

The Offshore Report: California

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

Working Paper #1

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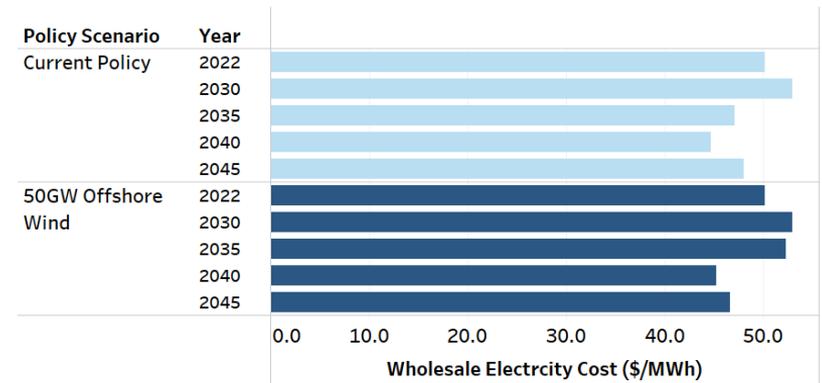
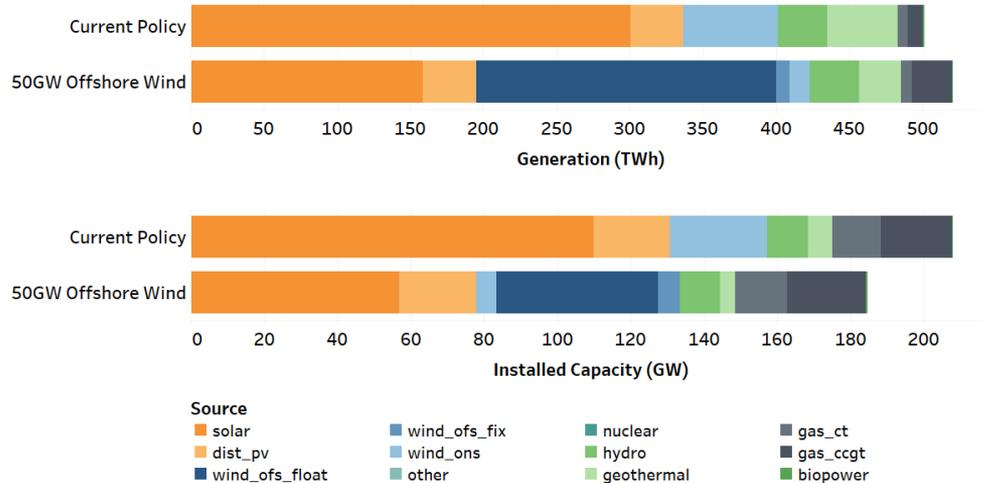
Berkeley Public Policy
The Goldman School

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Recommendation to CEC for AB 525: Consider deploying up to 50 GW OSW by 2045 to increase resource diversity without increasing wholesale electricity costs

Significant OSW (upto 50 GW by 2045) can be deployed by 2045 to increase resource diversity without increasing wholesale electricity costs



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:

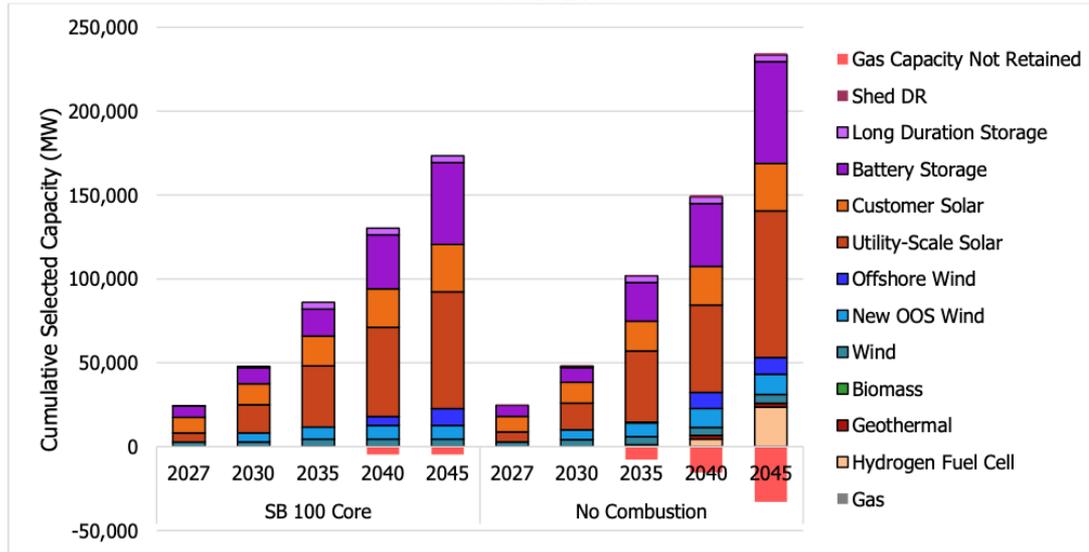
- 1. CA blessed with OSW resource: ~200 GW technical; 120 GW > 50% cap factor; summer and evening peaking*
- 2. Strong policies required for CA to achieve a diverse net zero grid with significant OSW*
- 3. 50 GW OSW can provide resource diversity for a net zero grid without increasing wholesale electricity 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

SB 100 plans rely on PV and battery storage without much resource diversity; does not fully consider clean power required for a net-zero economy by 2045

Figure 8: Cumulative Capacity Additions for the SB 100 Core and No Combustion Scenarios



Source: CEC staff and E3 analysis

Study: *Accelerated Timeline Scenarios*

Source: [CEC 2021 SB 100 Joint Agency Report](#)

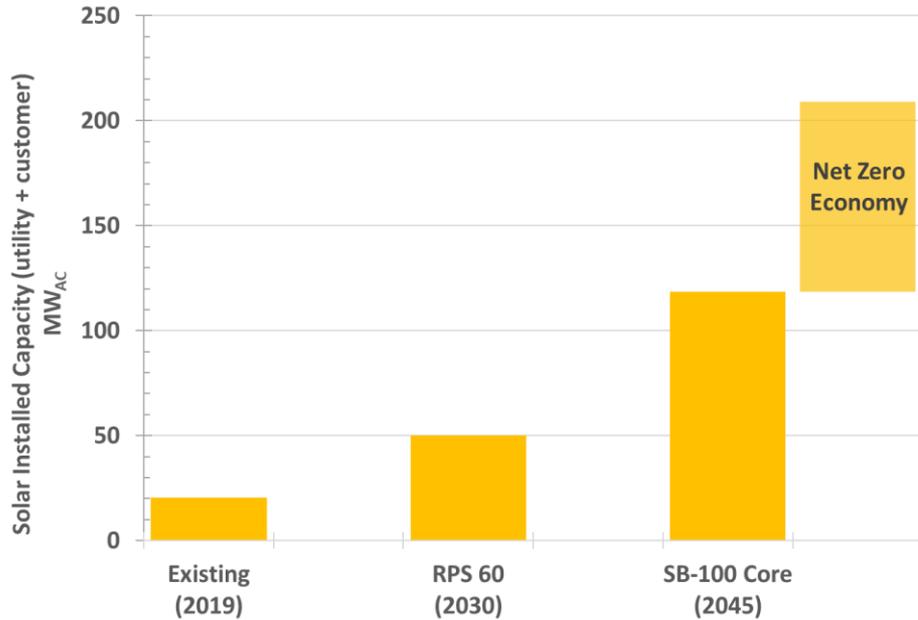
SB 100 Core and Study Scenarios:

>70% clean electricity from solar (120 GW) by 2045; wind limited to 10-15 GW.

Solar additions only support 80% economywide GHG emission reduction by 2050; could be significantly higher if net zero by 2045 goals are to be achieved

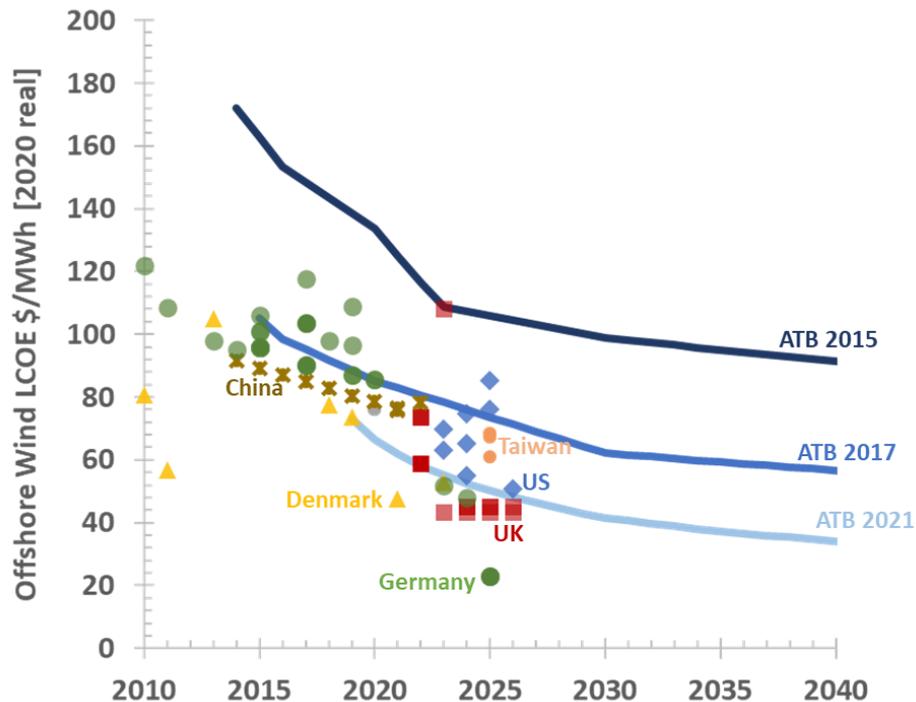
For example, [Princeton Net Zero America Study](#) estimates 230 GW to 280 GW of PV required to meet NZ goals in CA by 2050

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 plans a solar dominant grid with ~120 GW solar + ~50GW storage by 2045.
- However, if California relies only on solar for achieving net-zero emissions, solar capacity needed by 2050 would be in excess of 200-250GW + 50-100GW of storage.

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.

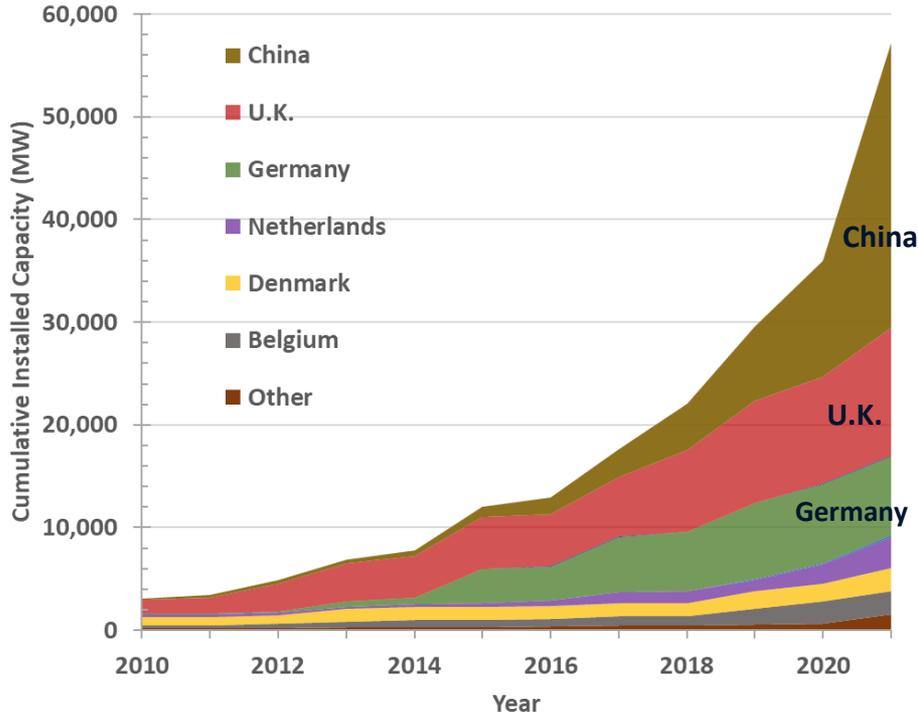
Colored dots

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

Note

All numbers are expressed in 2020 real US \$.

Globally, offshore wind installed capacity has reached about 60GW



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

China installed ~17GW of offshore wind capacity in 2021

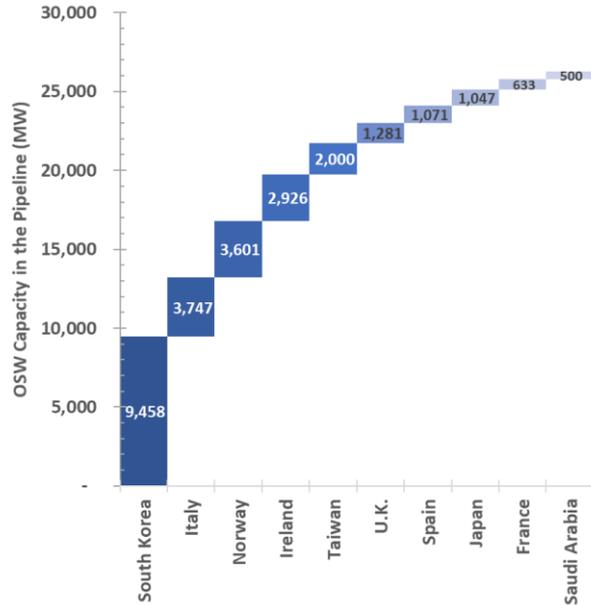
UK's electricity demand (~350 TWh/year) is similar order of magnitude of CA (~270 TWh/yr)

UK is planning to install 50GW of offshore wind (OSW) by 2030. Existing OSW = ~12 GW

We make a case for 50 GW OSW in CA by 2045 providing about 40% of the state's power supply of about 500 TWh/year in 2045

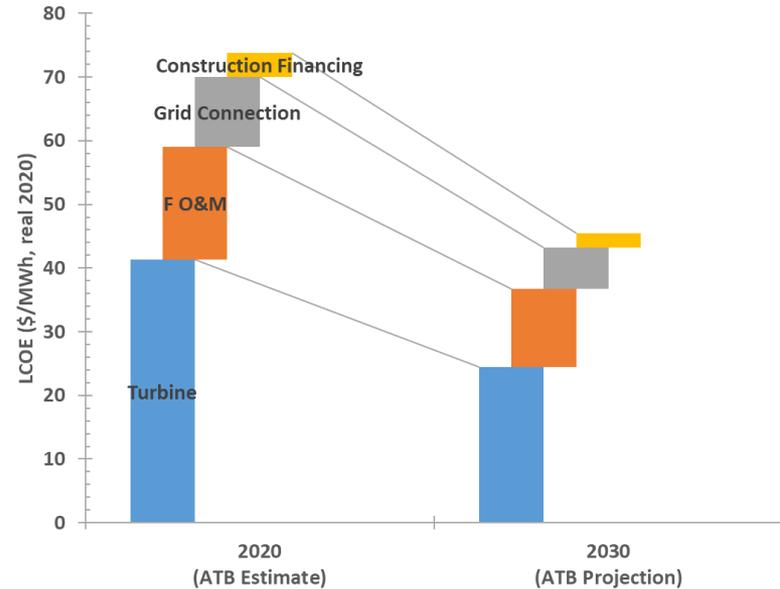
Globally, >25 GW of floating OSW is in the pipeline, while 40% cost reductions are projected by 2030

Floating OSW pipeline (Global)



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

Floating OSW LCOE (US)

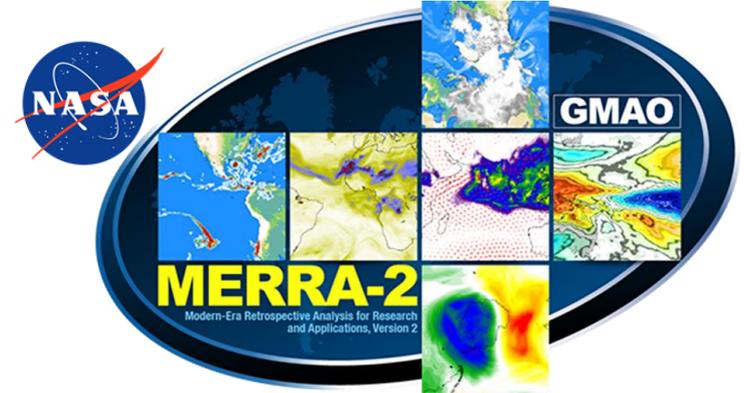
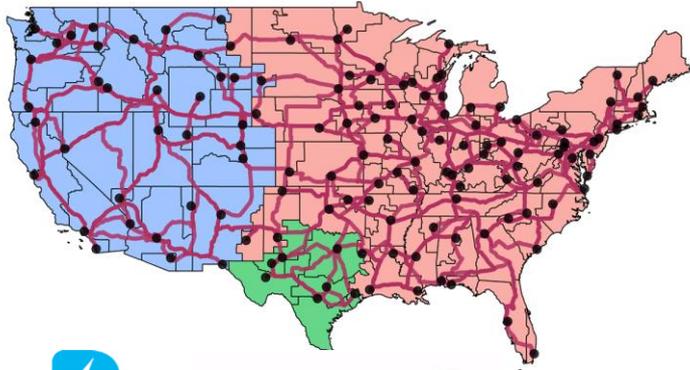


Data source: [NREL Annual Technology Baseline \(2021\)](#) - Advanced case
 See also [Beiter et al. 2020](#) (NREL)

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](#)

Overall 30 scenarios modeled with all combinations of the following parameters



Core Scenarios for Analysis

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

1. Current Policy

- 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. 50 GW Offshore Wind Case

- 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

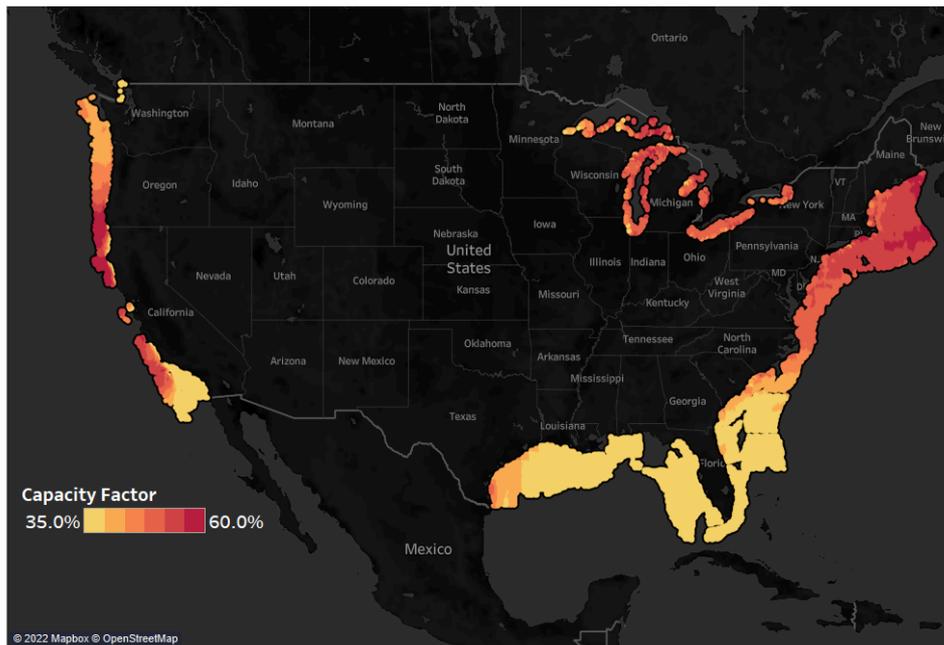
Key Findings

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
2. Strong policies required for CA to achieve a diverse net-zero grid with significant OSW
3. Significant OSW (upto 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
5. CA can become the global leader in the floating OSW technology; massive potential & need in countries like Japan, Korea etc.

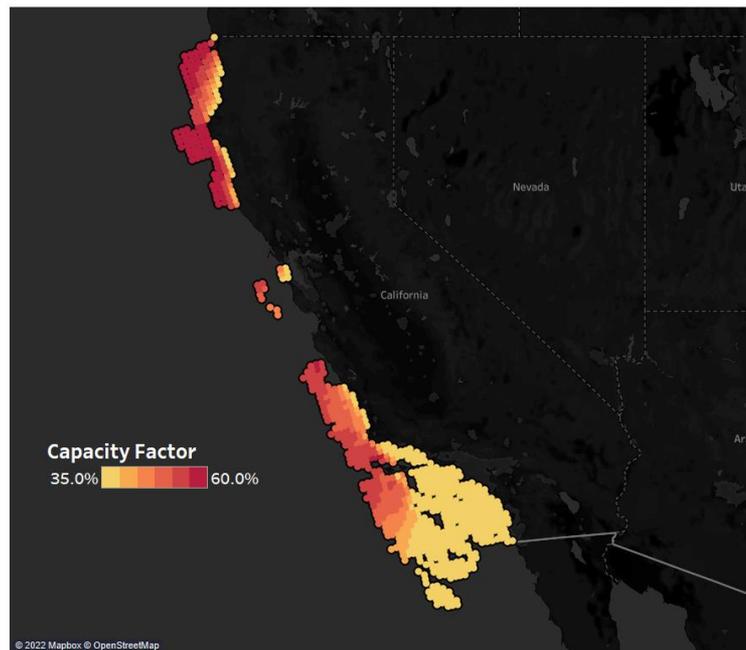
Finding #1: CA has one of the world's best offshore wind potential: 200 GW technical; 120 GW at >50% capacity factor; summer & evening peaking

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%



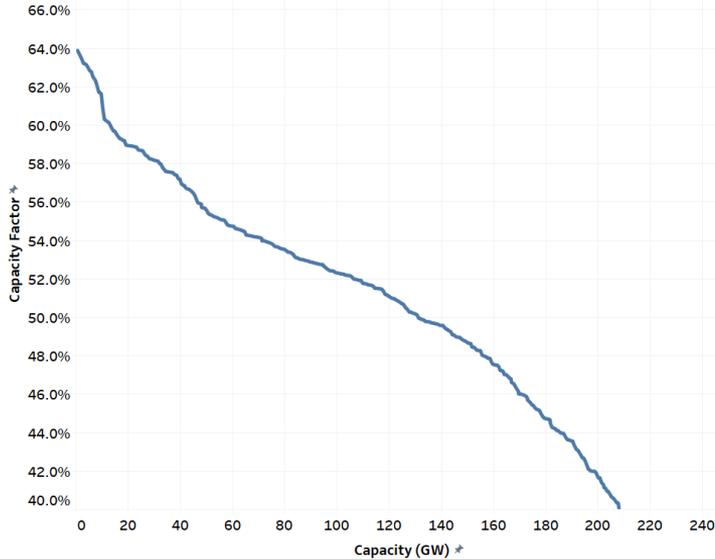
Most of the CA OSW potential is floating with >120GW at capacity factor >50%



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

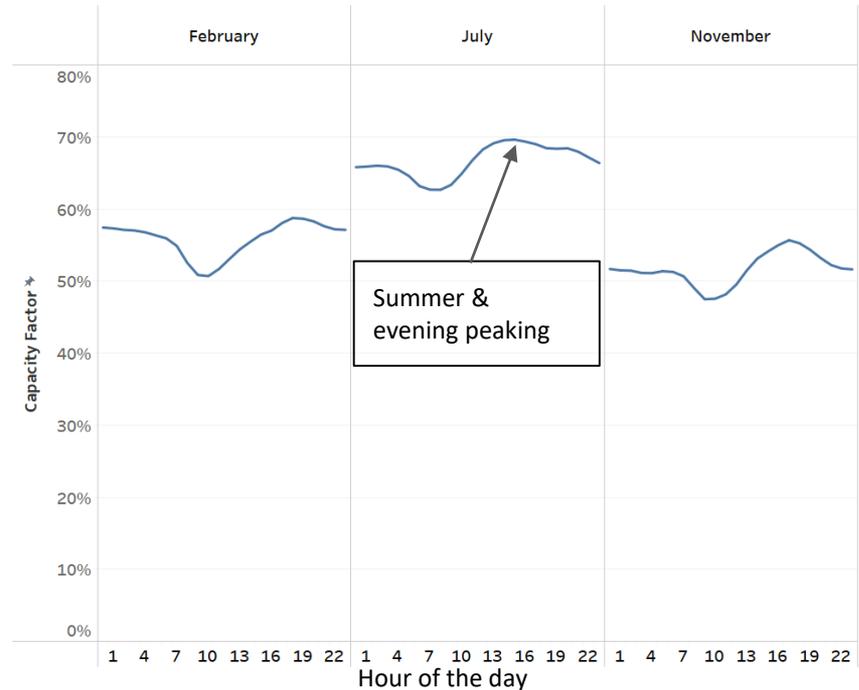
200 GW technical; 120 GW w/ capacity factor >50%; summer & evening peaking

Offshore wind supply curve



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

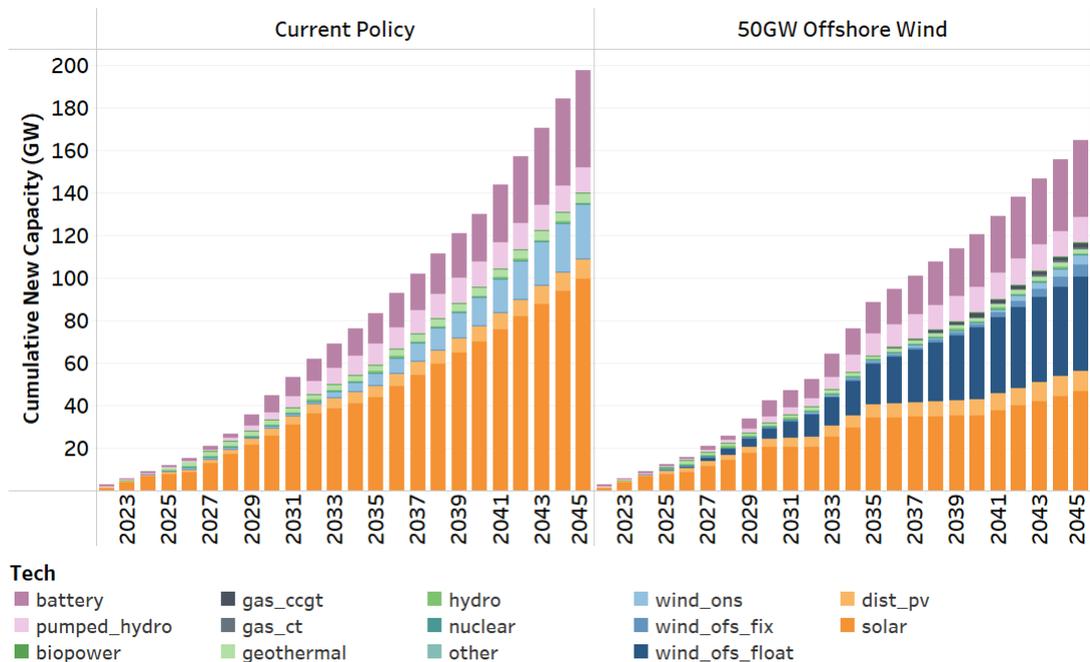
Hourly generation profile shows complementarity with solar and load



Finding #2: Strong policies are required for CA to achieve a diverse net-zero grid with significant OSW

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

Cumulative new capacity addition (GW) in CA
(2022-2045)



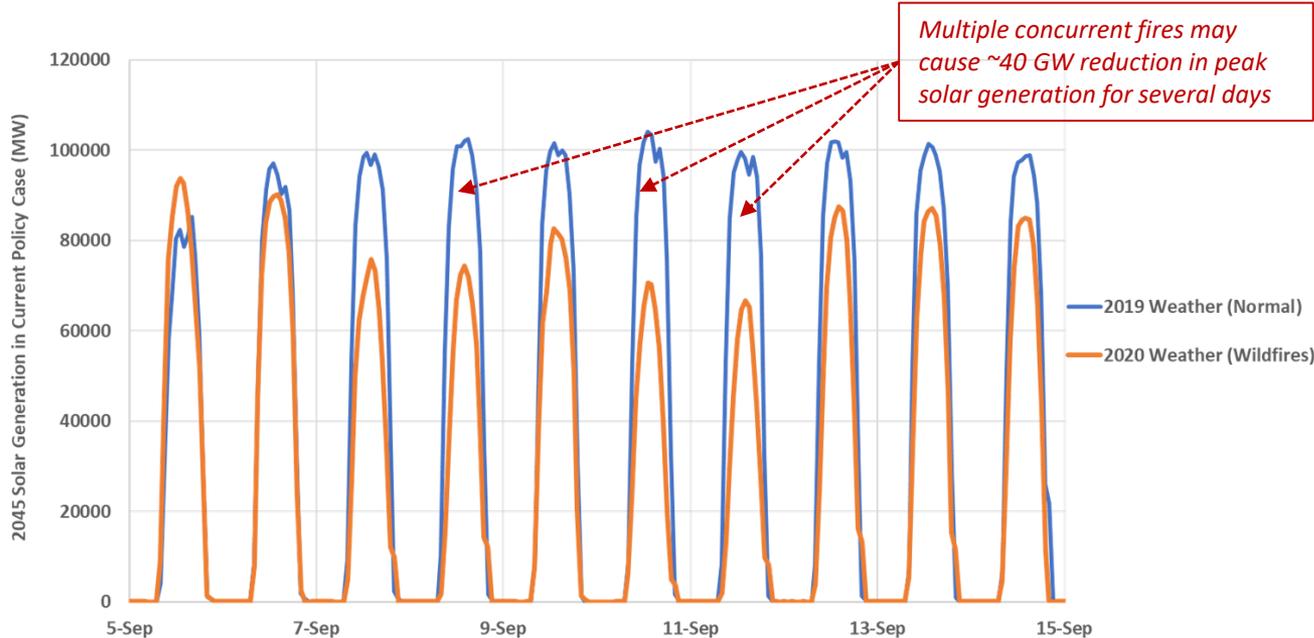
The Current Policy case assumes continuation of current state and federal policies which leads to a solar PV dominated zero emission grid in California by 2045.
(130 GW Solar + 53 GW storage)

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

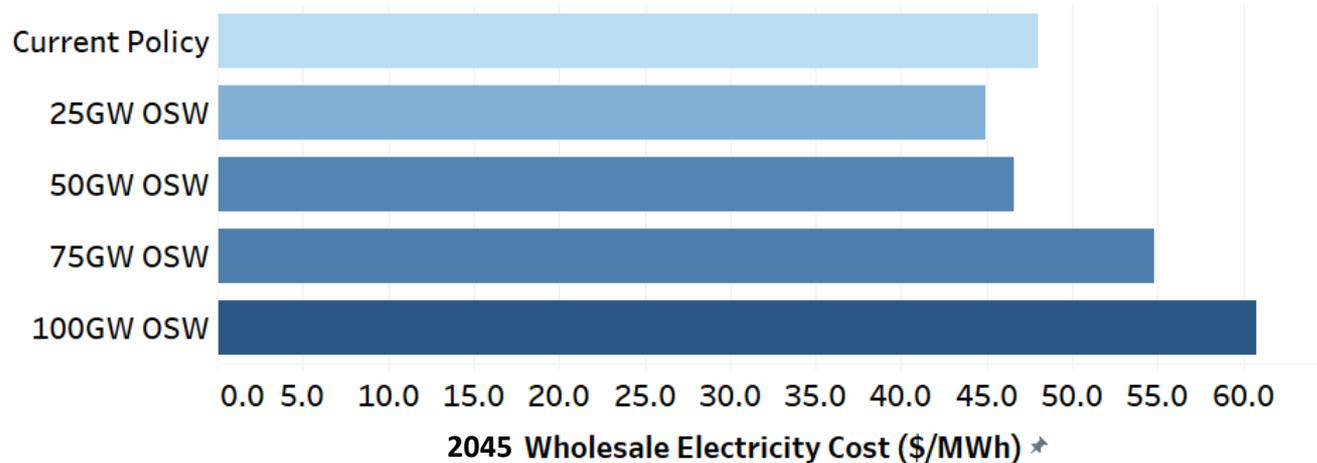


In 2020, due to multiple wildfires in September, CA solar generation dropped by ~15-20% for over a week.

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

Finding #3: Significant OSW (upto 50 GW by 2045) can be deployed to increase resource diversity without increasing wholesale electricity costs

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

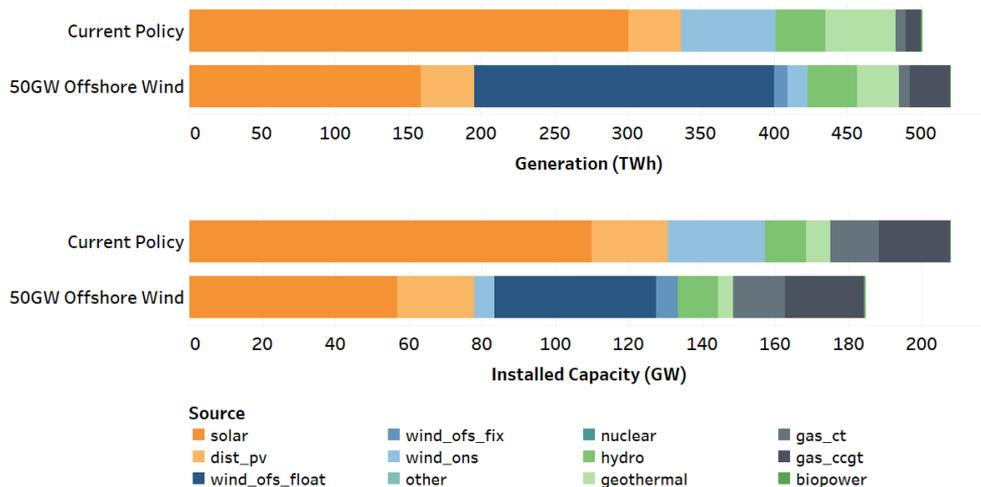


All cost numbers are in 2020 real \$.

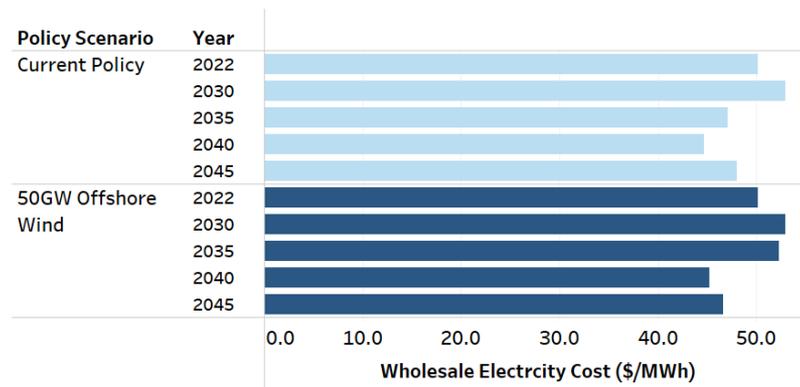
Wholesale electricity cost includes the fixed and variable costs of all (new + existing) power plants in the state, out-of-state import-export costs/revenue, and new bulk transmission as well as interconnection costs.

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

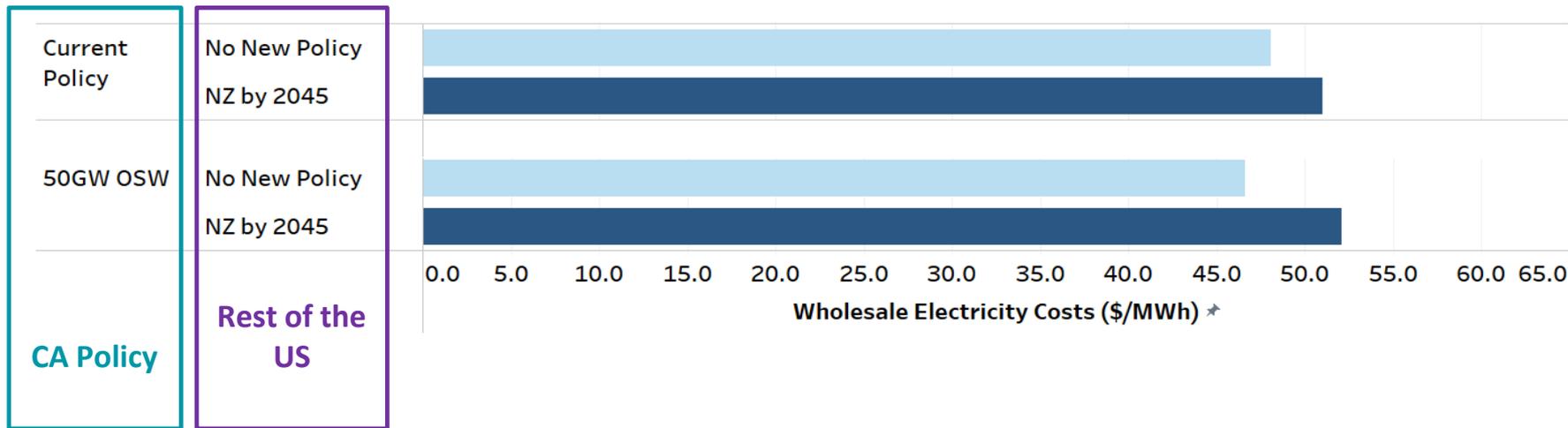


Average wholesale electricity cost (\$/MWh, 2020 real)



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

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

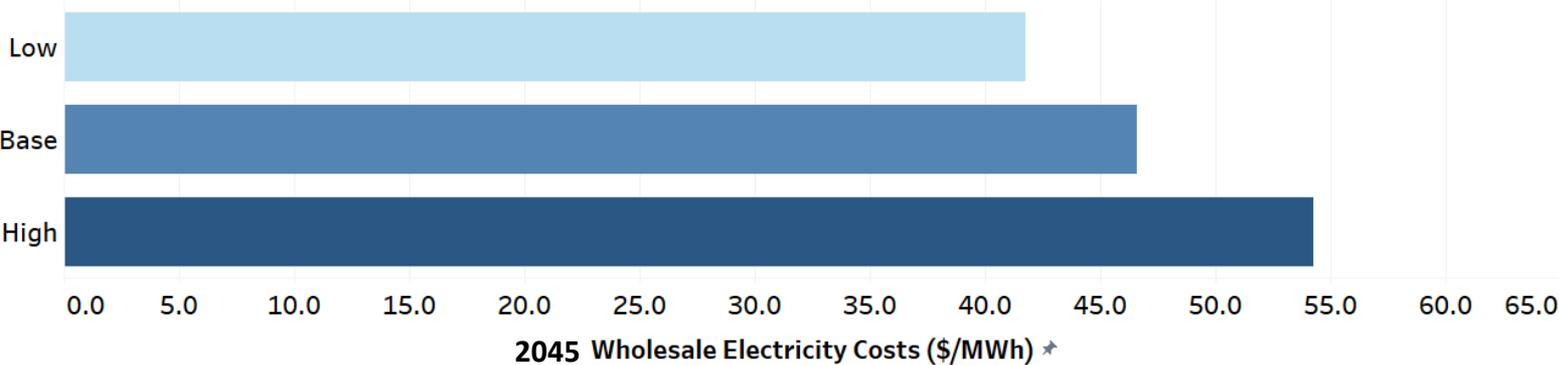


All cost numbers are in 2020 real \$.

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.

3.3 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)



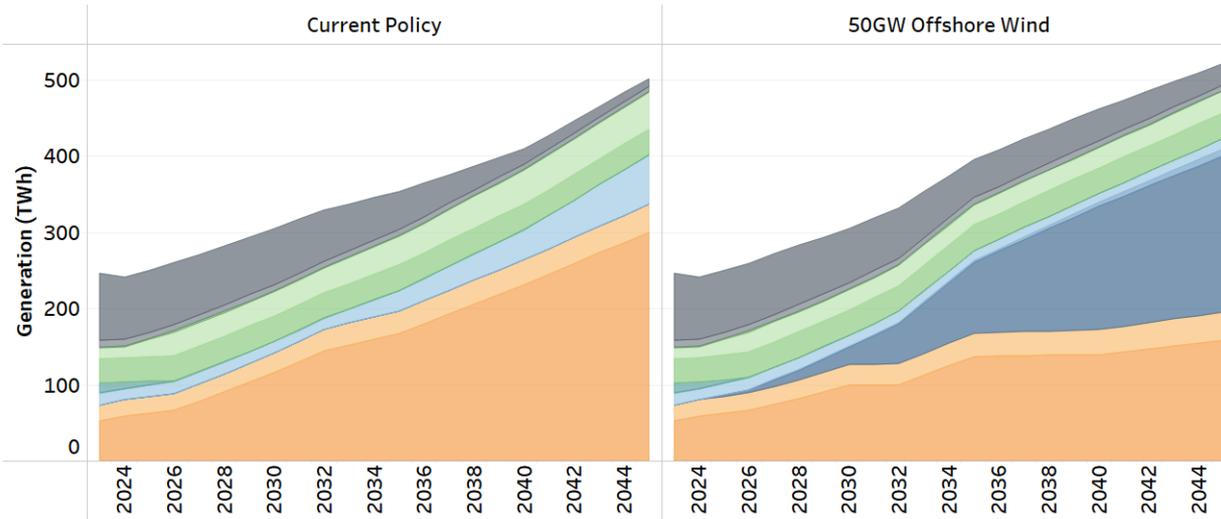
All cost numbers are in 2020 real \$.

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.

3.4 Significant OSW additions lead to a more diverse grid

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

Generation (TWh)

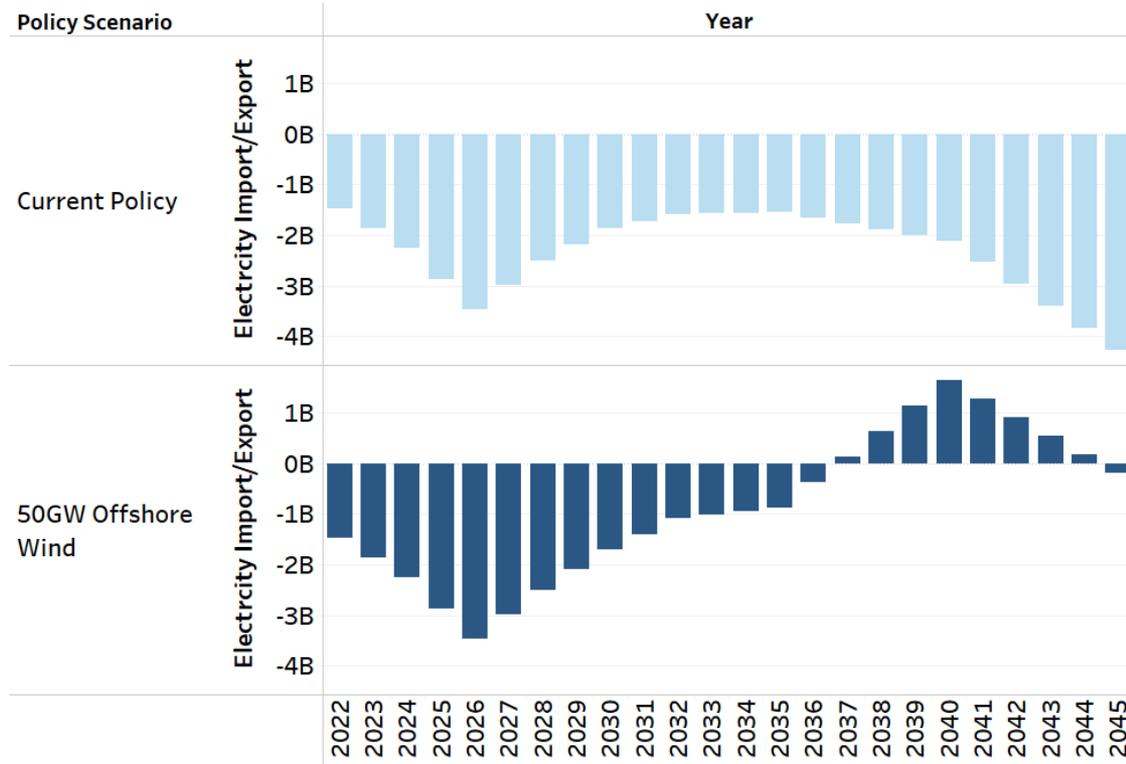


The Current Policy case leads to a solar PV dominated grid by 2045. Solar provides 70%, onshore wind 10% and other clean resources provide 15% of the total electricity supply.

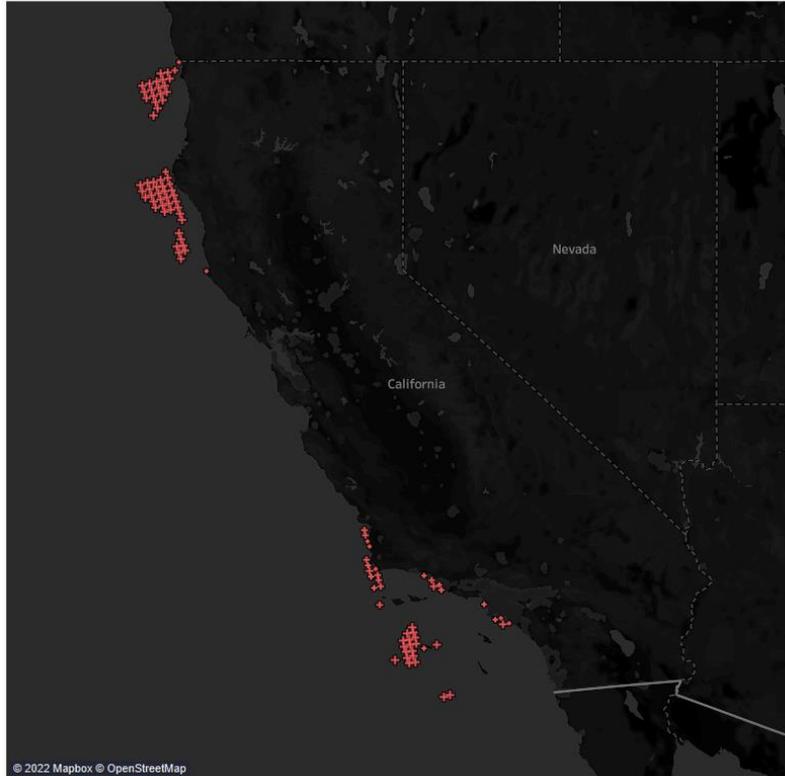
50GW OSW case leads to a more diverse grid. OSW and solar each provide ~40% of total electricity supply, onshore wind supplies 5%, and other clean resources supply 15% by 2045.

- Source
- gas_ccgt
 - gas_ct
 - biopower
 - geothermal
 - hydro
 - nuclear
 - other
 - wind_ons
 - wind_ofs_fix
 - wind_ofs_float
 - dist_pv
 - solar

3.5 Offshore Wind will significantly reduce unspecified electricity imports



3.6 In the 50GW OSW Case, OSW installations span in the north as well as in the south



Not to scale

Each point shows a wind farm of 40 turbines (600 MW).

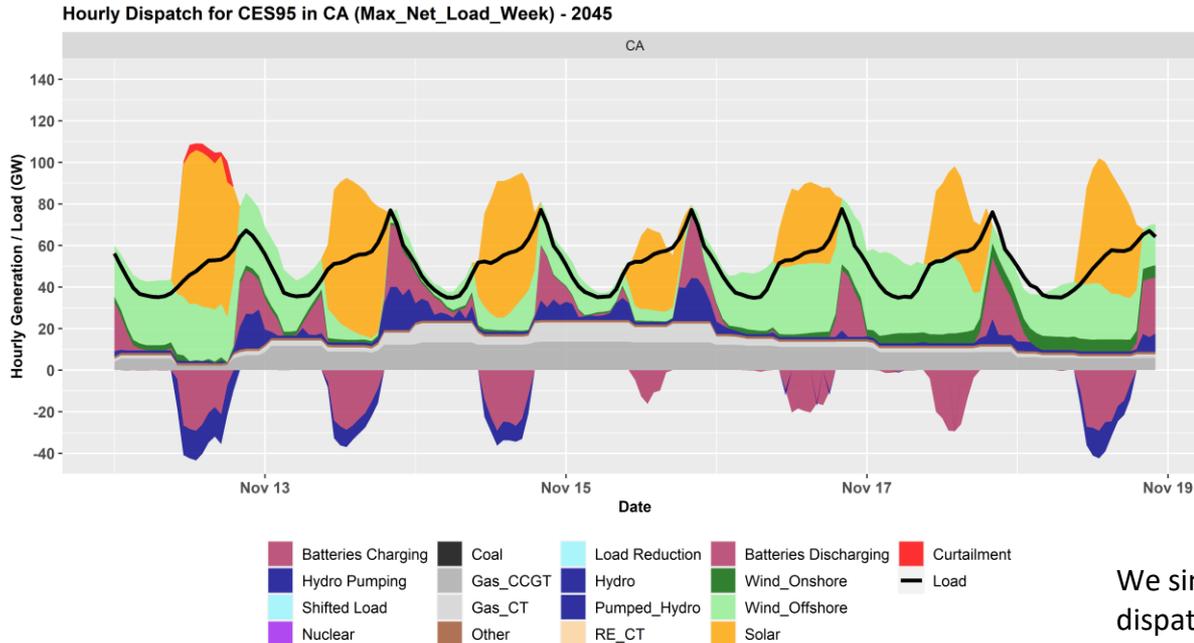
3.7 Transmission investment requirement for a zero emission grid (2022-2045)



Finding #4: Grid with significant OSW is dependable with less storage

4.1 Grid with significant OSW is dependable with less 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.

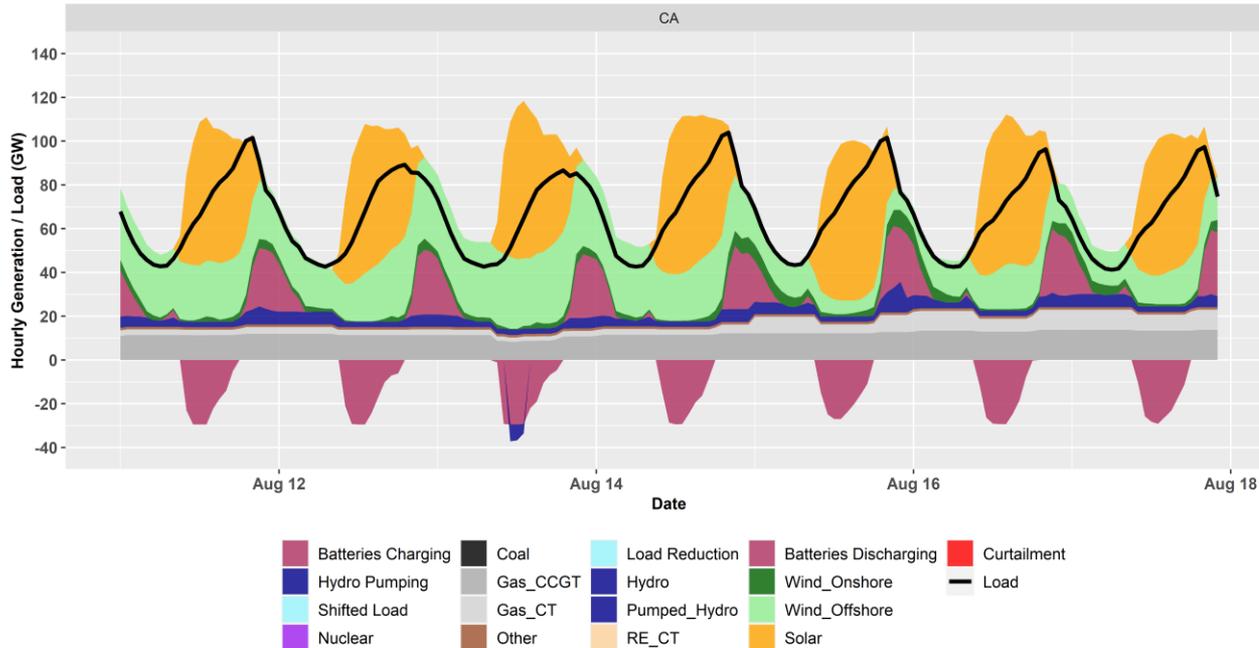
The grid is still dependable as the system dispatches gas to make up for this shortfall.

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 storage

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

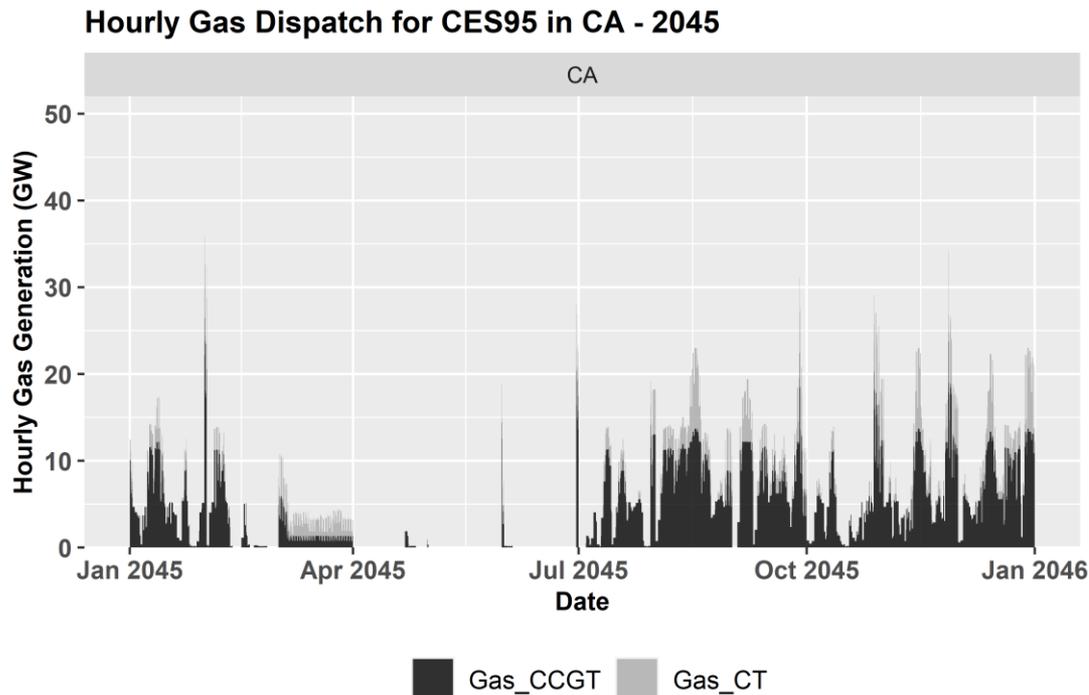
Hourly Dispatch for CES95 in CA (Max_Load_Week) - 2045



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.

4.3 ~35GW of gas may still be needed in 2025 for maintaining grid reliability in all scenarios



~35GW of gas may still be needed in 2045 for maintaining grid reliability

Average capacity factor of gas is ~10%

~15GW gas will be dispatched for <1% of the time (88 hours/year).

With flexible load (DR or TOU/peak rates), gas capacity requirement may reduce significantly.

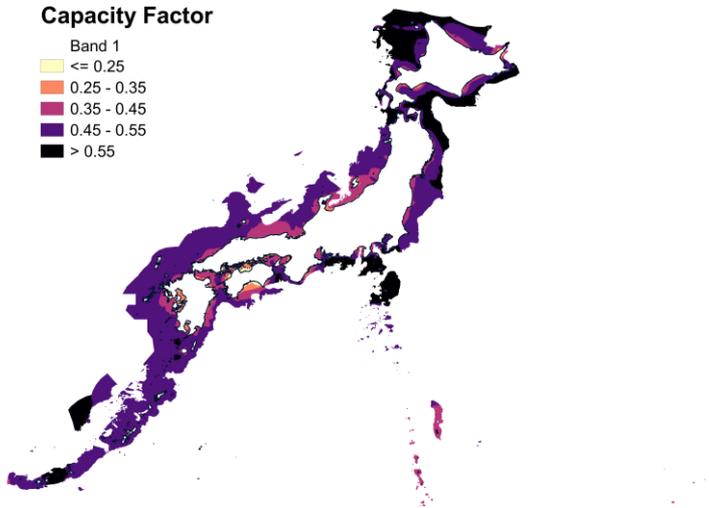
These findings are similar to the SB-100 core scenario results.

Finding #5: CA can become the global leader in the floating OSW technology

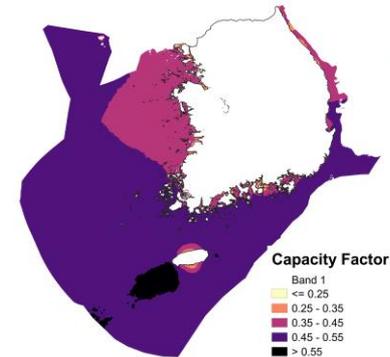
5. Significant global opportunity for floating OSW

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)

Recommendations

- **Consider deployment of upto 50 GW of Offshore Wind in California by 2045**
 - Critical for increasing the resource diversity & minimizing grid risk, especially in a net-zero economy
 - Wholesale electricity costs do not increase
 - Other countries like UK have already set similar targets in the 2030 timeframe (UK target 50 GW by 2030)
- **Need to evaluate supply chain, employment, and environmental constraints/impacts**
- **Further work required to assess the implications for grid reliability and transmission**
- **Develop strategic global partnerships with countries like U.K., Japan, and Korea**
 - CA can be a global OSW technology leader; significant climate and commercial benefits

Appendix 1: Marginal Contributions of This Study

CEC draft AB-525 Offshore Wind Report does not assess the maximum feasible offshore wind potential in California

AB-525 requirement:

The law directs that on or before June 1, 2022, the California Energy Commission (CEC) shall “evaluate and quantify the maximum feasible capacity of offshore wind to achieve reliability, ratepayer, employment, and decarbonization benefits and shall establish megawatt offshore wind planning goals for 2030 and 2045.”

Draft CEC AB-525 Report (pp 53):

Offshore Wind Technical Potential

Based on existing studies described in this report, nearly 21.8 GW of offshore wind technical potential of the 201 GW of the gross resource estimate has been identified and examined for technical feasibility. This number does not represent the quantification of maximum feasible capacity of offshore wind as defined in this report and required by Ab 525, it simply represents the offshore wind technical potential that has been studied.

Source: Draft AB-525 Offshore Wind Report (emphasis added)

Summary of the marginal contributions of this study

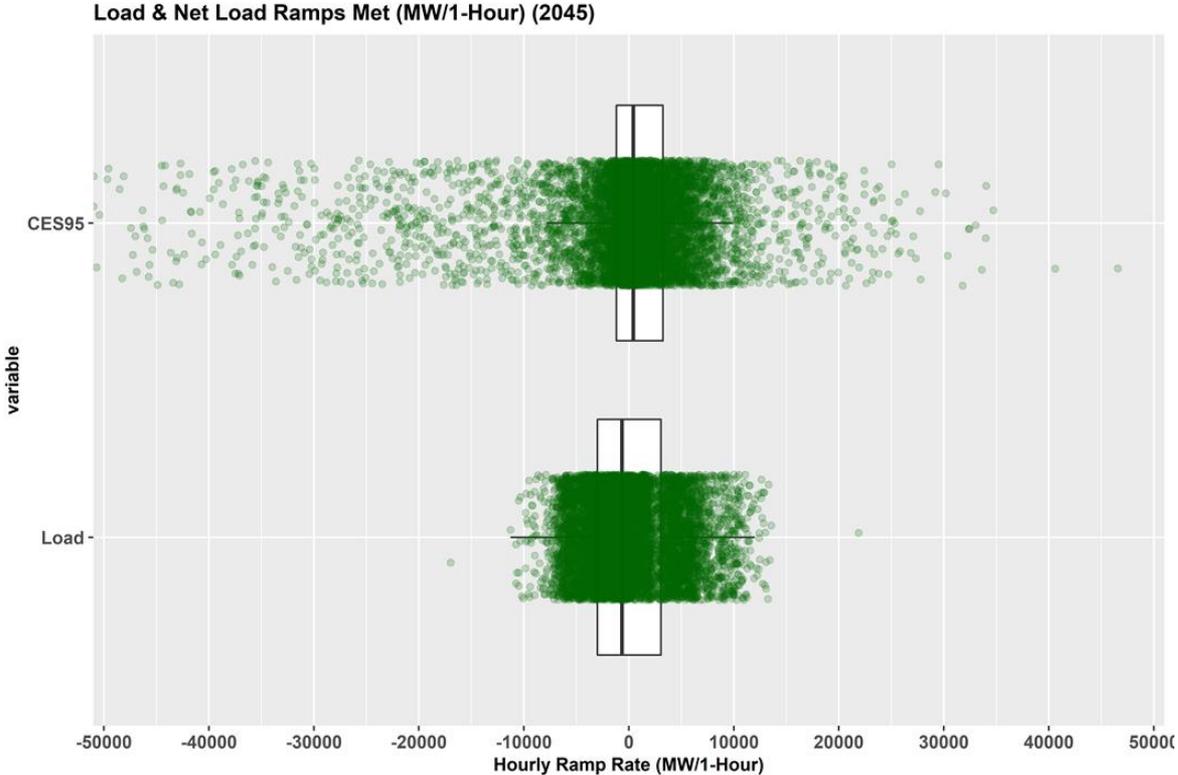
	CEC AB-525 and SB-100 Reports	UCB CA Offshore Wind Report
Zero emission for 100% retail electricity sales	Y	Y
Load w/high electrification	Y	Y
Load w/economy-wide net-zero emissions	N	N
Updated OSW potential	N	Y
Assessment of significant OSW in CA grid	N	Y
High resolution capacity expansion assessment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

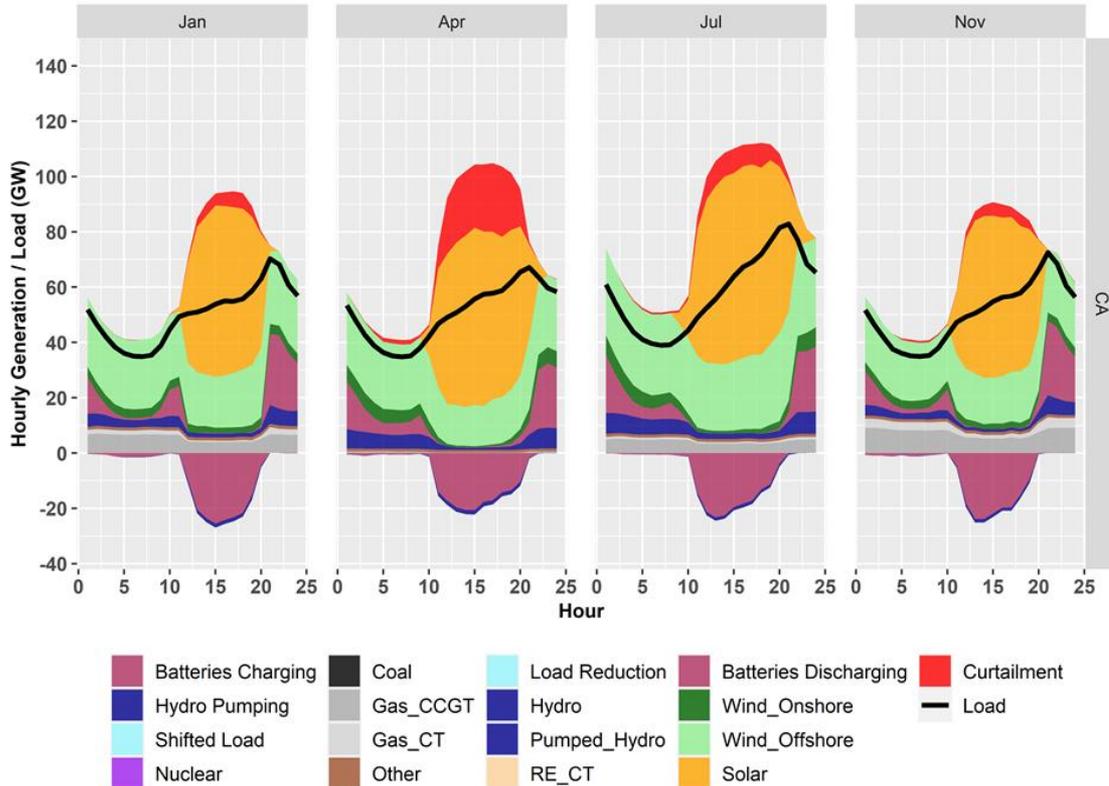
Appendix 2: Additional Modeling Results

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)

Average Hourly Dispatch for CES95 - 2045



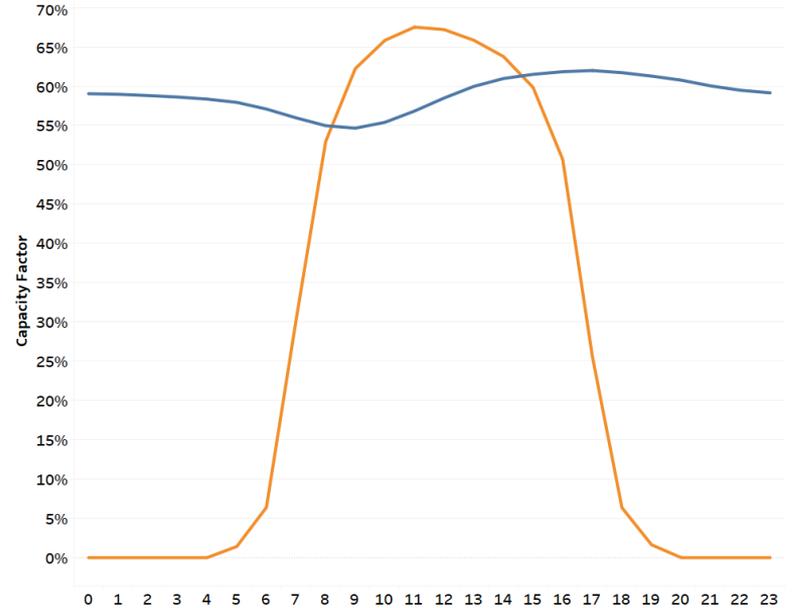
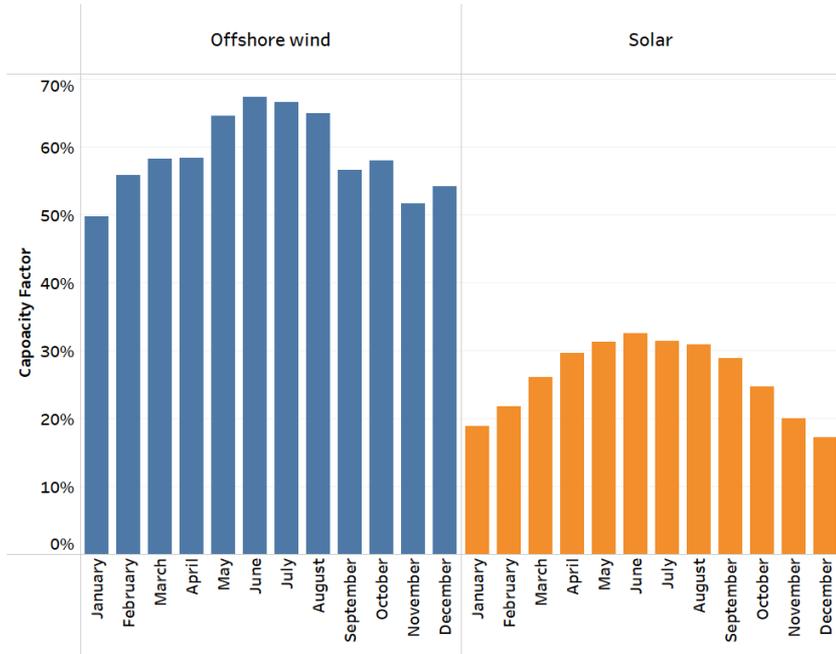
Solar and offshore wind have complementary profiles, which helps in reducing the battery storage requirement to a certain extent.

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 \(Optis, M, et al, 2020\)](#)
and [CA Floating Offshore Wind Cost Study by NREL \(Beiter, P, et al, 2020\)](#)

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	New CA20 Data Set
Minimum average wind speed (m·s ⁻¹)	7.0	7.0	7.0
Maximum water depth (m)	1,000	1,300	1,300
Array density (MW·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°, Which Runs Through San Francisco.

Bin (m·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°, 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

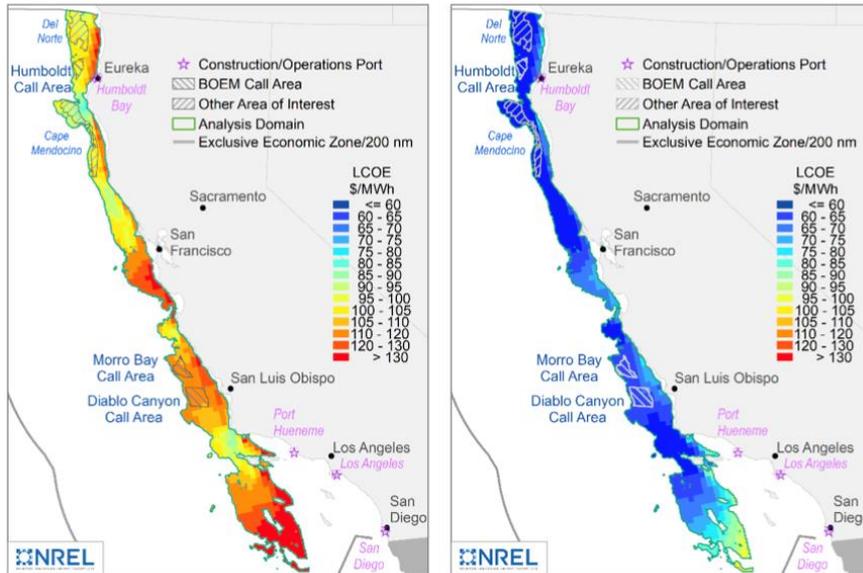


Figure ES-1. LCOE estimates (mid-case CapEx scenario) for the analysis domain offshore California estimated for a 2019 COD (left) and 2032 COD (right)

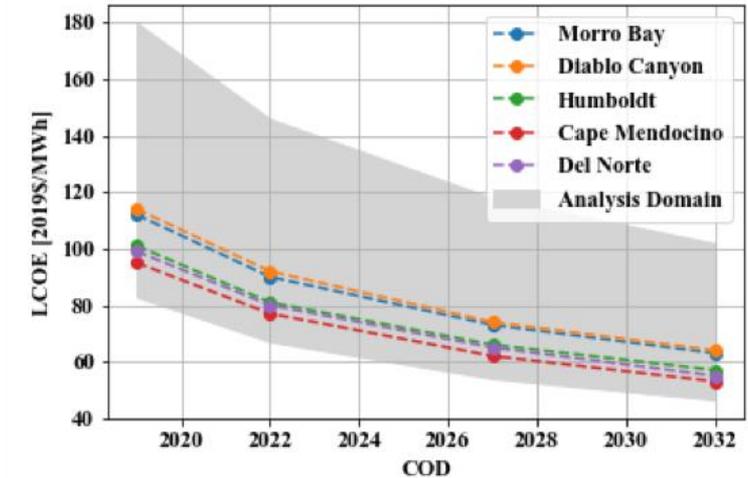


Figure ES-2. Estimated LCOE trajectory between 2019 and 2032 (COD)

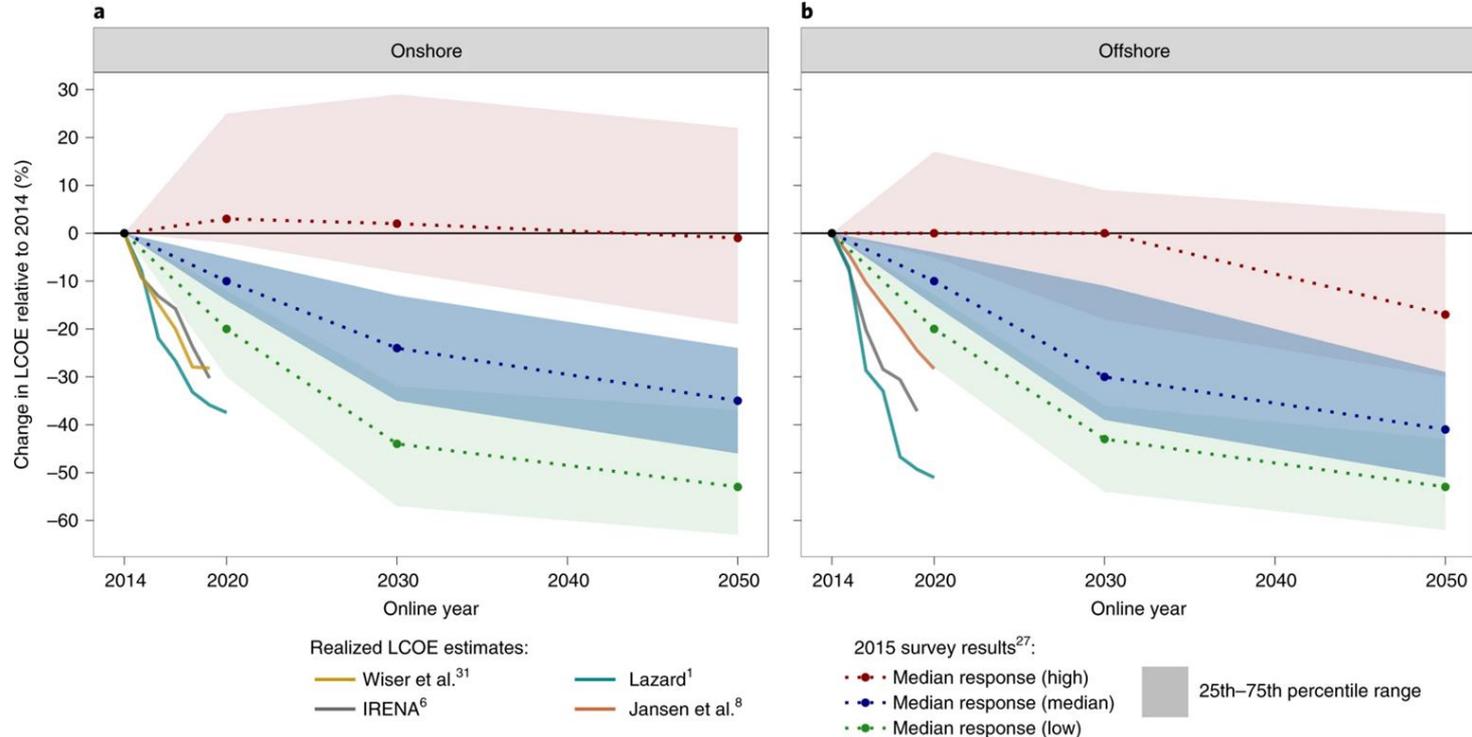
Table 18. Comparison Between the 2019-2020 IRP and NREL Cost and Performance Values

	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 Floating Offshore Wind Cost Study by NREL \(Beiter, P, et al, 2020\)](#)

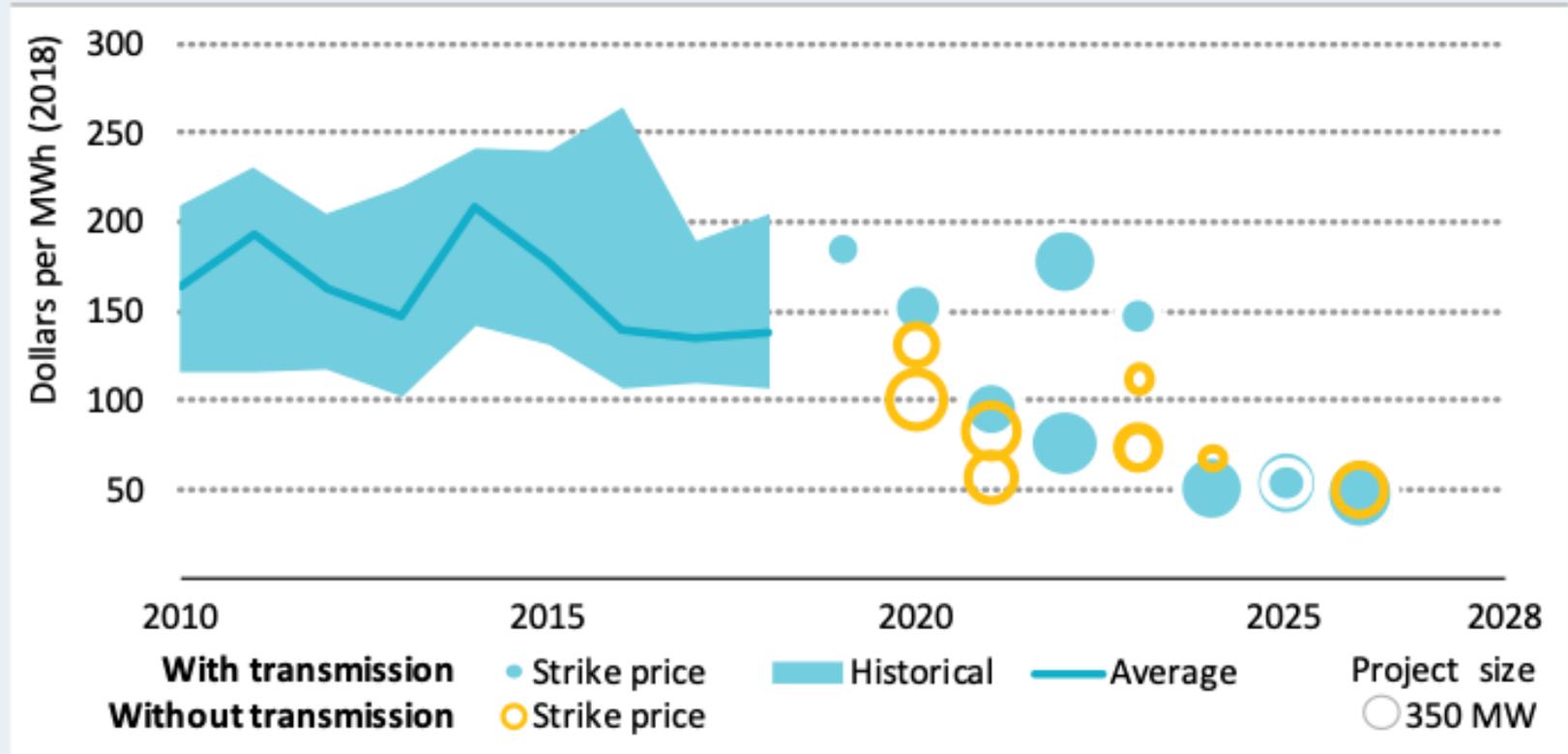
Appendix 4: Additional Material on Global Perspectives on OSW

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](#)

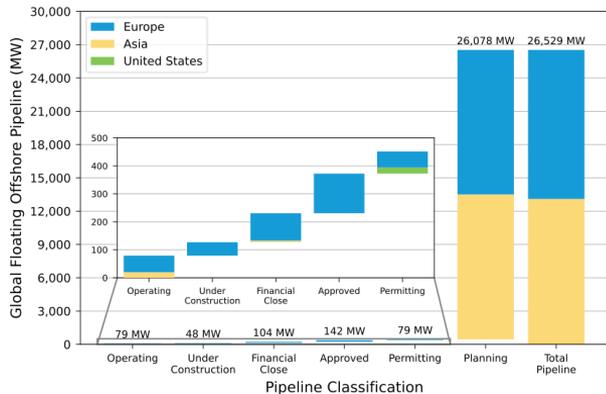


Figure 18. Total global floating offshore wind energy pipeline

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)

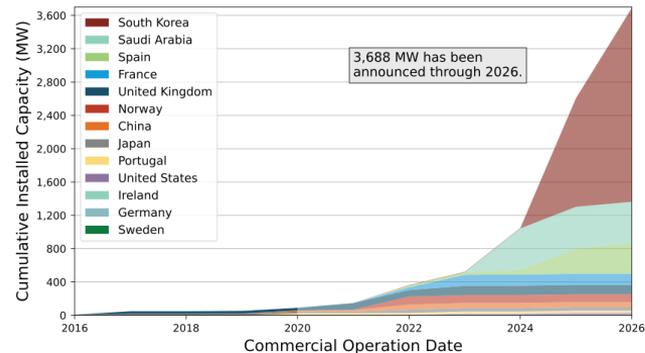


Figure 20. Cumulative floating offshore wind capacity by country based on announced COD through 2026

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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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