

Modeling the Contribution of Offshore Wind to the Grid Mix and Air Quality Implications: National Approach Results and Analysis

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10 December, 2019

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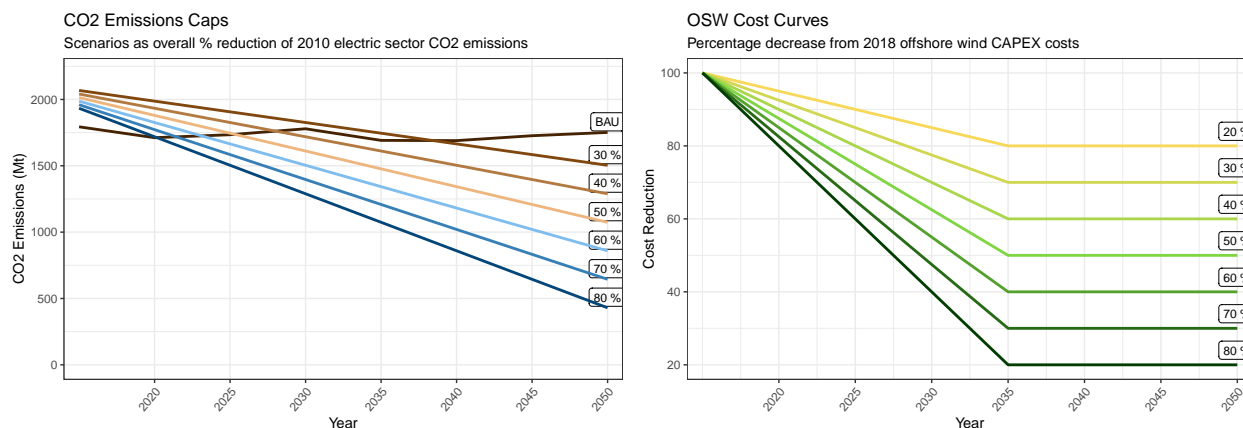
1 Scenarios

The nested parametric sensitivity analysis was built on combinations of two sets of scenarios:

1. Electric sector CO₂ emissions caps, as a linear decrease to a given % decrease from 2010 emissions by 2050
 - Business and usual emissions represent approximately a 20% reduction in CO₂ emissions

- Cost reductions of offshore wind, as a linear decrease to a given % decrease from 2010 costs by 2035, then level costs to 2050

- A 20% cost reduction is used as the base case, assuming very conservative technological advancement and little benefit of economies of scale
- Cost curves are set to resolve by 2035 as estimated based on NREL LCOE cost projections for offshore wind



2 LCOE

EIA's AEO 2019 provides the following values for the estimated levelized cost of electricity (capacity-weighted average) for new generation resources entering service in 2023 (2018 \$/MWh). Offshore wind has the highest total LCOE by a large margin. The second most expensive technology is biomass. The AEO LCOE was used in the calculation of offshore wind costs for the above cost curves, but LCOE is not directly used in the model.

Estimated LCOE capacity-weighted average for new generation resources entering service in 2023 (2018 \$/MWh)

Plant Type	Capacity Factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmission cost	Total system LCOE	Levelized tax credit	Total LCOE including tax credit
Dispatchable technologies								
Conventional CC	87	8.1	1.5	32.3	0.9	42.8	NA	42.8
Advanced CC	87	7.1	1.4	30.7	1.0	40.2	NA	40.2
Advanced CT	30	17.2	2.7	54.6	3.0	77.5	NA	77.5
Geothermal	90	24.6	13.3	0.0	1.4	39.4	-2.5	36.9
Biomass	83	37.3	15.7	37.5	1.5	92.1	NA	92.1
Non-dispatchable technologies								
Wind, onshore	44	27.8	12.6	0.0	2.4	42.8	-6.1	36.6
Wind, offshore	45	95.5	20.4	0.0	2.1	117.9	-11.5	106.5
Solar PV	29	37.1	8.8	0.0	2.9	48.8	-11.5	37.6
Hydroelectric	75	29.9	6.2	1.4	1.6	39.1	NA	39.1

Note:

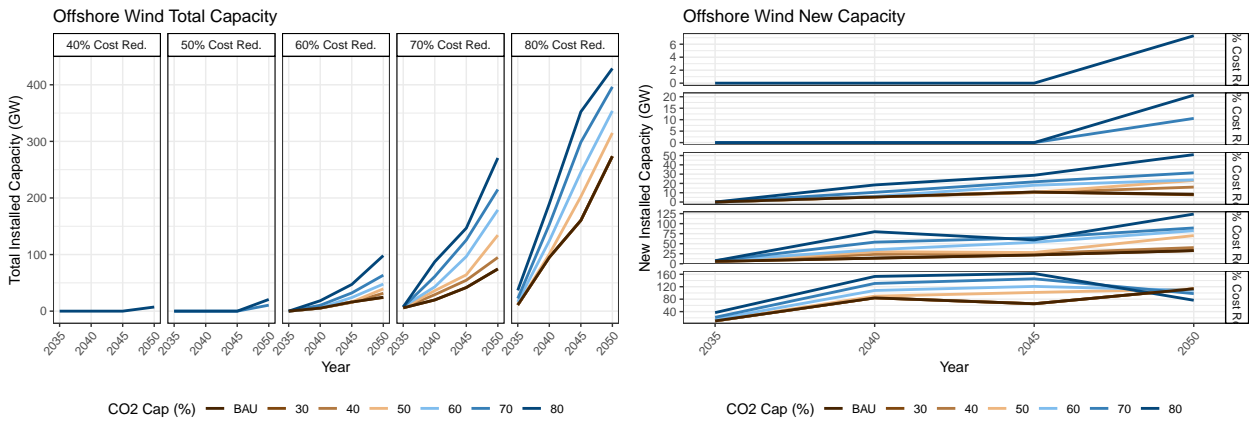
U.S. EIA Annual Energy Outlook 2019

3 Offshore Wind

As offshore wind is the primary technology being assessed in this research, we have explored many facets of offshore wind buildout. These facets are explored below, both at a regional and national cumulative level.

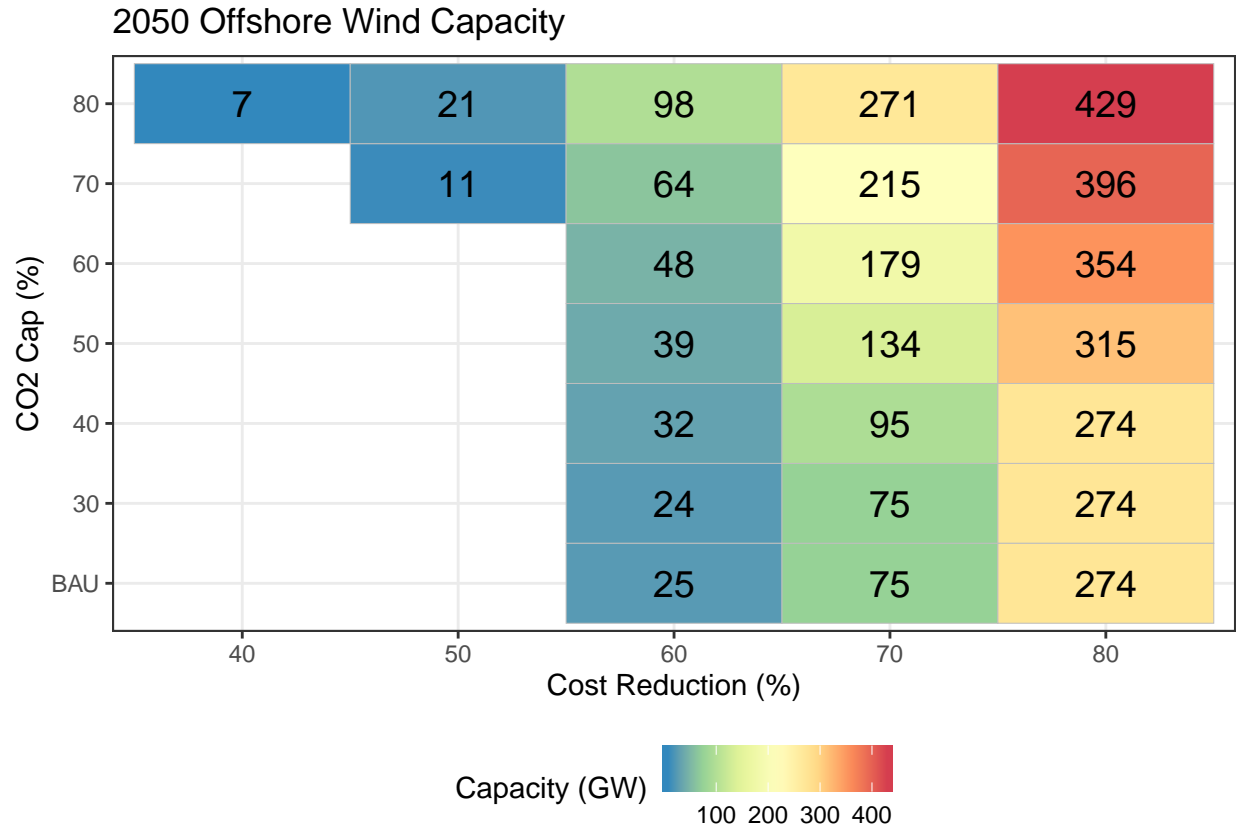
3.1 Capacity Buildout

Cumulative and new addition offshore wind capacity across all nine census regions, by cost and emissions reduction scenario.



3.2 Total Capacity

Total offshore wind capacity across all nine census regions in 2050, by cost and emissions reduction scenario.



Offshore Wind Total Installed Capacity (GW): 2050

CO2 Cap (%)	Cost Reduction (%)				
	40	50	60	70	80
BAU	-	-	25	75	274
30	-	-	24	75	274
40	-	-	32	95	274
50	-	-	39	134	315
60	-	-	48	179	354
70	-	11	64	215	396
80	7	21	98	271	429

3.3 Regions

Cumulative and new addition offshore wind capacity by region, emissions reduction, and cost reduction.

Average Installed Capacity (GW)

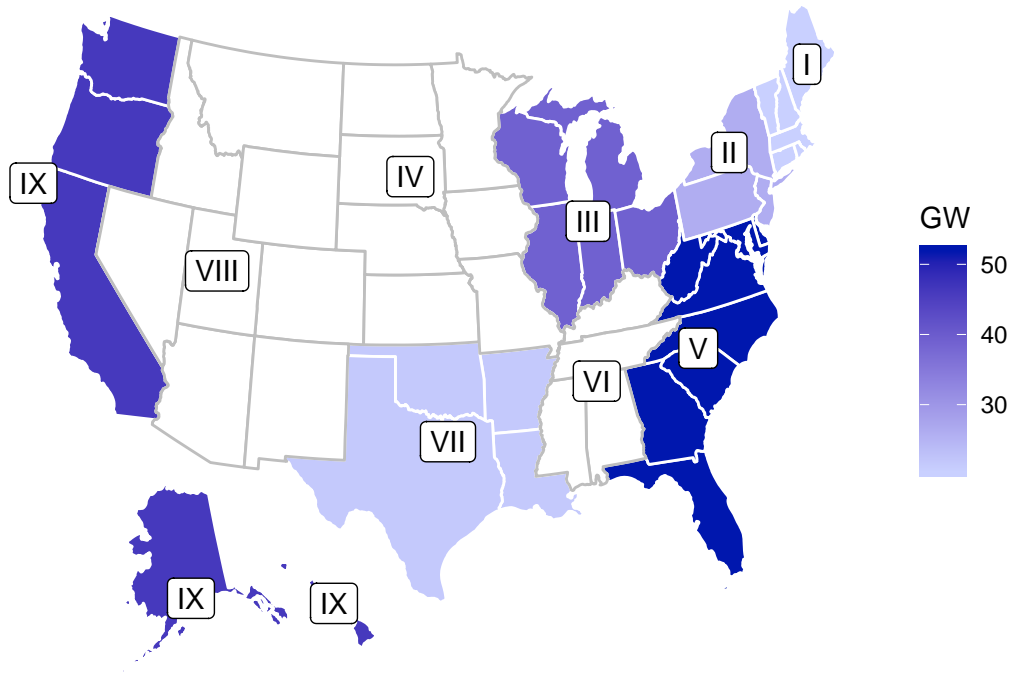
Region	2050 Total
R1	20.6
R7	21.7
R2	26.2
R3	39.1
R9	46.1
R5	51.8

Note:

Average is across all scenarios

Distribution of Offshore Wind Capacity

Average cumulative capacity across all scenarios

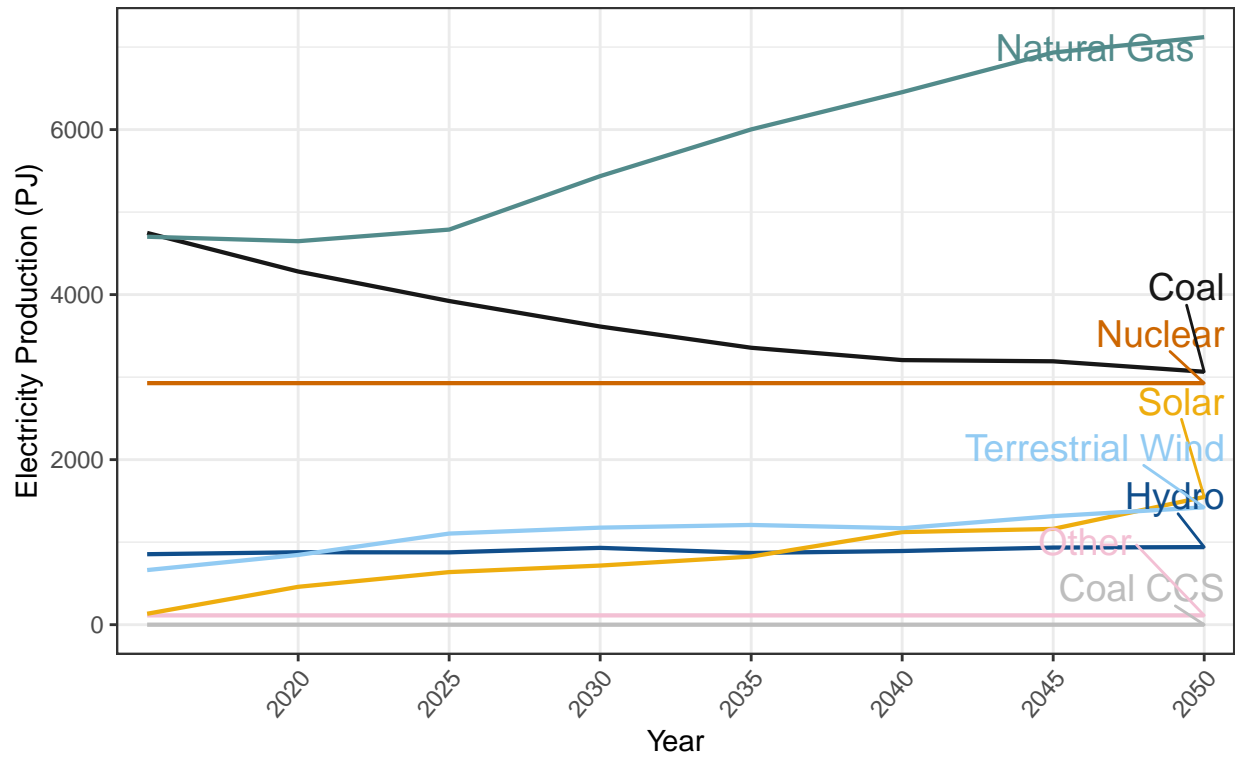


4 Grid Mix

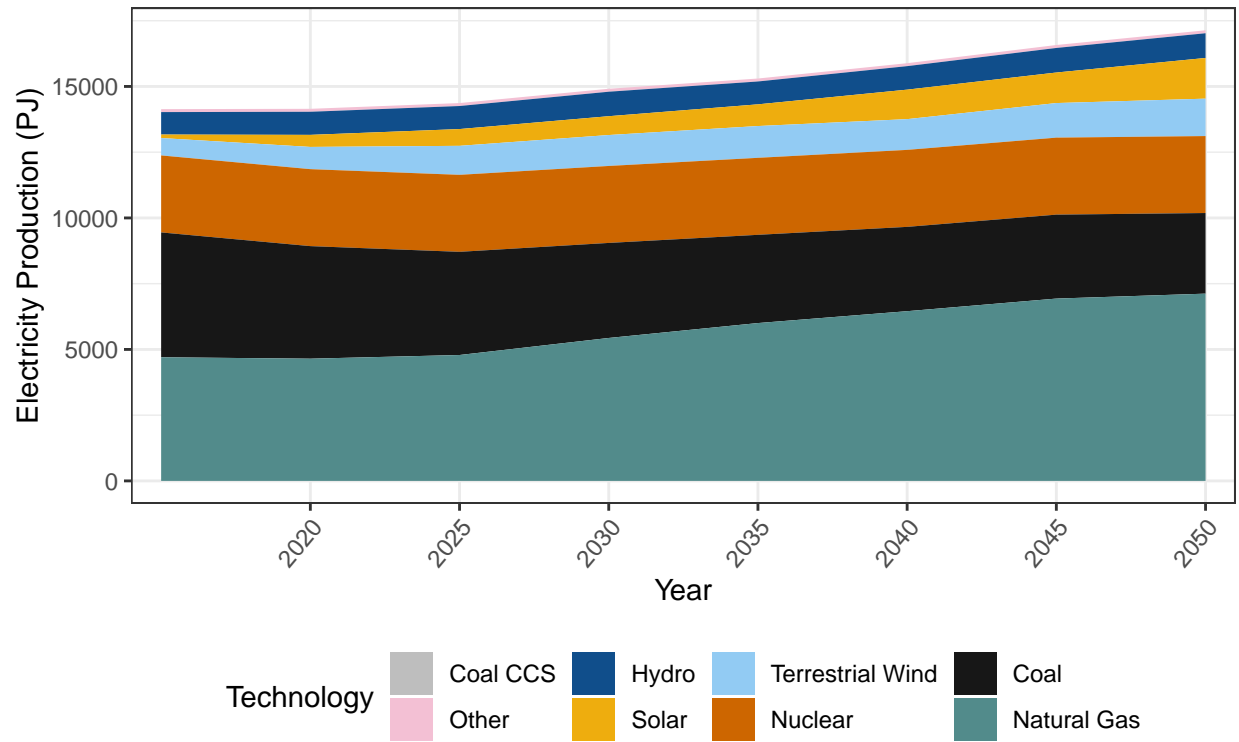
4.1 Baseline Production

Grid mix without any offshore wind cost reduction or emissions cap.

Electricity Production by Technology:
BAU & 20% Cost Reduction



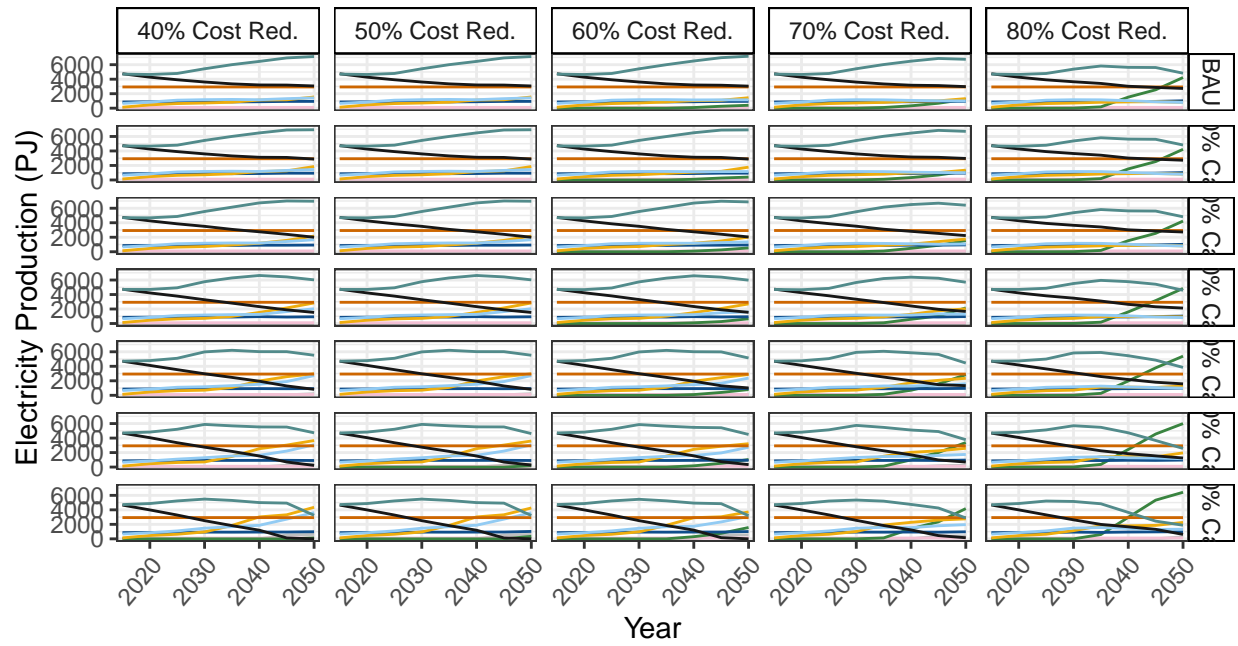
Electricity Production by Technology:
BAU & 20% Cost Reduction



4.2 All Scenarios

Complete Set

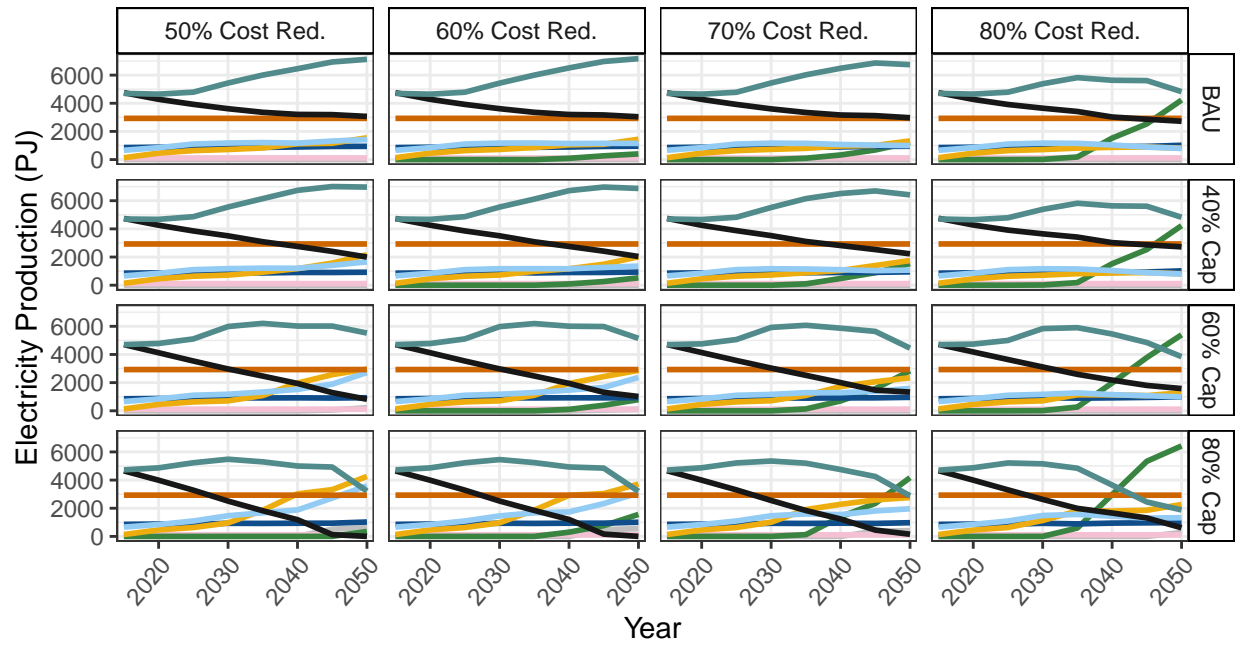
Electricity Production by Technology



Technology Coal CCS Offshore Wind Solar Nuclear Natural Gas
 Other Hydro Terrestrial Wind Coal

Parsed Set

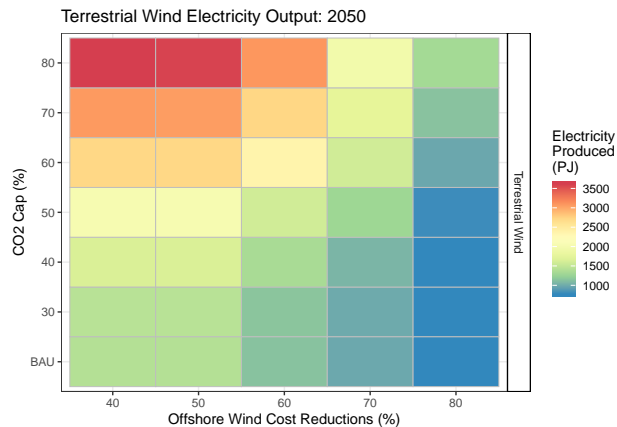
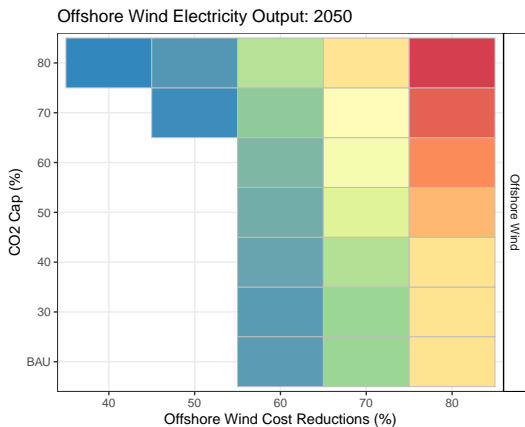
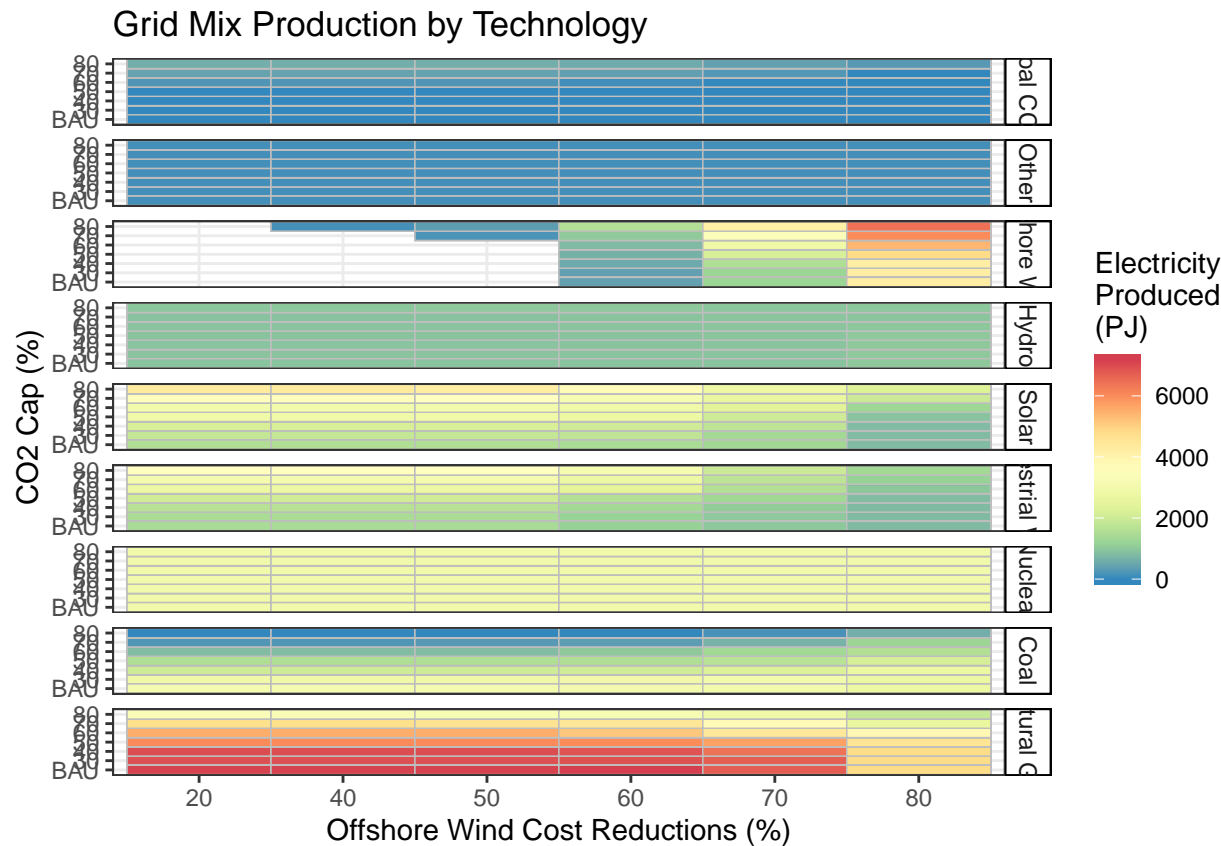
Electricity Production by Technology

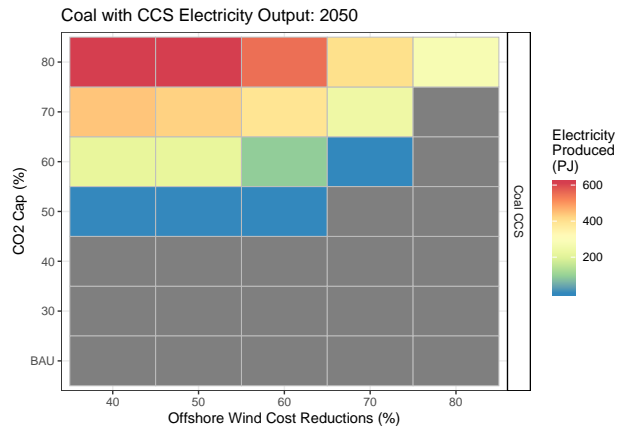
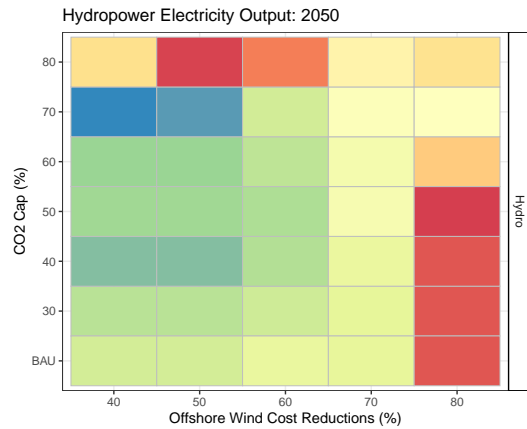
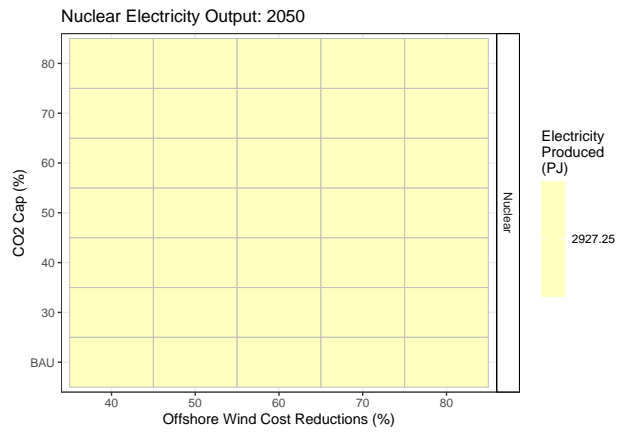
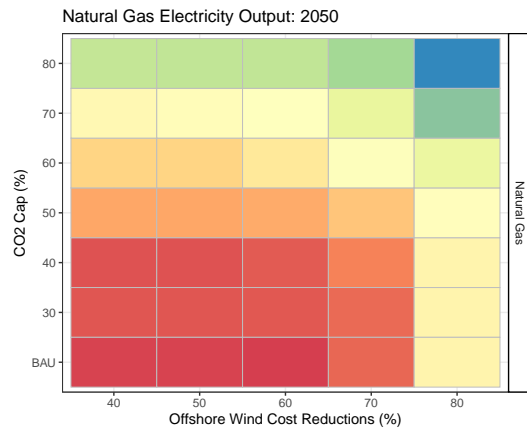
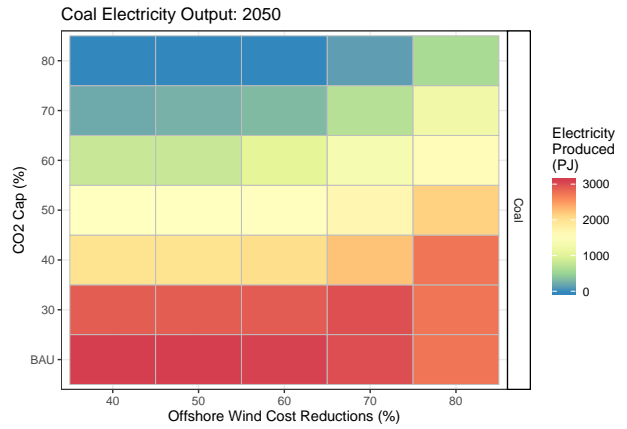
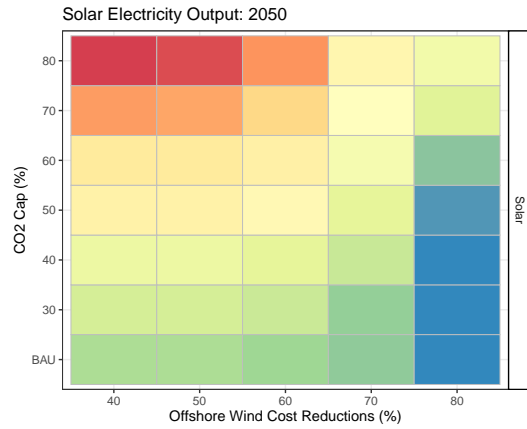


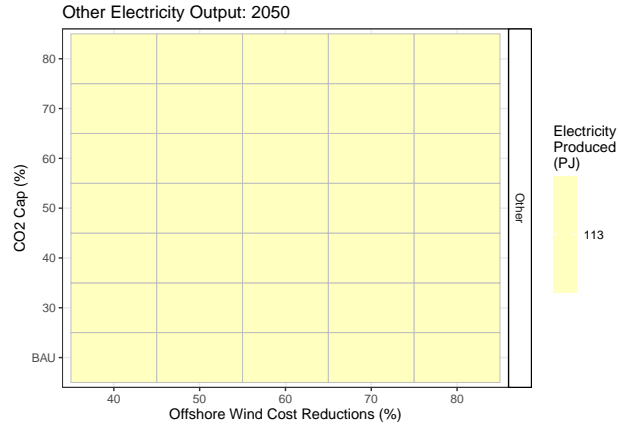
Technology

- Coal CCS
- Offshore Wind
- Solar
- Nuclear
- Natural Gas
- Other
- Hydro
- Terrestrial Wind
- Coal

4.3 Heatmaps







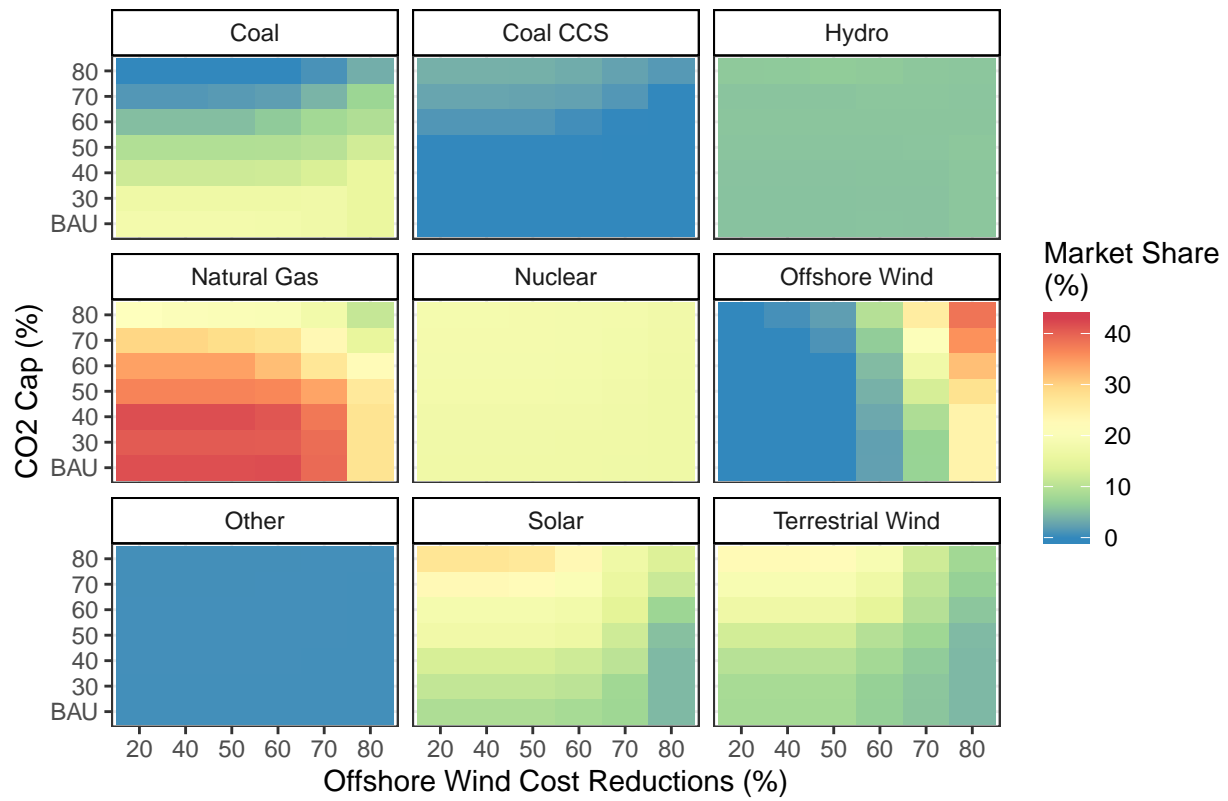
4.4 Market Share

2050 Percent Market Share by Technology

Technology	CO2 Cap (%)	Cost Reduction (%)					
		20	40	50	60	70	80
Coal	BAU	17.9	17.9	17.9	17.7	17.2	15.6
	30	16.9	16.9	16.9	16.9	17.2	15.6
	40	11.9	11.9	11.9	12.1	13.1	15.6
	50	9.3	9.3	9.3	9.4	9.9	12.3
	60	5.1	5.1	5.1	6.2	8.0	9.2
	70	1.4	1.4	1.7	2.1	4.2	7.4
	80	0.0	0.0	0.0	0.0	0.9	3.6
Coal CCS	BAU	0.0	0.0	0.0	0.0	0.0	0.0
	30	0.0	0.0	0.0	0.0	0.0	0.0
	40	0.0	0.0	0.0	0.0	0.0	0.0
	50	0.0	0.0	0.0	0.0	0.0	0.0
	60	1.3	1.3	1.3	0.6	0.0	0.0
	70	2.8	2.8	2.6	2.4	1.5	0.0
	80	3.8	3.8	3.8	3.4	2.5	1.6
Hydro	BAU	5.5	5.5	5.5	5.5	5.5	5.8
	30	5.5	5.5	5.5	5.5	5.5	5.8
	40	5.5	5.5	5.5	5.5	5.6	5.8
	50	5.7	5.7	5.7	5.7	5.7	5.9
	60	5.7	5.7	5.7	5.8	5.8	5.8
	70	5.6	5.6	5.7	5.8	5.9	5.7
	80	6.1	6.2	6.3	6.2	5.9	5.8
Natural Gas	BAU	41.5	41.5	41.5	41.7	39.1	27.7
	30	40.5	40.5	40.5	40.4	38.9	27.7
	40	41.6	41.6	41.6	41.0	37.8	27.7
	50	36.7	36.7	36.7	36.4	33.9	26.4
	60	34.1	34.1	34.1	31.6	26.9	22.5
	70	29.4	29.4	28.7	27.8	23.0	15.2
	80	21.1	20.3	20.0	19.8	17.6	11.2
Other	BAU	17.1	17.1	17.1	17.0	17.0	16.8
	30	17.1	17.1	17.1	17.1	17.0	16.8
	40	17.5	17.5	17.5	17.4	17.2	16.8

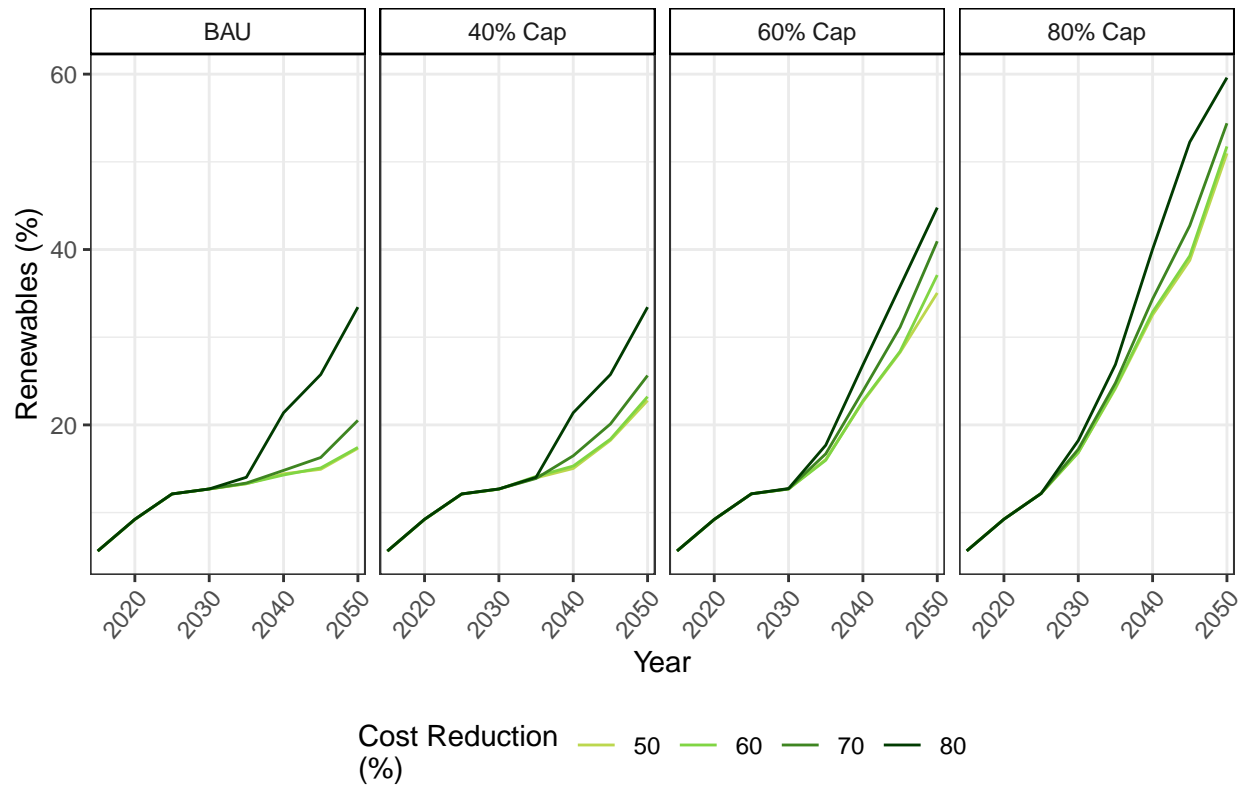
Nuclear	50	17.9	17.9	17.9	17.8	17.4	16.9
	60	18.1	18.1	18.1	18.0	17.7	17.1
	70	18.2	18.2	18.2	18.1	17.8	17.3
	80	18.3	18.3	18.2	18.1	17.9	17.4
Offshore Wind	BAU	0.0	0.0	0.0	2.3	7.1	24.2
	30	0.0	0.0	0.0	2.3	7.1	24.2
	40	0.0	0.0	0.0	3.1	9.0	24.2
	50	0.0	0.0	0.0	4.0	12.8	27.9
	60	0.0	0.0	0.0	4.8	17.1	31.5
	70	0.0	0.0	1.1	6.4	20.6	35.4
	80	0.0	0.8	2.1	9.7	25.5	38.2
Other	BAU	0.7	0.7	0.7	0.6	0.6	0.6
	30	0.7	0.7	0.7	0.7	0.6	0.6
	40	0.7	0.7	0.7	0.7	0.7	0.6
	50	0.7	0.7	0.7	0.7	0.7	0.6
	60	0.7	0.7	0.7	0.7	0.7	0.7
	70	0.7	0.7	0.7	0.7	0.7	0.7
	80	0.7	0.7	0.7	0.7	0.7	0.7
Solar	BAU	9.0	9.0	9.0	8.4	7.7	4.7
	30	10.8	10.8	10.8	10.3	7.8	4.7
	40	12.9	12.9	12.9	12.0	10.3	4.7
	50	17.3	17.3	17.3	16.5	12.0	5.3
	60	18.3	18.3	18.3	17.6	14.2	7.5
	70	22.8	22.8	22.3	19.9	15.8	11.6
	80	27.3	27.3	26.5	23.0	16.9	13.5
Terrestrial Wind	BAU	8.3	8.3	8.3	6.7	5.8	4.5
	30	8.5	8.5	8.5	6.8	5.8	4.5
	40	9.9	9.9	9.9	8.1	6.3	4.5
	50	12.4	12.4	12.4	9.7	7.7	4.7
	60	16.8	16.8	16.8	14.6	9.6	5.8
	70	19.1	19.1	19.0	16.9	10.6	6.8
	80	22.6	22.6	22.3	19.1	12.0	7.9

Technology Market Share: 2050



4.5 Renewable Contributions

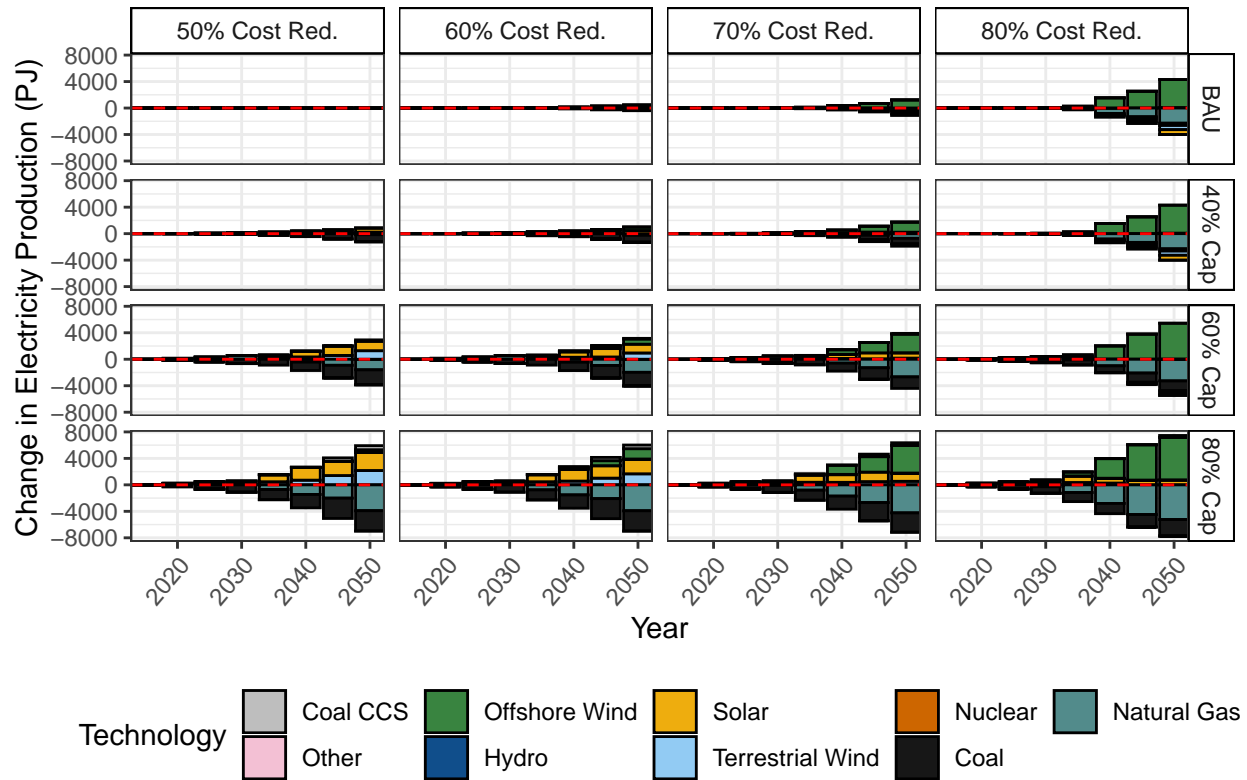
Renewable Technology Contribution to Electricity Production



4.6 Retirements and Additions

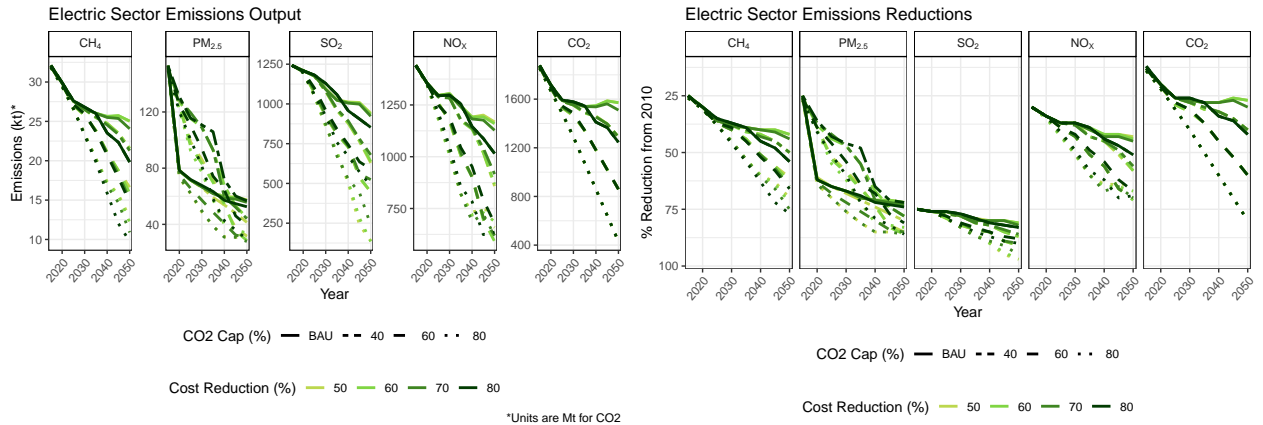
Summary Graph

Changes in Grid Mix over Baseline



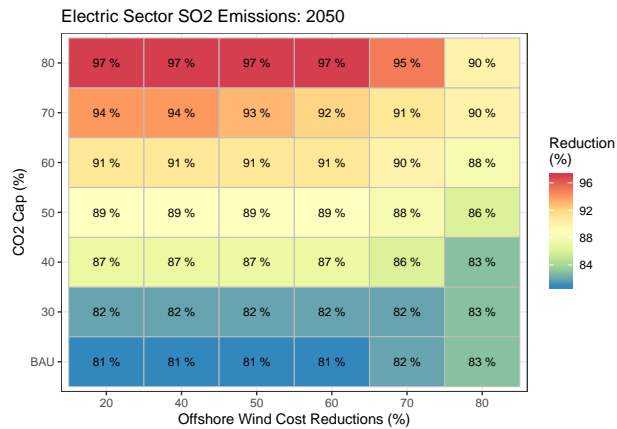
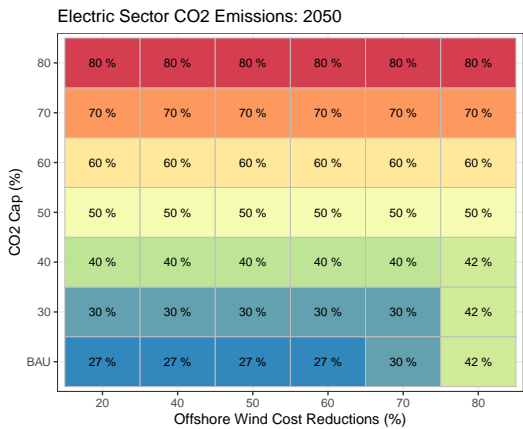
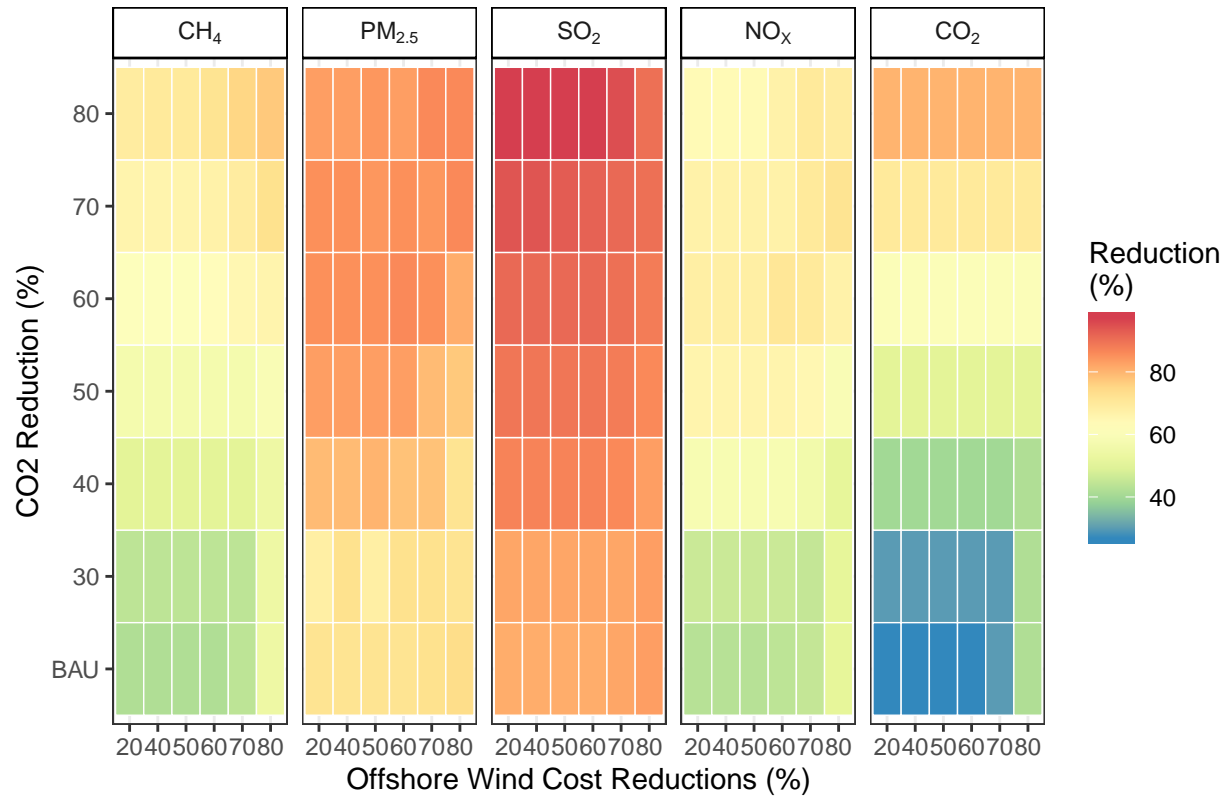
5 Emissions

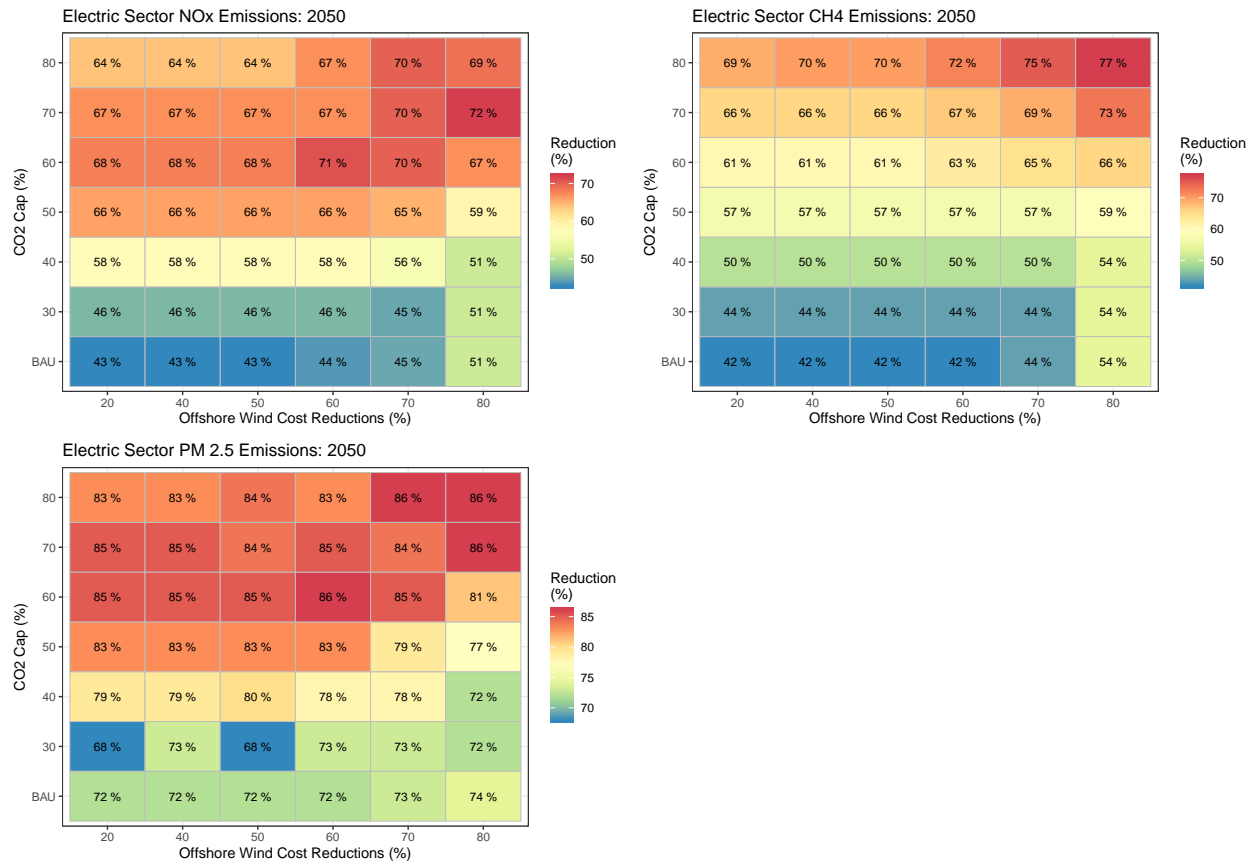
5.1 Emissions by Scenario and Commodity



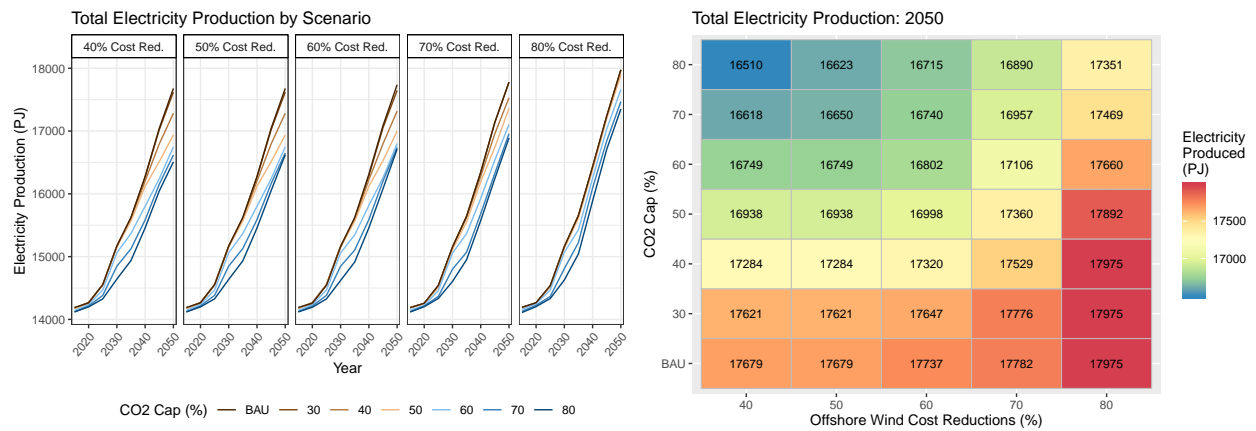
5.2 Emissions by Commodity - Percent Reduction

Electric Sector Emissions Reduction: 2050



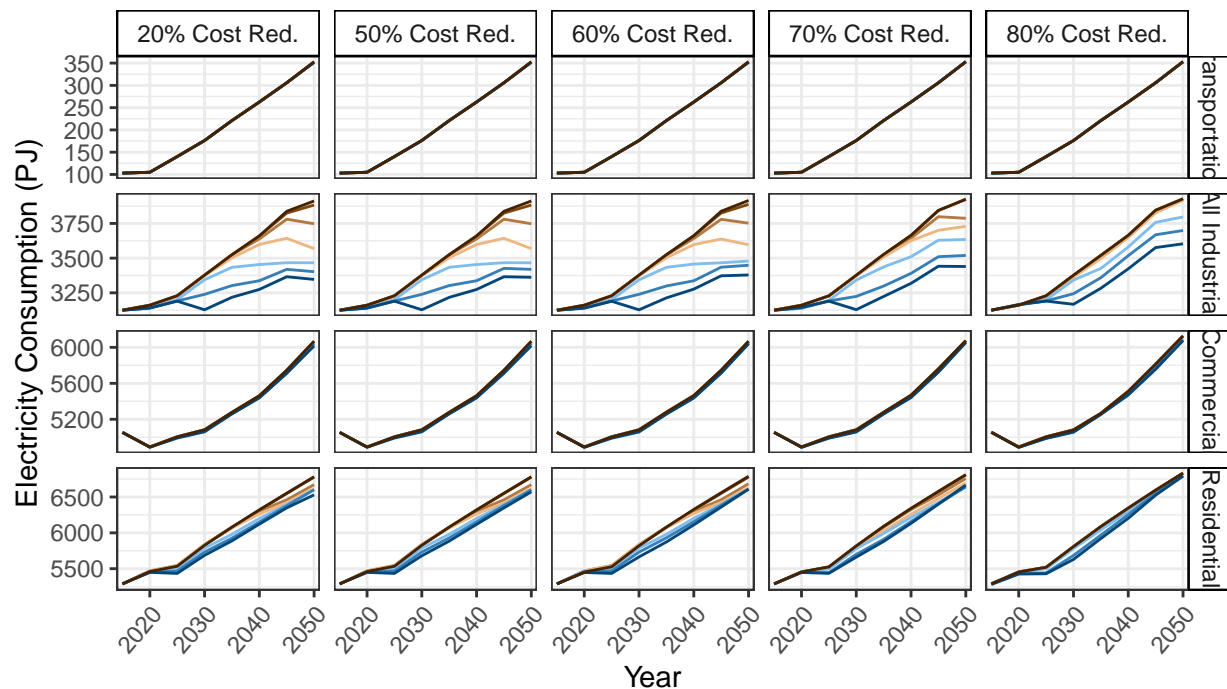


6 Total Electricity Production



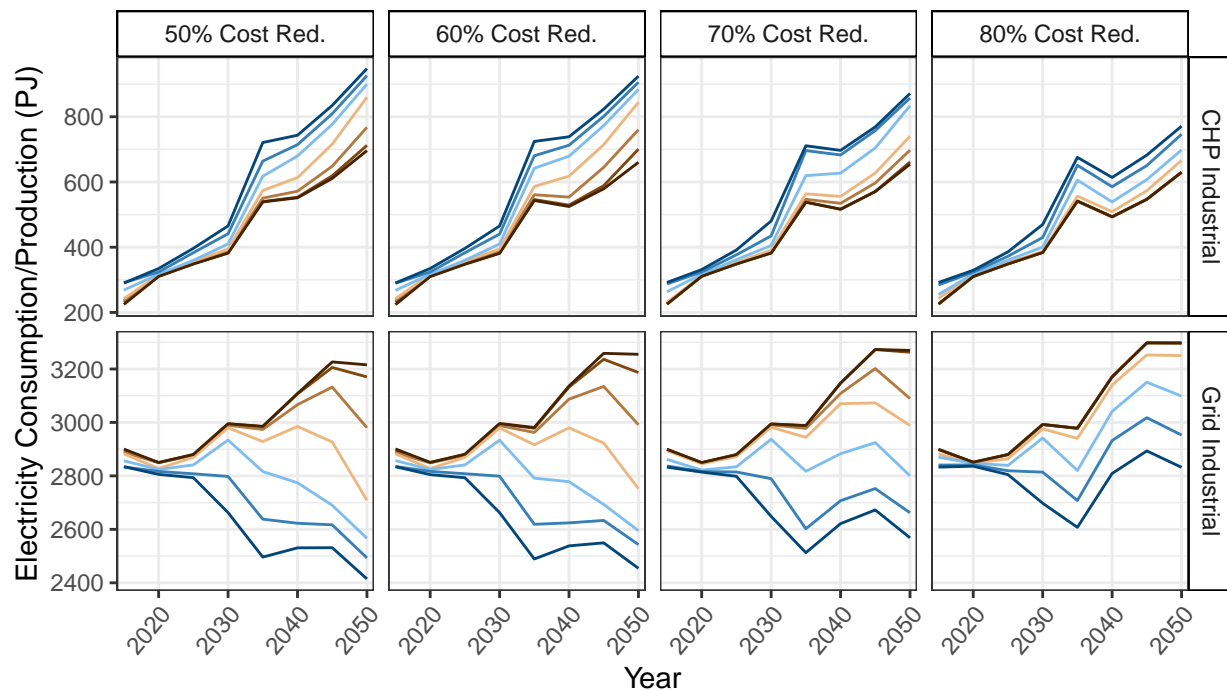
7 End Use ELC

Sector Electricity Consumption by Scenario



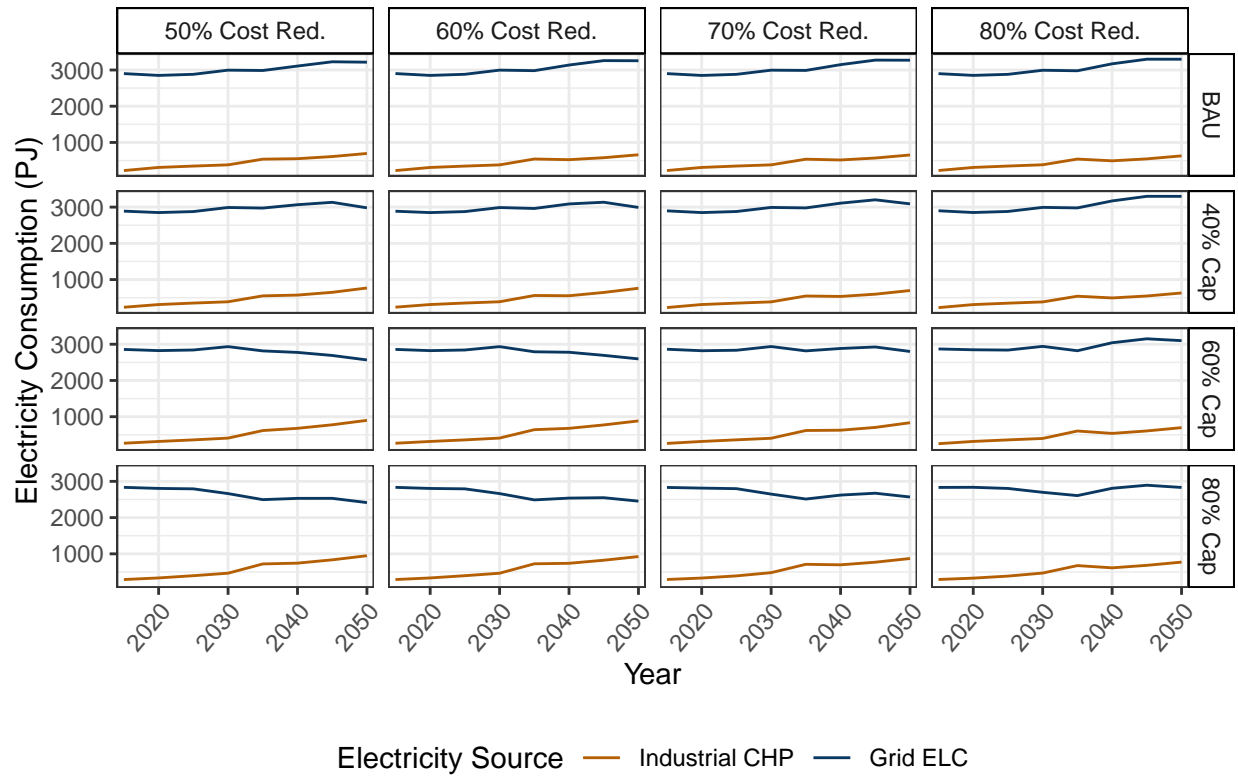
CO2 Cap (%) — BAU — 30 — 40 — 50 — 60 — 70 — 80

Sector Electricity Consumption/Production by Scenario

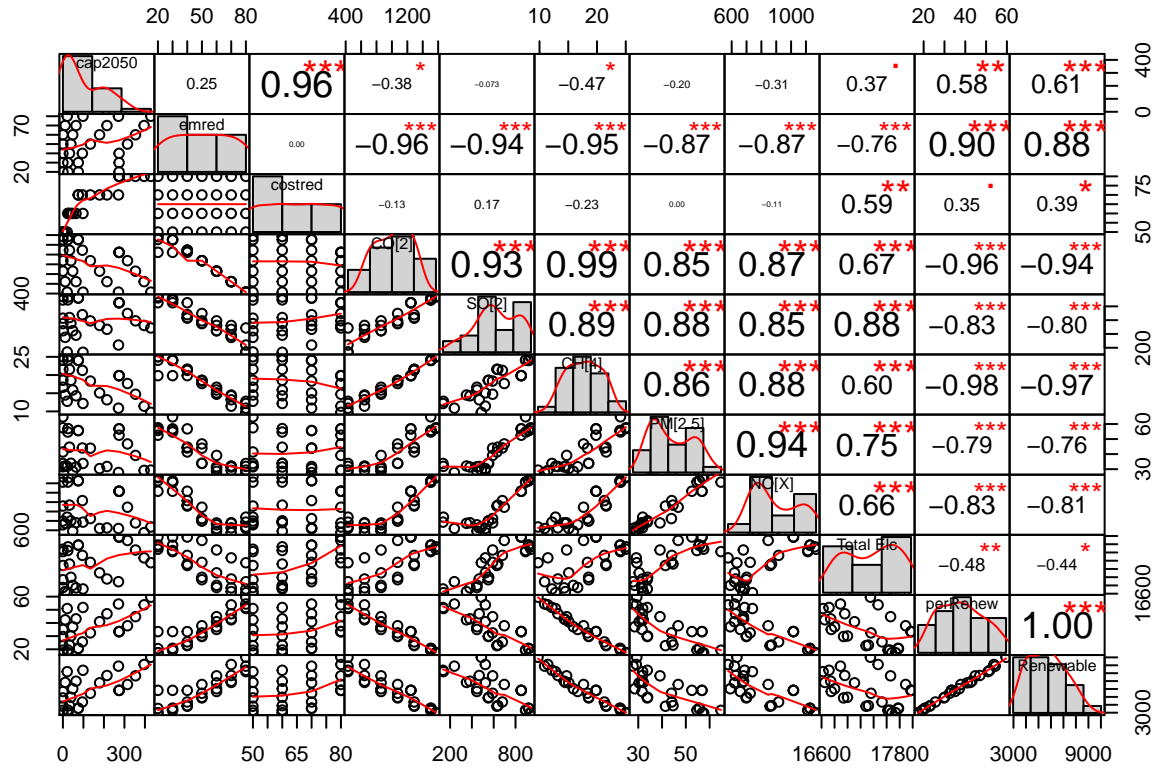


CO2 Cap (%) — BAU — 30 — 40 — 50 — 60 — 70 — 80

Industrial Electricity Consumption by Scenario



8 Correlations



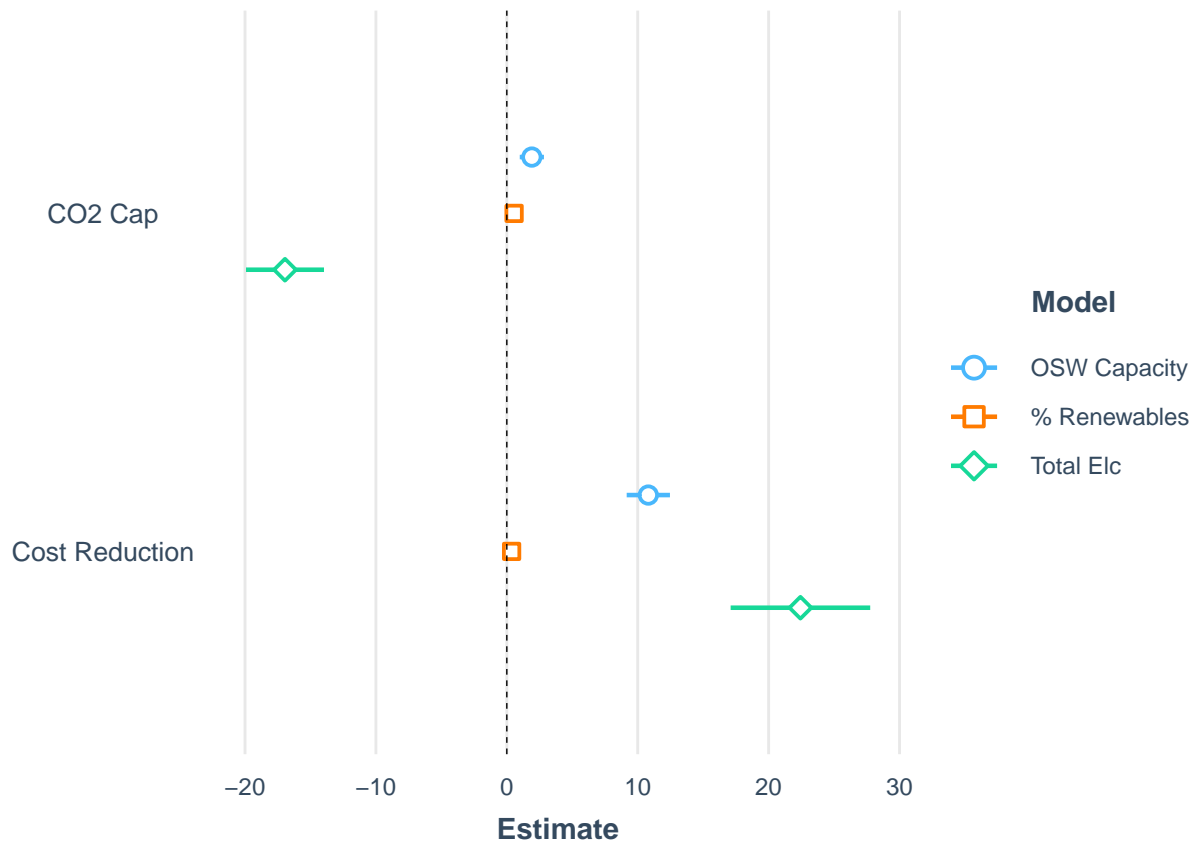
9 Regressions

9.1 Full set of models

OSW Capacity, % Renewables, and Total Elc Production Regressions

	OSW Capacity	% Renewables	Total Elc
CO2 Cap	1.91 *** (0.45)	0.56 *** (0.03)	-16.94 *** (1.45)
Cost Reduction	10.81 *** (0.80)	0.37 *** (0.06)	22.43 *** (2.59)
N	28	28	28
R2	0.89	0.93	0.89

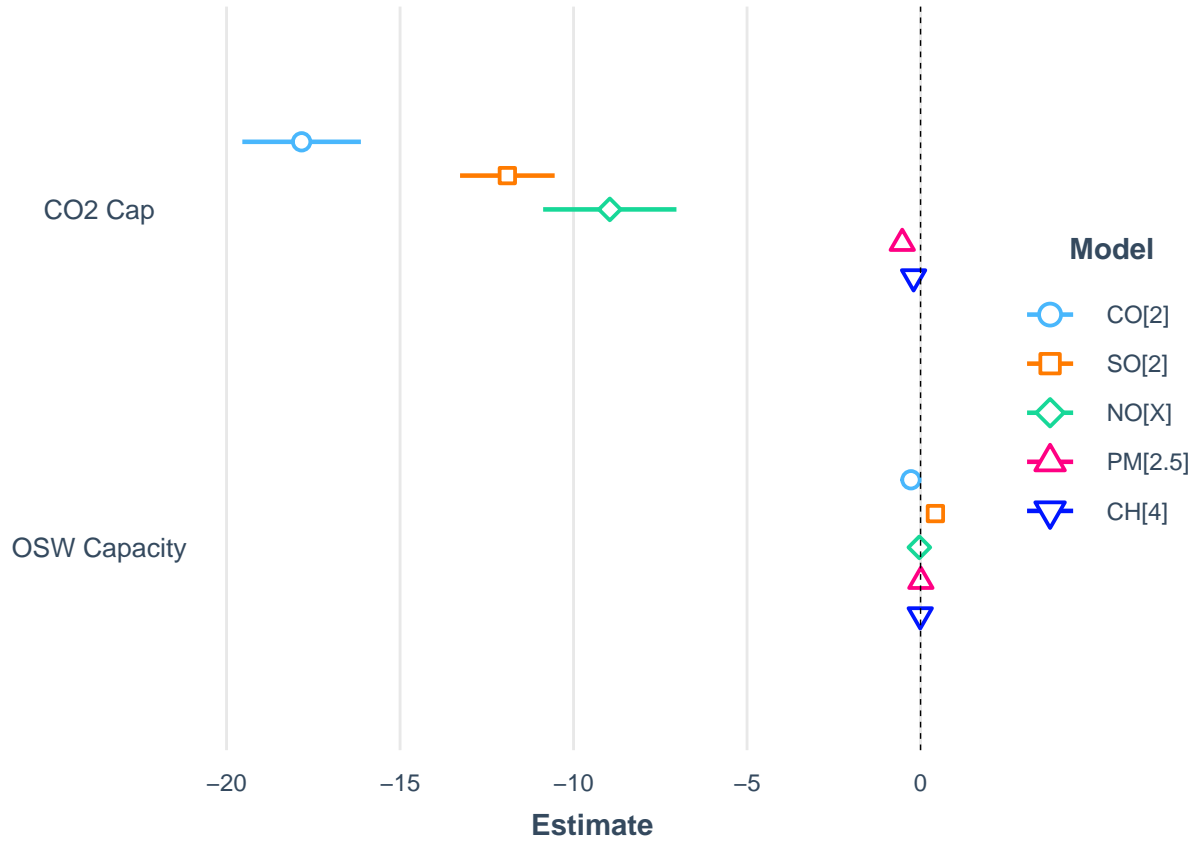
*** p < 0.001; ** p < 0.01; * p < 0.05.



Emissions Regressions

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
CO2 Cap	-17.84 *** (0.83)	-11.91 *** (0.66)	-8.96 *** (0.93)	-0.20 *** (0.01)	-0.53 *** (0.05)
OSW Capacity	-0.28 * (0.12)	0.43 *** (0.10)	-0.03 (0.14)	-0.01 *** (0.00)	0.01 (0.01)
N	28	28	28	28	28
R2	0.96	0.93	0.80	0.96	0.80

*** p < 0.001; ** p < 0.01; * p < 0.05.

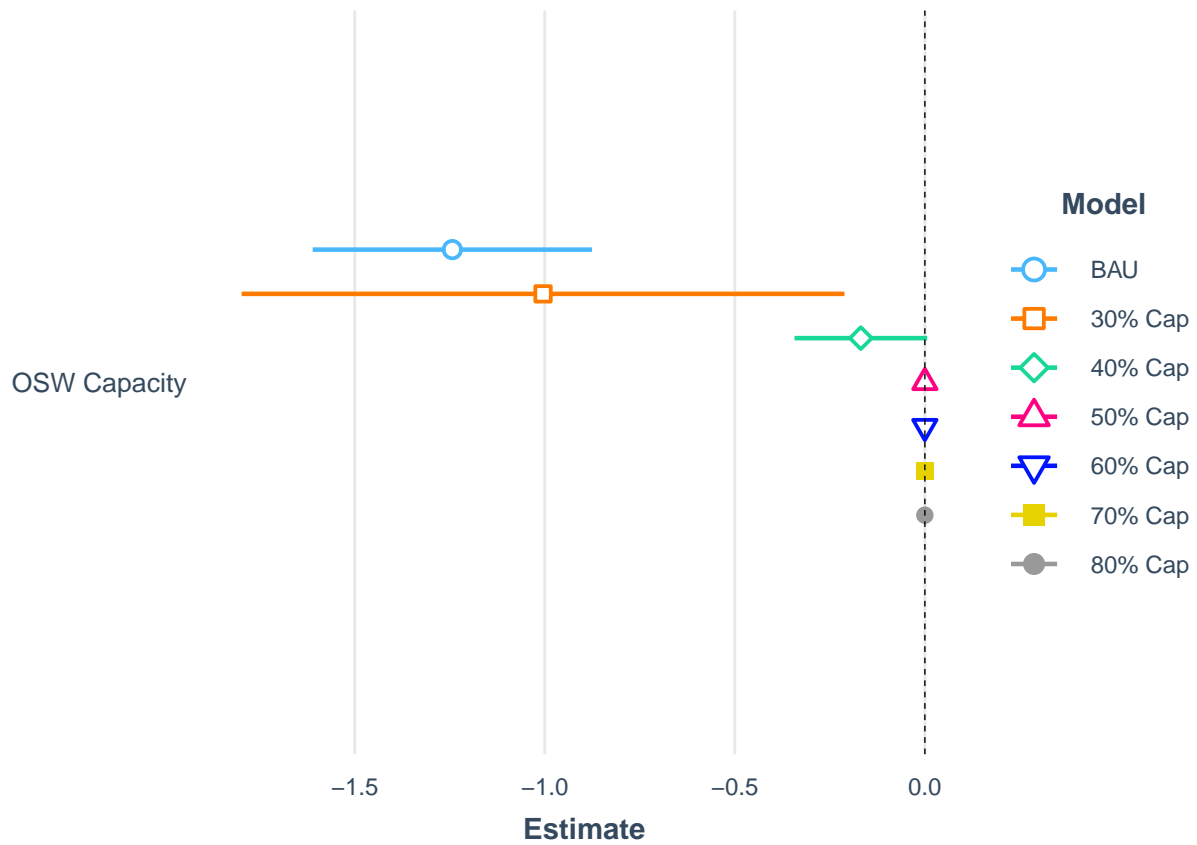


9.2 Emission-specific regressions by CO2 cap scenario

CO2

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-1.24 ** (0.09)	-1.00 * (0.18)	-0.17 (0.04)	0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)
N	4	4	4	4	4	4	4
R2	0.99	0.94	0.90	0.84	0.20	0.00	0.83

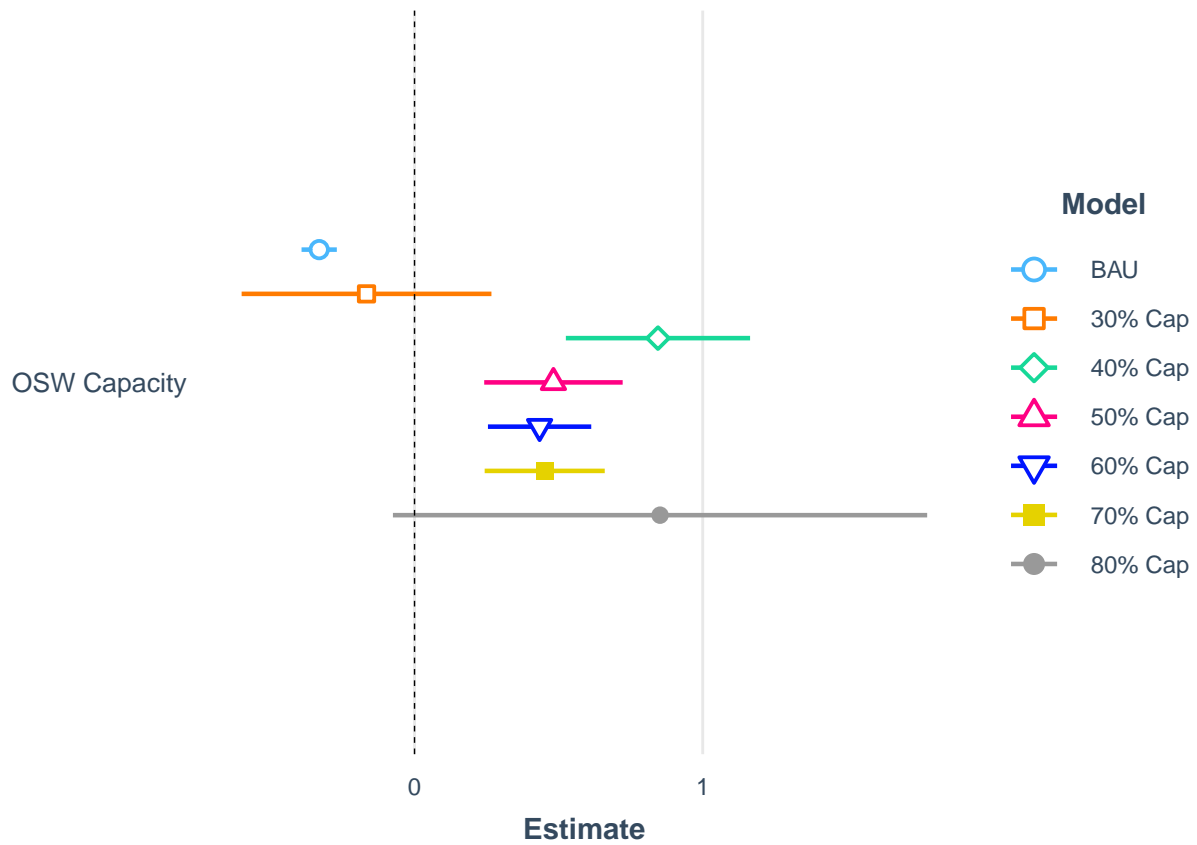
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



SO2

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.33 ** (0.01)	-0.17 (0.10)	0.84 ** (0.07)	0.48 * (0.06)	0.43 ** (0.04)	0.45 * (0.05)	0.85 (0.22)
N	4	4	4	4	4	4	4
R2	1.00	0.58	0.98	0.97	0.98	0.98	0.89

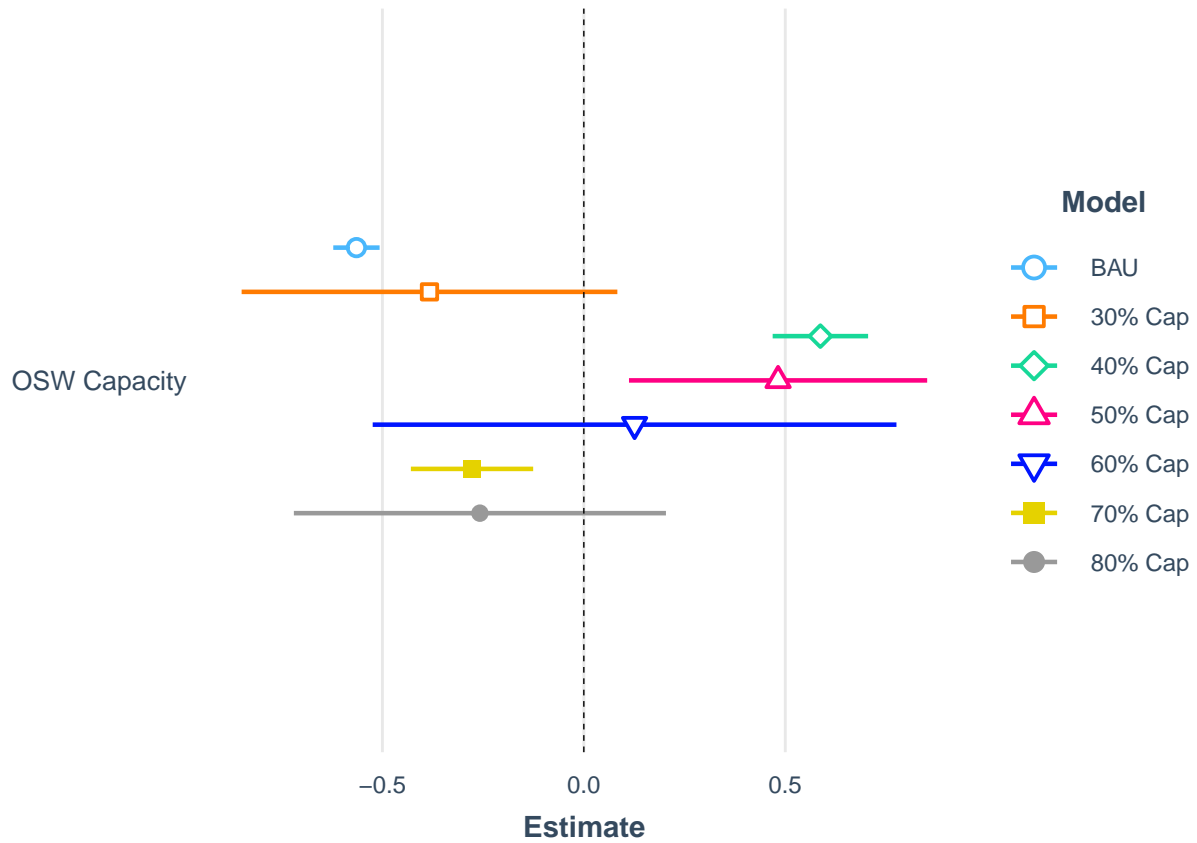
*** p < 0.001; ** p < 0.01; * p < 0.05.



NOx

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.56 *** (0.01)	-0.38 (0.11)	0.59 ** (0.03)	0.48 * (0.09)	0.13 (0.15)	-0.28 * (0.04)	-0.28 (0.11)
N	4	4	4	4	4	4	4
R2	1.00	0.86	1.00	0.94	0.26	0.97	0.74

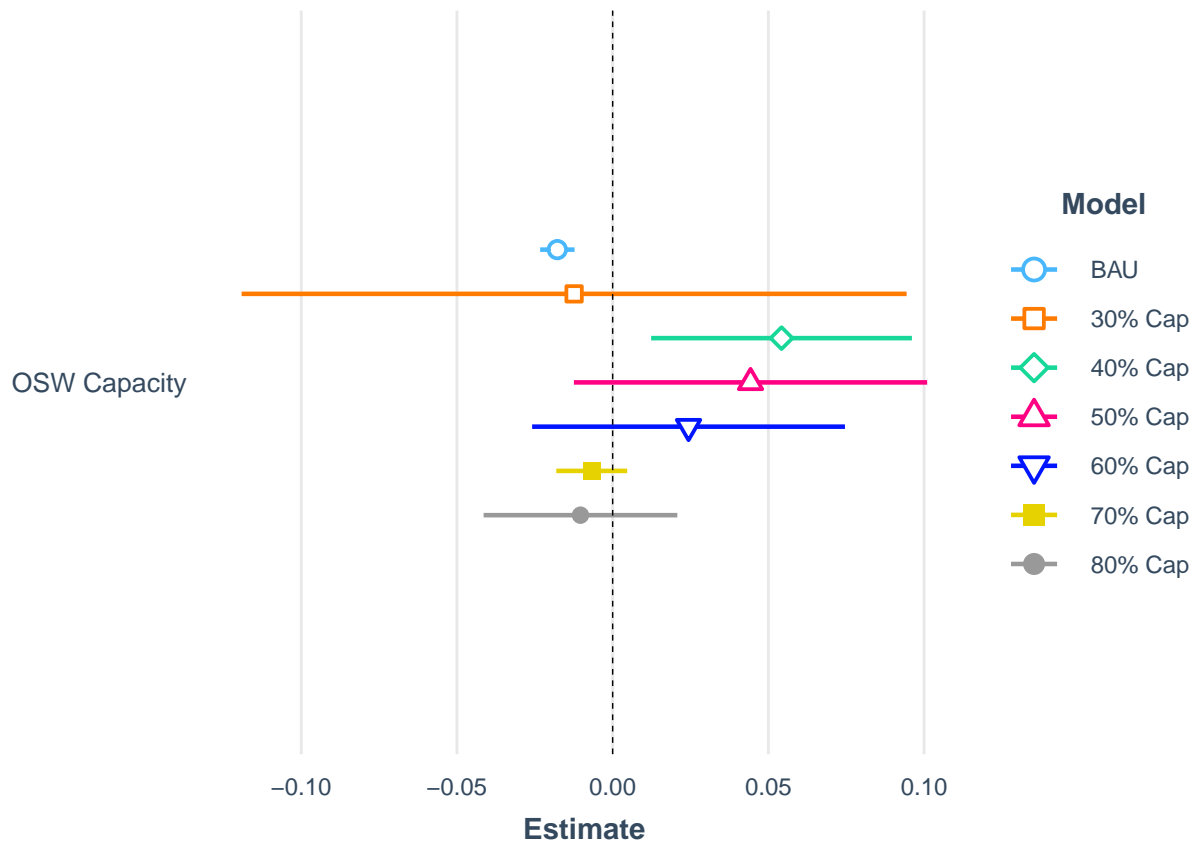
*** p < 0.001; ** p < 0.01; * p < 0.05.



PM 2.5

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.02 ** (0.00)	-0.01 (0.02)	0.05 * (0.01)	0.04 (0.01)	0.02 (0.01)	-0.01 (0.00)	-0.01 (0.01)
N	4	4	4	4	4	4	4
R2	0.99	0.11	0.94	0.85	0.69	0.76	0.51

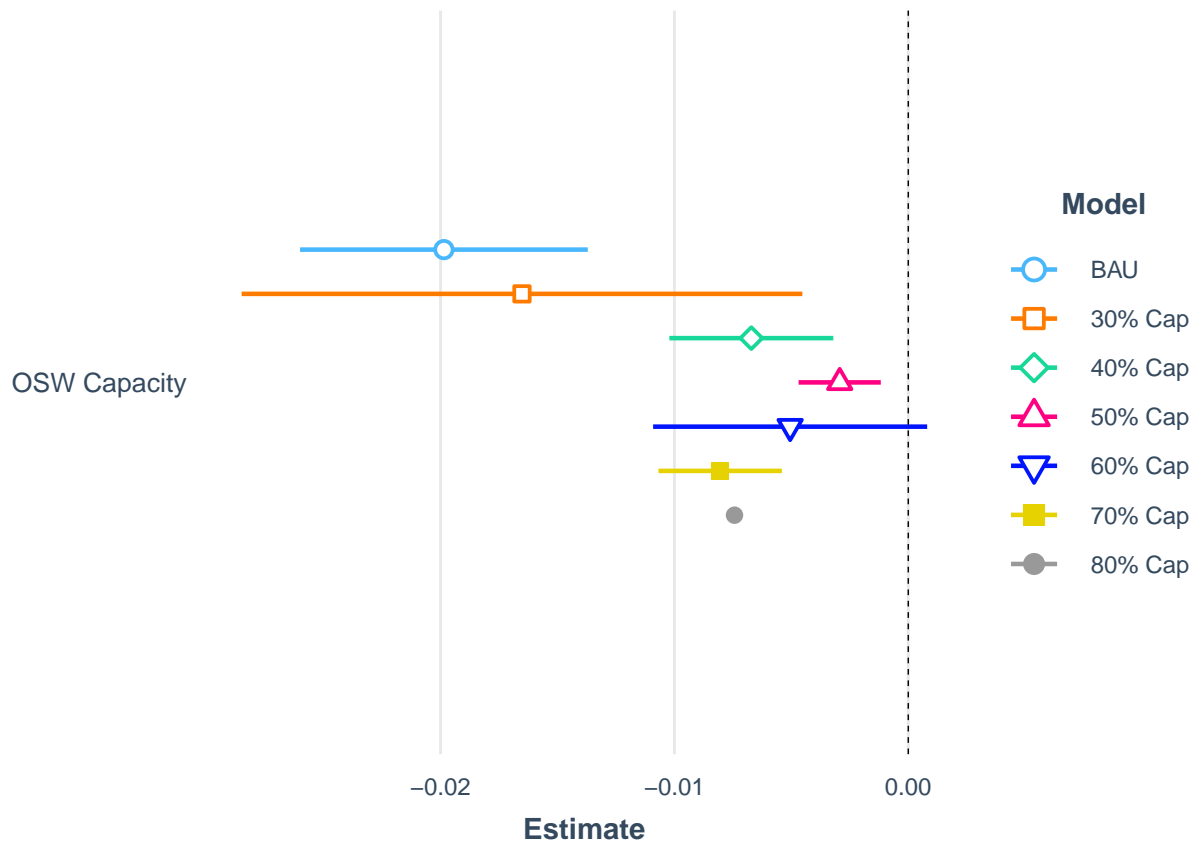
*** p < 0.001; ** p < 0.01; * p < 0.05.



CH4

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.02 ** (0.00)	-0.02 * (0.00)	-0.01 * (0.00)	-0.00 * (0.00)	-0.01 (0.00)	-0.01 ** (0.00)	-0.01 *** (0.00)
N	4	4	4	4	4	4	4
R2	0.99	0.95	0.97	0.96	0.87	0.99	1.00

*** p < 0.001; ** p < 0.01; * p < 0.05.



9.3 CO2 cap regressions by emissions type

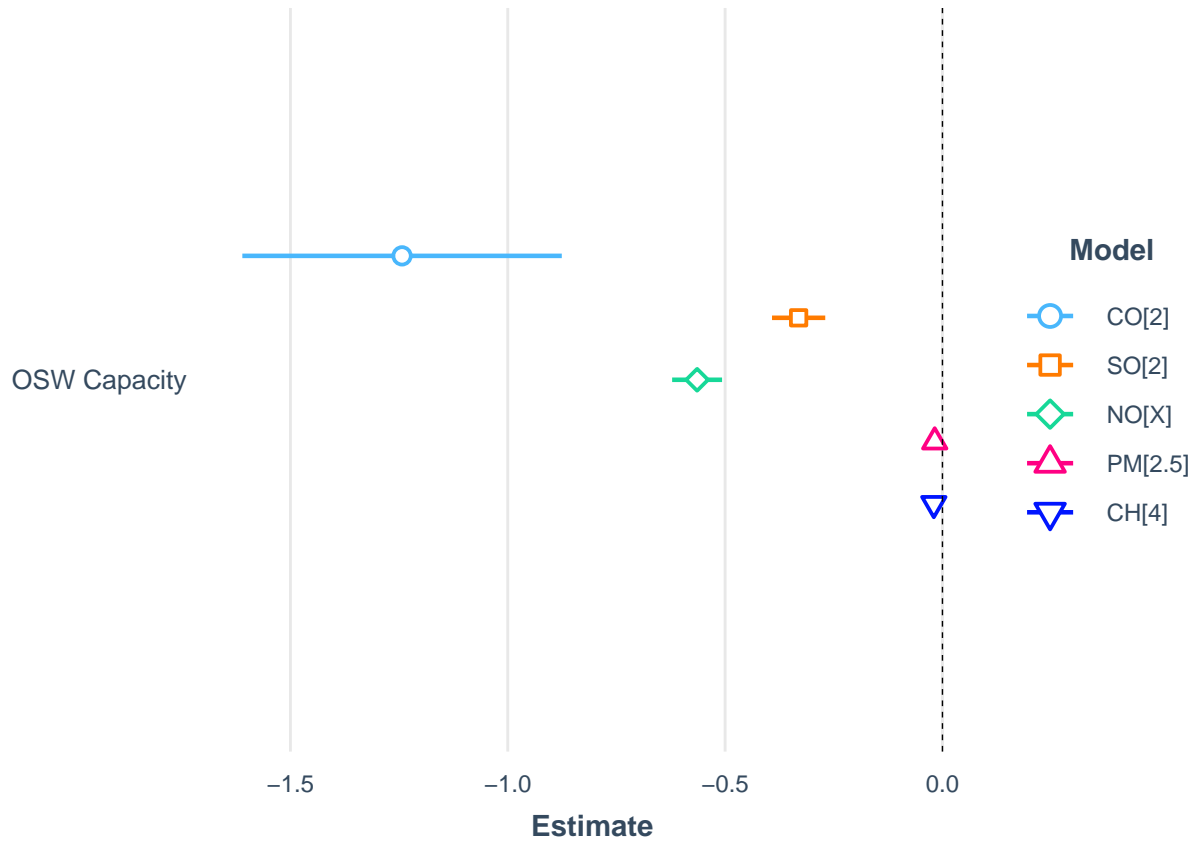
CO2		BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap
CO2.00	OSW Capacity	-1.24 **	-1.00 *	-0.17	0.00	-0.00	-0.00
CO2.00		(0.09)	(0.18)	(0.04)	(0.00)	(0.00)	(0.00)
CO2.00	R2	0.99	0.94	0.90	0.84	0.20	0.00
SO2.00	OSW Capacity	-0.33 **	-0.17	0.84 **	0.48 *	0.43 **	0.45 *
SO2.00		(0.01)	(0.10)	(0.07)	(0.06)	(0.04)	(0.05)
SO2.00	R2	1.00	0.58	0.98	0.97	0.98	0.98
NOx	OSW Capacity	-0.56 ***	-0.38	0.59 **	0.48 *	0.13	-0.28 *
NOx		(0.01)	(0.11)	(0.03)	(0.09)	(0.15)	(0.04)
NOx	R2	1.00	0.86	1.00	0.94	0.26	0.97
PM 2.50	OSW Capacity	-0.02 **	-0.01	0.05 *	0.04	0.02	-0.01
PM 2.50		(0.00)	(0.02)	(0.01)	(0.01)	(0.01)	(0.00)
PM 2.50	R2	0.99	0.11	0.94	0.85	0.69	0.76
CH4.00	OSW Capacity	-0.02 **	-0.02 *	-0.01 *	-0.00 *	-0.01	-0.01 *
CH4.00		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
CH4.00	R2	0.99	0.95	0.97	0.96	0.87	0.99

*** p < 0.001; ** p < 0.01; * p < 0.05.

BAU

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-1.24 ** (0.09)	-0.33 ** (0.01)	-0.56 *** (0.01)	-0.02 ** (0.00)	-0.02 ** (0.00)
N	4	4	4	4	4
R2	0.99	1.00	1.00	0.99	0.99

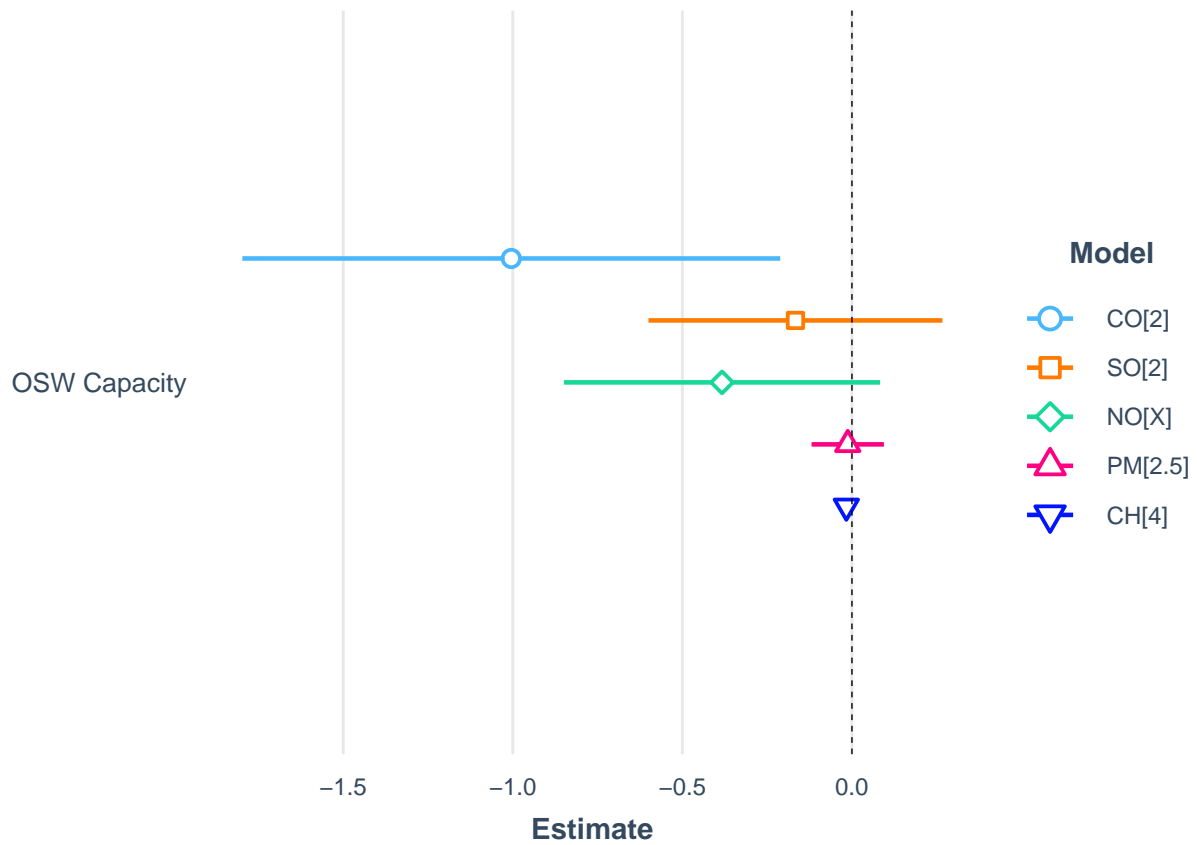
*** p < 0.001; ** p < 0.01; * p < 0.05.



30% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-1.00 * (0.18)	-0.17 (0.10)	-0.38 (0.11)	-0.01 (0.02)	-0.02 * (0.00)
N	4	4	4	4	4
R2	0.94	0.58	0.86	0.11	0.95

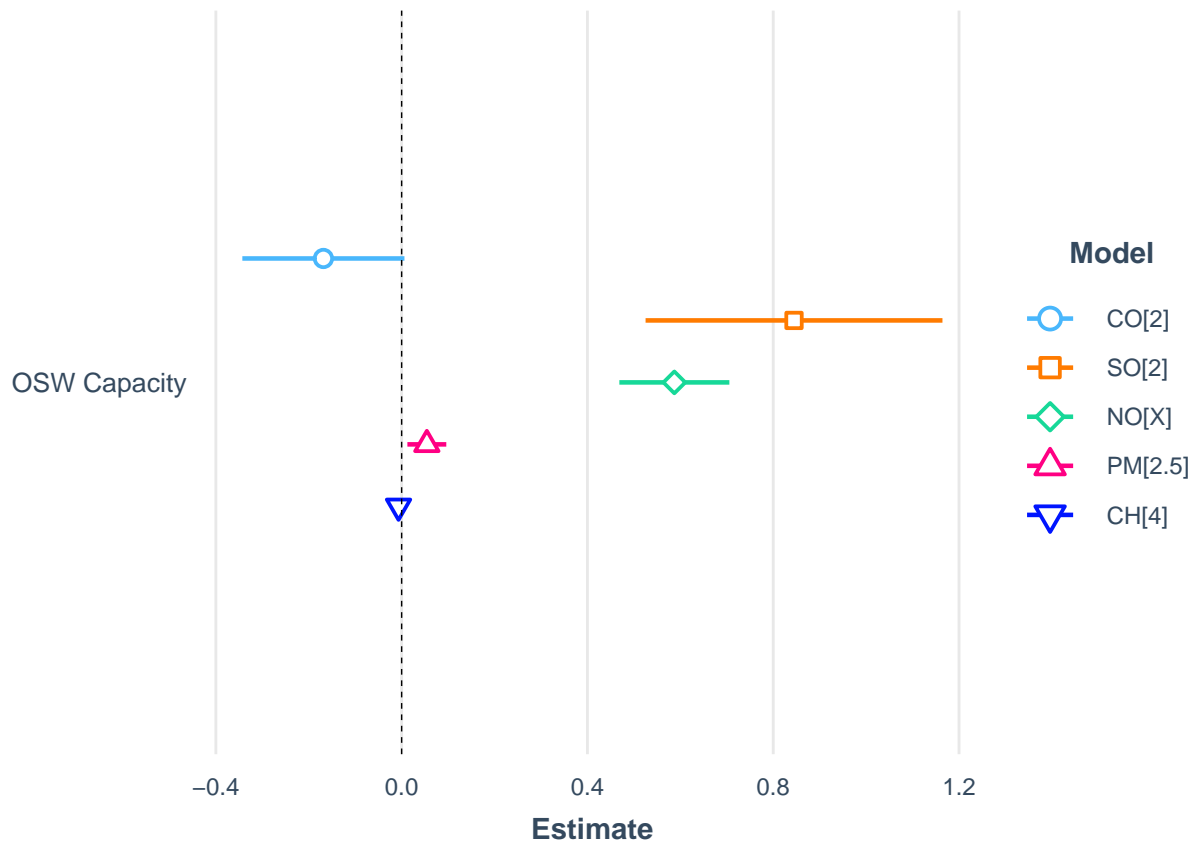
*** p < 0.001; ** p < 0.01; * p < 0.05.



40% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.17 (0.04)	0.84 ** (0.07)	0.59 ** (0.03)	0.05 * (0.01)	-0.01 * (0.00)
N	4	4	4	4	4
R2	0.90	0.98	1.00	0.94	0.97

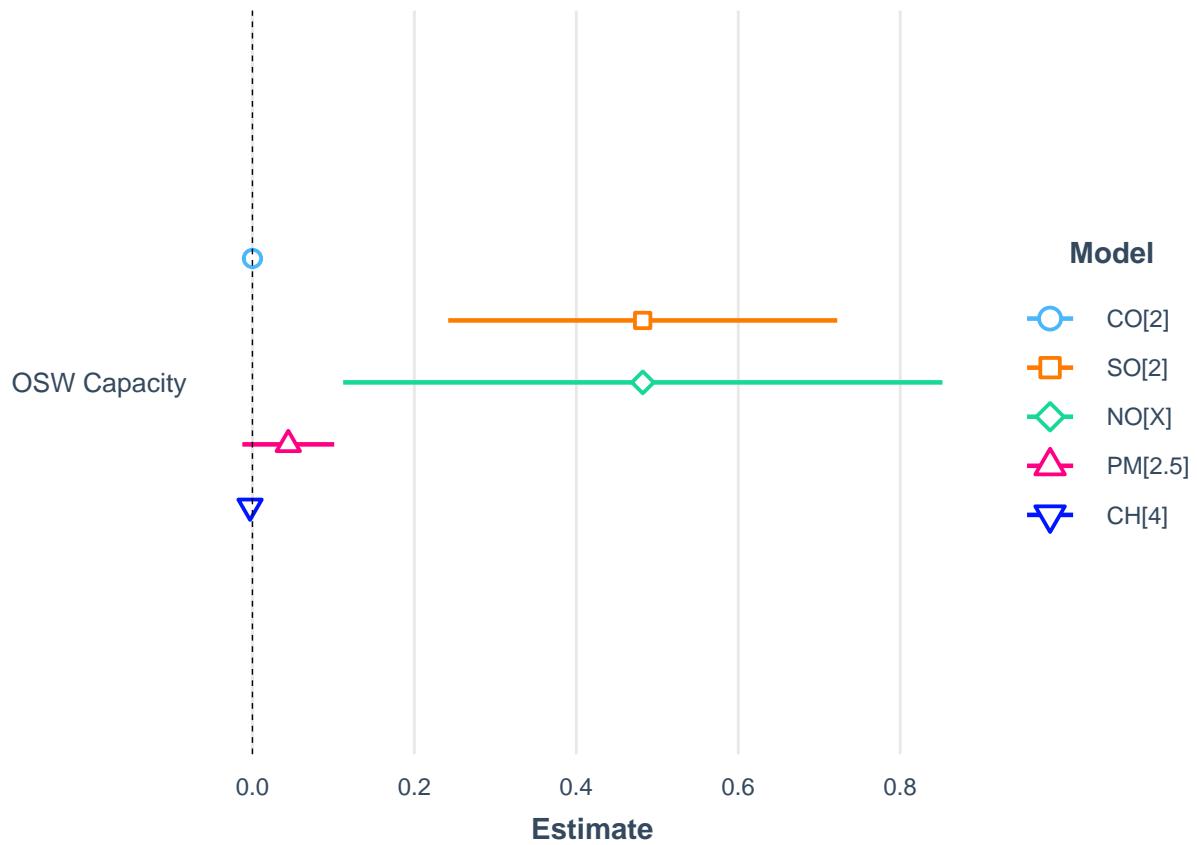
*** p < 0.001; ** p < 0.01; * p < 0.05.



50% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	0.00 (0.00)	0.48 * (0.06)	0.48 * (0.09)	0.04 (0.01)	-0.00 * (0.00)
N	4	4	4	4	4
R2	0.84	0.97	0.94	0.85	0.96

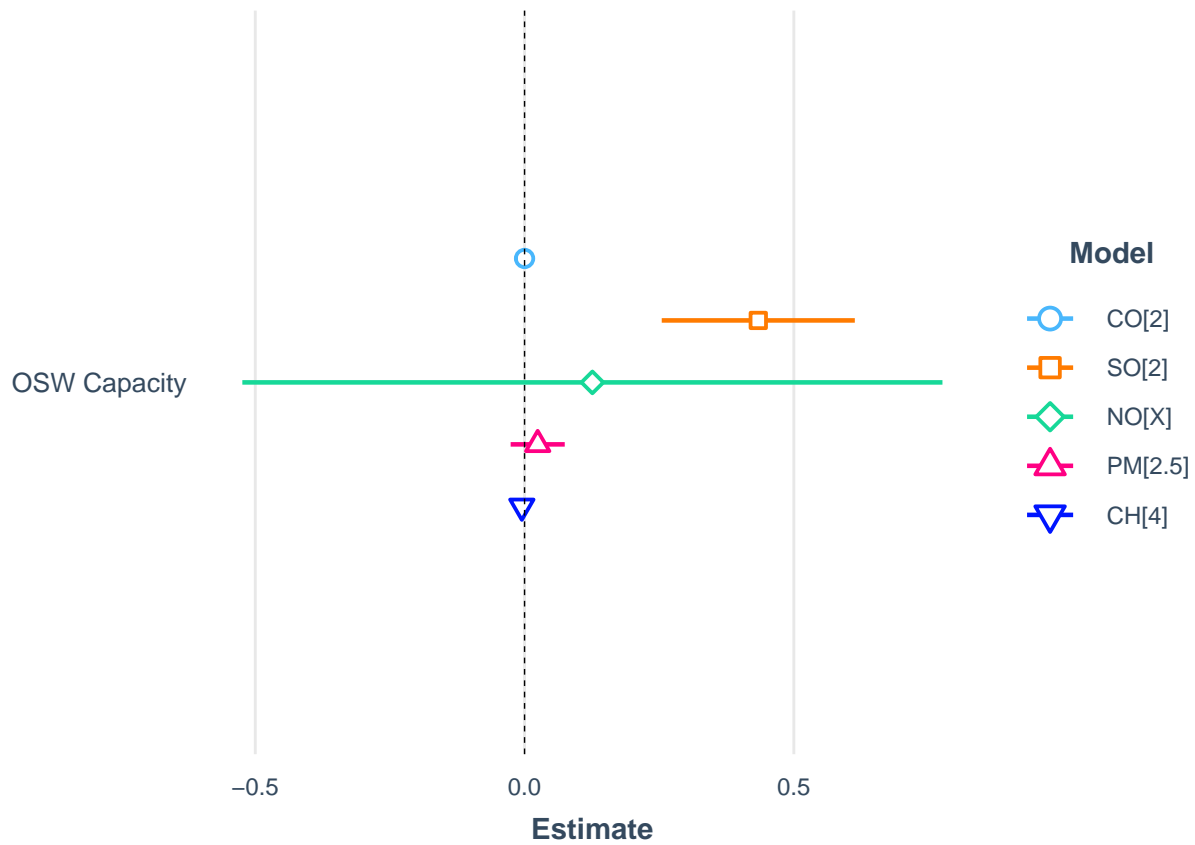
*** p < 0.001; ** p < 0.01; * p < 0.05.



60% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00 (0.00)	0.43 ** (0.04)	0.13 (0.15)	0.02 (0.01)	-0.01 (0.00)
N	4	4	4	4	4
R2	0.20	0.98	0.26	0.69	0.87

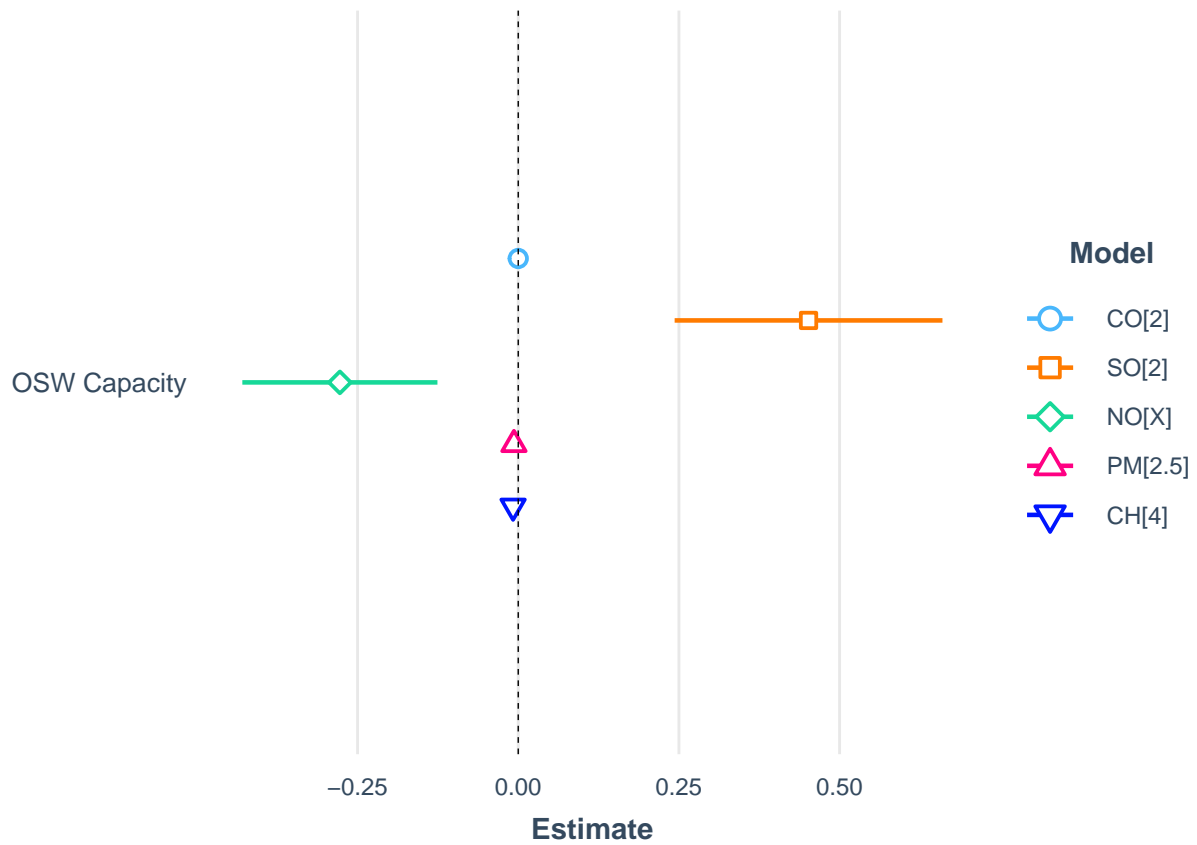
*** p < 0.001; ** p < 0.01; * p < 0.05.



70% CO₂ Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00 (0.00)	0.45 * (0.05)	-0.28 * (0.04)	-0.01 (0.00)	-0.01 ** (0.00)
N	4	4	4	4	4
R2	0.00	0.98	0.97	0.76	0.99

*** p < 0.001; ** p < 0.01; * p < 0.05.



80% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00 (0.00)	0.85 (0.22)	-0.26 (0.11)	-0.01 (0.01)	-0.01 *** (0.00)
N	4	4	4	4	4
R2	0.83	0.89	0.74	0.51	1.00

*** p < 0.001; ** p < 0.01; * p < 0.05.

