 2015–2021 for years through 2050 for fixed-bottom OSW projects. LCOE projections were revised downwards in almost every projection year during this period.

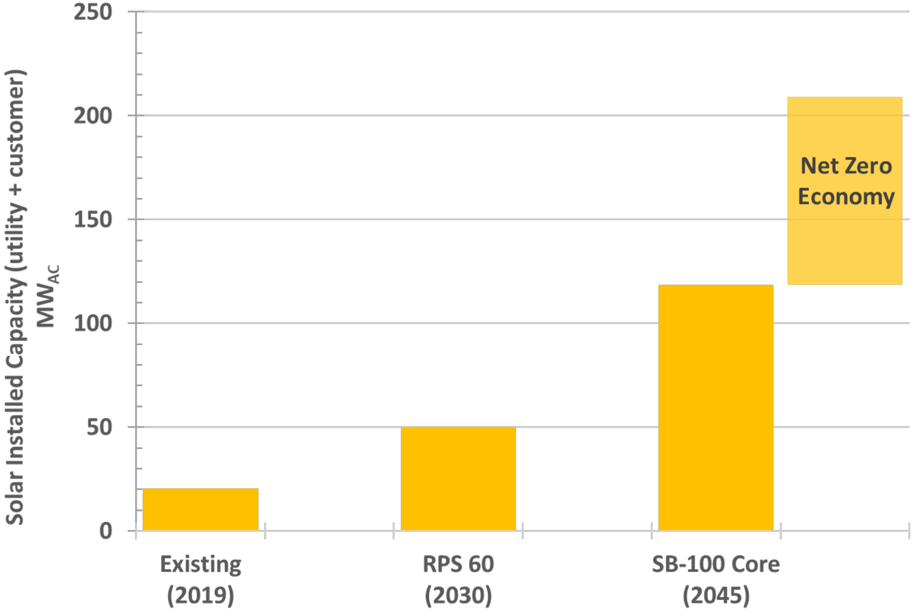
Colored dots

OSW auction prices are levelized (BNEF) and are mostly for fixed-bottom OSW projects.

Note

All numbers are expressed in 2020 real US $.

Solar dominant CA grid for a net zero economy may need ***double*** the solar capacity additions planned in the *SB-100* core scenario



SB 100 core scenario It is likely missing ~ 80 - 100 GW of PV (or equivalent) for a 2045 net zero goal

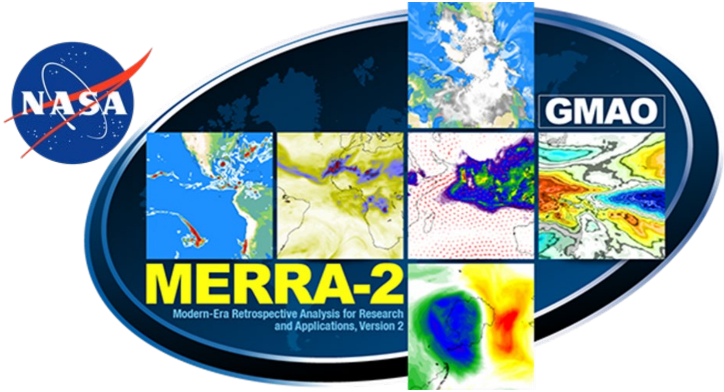
40 GW additional PV required for green H2 (source: CARB Scoping Plan)

CARB scoping plan assumes 80-100 MT CDR, could require ~ 100 TWh ~ 50 GW of additional PV

Reduction in hydro and increased cooling may further increase the need for clean electricity resources

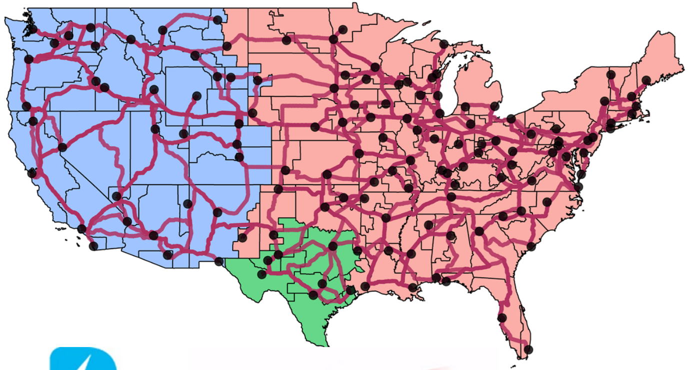
Hence we evaluate deployment of OSW at scale where it provides significant clean power, as we will likely need a lot of it, and probably should not just rely on PV

Data and Methods Summary



Offshore Wind Potential Assessment

- Estimated @150-meter hub height for 15 MW turbines;
- Used NASA MERRA- 2 satellite data w/ NREL SAM model;
- 600 MW wind farms modeled at 800 individual sites off the CA coast, selected after several exclusions



Power System Assessment

- WECC-wide simulation with CA specific targets
- Capacity expansion: NREL ReEDS v2021 (134 regions across the US; 35 in WECC; 4 in CA; 320 transmission corridors in US)
- Hourly dispatch: Plexos (>5,000 individual power plant level hourly dispatch in WECC)
- Cost projections: Fuel prices from EIA AEO 2021; clean technology costs from NREL ATB 2021

ReEDS

PLEXOS BY ENERGY EXEMPLAR

Overall 30 scenarios modeled with all combinations of the following parameters

CA Policy	Rest of the US Policy	CA OSW Deployment by 2045	Clean Technology Costs	Fossil Fuel Prices	Demand
SB-100 (NZ by 2045)	**No new policy**	***Least Cost***	Low (NREL ATB Low)	**Reference** (EIA Annual Energy Outlook 2022)	**High Electrification** (470 TWh by 2045) *Transport and buildings electrified*
	NZ by 2045	25 GW	**Base (NREL ATB Mid)**		
		50 GW	High (NREL ATB High)		
		75 GW			
		100 GW			

Core Scenarios for Analysis

Meet SB-100 goal in California by 2045 using one of the following two pathways:

1. <u>Current Policy</u>

- OSW deployment per the least cost capacity expansion
- Rest of the US continues with current policies
- Base technology costs (NREL ATB Mid Case)
- ⇒ Solar supplies ~70% of electricity supply by 2045

2. <u>50 GW Offshore Wind Case</u>

- CA OSW deployment is 50 GW by 2045
- Rest of the US continues with current policies
- Base technology costs (NREL ATB Mid Case)
- ⇒ OSW and solar each supply ~40% of electricity by 2045

Key Findings

1. CA has one of the world’s best offshore wind potential: 200 GW technical; 120 GW at >50% capacity factor; summer and evening peaking; potential could be much higher with future tech.

2. Strong policies required for CA to achieve a diverse net-zero grid with significant OSW

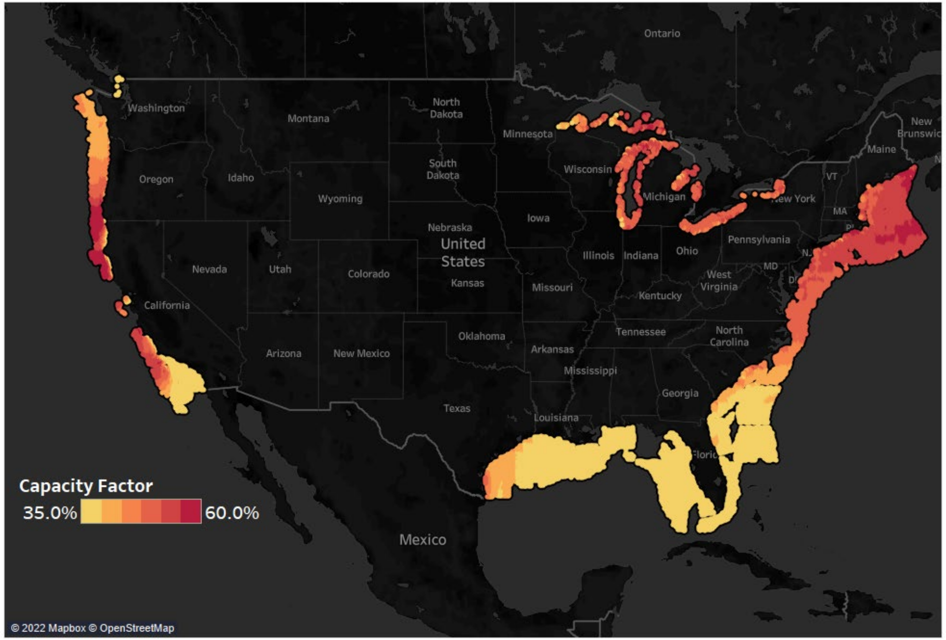
3. Significant OSW (15-20 GW by 2035 and up to 50 GW by 2045) can be deployed to increase resource diversity without increasing wholesale electricity costs

4. Grid with significant OSW is dependable with less storage and solar, which are cited as concerns in the CARB scoping plan in meeting in accelerated emission reduction goals

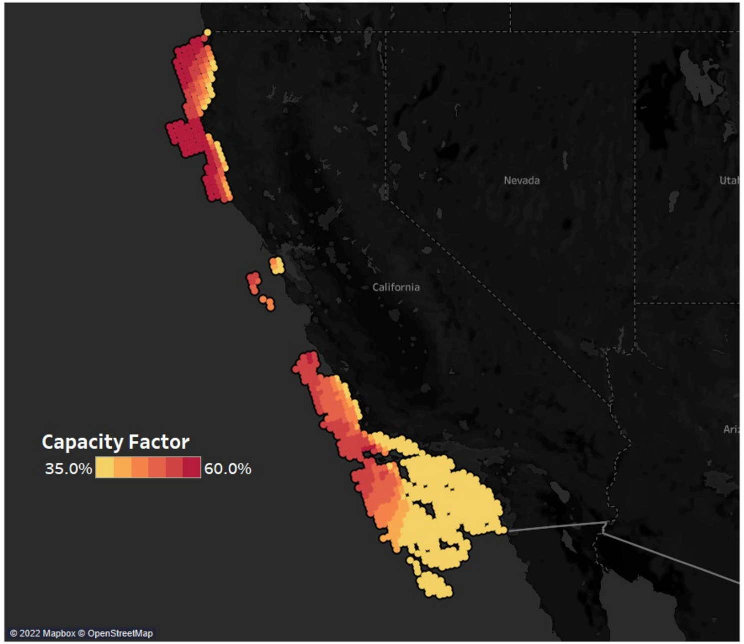
5. CA can become the global leader in the floating OSW technology; massive potential & need in countries like Japan, Korea etc.

1.1 Significant offshore wind potential in the US and California

U.S. OSW potential is well spread out with >1000 GW at a capacity factor >50%



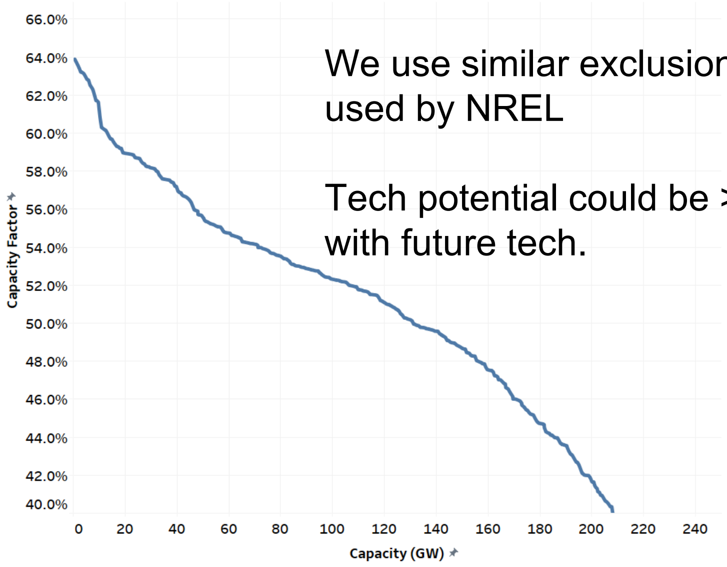
Most of the CA OSW potential is floating with >120GW at capacity factor >50%



1.2 CA has some of the best offshore wind potential in the world

200 GW technical; 120 GW w/ capacity factor >50%; summer & evening peaking

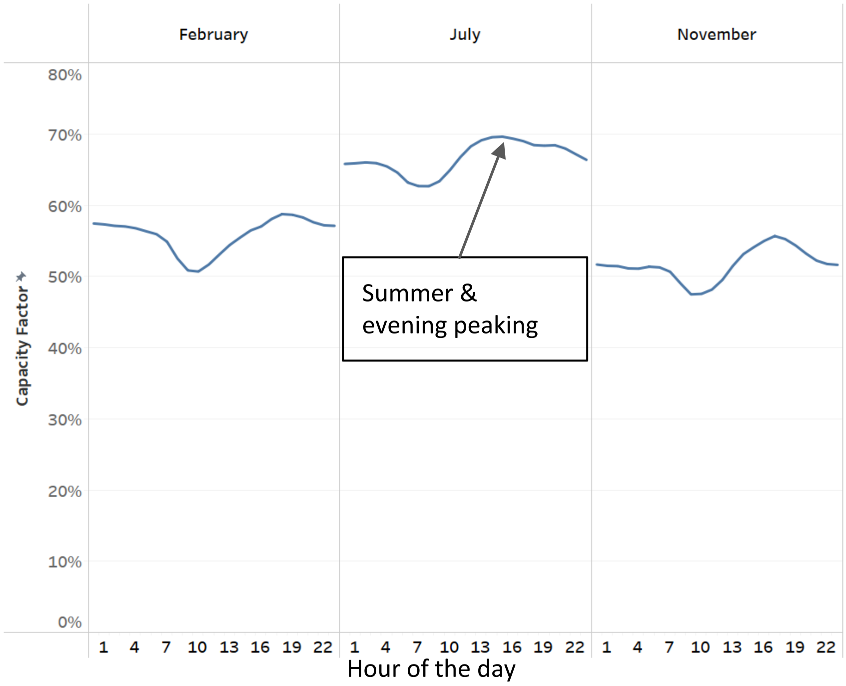
Offshore wind supply curve



We use similar exclusions as used by NREL

Tech potential could be > 4X with future tech.

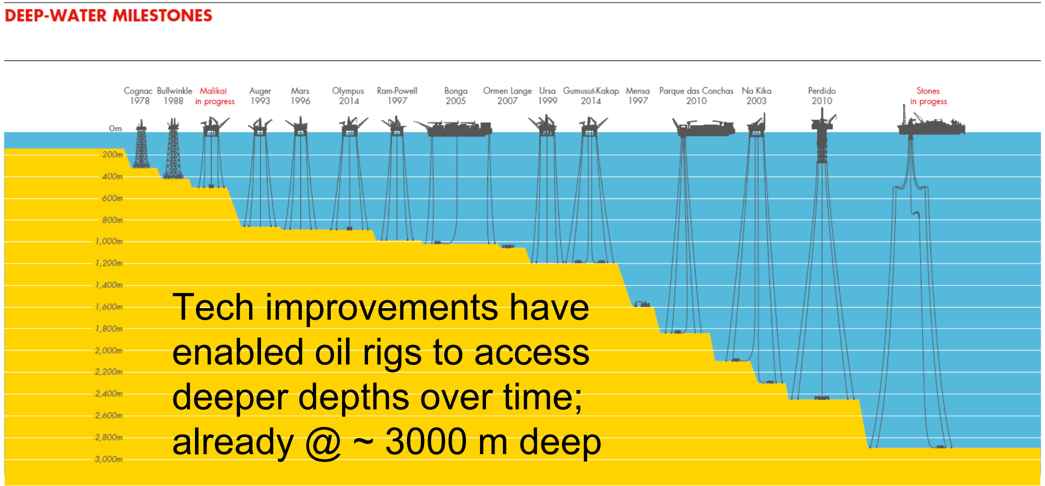
Hourly generation profile shows complementarity with solar and load

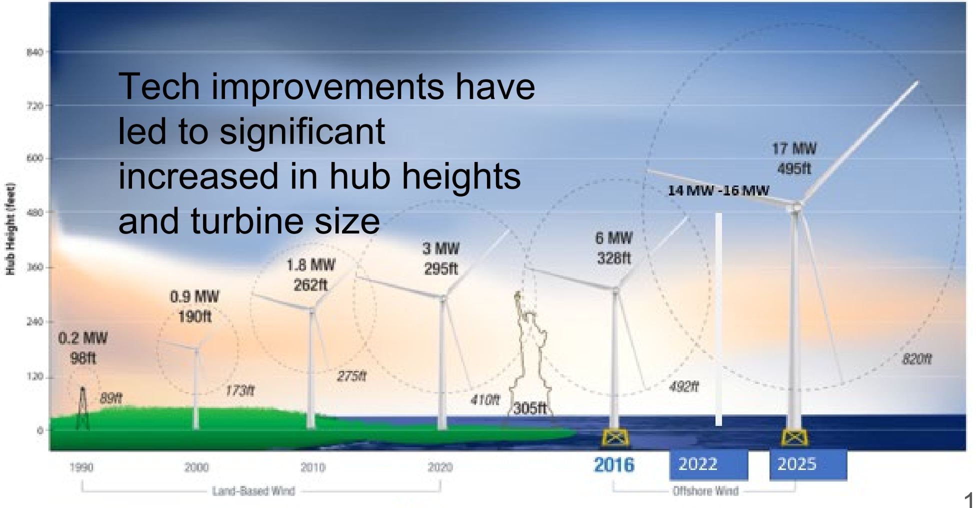


Our estimates are similar to the NREL California offshore wind potential study (Optis M, et al, 2020)

OSW potential likely to much higher with future technology and markets

- Increasing floating wind depth from 1300 m to 3000 m (deepest oil rigs) – tech potential appears to increase from 200 GW to 400 GW
- Doubling energy density (already achieved in EU), potential can be 2X
- Significant potential in Oregon that can be accessed
- Likely opportunity to deploy 50 GW (out of say 800 GW of future tech potential) in best locations while protecting the environment and addressing competing uses and concerns

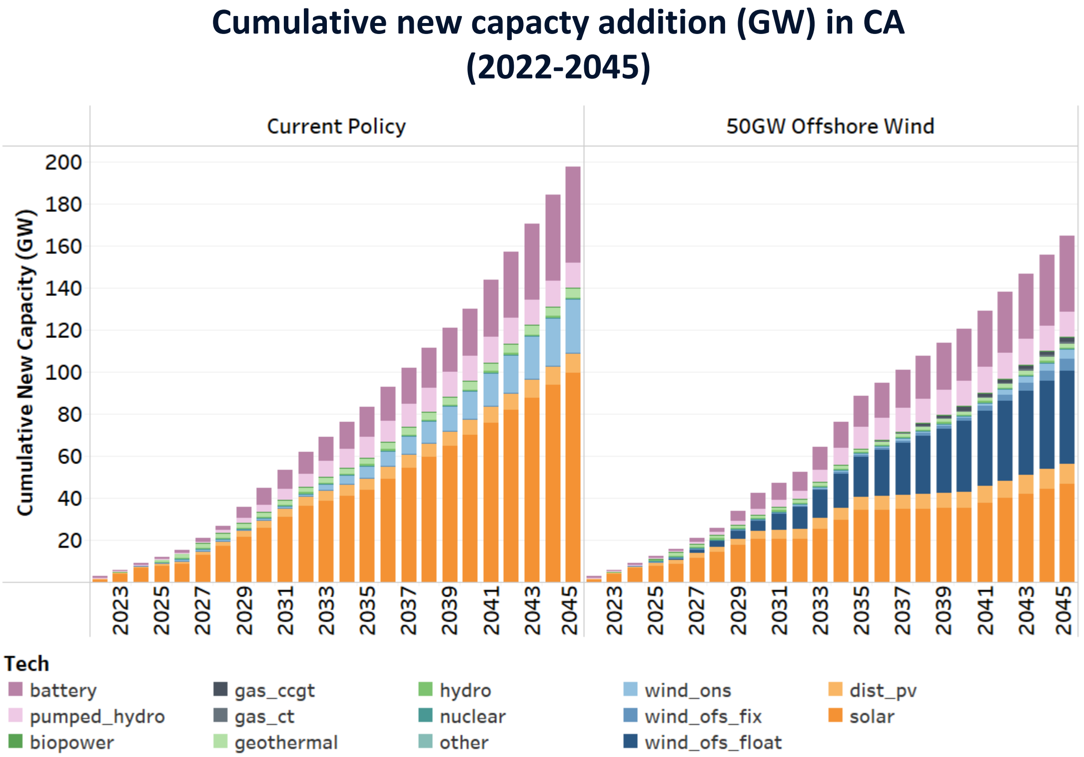




Wind Turbine Capacity (Megawatt) | Hub Height (feet)
Rotor Diameter (feet)

Source: DOE; Modified for later years based on latest market data

2.1 Strong policies are required for CA to achieve a diverse net-zero grid with significant OSW



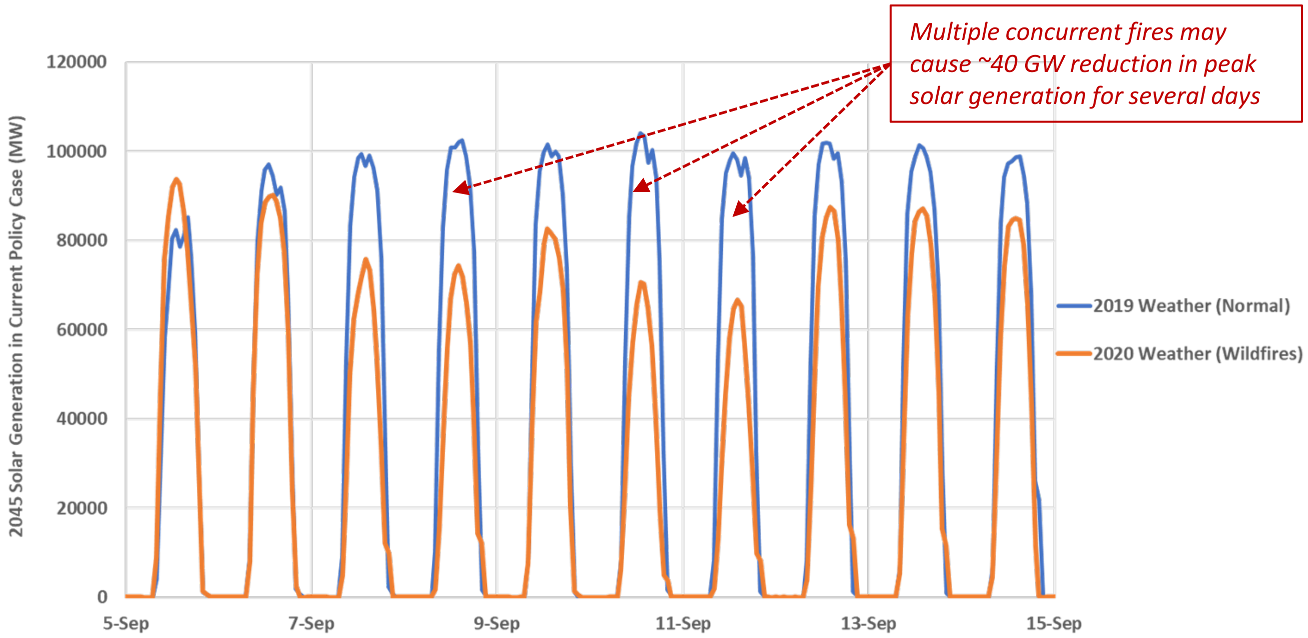
The Current Policy case assumes continuation of current state and federal policies which leads to a solar PV dominated zero emission grid in California by 2045.
(130 GW Solar + 53 GW storage)

The **50GW OSW case** results in a more diverse zero emission grid.
It reduces the solar (77 GW) + storage (44 GW) deployment.

Strong policies would be required for significant OSW additions
(~5 GW total by 2030 and ~3 GW/yr after 2030)

2.2 A solar only system faces increasing wildfire risk; which can be mitigated with a more diverse portfolio

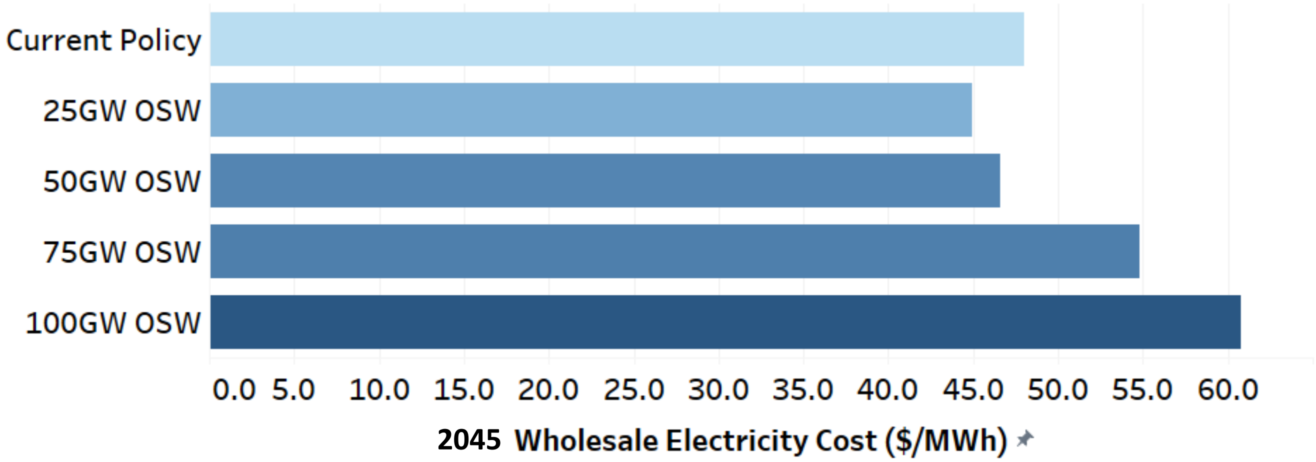
Chart shows simulated solar generation in 2045 in the Current Policy Case, using 2019 (normal) and 2020 (wildfire risk) weathers



In 2020, due to multiple wildfires in September, CA solar generation dropped by ~15-20% for over a week.

In the **Current Policy Case**, the peak solar generation risk in 2045 due to wildfires could be as high as **35-40GW.**

3.1 Deploying up to 50GW of OSW by 2045 increases resource diversity without increasing wholesale electricity costs (1/2)

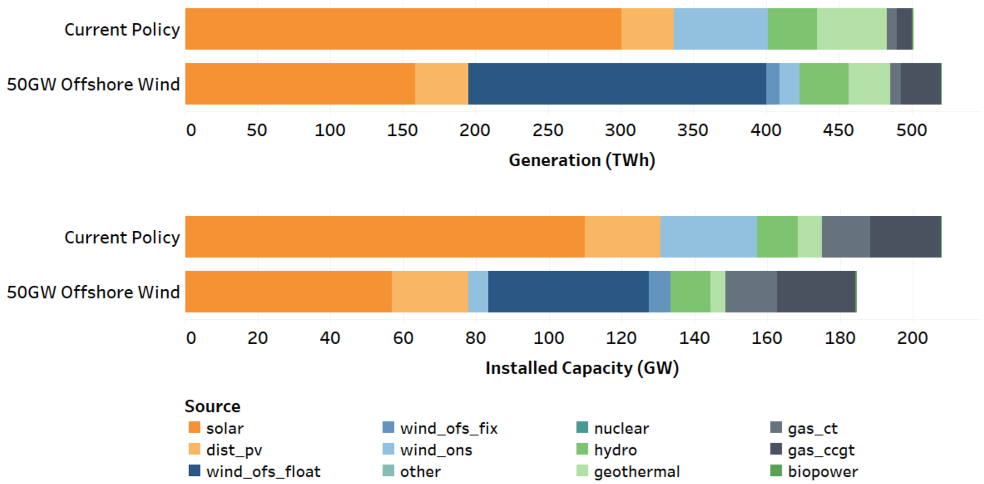


All cost numbers are in 2020 real $.

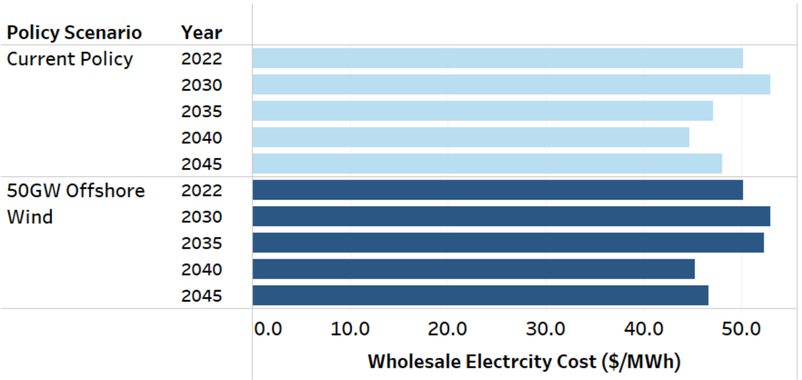
Wholesale electricity cost **includes the fixed and variable costs of all (new + existing) power plants in the state, out-of-state import-export costs/revenue, and new bulk transmission as well as interconnection costs.**

3.1 Deploying up to 50GW of OSW by 2045 increases resource diversity without increasing wholesale electricity costs (2/2)

Annual generation and installed capacity in 2045



Average wholesale electricity cost
($/MWh, 2020 real)

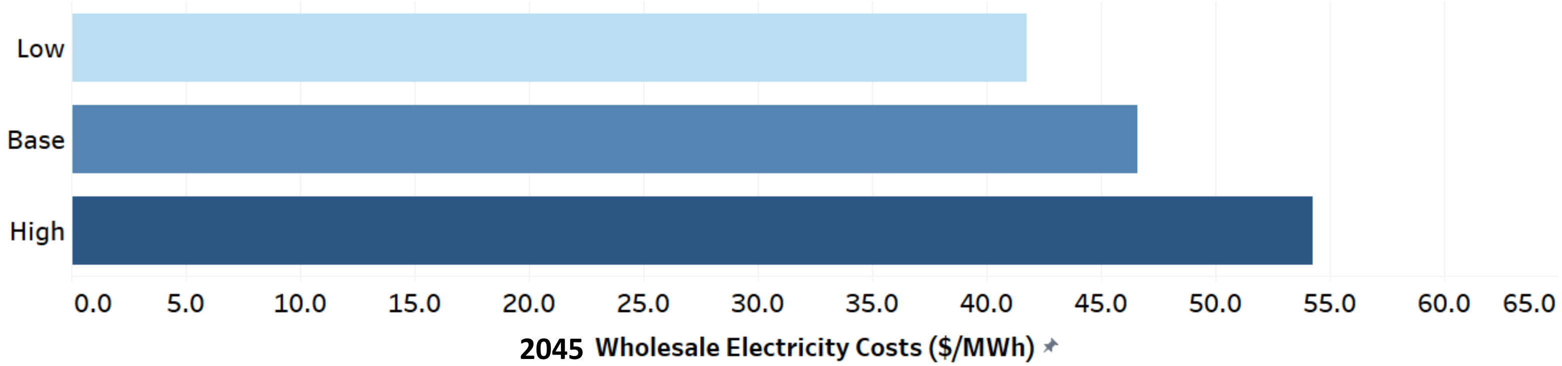


Average cost reduces compared to today; comparable with the Current Policy case

Note: 2035 costs are slightly higher for the OSW case than current policy but lower than 2022 costs

3.2 If OSW costs fall rapidly (ATB Low) CA benefits from even lower wholesale electricity costs

Clean Technology Costs
Low (NREL ATB Low)
Base (NREL ATB Mid)
High (NREL ATB High)

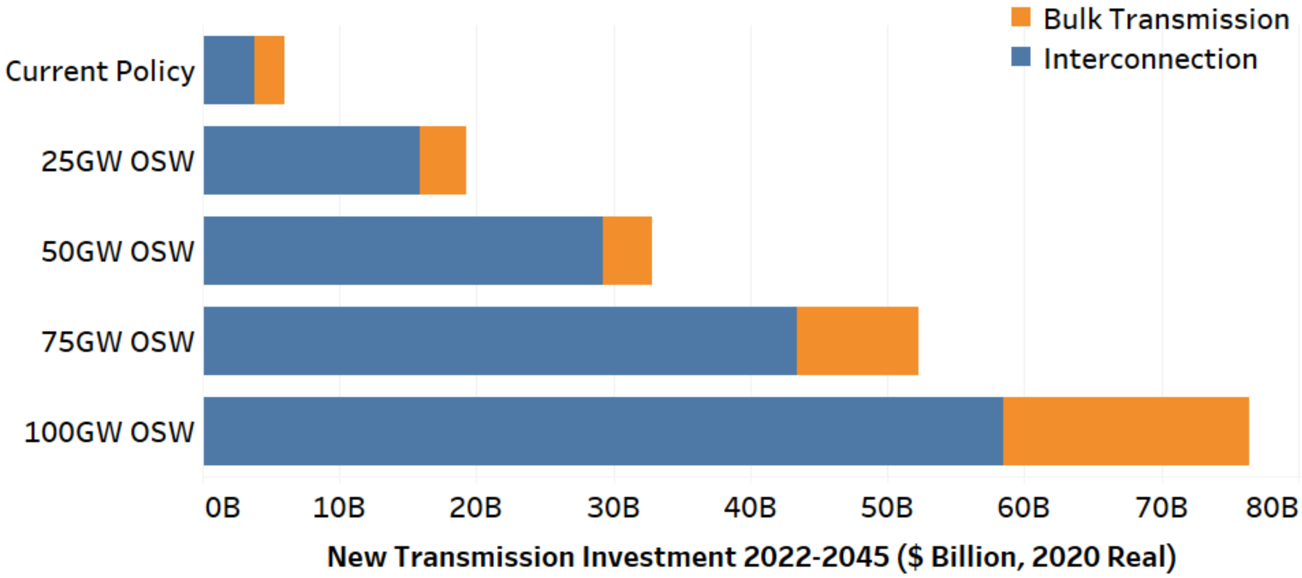


All cost numbers are in 2020 real $.

Some recent studies (e.g. Way et al 2021) have shown that faster deployment leads to lower costs

50 GW deployment may increase the probability of the low cost case

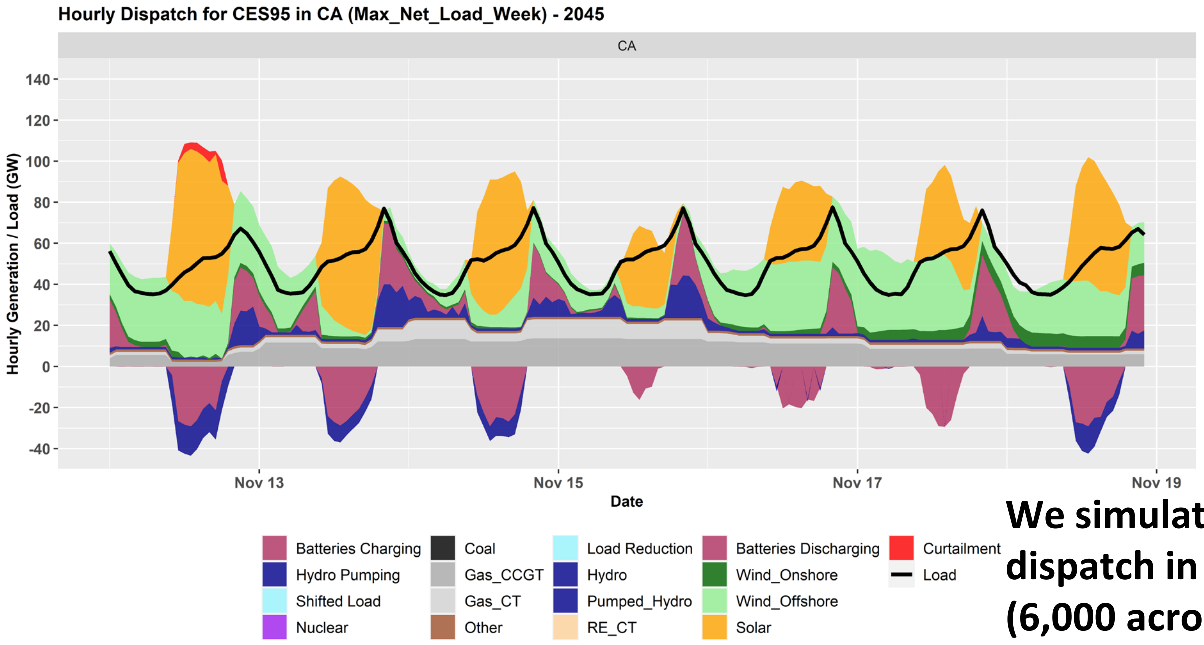
3.3 Transmission investment requirement for a zero emission grid (2022-2045)



A backbone transmission may reduce these costs significantly: Key area of future work

4.1 Grid with significant OSW is dependable with less solar and storage

CA dispatch in the 50GW Offshore Wind Case during the highest residual load week (2045)

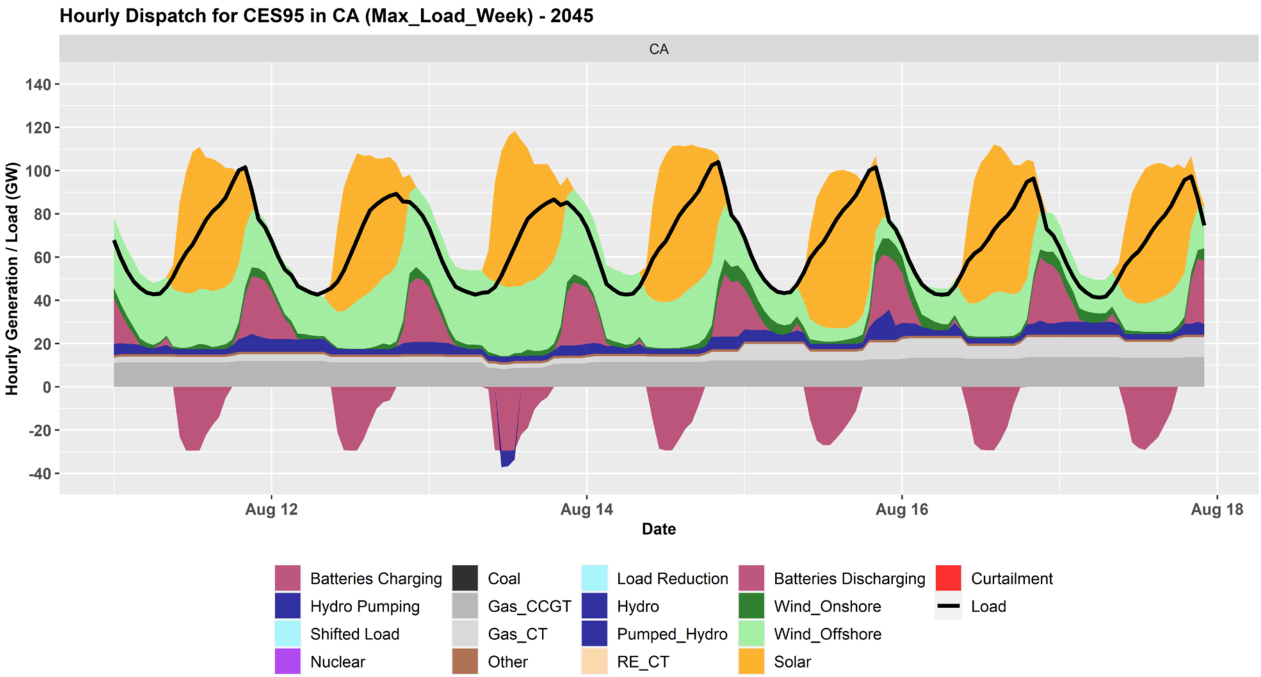


In the 50 GW OSW case, residual load in 2045 will be the highest in fall / early winter due to reduction in solar generation and 1-2 days of low wind generation.

We simulated hourly system operations and dispatch in 2045 at individual power plant (6,000 across WECC) and across 80 transmission corridors.

4.2 Grid with significant OSW is dependable with less solar and storage

CA dispatch in the 50GW Offshore Wind Case during the peak load week (2045)



The system peak load would nearly double by 2045 (~100 GW on August 15 at about 6 PM).

Solar, OSW, and battery storage work in tandem to meet the peak load.

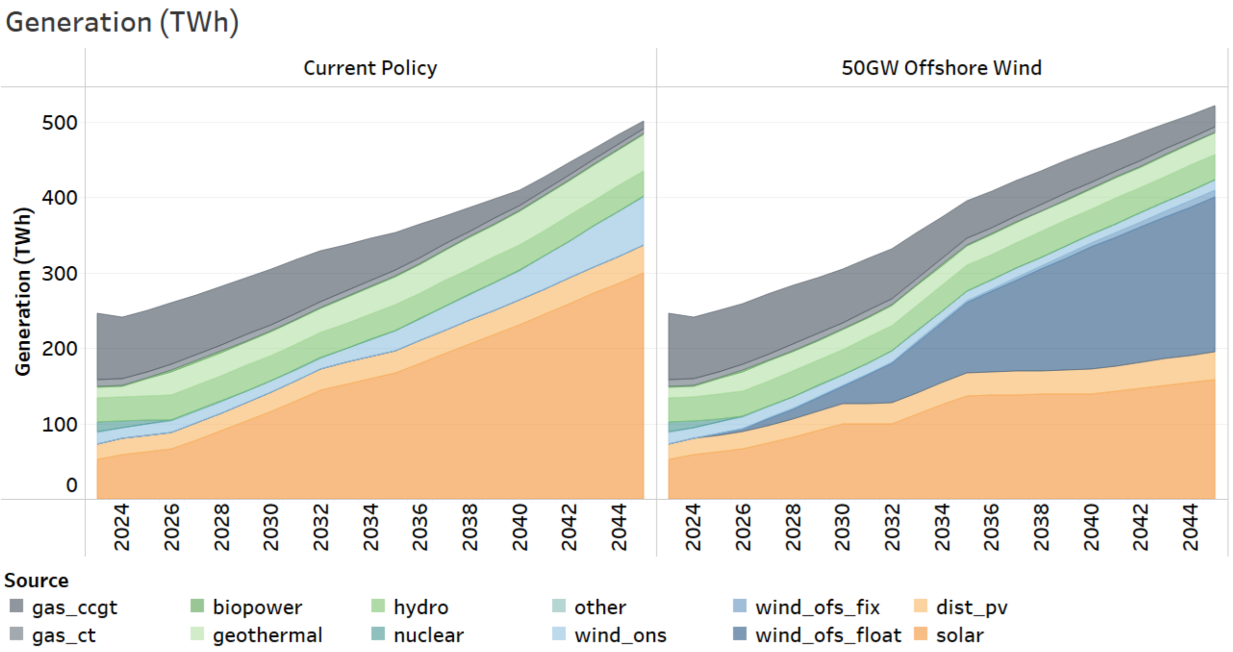
Summary of Recommendations

- **Consider a planning goal of ~15-20 GW by 2035 and ~50 GW by 2050**
  - Critical to ensure sufficient and diverse clean power supply to support net zero economy by 2045. Current plans (SB 100 Joint Report) appear to be missing ~ 100 GW PV equialent electricity that maybe required for green H2 and CDR
  - More assessment needed to indentify strategies for the required infrastructure and environmental safeguards
- **Evaluate a procurement target/mandate to provide market certainty and economies of scale to further drive down floating OSW costs**
- **Evaluate a backbone multi GW sub-sea transmission that reduces interconnection and transmission timelines and costs**
- **Support floating OSW RD&D**

Additional Results

Significant OSW additions lead to a more diverse grid

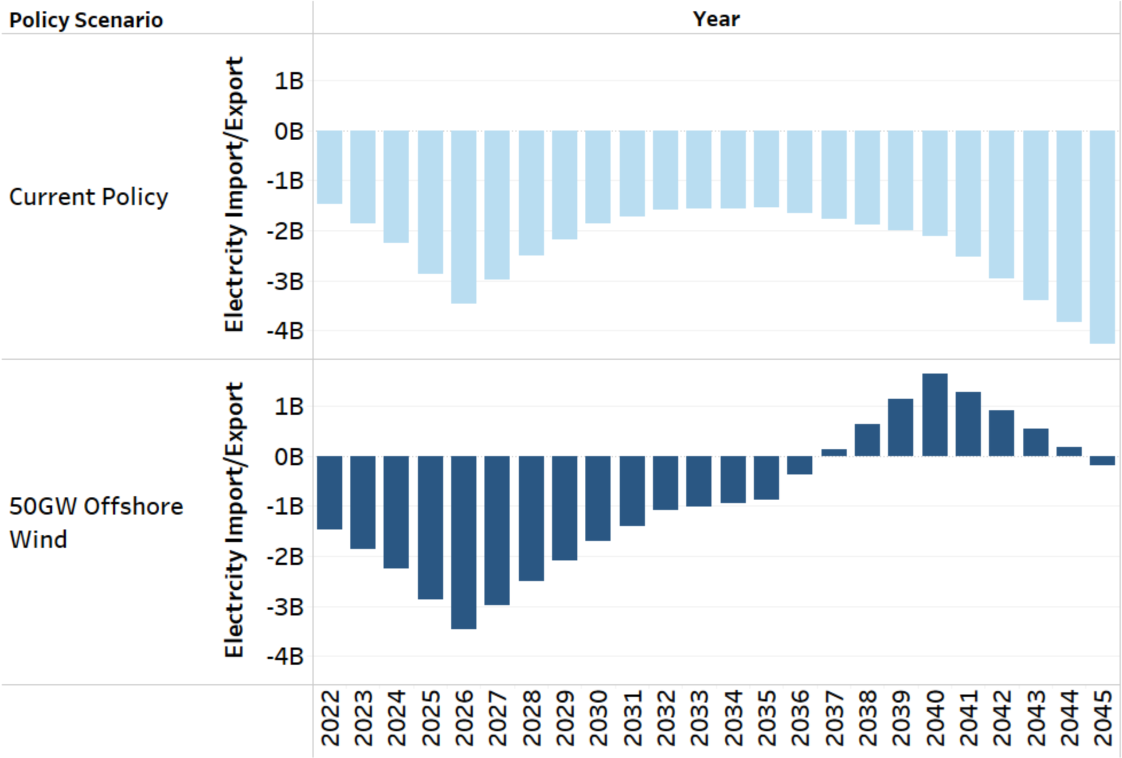
Annual energy generation in CA (Current Policy and 50 GW OSW Case)



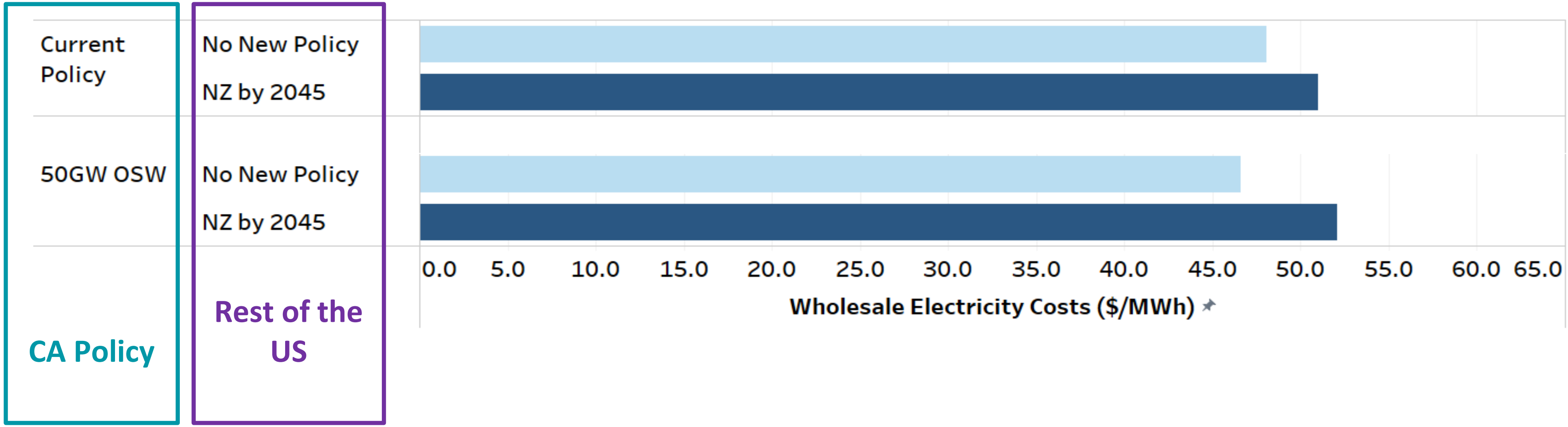
The Current Policy case leads to a solar PV dominated grid by 2045.
Solar provides 70%, onshore wind 10% and other clean resources provide 15% of the total electricity supply.

50GW OSW case leads to a more diverse grid. OSW and solar each provide ~40% of total electricity supply, onshore wind supplies 5%, and other clean resources supply 15% by 2045.

Offshore Wind will significantly reduce unspecified electricity imports



If rest of the US also achieves a net-zero grid by 2045, wholesale electricity costs still do not increase beyond 2022 levels

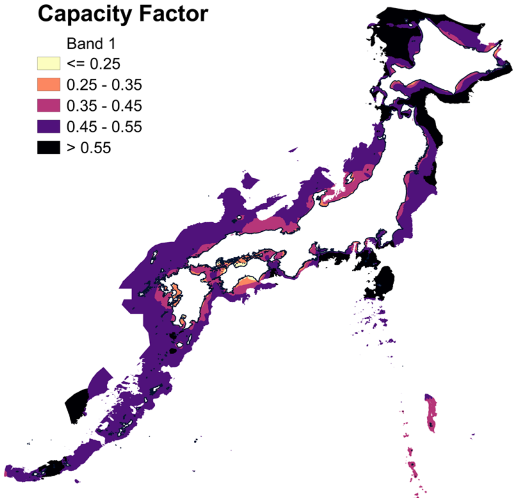


Wholesale electricity cost includes the fixed and variable costs of all (new + existing) power plants in the state, out-of-state import-export costs/revenue, and new bulk transmission as well as interconnection costs.

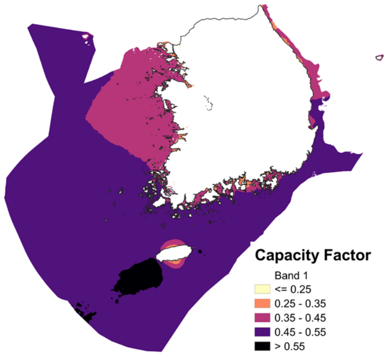
All cost numbers are in 2020 real $.

Significant global opportunity for floating OSW
e.g. in Japan and Korea, OSW is critical even for short-medium term decarbonization

Japan : 750 GW OSW potential with capacity factor >50%



Korea : 650 GW OSW potential with capacity factor >40%



Both countries have poor quality of land-based wind (~20-25%) & solar (~15-18%) resources, and high (~70% of energy) + expensive imports (~$8-15/mmbtu)

One Page Summary

Challenge: SB 100 plans rely on PV to achieve zero emission grid by 2045 without much resource diversity, which may lead to deployment and climate change induced risk

OSW Opportunity: Plummeting costs; scaled up deployment [UK auctions @$50/MWh; 50 GW target by 2030], GWs of floating OSW under planning globally; CA is blessed with high OSW potential

Our study: We consider latest OSW technology and cost trends to assess significant deployment in the CA grid by 2045 by conducting state-of-the-art capacity expansion (ReEDS) and production cost modeling (Plexos) of the CA-WECC power system

Findings:

1. CA blessed with OSW resource: ~200 GW technical; 120 GW> 50% cap factor; summer and evening peaking
2. Strong policies required for CA to achieve a diverse net zero grid with significant OSW
3. 50 GW OSW can provide resource diversity for a net zero grid without increasing wholesale electricity costs
4. Grid with significant OSW is dependable with less storage
5. CA can become the global leader in the floating OSW technology; massive potential & need in countries like Japan, Korea etc.

Recommendation:
Consider deploying upto 50 GW of OSW in California by 2045

Appendix 1:
Marginal Contributions of This Study

Summary of the marginal contributions of this study

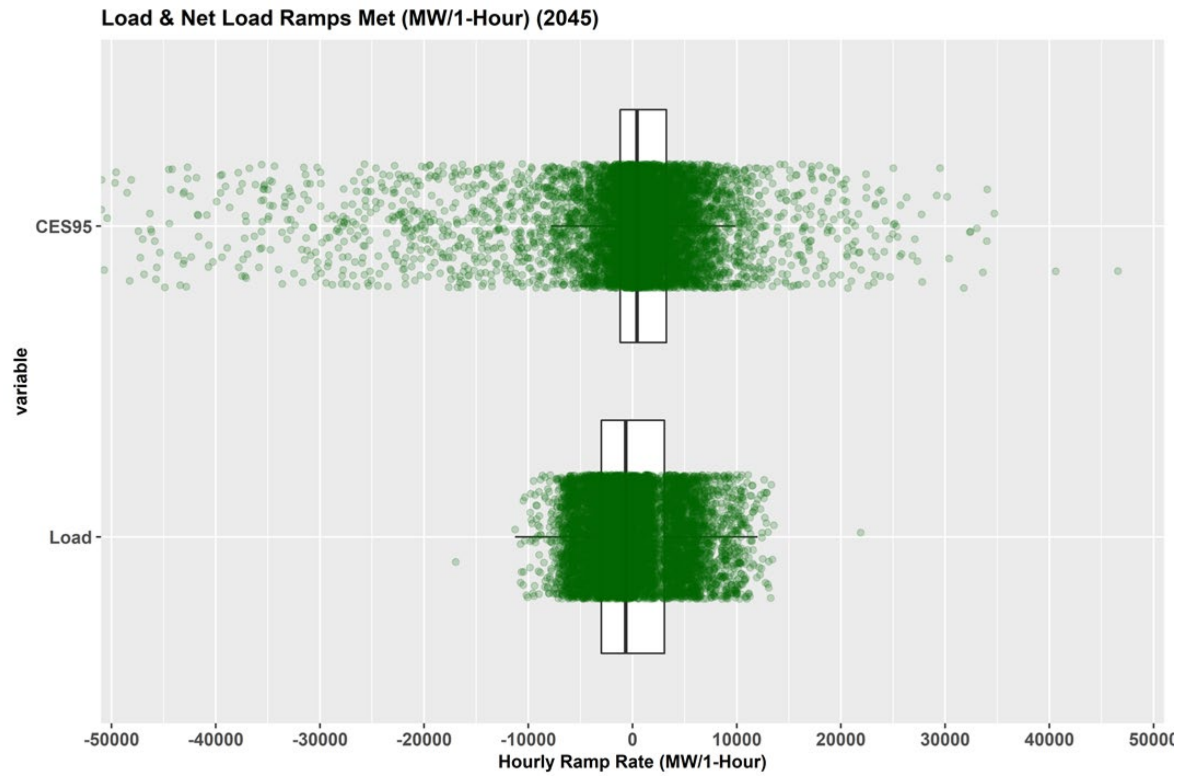
	CEC AB 525 and SB 100 Reports	UCB CA Offshore Wind Report
Zero emission for 100% retail electricity sales	Y	Y
Load w/high electrification	Y	Y
Load w/economy-wide net-zero emissions	N	N
Updated OSW potential	N	Y
Assessment of significant OSW in CA grid	N	Y
High resolution capacity expansion assessment	N	Y
Hourly grid dispatch assessment	N	Y
Bulk transmission assessment	N	Y
WECC wide assessment	N	Y

Marginal contributions of this study

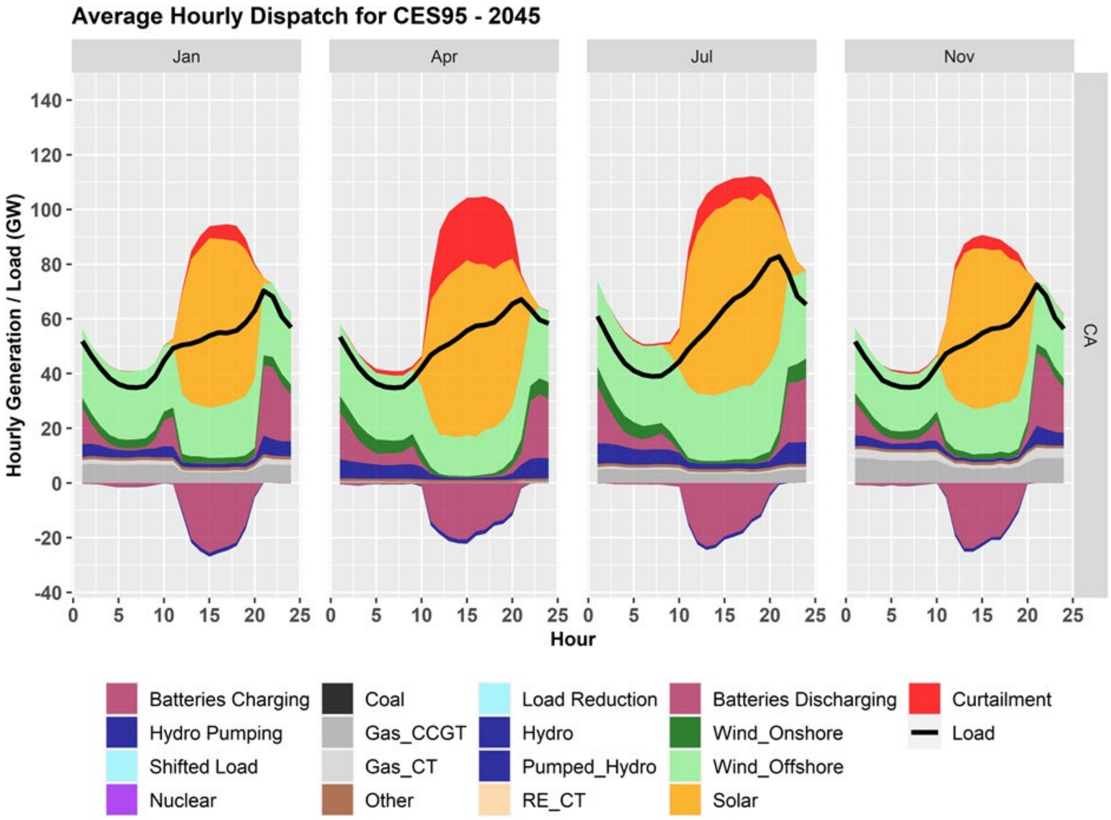
	CEC AB 525 and SB 100 Reports	UCB CA Offshore Wind Report
Zero emission for 100% retail electricity sales	**Y**	**Y**
Load w/high electrification	**Y** (load by 2045 = ~440 TWh)	**Y** (load by 2045 = ~470 TWh)
Load w/economy-wide net-zero emissions	**N** (80% GHG reduction by 2050)	**N** (90% GHG reduction by 2050)
Updated OSW potential	**N** (OSW potential of 21.8 GW ONLY from the current call areas)	**Y** (OSW potential of >200GW per NREL, not limited to the current call areas)
Assessment of significant OSW in CA grid	**N** (Max OSW deployment = 10GW by 2045, which would be ~8% of supply)	**Y** (OSW deployment of 25 to 100 GW by 2045)
High resolution capacity expansion assessment	**N** (Single region model for CA)	**Y** (4-regions in CA; 35 across WECC)
Hourly grid dispatch assessment	**N** (No dispatch simulated)	**Y** (Houly dispatch at power plant level in PLEXOS)
Bulk transmission assessment	**N** (OSW transmission assessment per CAISO transmission plan ~3GW OSW by 2032)	**Y** (WECC-wide bulk transmisson & interconnection assessment in ReEDS)
WECC wide assessment	**N** (Single region model for CA)	**Y** (35 regions across WECC, including major interstate flows)

Appendix 2:
Additional Modeling Results

Ramping requirements will increase significantly by 2045, however, the grid will be able to meet them due to high battery storage capacity



Average hourly dispatch in CA in key months (50 GW OSW Case)



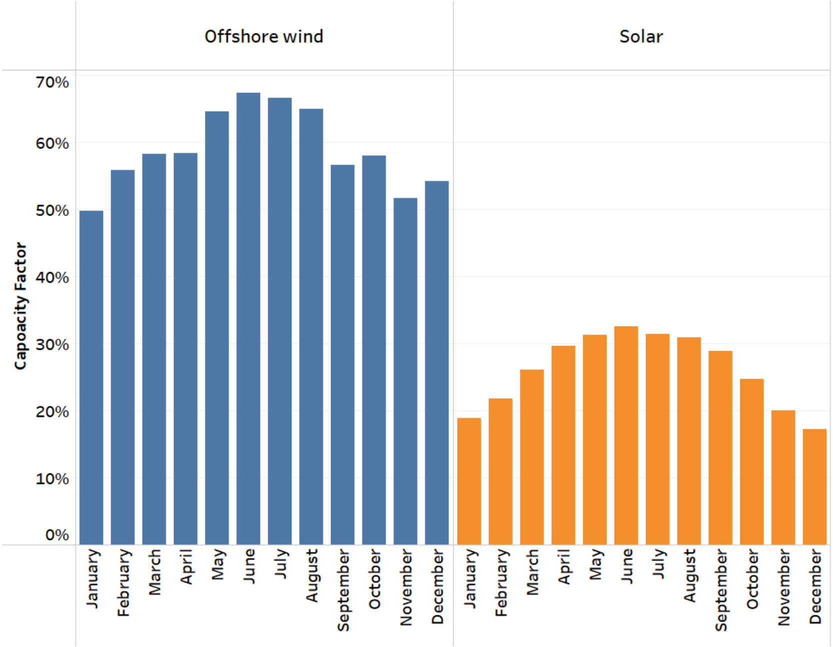
Solar and offshore wind have complementary profiles, which helps in reducing the battery storage requirement to a certain extent.

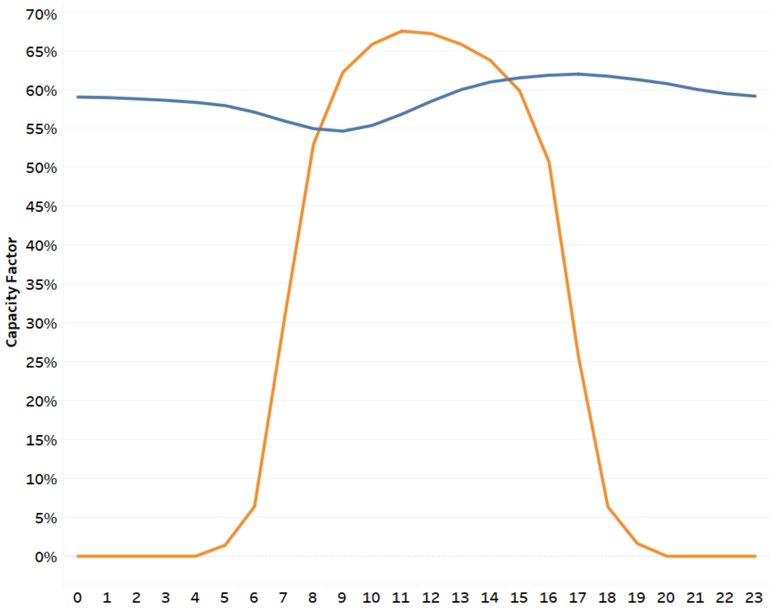
The state avoids most of the unspecified imports from out-of-the-state.

RE curtailment will be the highest in spring.

Batteries charge and discharge almost every day (~250 full charge/discharge cycles in a year).

Monthly and average hourly capacity factors in CA for OSW and Solar





Appendix 3:
Excerpts from CA Offshore Wind Potential Study by NREL (Optis, M, et al, 2020)

NREL CA OSW Potential Estimates

Table B. Comparison of Gross and Technical Potential Estimates from 2016 Report and This Report

Metric	2016 Report	This Report WIND Toolkit	This Report New CA20 Data Set
Minimum average wind speed ($m{\cdot}s^{-1}$)	7.0	7.0	7.0
Maximum water depth (m)	1,000	1,300	1,300
Array density ($MW{\cdot}km^{-2}$)	3.0	3.0	3.0
Gross potential (km^2)	566,058	566,058	566,058
Gross potential (gigawatts [GW])	1,698	1,698	1,698
Technical potential (km^2)	49,916	64,048	67,067
Technical potential (GW)	150	192	201

Table 9. Technical Potential Estimates from CA20 Data Set by Wind Speed Bins. Northern and Southern Potentials are Split Based on a Line at 37.8^o, Which Runs Through San Francisco.

Bin ($m{\cdot}s^{-1}$)	Northern CA (MW)	Southern CA (MW)	Total (MW)
7.0–7.5	2,845	14,636	17,480
7.5–8.0	3,086	16,106	19,192
8.0–8.5	3,540	19,787	23,327
8.5–9.0	4,233	21,388	25,621
9.0–9.5	5,313	33,465	38,778
9.5–10.0	6,972	26,836	33,808
10.0–10.5	12,268	549	12,817
10.5–11.0	15,540	0	15,540
11.0–11.5	8,404	0	8,404
11.5–12.0	6,234	0	6,234
Total	68,435	132,767	201,202

Table 10. Technical Potential Estimates from CA20 Data Set by Distance to Shore. Northern and Southern Potentials are Split Based on a Line at 37.8^o, Which Runs Through San Francisco.

Bin (Nautical Miles)	Northern CA (MW)	Southern CA (MW)	Total (MW)
<3	6,643	9,094	15,737
3–15	36,364	53,143	89,507
>15	25,428	70,530	95,958
Total	68,435	132,767	201,202

Source: CA Offshore Wind Potential Study by NREL (Optis, M, et al, 2020)

NREL CA OSW LCOE Estimates

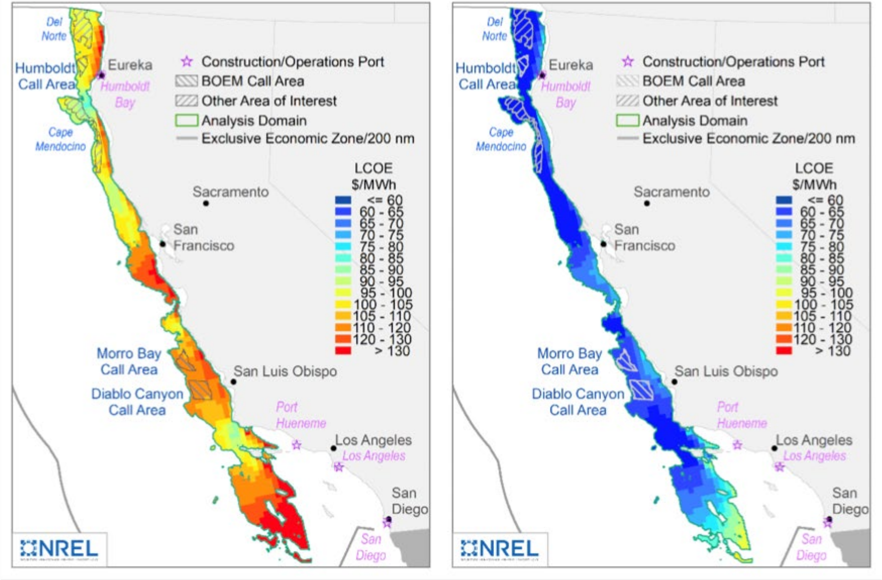


Figure ES-1. LCOE estimates (mid-case CapEx scenario) for the analysis domain offshore California estimated for a 2019 COD (left) and 2032 COD (right)

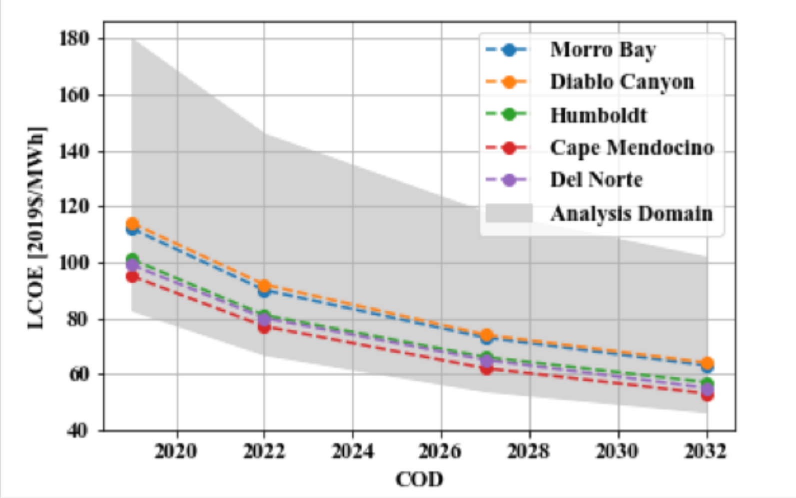


Figure ES-2. Estimated LCOE trajectory between 2019 and 2032 (COD)

Source: CA Offshore Wind Potential Study by NREL (Optis, M, et al, 2020)

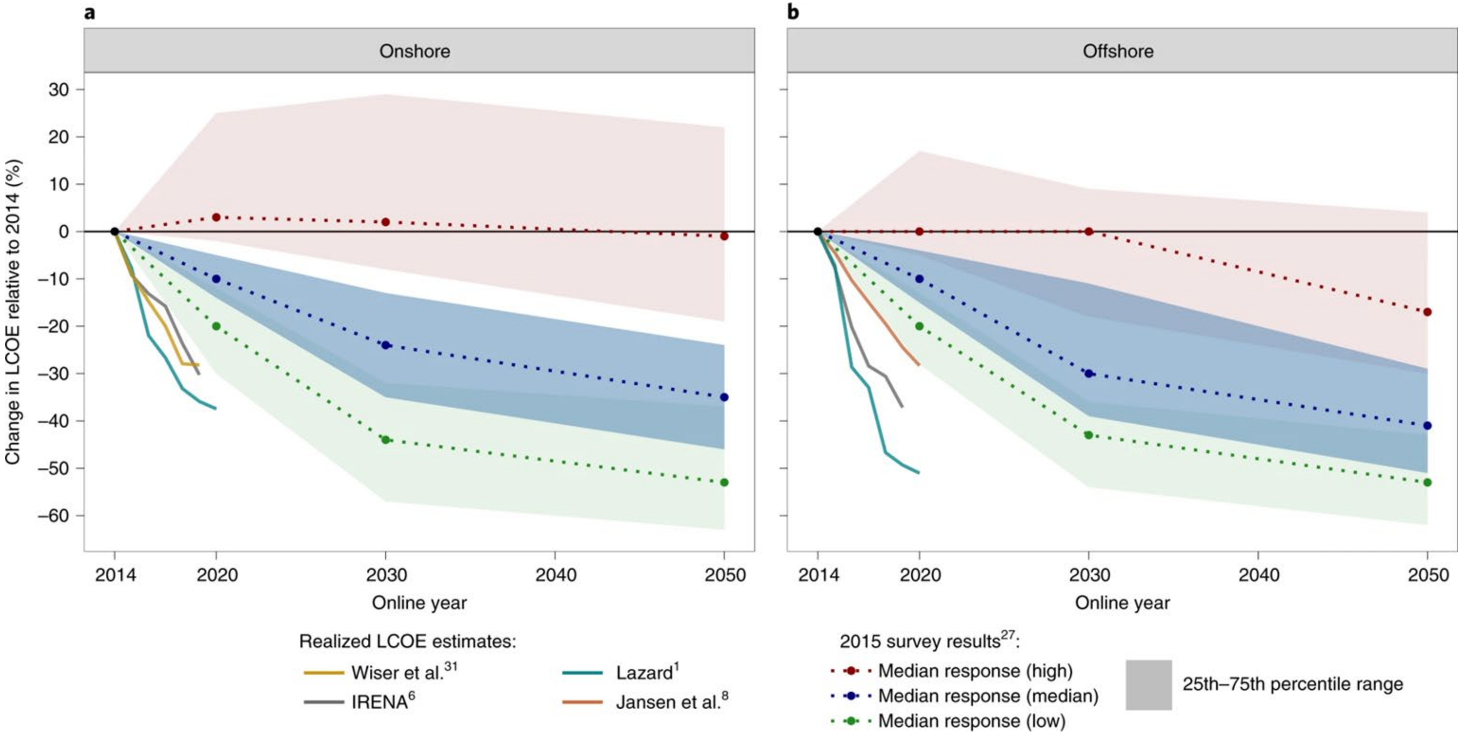
Table 18. Comparison Between the 2019-2020 IRP and NREL Cost and Performance Values

	Net Capacity Factor (%)		CapEx ($/kW)		OpEx ($/kW-yr)		LCOE ($/MWh)	
	2019–2020 IRP	NREL 2020	2019–2020 IRP	NREL 2020	2019–2020 IRP	NREL 2020	2019–2020 IRP	NREL 2020
COD	2030							
Morro Bay	55	49	3,791	3,139	71	64	76	67
Diablo Canyon	46	48	4,042	3,128	71	63	96	68
Humboldt	52	53	3,791	3,064	71	62	81	61
Cape Mendocino	53	55	3,791	2,976	71	64	79	57
Del Norte	52	55	3,791	3,076	71	64	81	59

Source: CA Offshore Wind Potential Study by NREL (Optis, M, et al, 2020)

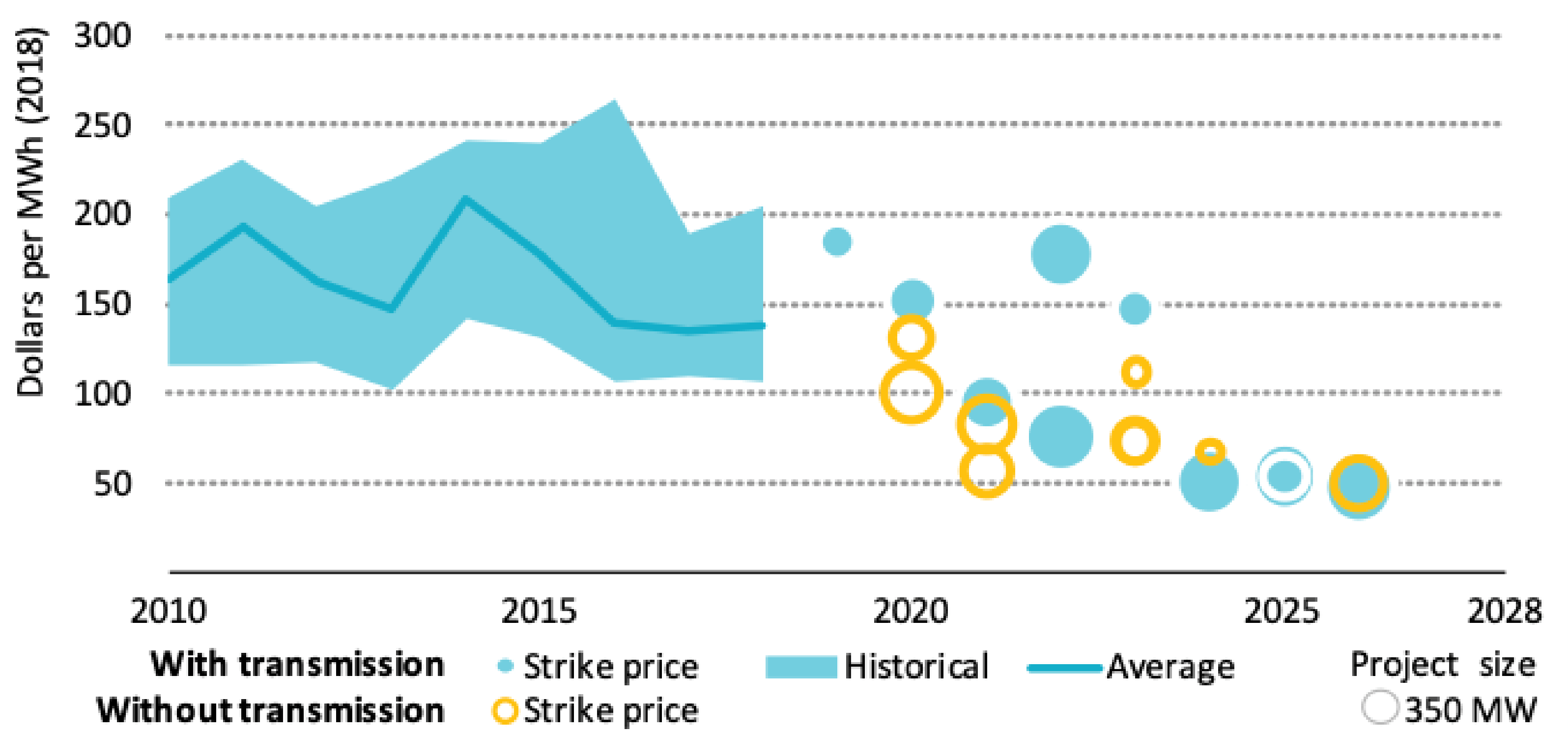
Appendix 4:
Additional Material on Global Perspectives on OSW

OSW cost reductions have occurred much earlier than most aggressive predictions of cost reductions



Results from the 2015 expert elicitation compared with recent published estimates of realized LCOE (Wiser et al 2021)

Figure 8 ▹ Historical LCOE of offshore wind and strike prices in recent auctions in Europe



Source: [IEA Offshore Wind Outlook 2019]

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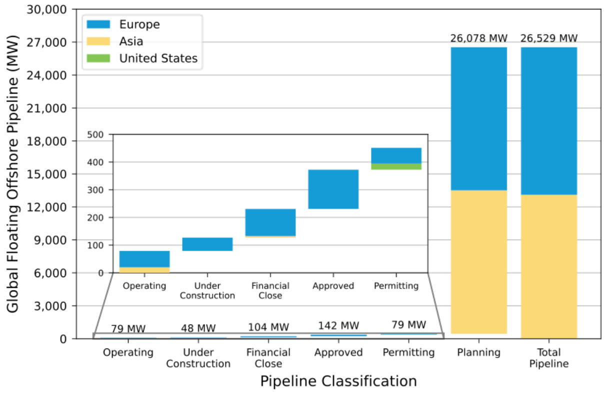

Figure 18. Total global floating offshore wind energy pipeline

There are currently 11 floating offshore wind energy projects installed around the world representing 79 MW of capacity. Five projects (59 MW) are installed in Europe and six (20 MW) are in Asia. There are an additional 15 projects representing approximately 293 MW that are currently under construction or have achieved either financial close or regulatory approval. Four projects (79 MW) have advanced to the permitting phase, and another 87 are in the early planning stages (26,078 MW). Overall, the 2020 global floating offshore wind energy pipeline represents approximately 26,529 MW of capacity.

Source: DOE's Offshore Wind Market Report (2021)

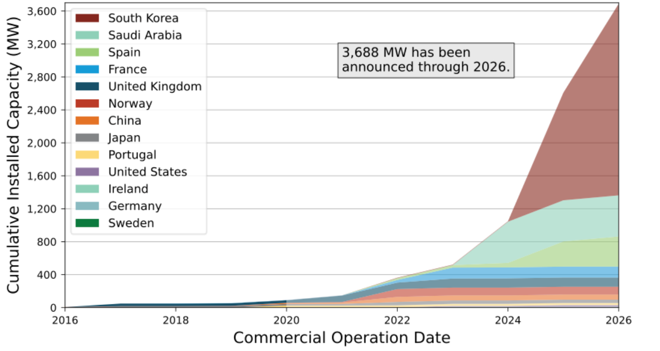

Figure 20. Cumulative floating offshore wind capacity by country based on announced COD through 2026

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Table 14. Global Floating Offshore Wind Energy Pipeline

Country	Operating (MW)	Under Construction (MW)	Financial Close (MW)	Approved (MW)	Permitting (MW)	Planning (MW)	Grand Total (MW)
China			5.5			68	73.5
France	2			113.7		517	632.7
Germany			2.3			8	10.3
Ireland						2,926	2,926
Italy						3,747	3,747
Japan	19.006					1,028	1,047.006
Norway	2.3		91.6			3,507	3,600.9
Portugal	25					125	150
Saudi Arabia						500	500
South Korea	0.75					9,457	9,457.75
Spain			2.225	8	25	1,036	1,071.225
Sweden	0.03			10			10.03
Taiwan						2,000	2,000
United Kingdom	30	48	2	10	32	1,159	1,281
United States					22		22
Total	79.086	48	103.625	141.7	79	26,078	26,529.41

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